Real-Time Air Quality Monitoring Using Iot Sensors

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Abstract—**Urban air pollution poses severe health and environmental risk, yet traditional air quality monitoring systems are often expensive and limited in coverage. With the goal of offering a practical and affordable way to measure pollution levels in cities, this research investigates the application of IOT- enabled sensors for air quality monitoring. With the use of a hybrid sensor network that consists of both stationary and mobile sensor nodes placed throughout cities, this study suggests an Internet of Things-based air quality monitoring system. This study aims to give policymakers, urban planners, and the general public practical insights to reduce air pollution and enhance environmental and public health outcomes. The research's main conclusions include improved coverage, high sensor sensitivity data correctness and calibration, etc. The methodology involves selecting IOT sensors for pollutants such as CO(Carbon Monoxide), NO2(Nitrogen Dioxide), and SO2(Sulphur Dioxide) and integrating them with microcontrollers for data acquisition. In urban pollution hotspots, sensors are placed to provide real-time monitoring and easily navigable alerts. Lastly, policymakers are assisted in putting protective measures into place by impact assessments and suggestions. Urban air quality monitoring, Smart City integration, industrial emission monitoring, etc. are examples of practical applications for this research concept. According to the study's findings, an IoT-based air quality monitoring system offers real-time tracking of several pollutants, facilitating data-driven decision-making, dynamic adaption, and prompt alarms for better urban air quality management. In order to facilitate real-time data collection and analysis, this study introduces an Internet of Things (IoT)-based air quality monitoring system that combines inexpensive, multi-pollutant sensors (CO, NO, SO, PM2.5, PM10, and O) with wireless connectivity options like LoRaWAN, 5G, and cloud-based APIs. Furthermore, machine learning models and analytics driven by AI are used for early warning alerts, predictive insights, and automatic data calibration.**

Index Terms— **Air Quality Monitoring, IoT Sensors, Machine Learning, Smart Cities, Prediction Models.**

I. INTRODUCTION

Urban air pollution has become a serious problem, which has effects on human health, environment and other crucial factors. Air quality has deteriorated due to rapid urbanization, industrial expansion and increase vehicle emissions, which has significantly increased the risk of cardiovascular diseases and other health issues. Traditional air quality monitoring systems fails to provide real-time localized and adaptive pollution estimates because they rely on statistical models and centralized static stations. Hence there is an increasing demand for a real- time air monitoring. In order to overcome these limitations, this study proposes an Internet of Things (IoT)-enabled air quality monitoring system that uses a mobile sensor network, multi-pollutant sensors, and low-power wireless communication to continuously monitor air pollution levels in real time. This research proposes and internet of things (IOT) based air quality monitoring system that uses low power wireless communication and multi-pollutants sensors (CO, NO2, SO2, PM2.5, PM10, O3, etc) to deliver continuous and real time tracking of air pollution. The system integrates IoT sensors with controllers to measure the real-time sensor reading. These sensors will be fixed in stationary locations as well as on moving devices such as drones and vehicles. In contrast to traditional systems which used to depend on historical data and predictive models, this method guarantees real time warnings, integration of mobile and stationary sensors and immediate data collecting for efficient environmental management. Additionally, AI-driven analytics also improve sensor calibration and prediction insights, which helps policymakers to implement efficient pollution control strategies. In order to reduce air pollution and enhance environmental and public health outcomes, this research attempts to assist policymakers, urban planners, and the general public. This system is an effective and scalable solution for modern air quality management, with real-world uses in smart cities, industrial emission monitoring, and urban planning. According to the study's findings, an IoT- based air quality monitoring system offers real-time tracking of several pollutants, facilitating data-driven decision-making, dynamic adaption, and prompt alarms for better urban air quality management. An AI-driven alert system that links to emergency response and government networks to deliver real- time warnings is presented in new research as a solution to these shortcomings. It informs the public of dangerous pollution levels through smart billboards, SMS, and notifications from mobile apps. Additionally, the system is integrated with weather forecasting models to provide early alerts and detect patterns in pollution.

Demonstration of the efficiency of an air quality monitoring system based on a wireless sensor network, which allows for better pollution control in urban settings and real-time data collection [2]. The adaptive IoT-based air quality monitoring node that was developed supports sustainable development goals, improves real-time tracking of air pollution, and can connect to several networks [22]. For better monitoring and decision-making, a geostatistical data fusion method efficiently combines low-cost sensor observations with urban air quality models to create precise, high-resolution, nearly real-time air pollution maps [5]. The developed Internet of Things (IoT)- based air quality monitoring system helps alleviate Malaysia's air quality reporting delays by offering a dependable and cost- effective real-time solution for measuring air pollution levels, especially PM2.5 [9].

By showing how home activities affect pollution levels and emphasizing the advantages of natural ventilation in enhancing air quality, the Internet of Things- based e-nose system efficiently monitors indoor air quality in real-time [10]. Commercial low-cost sensor platforms can improve citizen engagement and air quality monitoring, but their data quality varies greatly, requiring careful calibration and assessment for dependable applications [6]. Incorporating IoT and machine learning into air pollution monitoring improves accuracy, lowers expenses, and increases depend- ability, supporting proactive environmental management in smart cities [24]. Artificial Neural Network (ANN) models show possibilities for more accurate air quality predicting in metropolitan settings by outperforming Multiple Linear Regression (MLR) models in predicting the daily maximum surface ozone concentration [3]. Through the analysis of sensor data, the deep learning-based indoor air quality prediction system, accurately and efficiently predicts air quality, surpassing conventional techniques. This system uses GRU models (Gated Recurrent Unit Network) [7]. Compared to other models, the Spatio-Temporal Kriging (STK) model more accurately predicts Beijing's daily exposure to PM2.5, incorporating both temporal and spatial fluctuations in air pollution [8]. Instead of employing real-time sensor data, many studies rely on statistical models and historical data, such as regression models and interpolation techniques, which causes delays in pollution assessment. For example, the usage of spatio-temporal kriging models by Gilliland et al. (2005)[1] and Lin et al. (2018)[8] restricts their capacity to adjust to real-time circumstances. Rather than depending on historical data and predictive models, the new research incorporates real-time IoT sensors. It has direct sensor readings combined with ongoing, real-time monitoring provide immediate pollution tracking and emergency reaction capabilities. Limited Pollutant Detection Scope: In order to avoid giving a thorough evaluation of the quality of the air, many studies concentrate on monitoring just one or a small number of pollutants (such as CO and NO). For instance, Liu et al. (2012) [2] ignore other important contaminants because they concentrate primarily on CO detection. Instead of concentrating on a single pollutant, the current study uses multi-pollutant sensors (CO, NO, SO, PM2.5, PM10, O, etc.). Some studies, like those by Tastan et al. (2019) [10] and Kadri et al. (2017) [4], only address indoor air quality, which limits their applicability to more comprehensive urban pollution control. To guarantee a more thorough environmental impact, this new system, is made for outdoor air quality monitoring at the urban scale, expanding its coverage to include residential areas, traffic zones, and industrial locations. Static sensor networks are used in many research, including those by Zhang Woo (2020) [13] and Schneider et al. (2017) [5], which limits their ability to adapt to shifting urban pollution circumstances. On the other hand, this study combines stationary sensors with mobile sensor deployment on cars and drones to improve spatial coverage and allow for real-time pollution fluctuation adaptability. User accessibility is decreased by a number of research, like Hawari et al. (2019) [9], which rely on outdated data transmission techniques like GSM-based SMS alerts with little cloud integration. For effective, low-power, long-distance data transfer, this study makes use of LoRaWAN, 5G, and cloud-based APIs. To ensure smooth user interaction, real-time data is saved in the cloud and made available via dashboards, web platforms, and mobile apps. There aren't many studies that concentrate on extensive urban monitoring or offer real-time data for emergency response and policymaking. For example, Ng Da- hari (2020) [11] have a limited deployment that is restricted to academic and industrial locations. On the other hand, this solution uses machine learning models and AI-driven analytics to provide automated alerts and predictive insights. Policymakers and urban planning agencies have immediate access to the data, which supports choices about public health and environmental rules. Environmental factors like humidity, temperature changes, and slow sensor deterioration over time frequently have an impact on sensor accuracy [18, 19, 25]. Few research, meanwhile, provide reliable calibration methods to guarantee long-term dependability [22, 24]. New research presents AI-based auto-calibration methods that dynamically modify sensor values in order to overcome these difficulties. To improve accuracy, it also cross-checks IoT sensor data with reference-grade monitoring stations. Self-cleaning and adapt- able sensor modules are also incorporated into the research to enhance performance in inclement weather. Some studies focus mostly on gathering data, but they don't have real- time alert systems for unexpected increases in pollution [18, 19, 24]. Furthermore, emergency response systems and policy frameworks are not integrated [21, 23]. Real-time monitoring is absent when predictive modeling is used using past data. This approach does not provide real-time, current information; instead, it makes predictions about the future based on historical data. This implies that it might overlook unexpected changes [3]. It is challenging to compare sensors because of their potential to provide inaccurate results and the absence of standard guidelines for their operation [6]. Deep learning- based indoor air quality monitoring is effective in enclosed areas but is not applicable to outdoor air quality [7]. Programs are used in machine learning to examine data and identify trends. Based on historical data, it then employs those patterns to forecast future occurrences, such as modifications in air quality [20]. Only a few gases, such as carbon dioxide and ammonia, can be detected by a single MQ135 sensor, which restricts the system's ability to monitor other harmful pollutants [12]. The system's capacity to provide comprehensive, real- time air quality information is limited by its exclusive focus on web monitoring and a small number of pollutants [14]. LoRa technology works well for indoor monitoring but isn't use for outdoor environmental monitoring. This restricts the system's ability to track air quality of outdoor environment in real time [15]. ThingSpeak is an online platform that collects and displays real-time data from sensors. It helps people to track air quality from anywhere, using the internet [16]. Edge computing means handling data near its source instead of sending it far away to a central server. This fastens and prevents too much strain on the network[17].

II. METHODOLOGY

In order to enable continuous and adaptive tracking of urban air pollution, this project focuses on developing an Internet of Things (IoT)-based real-time air quality monitoring system that combines wireless communication, cloud computing, multi-pollutant sensors, and AI-driven analytics. By guaranteeing real-time data gathering, enhanced spatial coverage, and AI-based calibration procedures, the system is intended to address the drawbacks of conventional air quality monitoring methodologies.

The deployment of both mobile and fixed sensors, real- time data transmission, cloud-based storage, machine learning models for predictive analytics, and automated alarm systems for emergency response are all part of the methodology's organized approach. For efficient environmental management, the implementation entails sensor positioning, wireless communication configuration, data processing, visualization, and interaction with governmental networks.

A] Sensor Installation and Information Gathering:

To guarantee precise pollution detection, the system uses a thorough sensor installation and information-gathering methodology. It makes use of temperature and humidity sensors as well as CO, NO, SO, PM2.5, PM10, and O sensors. While mobile sensors are incorporated into automobiles and drones, stationary sensors are positioned strategically in residential areas, traffic crossroads, and industrial zones to improve spatial coverage and flexibility to real-time pollution variations. To preserve long-term measurement accuracy, AI- based self-calibration methods also dynamically modify sensor settings. The system makes use of cutting-edge wireless net- work technologies like LoRaWAN, 5G, and Wi-Fi to facilitate effective communication and data transfer while guaranteeing low-power, long-distance data transfer. By integrating edge computing, sensor data is preprocessed before being sent to cloud servers, which improves efficiency and lowers network congestion. Data transfer to cloud storage is made easy and instantaneous using the MQTT (Message Queuing Telemetry Transport) protocol. Additionally, real-time data processing and storage are done through cloud-based platforms such as AWS, Google Cloud, or ThingSpeak.

B] AI analytics and machine learning:

To find patterns and predict future changes in air quality, AI-based predictive models examine both historical and current pollution data. Anomaly detection is another feature of the system that automatically creates intelligent alerts to notify users of unanticipated spikes in pollutants. The weather models incorporate meteorological data, such as temperature, humidity, and wind speed, to improve prediction accuracy. Real-time pollution statistics are shown on web dashboards, mobile applications, and smart billboards for the purpose of raising public awareness and visualizing data. When pollution levels above safety criteria, public display boards, push notifications, and SMS are used to send out emergency notices. The technology also guarantees smooth interaction with legislators, urban planners, and environmental organizations, giving them immediate access to vital air quality data. IoT sensor data is cross-referenced with reference-grade monitoring stations to confirm accuracy and certify system performance. Data transfer speed, sensor calibration efficacy, AI model accuracy, and energy usage are used to evaluate the system’s efficiency. To guarantee dependability, pilot testing is carried out in metropolitan settings prior to full-scale deployment. Temperature and humidity sensors improve accuracy, and the system uses CO, NO, SO, PM2.5, PM10, and O gas sensors to measure air quality. Microcontrollers like the Raspberry Pi, Arduino, and ESP32 are used to control sensor interfaces. 5G, Wi-Fi, and LoRaWAN wireless modules provide real-time data transmission. Data processing and storage are done on cloud platforms such as AWS, Google Cloud, and ThingSpeak. For thorough identification, the proposed study makes use of real-time Internet of Things-based air quality monitoring using multi-pollutant sensors (CO, NO, SO, PM2.5, PM10, and O). It guarantees urban-scale deployment across industrial, transportation, and residential sectors, in contrast to studies that are indoor-focused. Adaptability is increased by a hybrid sensor network that combines stationary and mobile sensors (drones, cars). Effective, long-distance communication is ensured by data transmission over LoRaWAN, 5G, and cloud APIs. AI-powered analytics offer automated alerts and predictive insights. Accessibility is enhanced by web-based visualization, mobile apps, and interactive dashboards. By connecting real-time data to regulatory bodies, the system facilitates policy-driven decision-making while guaranteeing scalability, adaptability, and enhanced pollution control. To get around the need for past data, the proposed study uses sophisticated multi-pollutant sensors to conduct real-time IoT- based air quality monitoring. For thorough pollutant detection, the system combines CO, NO, SO, PM2.5, PM10, and O sensors. This research focuses on deployment at the urban scale, encompassing residential, transportation, and industrial regions, in contrast to earlier studies that were restricted to indoor contexts. To increase flexibility, a hybrid sensor net- work that combines stationary and mobile sensors on cars and drones is used. For effective, long-distance communication, data transmission makes use of LoRaWAN, 5G, and cloud- based APIs. Real-time data processing via AI-driven analytics and machine learning models allows for automated warnings and predictive insights. For user accessibility, the system offers web-based visualization, mobile applications, and interactive dashboards. Connecting real-time data to regulatory bodies and urban planning facilitates policy-driven decision-making. The strategy guarantees improved environmental impact, scalability, and real-time adaptation. The goal of the research is to fill important gaps in earlier studies and enhance air pollution control by incorporating smart monitoring systems. To guarantee reliable readings, AI-based auto-calibration systems regularly modify sensor settings. To improve measurement accuracy, IoT sensor data is further cross-validated using reference- grade monitoring stations. Sensor modules with adaptive and self-cleaning capabilities have been created to further enhance performance under harsh weather conditions.

III. IMPLEMENTATION

Figure.1. shows a system that includes wireless connection, sensor-based data collecting, and data processing for viewing and interaction with government sensors is described in the flowchart that is supplied. The first step in the process is sensor implementation, which involves deploying both stationary and mobile sensor types to gather data. These sensors transmit the collected data via wireless communication to a central pro- cessing system. The data processing unit analyzes the received information, which is then visualized for better interpretation. Finally, the processed data is utilized for interaction with governmental sensors, potentially for monitoring, decision- making, or regulatory compliance. This system is designed to provide real-time data acquisition and enhance communication between independent and governmental sensor networks.

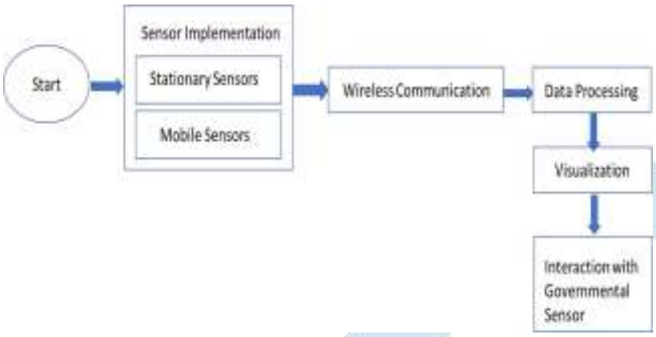

Fig. 1. Methodology Process Flow

The Figure.2. shows a block diagram of Real-Time Air Quality Monitoring using IoT Sensor with cloud integration. The circular Nodes represent Sensor. These are the basic part of the network. They collect the information from the surrounding, such as carbon monoxide (CO), nitrogen dioxide (NO2), sulphur dioxide (SO2), and particulate matter (PM2.5). They are fixed in different locations and send information to Cluster heads. The Triangular Nodes represents Cluster heads. These are responsible for data collecting and organizing. Each cluster head collects data from multiple sensors through link to backbone and this data forwards to another cluster head or Sink Gateway. The Rectangular Node represent a Sink Gateway. This is the central node it collects data from the multiple Cluster heads through link to base station. This data it processes before forwarding it to the cloud. After processing data it forward to cloud via Communication link to cloud. The Cloud Store and analyzse the data for monitoring air.

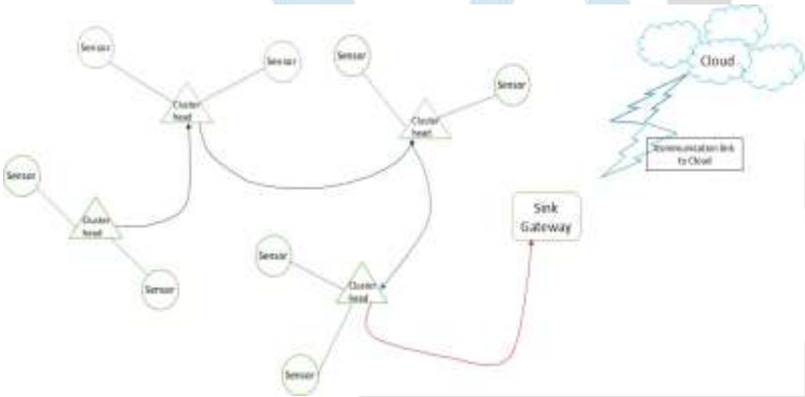

Fig. 2. System Block Diagram

IV. Results and Discussion

A] Results

Figure.3. shows that, the integration of IoT-based monitor- ing has greatly facilitated the identification and prevention of air pollution. Authorities can now respond quickly to pollution updates and alerts with real-time IoT sensors, unlike previous methods that relied on past data. The utilization of multi- gas sensors for CO, NO2, SO2, PM2.5, and other pollutants enhances the understanding of air quality by detecting more hazardous gases. While traditional monitoring was confined to indoor environments, new systems now cover outdoor and city areas, making it easier to measure pollution levels on a larger scale. Figure.1 lists past shortcomings in pollution monitoring together with the most recent research fixes for them. It highlights innovations such as Mobile sensors on vehicles and drones are a significant improvement from fixed sensor networks. Moving sensors are used to monitor pollution in different areas, such as high-traffic roads and industrial zones, which increases the reliability of data. Data transmission has been made faster and more efficient with LoRaWAN, 5G plus cloud technology integration to provide real-time pollution data. Also, the use of AI-based analytics helps to interpret data and send automatic notifications, which improves scalability and policy choices. Better decision-making and emergency re- sponses are supported by these advancements, which result in quicker, more effective, and wider environmental monitoring.

Fig. 3. Solutions Provided in New Research Idea

Problems	Solutions in New Research	Advantage
Dependency on Historical Data	Real-time IoT sensor data	Quick pollution updates and alerts
Restricted pollutant detection	Multi-gas sensors(CO, NO2, SO2, PM2.5,etc)	Thorough assessment of air quality
Indoor focused monitoring	Outdoor & urban-scale implementation	Broader environmental approach
Data transmission	LoRaWAN, 5G, Cloud support	Faster, long-range, efficient communication
Fixed sensor networks	Mobile sensors	Dynamic, adaptive pollution tracking

B] Discussions

IoT-based monitoring of air quality is shown to be significantly more effective than previous methods, according to the findings. This allows people and authorities to provide real-time updates on the condition of pollution problems, such as changing traffic flow or controlling factory emissions. The implementation of pollution control regulations and environ- mental protection is made more accessible to governments. However, certain matters remain unresolved. Sensors must be properly calibrated to provide accurate readings due to the unpredictable weather conditions. There are security concerns regarding the protection of pollution data from hacking or tampering. In addition, a large network of sensors can be difficult to scale because of the high cost involved in setting up and maintaining it. Improvements to such systems require future research aimed at improving accuracy of sensors, data security, and expanding network capacity at lower costs. By integrating IoT monitoring with smart city initiatives, such as traffic management, industrial emissions reduction, and urban planning, pollution reduction can be further reduced. By utilizing IoT, real-time monitoring of air quality can help citizens protect themselves, support environmental policies, and contribute to the improvement of urban living. The technology is highly effective.

V. CONCLUSION

The development of a real-time air quality monitoring system based on IoT technology marks a major improvement over conventional methods of assessing air pollution. The environment and public health are seriously threatened by urban air pollution, which calls for effective monitoring systems. Real-time, localized pollution estimates are not provided by traditional air quality monitoring systems because they are constrained by static sensors and statistical algorithms. This study introduces an Internet of Things (IoT) sensors with cloud-based analytics, we can provide immediate updates on pollution levels, allowing for quicker, continuous and more effective real-time tracking of air pollution. This strategy makes use of both stationary and mobile sensors to provide effective environmental management, dynamic adaptation, and immediate pollution alerts. The incorporation of multi-gas detection sensors, mobile sensor networks, and AI-driven analytics offers a thorough approach to monitoring pollutants, overcoming the limitations of relying on historical data and stationary sensor networks. Additionally, using LoRaWAN and 5G for data transmission boosts communication efficiency, facilitating smooth data collection and analysis. Policymakers and researchers can reduce urban air pollution and safeguard public health with the help of the suggested approach, which is scalable and efficient.

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