To Design & Develop An IoT-Enabled Real-Time Air Quality Monitoring System For Different Industrial Zone

MAJOR PROJECT REPORT

SEMESTER- 3

FOUR-YEAR UNDERGRADUATE PROGRAMME

(DESIGN YOUR DEGREE)

SUBMITTED TO

UNIVERSITY OF JAMMU, JAMMU

SUBMITTED BY:

TEAM MEMBERS	ROLL NO
Avichal Badyal	DYD-23-2
Bhoomi Samnotra	DYD-23-3
Divya Verma	DYD-23-4
Gourav Sharma	DYD-23-6
Narayan Choudhary	DYD-23-12
Pawandeep Singh	DYD-23-15

UNDER THE MENTORSHIP OF

Dr. Jatinder Manhas

Submitted on: ____ January 2025

ACKNOWLEDGMENT

We can acknowledge all those who helped and guided us during our research work. First and foremost, we thank almighty god from the depth of our hearts for generating enthusiasm and granting us spiritual strength to pass through this challenge successfully.

I sincerely thank Prof. Umesh Rai, Vice Chancellor of the University of Jammu, for his continuous support throughout our project. I also extend my heartfelt thanks to Prof. Dinesh Singh, Padma Shri awardee and Chairman of the Higher Education Council, J&K UT, for his encouragement and backing. I am deeply grateful to Dr. Jatinder Manhas for their constant guidance and support at every project stage. Their knowledge, feedback, and encouragement have been a great help in shaping our research and making sure it meets high standards. I thank Prof. Alka Sharma, our Head of Department, for her unwavering support in helping us complete this project. I would also like to thank my classmates for their valuable contributions. Their willingness to share ideas, work together, and offer assistance has made a big difference in overcoming challenges and achieving our goals. Finally, I am truly thankful to everyone who supported us. Without their combined efforts, this project would not have been successful.

CERTIFICATE

The report titled **"To Design & Develop An IoT-Enabled Real-Time Air Quality Monitoring System For Different Industrial Zone"** was done by including group members-(Avichal Badyal, Bhoomi Samnotra, Divya Verma, Gourav Sharma, Narayan Choudhary and Pawandeep Singh). This project served as a significant undertaking for Semester 2 of their academic program. Under the supervision and guidance of **Dr. Jatinder Manhas** for the partial fulfillment of the Design Your Degree, Four Year Undergraduate Programme at the University of Jammu, Jammu, and Kashmir. This original project report has not been submitted elsewhere for academic recognition.

Signature of Students

Avichal Badyal

Bhoomi Samnotra

Divya Verma

Gaurav Sharma

Narayan Choudhary

Pawandeep Singh

Prof. Alka Sharma	Mentors
Director, SIIEDC, University of Jammu	Dr. Jatinder Manhas

ABSTRACT

INDEX

INTRODUCTION

Air pollution has emerged as one of the most critical challenges facing humanity in recent years. The World Health Organization (WHO) identifies air pollution as a major environmental risk to health, responsible for millions of premature deaths annually. Beyond its direct impact on human health, air pollution exacerbates climate change, reduces agricultural productivity, and disrupts ecosystems, making it a multidimensional crisis. A significant source of this problem lies in industrial zones, where manufacturing and processing activities release a variety of harmful pollutants into the atmosphere. Industrial zones are hubs of economic activity, essential for manufacturing goods and driving economic growth. However, these benefits often come at a cost to environmental and public health. The emissions from factories and industrial processes contribute significantly to atmospheric pollutants, including particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO2), carbon monoxide (CO), and volatile organic compounds (VOCs). Each of these pollutants poses severe health risks. For instance, PM can penetrate deep into the lungs and bloodstream, causing respiratory and cardiovascular diseases, while VOCs and CO can lead to neurological damage and even fatalities with prolonged exposure. Moreover, NOx and SO2 are precursors to acid rain, which damages crops, aquatic life, and infrastructure, further amplifying their environmental impact. One of the primary challenges in addressing industrial air pollution is the lack of effective monitoring systems that can provide continuous and actionable data. Current air quality monitoring methods largely rely on manual sampling and laboratory analysis. While these methods can provide precise measurements under controlled conditions, they are not suitable for real-time, large-scale deployment. These traditional approaches are hindered by several limitations, including high operational costs, time delays, and restricted spatial coverage. Such constraints mean that pollution spikes are often detected too late, leaving little room for timely interventions. Furthermore, the sporadic nature of data collection makes it difficult to track trends, correlate emissions with specific industrial activities, or ensure compliance with environmental regulations. As industrial activities grow and urban areas expand, the need for a more efficient and dynamic approach to air quality monitoring becomes increasingly evident. The advent of the Internet of Things (IoT) has introduced new possibilities in this domain. IoT technology enables the creation of interconnected systems where sensors, communication networks, and data processing units work seamlessly to monitor environmental parameters in real time. By leveraging IoT, it is possible to design monitoring systems that can operate autonomously, providing continuous updates on air quality and enabling stakeholders to respond proactively to pollution incidents.

An IoT-enabled air quality monitoring system offers several advantages over traditional methods. First, it enables real-time data collection and transmission, ensuring that pollution levels are continuously tracked and reported. This immediacy is crucial in industrial zones, where pollutant levels can rise sharply due to specific activities, such as peak production times or equipment malfunctions. Second, the system provides spatially distributed monitoring, as multiple sensors can be deployed across an industrial area to capture data from various points. This allows for a more comprehensive understanding of air quality and helps pinpoint pollution hotspots. Third, the integration of cloud-based platforms facilitates the storage, analysis, and visualization of data. Stakeholders can access live data feeds, historical trends, and automated alerts when pollutant levels exceed safe thresholds, enabling informed decision-making and faster response times. This project seeks to harness the potential of IoT technology to address the air pollution crisis in industrial zones. The proposed system will incorporate advanced sensors capable of detecting a wide range of pollutants, such as PM2.5, NOx, SO2, and VOCs. These sensors will be connected to a data aggregation unit that processes the collected information and transmits it to a cloud platform for analysis and visualization. The system's dashboard will display real-time pollutant levels and provide automated notifications when critical thresholds are breached. Additionally, the collected data can be analyzed to identify correlations between industrial activities and pollution patterns, helping industries adopt cleaner practices and comply with environmental regulations. The impact of this project extends beyond technological innovation. By providing a scalable and cost-effective solution, it aims to empower industries, regulators, and communities to work together toward a healthier and more sustainable future. Regulatory authorities can use the system to ensure compliance with emission standards, while industries can leverage insights to optimize their processes and reduce their environmental footprint. Furthermore, communities living near industrial zones will benefit from improved air quality, reducing health risks and enhancing their quality of life.

In conclusion, the integration of IoT technology into air quality monitoring represents a transformative approach to tackling one of the most pressing environmental issues of our time. This project not only addresses the limitations of traditional monitoring methods but also paves the way for smarter, data-driven environmental management. By bridging the gap between technological advancement and environmental stewardship, it offers a path toward mitigating industrial air pollution and safeguarding the health and well-being of future generations.

Motivation of the Study

Industrial zones are essential for economic growth and manufacturing but often become hubs of significant air pollution, posing grave risks to public health and the environment. The limitations of traditional air quality monitoring methods, such as their inability to provide continuous and actionable data, emphasize the need for a more effective solution. The motivation for this study stems from the increasing demand for real-time, accurate, and spatially distributed air quality data to address the health and environmental challenges posed by industrial pollution.

The advent of IoT technology offers an opportunity to revolutionize how air quality is monitored and managed. By enabling real-time data collection, seamless communication, and predictive analytics, IoT systems have the potential to bridge the gap between traditional monitoring limitations and modern environmental management needs. This study is driven by the aspiration to create a sustainable, scalable, and impactful solution that not only monitors but also mitigates industrial pollution effectively.

2.1 Problem Statement

Industrial zones are major contributors to air pollution, emitting harmful pollutants that exceed permissible limits and pose significant health and environmental risks. Traditional air quality monitoring methods, such as periodic manual sampling, fail to provide continuous data, leading to delayed interventions and inadequate pollution management. The absence of real-time, spatially distributed monitoring further exacerbates the problem, leaving communities vulnerable to the harmful effects of pollution.The lack of effective monitoring systems hinders efforts to identify pollution hotspots, track trends, and enforce environmental regulations. This calls for an advanced solution that combines real-time data collection, automated alerts, and actionable insights to address the challenges of industrial air pollution effectively.

2.2 Objectives

The primary objectives of this project include developing a low-cost IoT-enabled air quality monitoring system using advanced sensors and ensuring its ability to collect and transmit data in real time to a cloud platform. An intuitive dashboard will be created to visualize real-time pollutant levels and historical trends, facilitating comprehensive analysis. To enhance its functionality, an automated alert mechanism will be implemented to notify users when pollutant levels exceed critical thresholds. Moreover, the project aims to analyze correlations between industrial activities and air quality variations, helping identify peak pollution periods and enabling proactive measures.

1. Proposed Methodology

3.1 Identifying the Problem Statement

The methodology starts by clearly defining the problem—monitoring air quality in industrial zones. The main pollutants (e.g., CO, CO_2, SO_2, PM2.5) affecting the air quality are identified, and the need for a real-time, automated system to track these pollutants is established.

3.2 Defining Objectives

After the problem is identified, the next step is to set specific, measurable objectives for the air quality monitoring system. These could include:

- Monitoring key pollutants in real-time.
- Triggering alerts when pollutant levels exceed predefined thresholds.
- Providing a user-friendly interface for data visualization.
- Storing and analyzing data for long-term trends.

3.3 System Design and Architecture

This step focuses on designing the system to meet the identified objectives.

3.4 Select Deployment Site

In this stage, the ideal deployment site is selected within the industrial zone. The site should be representative of typical air quality conditions and capable of supporting the installation of necessary equipment (e.g., sensors, power supply, communication modules).

3.5 Field Deployment

The system is deployed in the selected site. Sensors and devices are installed and connected to the Raspberry Pi. Power supply and communication modules are set up to ensure data transmission and real-time monitoring.

3.6 System Testing

After field deployment, the system undergoes thorough testing to ensure that all components function correctly. This includes checking sensor accuracy, data transmission, communication reliability, and system responsiveness under different conditions.

3.7 Data Collection

Once the system is tested and operational, real-time data collection begins. The sensors collect air quality data, which is processed by Raspberry Pi and stored locally or transmitted to the cloud for further analysis.

3.8 Monitor Performance

During this phase, the system's performance is continuously monitored to ensure that it is operating as expected. Any discrepancies or issues with data collection, transmission, or system operation are identified and addressed.

3.9 Data Analysis

The data collected is analyzed for trends, pollutant levels, and patterns over time. This analysis helps identify potential pollution hotspots, peak pollution times, and any environmental factors affecting air quality.

3.10 Send Alerts to the Users

When pollutant levels exceed safe limits or predefined thresholds, the system triggers alerts. These alerts could be in the form of visual notifications (LED lights), audible alarms (buzzers), or even messages sent to users via mobile applications or email, ensuring that timely actions can be taken.

3.11 Evaluate System Effectiveness

After a certain period of operation, the effectiveness of the system is evaluated. This involves assessing whether the system meets its objectives, such as timely data collection, accurate readings, reliable alerting, and overall system performance.

3.12 System Refining

Based on the evaluation results, the system is refined to enhance performance. This could involve recalibrating sensors, upgrading communication protocols, optimizing data analysis methods, or improving user interface features. Continuous improvement ensures that the system remains effective and adaptable to changing environmental conditions.

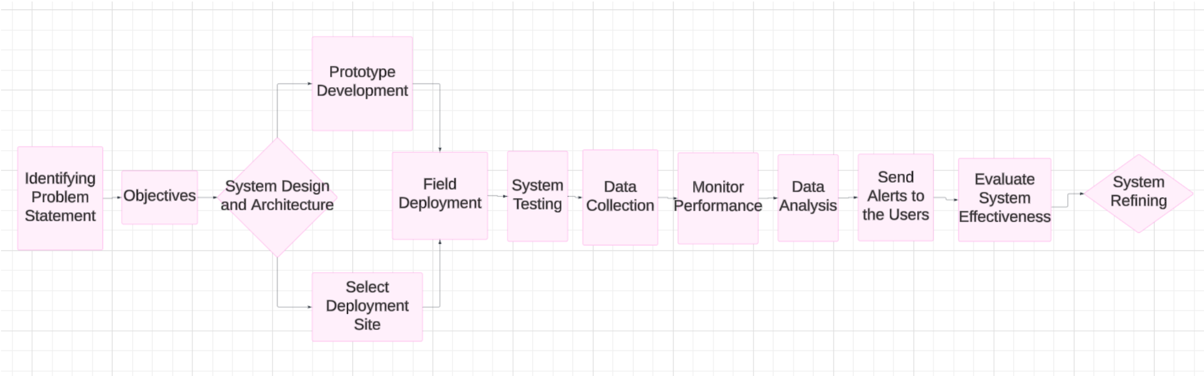


Fig 1: Methodology Flow Chart

Scope Identification

The proposed air quality monitoring system is designed to address industrial applications, environmental impact, public health, research, and policy development needs. This system is specifically tailored for industries emitting high levels of pollutants, such as manufacturing plants, power plants, and chemical processing units. By offering real-time air quality monitoring, it helps industries comply with environmental regulations and optimize operations to reduce emissions. Furthermore, the system continuously collects air quality data, identifying pollution hotspots and trends, enabling stakeholders to implement effective mitigation strategies that minimize environmental damage. For communities residing near industrial zones, timely alerts and improved air quality contribute to reducing health risks and enhancing the overall quality of life. Additionally, the data generated by the system can support academic research and policymaking, aiding in drafting effective regulations and sustainability frameworks. With its modular design, the system is scalable and adaptable for diverse industrial zones, addressing global air quality challenges.

Review of Literature

The integration of IoT in air quality monitoring has garnered significant attention in recent years due to its potential to address the limitations of traditional systems. Several researchers have proposed innovative solutions to develop cost-effective, real-time, and scalable monitoring systems for industrial applications. This study analyzes 36 research papers published after 2014. The studies highlight various approaches, methodologies, and applications, demonstrating the transformative potential of IoT and AI in creating actionable environmental solutions. A significant advancement in air quality monitoring is the LoRaWAN-IoT AQMS system developed by Waheb A. Jabbar et al., (2022)[1]. This system uses NO2, SO2, CO, CO2, and PM2.5, which are interfaced with an Arduino microcontroller supported by Lora that facilitates real-time data streaming. Solar power is adopted for sustainability, and the data is uploaded onto ThingSpeak dashboards and the main computer through an app in Virtuino. The rapidly rising population and growth rate in industrial activity are the reasons for the spread of air pollution and also the need for a scalable, cost-effective monitoring solution. The whole architecture is based on Arduino sensing nodes, where the LoRa technology is deployed to deliver the acquired data to a central platform for user access. The testing met thoroughly reliable data collection and transmission validated against Aeroqual devices to underpin the effectiveness of the system with environmental monitoring. Similarly, Mehmet Taştan, 2022[2] Cooking or smoking at home rapidly deteriorates IAQ; thus, this paper proposes an economically affordable smart home system that will monitor PM1, PM2.5, PM10, and carbon dioxide concentration, providing real-time alerts for exceeding the overconcentration threshold. Indoor pollution poses serious health risks particularly during the act of cooking or smoking; hence, affordable monitoring solution needs to be worked on. For communication, the apparatus includes ESP8266-12E, while for PM and CO2 detection it has PM and CO2 sensors. Pearson Correlation Coefficient is calculated to explain the associated household IAQ variations. Tests show that high peaks result during their cooking, giving an insight that they require evacuation-facilitated implementation of a good kitchen exhaust solution and air purification. In urban and industrial contexts, researchers such as Yingbo Zhu et al., 2022[3] This research paper investigates an Internet of Things (IoT) air quality monitoring system designed for urban and industrial settings. It employs a variety of sensors to track pollutants such as CO2, NOx, and PM10, and provides real-time data visualization and alert functionalities. Increased urbanization and industrial expansion have raised the need for more sophisticated air quality monitoring solutions. The device combines gas sensors and an

Arduino microcontroller, by sending data to cloud applications through Wi-Fi. A mobile application showcases patterns and triggers an alert when air quality is harmful, offering a straightforward, cost-efficient, and scalable air quality monitoring solution. Dharmendra Singh et al., 2021[4] This review examines sensors and systems utilized for managing air quality, categorizing them as ground-based, aerial, satellite-based, digital, and hybrid technologies. The research is centered on leveraging IoT, geospatial technologies, and machine learning to enhance monitoring capabilities. Given the detrimental impact of air pollution on health, ecosystems, and climate, there is a pressing need for innovative solutions. Through case studies, the performance of integrated systems that combine IoT and AI for addressing air quality issues on a large scale is demonstrated. The studies demonstrated the efficacy of integrated systems in addressing the complexities of air pollution on regional and global scales. Machine learning and predictive analytics have revolutionized air quality monitoring. For instance, Andriy Palamar et al., 2022[5] This paper suggests an Internet of things (IoT) based air quality monitoring system aimed at PM2.5 concentration forecasting based on edge computing. Convolutional Neural Networks (CNN) and Long Short-Term Memory (LSTM) models learn from time-dependent and on-line data for good predictions of pollutants. The system overcomes the usual constraints of centralized cloud computing by using local IoT nodes for data analysis. Validation results demonstrate better accuracy in estimating PM2.5 concentrations, optimizing bandwidth allocation and lowering latency and costs. The edge-based method guarantees optimal use of the resources for real-time applications. Similarly, Claudia Banciu et al., 2024[6] This study investigates the use of IoT devices combined with machine learning algorithms to monitor and predict air quality. The system measures parameters including temperature, humidity, levels of PM10, and PM2.5, and data are sent to the Thing Speak platform in the cloud for analysis. A regression model based on TensorFlow predicts Air Quality Index (AQI), and offers real-time data, therefore, useful for avoiding health hazards. The main results show the higher accuracy of the random forest models with 100 estimators, with a low Mean Absolute Error (MAE) of 0.2785 for AQI 10 and 0.2483 for AQI 2.5. By combining the features of IoT and predictive analytics, this study particularly focuses on integrating pollution hotspot identification by using the IoT and helping decision-makers take effective management of the pollution hotspot issue. Through the solutions to issues such as sensor calibration and connectivity, the work offers a scalable infrastructure for environmental monitoring and public health. Indoor air quality monitoring has emerged as a vital area of research. Studies like those by Dylan Wall et al., 2021[7] In this work, public health and safe social contact focused on the Internet of Things (IoT) is proposed. Bosch

BME680 sensors read IAQ parameters such as temperature, humidity, and volatile organic compounds (VOCs). The data is processed in the edge computing node and used in the web-based dashboard. Two 2-week data collection periods showed strong correlations between environmental factors and IAQ, highlighting the impact of cooking and cleaning activities. Real-time dashboards improved user awareness and this in turn triggered early interventions, eg, re-evaluation of ventilation to enhance the quality of indoor air. Nurul Azma Zakaria et al., 2018[8] This paper is designed to develop a wireless IoT-based indoor air quality monitoring device using MQ-135 sensors, Raspberry Pi 2 board and ThingSpeak for data storage and visualization. The system captures air quality, temperature, and humidity data, issuing email alerts for unhealthy conditions. It illustrates a scalable, low-cost method for the continuous monitoring of indoor pollution. Industrial air pollution monitoring has also seen remarkable advancements. S. Ramalingam et al., 2019[9] This study introduces an IoT-based solution for monitoring and controlling industrial pollution levels. By means of Raspberry Pi and Blynk Server, the system can read combined temperature/humidity and toxic gas readings, reporting them in real time by means of a mobile app. In the system, the DHT11 and gas sensors are used to capture the data and which is transmitted to the Blynk Server to be visualized. Alerts are triggered when pollutant thresholds are breached. The system is practical, affordable, and scalable for many industrial applications with the benefits of also providing transparency and reactive pollution control measures. Similarly, Tuyen Phong Truong et al., 2021[10] This paper introduce the Environmental Monitoring System (EnMoS), an IoT-based air quality monitoring framework leveraging LoRa technology. Sensors measure PM2.5, PM10, CO2, temperature, and humidity. Data is uploaded to a live database for calculating the Air Quality Index (AQI) and can be visualized through an interactive web platform. One observation case study with three sensing nodes confirmed the applicability of the system to urban and industrial deployments. The attention in the study is given to the process of community literacy and technological participation in reducing the negative impact of pollution. The role of affordability and accessibility in advancing air quality monitoring cannot be overstated. Several studies, such as those by Akshata Tapashetti et al., 2016[11] This paper describes an affordable, IoT-based, air quality monitoring unit designed for urban pollution. Sensors measure gases, e.g., CO and HCHO, and the measured data is sent to the cloud for visualization and alerts in real time. The system mitigates the increasing effects of fossil fuel emissions on air quality, especially in urban environments, through the delivery of actionable information to users. Integration with AWS IoT allows for secure data handling, while Python scripts facilitate the automatic triggering of alerts in the case of threshold crossing. Scalability for schools, playgrounds, and high-traffic environments is shown with the prototype, priced at $170, which points to the massive deployment of this system. The authors draw attention to the importance of fine-grained air quality data in fostering public understanding and informing policy decisions. Similarly, Jagriti Saini et al., 2021[12] This systematic review evaluates low-cost sensors for indoor air quality (IAQ) monitoring, highlighting their effectiveness and limitations. The study analyzes 40 research papers published after 2015, covering sensors for parameters such as CO, CO2, PM2.5, and VOCs. Results indicate that 32 sensors were pre-calibrated, while 38 required field calibration. The review underscores the need for reliable and accurate sensors, noting that most existing devices lack comprehensive calibration and accuracy specifications. Cost analysis revealed that affordable sensors are available under $20, but their performance is often suboptimal. The study provides insights into sensor selection for future IAQ monitoring systems and emphasizes the importance of addressing technical challenges like calibration and response time. Integrating IoT with AI technologies has enabled researchers to develop advanced frameworks for environmental monitoring. For example, Ahmed Samy Moursi et al., 2021[13] This paper introduces an IoT-enabled system for PM2.5 monitoring and prediction using edge computing. CNN and LSTM networks are trained on three years' worth of historical data and deliver locally scalable, resource-light pollutant prediction. Similarly, Geetha Mani et al., 2021[14] This study presents an AI-powered IoT-based air pollution monitoring and forecasting system. The system uses IoT sensor nodes to measure air pollutants such as CO, NH3, and O3 in the Vijayawada region. Data collected from these nodes is processed using machine learning models, including Naive Bayes, AR, ARMA, and ARIMA, to forecast pollutant levels. A hardware prototype featuring Raspberry Pi and Arduino components was developed, and an online dashboard was created using Firebase for real-time and forecasted data visualization. The system demonstrated high accuracy, with ARIMA outperforming other models in terms of Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The research highlights the potential of IoT and AI integration for cost-effective and scalable air pollution monitoring solutions. The study by Chavi Srivastava et al., 2019[15] addresses the urgent need for real-time air monitoring systems by proposing an IoT-based solution using Arduino. Air quality data from air monitoring stations are considered big data, which are analyzed for emissions, including smog and methane as well as noise, in real time. The system combines IoT with cloud storage dynamic for real-time transmission and decision-making in air quality. Using Arduino Mega 2560 with MQ-series gas sensors and noise detector, the readings are shown on a TFT screen, saved on SD cards, and streamed to ThingSpeak IoT platform for analysis. Bayesian theorem is used in pollution prediction, and neural networks serve in data normalization and prediction. Results demonstrate the system's effectiveness in capturing air pollutants and visualizing trends, offereing an scalable and actionable system for environmental monitoring. Qilong Han et al., 2019[16] This paper presents a Zigbee-based wireless sensor network (WSN) for monitoring air quality in industrial areas. The system is designed primarily for manufacturing environments, targeting the contaminants of CO, NO2, and PM. Sensors embedded in Zigbee nodes transfer data through repeaters to cloud platforms, subsequently being characterized using LSTM to predict pollution. Traceability techniques identify emission sources according to wind direction and emission data. Deployment in a Northern China factory validated the system's reliability, making it a low-cost, scalable solution for industrial pollution monitoring. The study by Kinnera Bharath Kumar Sai et al., 2019[17] This paper presents the measurement of air quality via MQ135 and MQ7 sensors combined with IoT platforms (e.g., ThingSpeak) for real-time monitoring. Machine learning algorithms identify trends and forecast pollution, respectively, and deliver practically meaningful results. Results show the successful monitoring with subsequent analysis and awareness of critical levels of pollution. The combination of IoT and machine learning provides a very powerful platform for environmental monitoring. Tyrel Glass et al., 2020[18] This study is aimed at developing low-cost sensitive air quality sensors that are networked with the LoRaWAN Internet-Of-Things (IoT) networks. Sensors make measurements of pollutants such as CO and NO2 that deliver very fine-resolved data for urban areas. Field testing showed good association with the reference devices and confirmed the accuracy of the system. This scalable, cheap solution opens the road for the development of wider urban sensor networks. Wei Jian Ng et al., 2020[19] This paper enhances IoT-based air monitoring by integrating real-time data collection and mobile app interfaces. Sensors acquire environmental data and send it to a mobile app, "AirProp," to be visualized and sent as an alarm. The system is shown to be robust in tracking temperature, humidity, and CO levels, thereby is promising for urban and industrial purposes. Its user-friendly design promotes public awareness of air quality. Olakunle Elijah et al., 2018[20] This paper reviews the integration of IoT and data analytics in agriculture, highlighting benefits such as operational efficiency and sustainability. Case studies show the use of IoT in precision farming, greenhouse management, and animal tracking. Although, challenges exist, such as high cost and data privacy, the paper highlights the role of IoT in transforming agricultural innovation. Similarly, Temesegan Walelign Ayele et al., 2018[21] This study propose an IoT-based system for monitoring and predicting air pollution using machine learning algorithms, focusing on pollutants like CO, NO2, and SO2. By sensed data, long short-term memory (LSTM) networks are utilized to perform predictive modeling. Results show that high accuracy in prediction leads to proactive air quality management. C. Balasubramaniyan et al., 2016[22] This paper describes an Air Quality Monitoring System (AQMS) based on IoT which is implemented by using a Raspberry Pi. The system collects data on pollutants like CO, CO2, NH3, and NOx, transmitting it to ThingSpeak for visualization. Real-time notifications and precise data acquisition demonstrate its feasibility in a variety of settings, with a scaling-up potential for air quality monitoring. Daudi S. Simbeye, 2017[23] In this paper, an industrial air pollution monitoring system based on a wireless sensor network (WSN) has been proposed. The system employs nodes equipped with sensors which are used in monitoring pollutants like ozone and carbon monoxide, sending data to a central server for realtime analysis. It is an effective, simple, and low-cost way to achieve regulatory compliance and public safety. Kennedy Okokpujie et al., 2018[24] This paper describes an intelligent air pollution monitoring system on Arduino. It takes measurements of pollutants in real-time and stores this information in a cloud server for visualisation. Alerts are activated for bad levels, offering a simple, inexpensive way to alert people of air quality. B. Thiyaneswaran et al., 2021[25] This research focuses on air quality monitoring in steel, material, and copper processing industries. Using MQ series sensors and an Arduino Nano controller, the system measures CO, CO2, NO2, and CH4 levels. Data is transmitted to a cloud server and visualized through a mobile application, with real-time alerts provided via sound and light alarms. The device was tested in polluted industrial environments, demonstrating its reliability in identifying harmful gas levels. Results showed that the system effectively monitors and reports gas concentrations, ensuring workplace safety and compliance with environmental standards. The study emphasizes the importance of affordable and accessible monitoring systems in industrial settings. Jitendra Pramanik et al., 2021[26] This study introduces an IoT-based framework for ambient air quality monitoring in underground coal mines. The system leverages MEMS technology, wireless sensor networks (WSNs), and IoT to track toxic gases such as CO, CO2, CH4, NOx, and H2S in real time. Traditional monitoring methods, reliant on manual sampling and laboratory analysis, are inefficient and time-consuming. In contrast, the proposed system integrates gas sensors with communication infrastructure to provide continuous data. The use of dual-beam IR-LED gas sensors ensures accurate detection of pollutants, while cloud-enabled analytics and machine learning techniques support early warning mechanisms. The system's design incorporates industrial best practices to enhance miner safety and improve operational efficiency. Results from prototype testing validate its sensitivity, stability, and suitability for real-world deployment. The study emphasizes the need for automated, real-time monitoring systems to address safety challenges in the mining sector. Anabi Hilary Kelechi et al., 2022[27] his work reports an inexpensive air quality monitoring system based on Arduino and ThingSpeak. The system is equipped to measure contaminants CO and CO2, and reports can be visualized in real-time as well as set up to alert the user. It emphasizes affordability and accessibility for widespread adoption.

Kalyani A. et al., 2021[28] This paper proposes "Oxygen Tocsin", an air quality monitoring system based on cloud and IoT technology, which is suitable for industrial and mining Applications. The device monitors oxygen levels and identifies toxic gases (carbon monoxide, nitrogen dioxide and chlorine). Using sensors interfaced with Arduinos and Raspberry Pi, data is analyzed in GCloud for real-time monitoring and notifications. The system is capable of facilities identification of oxygen-deprived spaces <19.5% oxygen) as well as recommending safe place. It is intended to reduce health hazards associated with the use of phosgene and nitrogen dioxide and contains substantial scalability to mining and chemical plants. Previous studies reviewed include Angrisani et al.'s MQTT-based remote monitoring and Saini and Dutta's cost-effective system recommendations. The paper confirms the system performance under laboratory conditions and highlights the future applications of the system to enhance workplace safety. Jyoti N. Shrote et al., 2023[29] In this study, a smart air pollution-monitoring system based on IoT and Raspberry Pi has been developed with the capability of real-time data acquisition and analysis. The system monitors CO2, LPG, PM2.5 and PM10 pollution by both commercial sensors and uploads data to the cloud through ThingSpeak, for visualization on the cloud. The portable configuration takes advantage of an LCD for local presentation of air quality parameters. In the context of tackling global air pollution, the system focuses on deployment at a low cost, and on measurements and monitoring at real-time. The authors combine historical views on gas sensor evolution and the contribution of automation to improvements in accuracy and reliability. By combining IoT, sensors, and cloud technologies, the study delivers a practical solution for urban and industrial applications. Umesh Kumar Lilhore et al., 2022[30] This paper discusses a machine-learning-based IoT traffic management system for urban environments. Using adaptive algorithms, the system uses IoT sensors to monitor the location of the vehicles and forecast congestion areas. By performing anomaly detection with DBSCAN clustering, it is possible to further optimize signal timings resulting in decreased vehicle waiting times and improved traffic flow efficiency. Comparative analyses of IoT-based transport systems are presented, with a particular focus on timeliness and scalability. The study confirms the effectiveness of the system by simulation and provides thereby clues for the use of the IoT in smart city management on a larger scale. Montaser N.A.

Ramadan et al., 2024[31] This paper presents a real-time internet of things-based AI-based monitoring prediction system for industrial air pollution, particularly concerning chrome plating. It integrates IoT sensors with AI models, such as LSTM and Random Forest, to detect pollutants like NH3, CO, NO2, CH4, and PM2.5. The system estimates air pollution concentrations and can therefore trigger protective actions such as turning on exhaust fans before air pollution levels become dangerous. Using field validation in on the industrial area of Istanbul, the paper shows that the system can be used to assist in improving air quality and to comply with the regulations. Literature reviews describe progress in IoT and AI technologies and how they are being used in environmental monitoring. Challenges such as sensor calibration and data fusion are addressed by novel approaches, with an emphasis on demonstrating the system's viability in a dynamic industrial environment. Chetan B.V. et al., 2021[32] This study proposes an IoT-based air and sound pollution monitoring system using Raspberry Pi. Sensors measure air quality, noise, temperature, and humidity and data is sent to the ThingSpeak platform for plotting. Python scripts facilitate data analysis, and anomaly detection triggers user notifications. The modular architecture of the system consists of an Air Quality Index Monitoring Module and a Sound Intensity Detection Module allowing a wide range of environmental monitoring. Results show the system has been useful for detecting pollution patterns and allowing timely action. Tanaji Kamble et al., 2022[33] This research introduces an IoT-based air pollution monitoring system using Raspberry Pi and gas sensors such as MQ2 and MQ7. The system acquires the presence of pollutants, i.e., LPG, CO and methane) and monitors environmental parameters such as temperature and humidity. There is visualization of data on an LCD and uploaded to the ThingSpeak site. The work makes a case that low-cost, high-throughput technology is key to monitoring air quality in urban and industrial environments, focusing the potential of IoT to limit pollution and save lives. Hemanth Karnati, 2023[34] This paper develops a portable air quality detection device integrating MQ135 and MQ3 sensors for monitoring CO2, smoke, benzene, and NH3. The system is based on cloud based data visualization on ThingSpeak, and uses machine learning for real-time analysis. To overcome urban air pollution challenges, the device offers location-based information to users, which facilitate users to take the right decision. This research highlights the importance of affordable, portable solutions to increase public visibility and government policy deliberation. Mr. Sarthak A. Dhumal et al., 2024[35] In this work, the air and sound pollution<startofturn>user In the future, the specific challenges of improving children's ability to engage with data will require personalized skills training based on children's existing knowledge, alongside feasible tools and techniques for enhancing specific skills such as selective attention and working memory. Sensor collected data is sent to cloud platforms for real-time visual presentation and alarms. The ease of access and cost of the system makes it a powerful instrument for community-based awareness and participation. The combination of the Internet of Things (IoT) with mobile technologies can generate actionable information, which can lead to better urban environmental management. Ramik Rawal, 2019[36] This work investigates air quality monitoring via IoT platforms (e.g., ThingSpeak). Sensors can be used to collect levels of CO and PM2.5, and real-time data are currently made available to the public through web-based dashboards. The study is concerned with the mitigation of air pollution in severely affected urban regions such as New Delhi itself, with a particular emphasis on the contribution of an IoT environment in raising public awareness and promoting health. Through sensor calibration error correction and power consumption optimization, the system provides accurate and economical surveillance. The results highlight the need for using IoT to access in-situ environmental data for informing policy and personal behaviors

Table 1

Serial No.	Title of Paper	Year of Publication	Methodology Adopted	Conclusion
1	AI-powered IoT-based Real-Time Air Pollution Monitoring and Forecasting	2016	AI algorithms integrated with IoT sensors for real-time prediction	Enhanced forecasting accuracy and proactive pollution control
2	IoT-Enabled Air Quality Monitoring System (AQMS) using Raspberry Pi	2016	Integrated sensors with Raspberry Pi for air quality	Improved detection accuracy and cost-efficiency
3	IoT-Enabled Air Quality Monitoring Device: A Low-Cost Health Solution	2016	Low-cost portable sensors with IoT connectivity	Demonstrated real-time monitoring for health safety
4	Industrial Air Pollution Monitoring System Based on Wireless Sensor Networks	2017	Sensor network solutions for pollution tracking	Improved industrial regulatory compliance
5	Wireless Internet of Things-Based Air Quality Device for Smart Pollution Monitoring	2018	Wireless IoT air quality systems	Increased monitoring precision for urban settings
6	A Smart Air Pollution Monitoring System	2018	Smart sensor deployment with IoT integration	Enabled efficient and distributed pollution sensing
7	Air Pollution Monitoring and Prediction Using IoT	2018	Predictive algorithms for pollution data	Enhanced forecasting capabilities

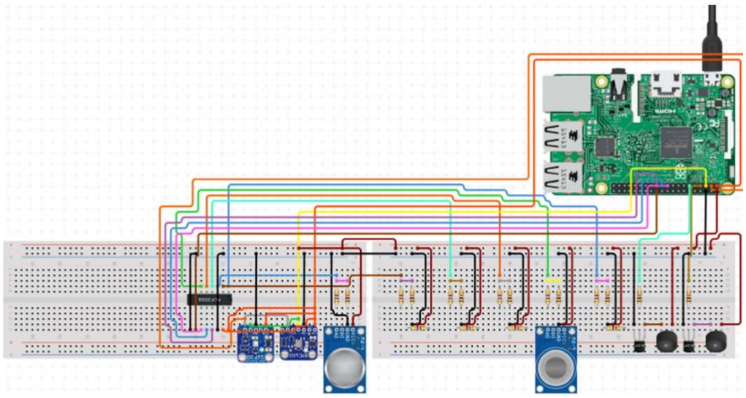
8	An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges	2018	IoT use cases in agriculture	Outlined benefits and key technological gaps
9	IoT-Enabled Air Monitoring System	2019	Custom IoT-enabled monitoring architecture	Improved pollution tracking for rural areas
10	A Wireless Sensor Network for Monitoring Environmental Quality in the Manufacturing Industry	2019	IoT sensors for industrial emissions	Increased data granularity and visualization
11	IoT-Based Air Quality Monitoring System Using MQ135 and MQ7 with Machine Learning Analysis	2019	Machine learning-enhanced IoT sensors	Provided data-based pollution prediction
12	IoT-Enabled Smart Industrial Pollution Monitoring and Control System Using Raspberry Pi with BLYNK Server	2019	Raspberry Pi with remote control features	Real-time automation for pollutant management
13	Sensors for indoor air quality monitoring and assessment through Internet of Things: A systematic review	2020	Comprehensive review of IoT sensor technologies for indoor environments	Identified effective sensor combinations for various pollutants
14	Enhancement of Real-Time IoT-Based Air Quality Monitoring System	2020	Upgraded system sensors and software	Boosted monitoring reliability and scalability
15	IoT-Enabled Low-Cost Air Quality Sensor	2020	Economical sensor array for real-time tracking	Reduced setup cost for industrial sites
16	IoT-based air quality measurement and alert system for steel, material, and copper processing industries	2021	Specialized industrial sensors connected to IoT alert systems	Reduced health risks by timely pollution alerts
17	IoT enabled Cloud-Based application for Air Quality Monitoring System - “O2 TOCSIN”	2021	IoT sensors integrated with a cloud-based application for air quality data	Reliable real-time air quality tracking with a user-friendly interface
18	Design of a Low-cost Air Quality Monitoring System Using Arduino and ThingSpeak	2021	Arduino microcontroller with ThingSpeak integration for air quality visualization	Demonstrated low-cost, scalable monitoring capabilities
19	A Raspberry-Pi Based Embedded System to Monitor Air and Sound Pollution Using IoT	2021	Raspberry Pi microcontroller with integrated air and noise sensors	Combined air and noise pollution monitoring with IoT connectivity

20	Design and Development of an IoT-Based Air Quality Monitoring System	2021	IoT-enabled sensors connected to cloud platforms for air quality analysis	Improved detection of hazardous pollutants in real time
21	Development of an Internet of Things solution to monitor and analyze indoor air quality	2021	Multi-sensor IoT framework with cloud-based analytics	Improved understanding of indoor air pollution trends
22	An IoT-enabled system for enhanced air quality monitoring and prediction on the edge	2021	Edge computing with IoT sensors for low-latency data processing	Improved responsiveness and reduced cloud dependency
23	Sensors and systems for air quality assessment monitoring and management: A review	2021	Review of sensor networks and IoT frameworks	Identified opportunities for enhanced monitoring
24	LoRaWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring	2022	LoRaWAN with NO2, SO2, CO, and PM2.5 sensors integrated with ThingSpeak	Validated data reliability and system scalability in outdoor settings
25	Smart Air Quality Monitoring IoT-Based Infrastructure for Industrial Environments	2022	Wireless sensor networks integrated with IoT for real-time industrial air quality data	Enhanced industrial pollution monitoring efficiency
26	A low-cost air quality monitoring system based on Internet of Things for smart homes	2022	IoT-based sensors and microcontrollers for cost-effective air quality monitoring in smart homes	Demonstrated affordability and reliability in residential use
27	Remote Air Pollution Monitoring based on Internet of things	2022	Cloud-based IoT architecture using gas and particle sensors for remote monitoring	Improved accessibility and control over air quality data remotely
28	IoT-Based Air Pollution Monitoring System using Raspberry Pi	2022	MQ-series gas sensors integrated with Raspberry Pi for pollution monitoring	Enhanced real-time data analysis for multiple pollutants
29	Design and Implementation of an ML and IoT based Adaptive Traffic Management System for Smart Cities	2022	IoT sensors combined with machine learning to optimize traffic flow and reduce pollution	Adaptive traffic management reduced congestion and pollution
30	Air Quality Monitoring System	2022	Integrated IoT sensors for gas detection	Improved pollution tracking and alerts

31	LSTM-Based IoT-Enabled CO2 Steady-State Forecasting for Indoor Air Quality Monitoring	2023	LSTM model used with IoT sensors to forecast CO2 levels for indoor environments	Improved prediction accuracy for steady-state CO2 monitoring
32	Smart Air Pollution Monitoring System Using IoT and Raspberry Pi	2023	Raspberry Pi-based system with gas sensors for continuous air quality monitoring	Improved accuracy and data processing capabilities
33	IoT-Based Air Quality Monitoring System with Machine Learning for Accurate and Real-Time Data Analysis	2023	Machine learning with IoT deployment	Enhanced real-time forecasting accuracy
34	Performance Evaluation of IoT-Based Air Pollution Monitoring System: A Review	2024	Review of IoT technologies and sensor systems for pollution monitoring	Identified key performance factors and system challenges
35	Real-Time IoT-Powered AI System for Monitoring and Forecasting of Air Pollution in Industrial Environment	2024	AI-driven IoT integration	Forecasting accuracy increased
36	Monitoring and Predicting Air Quality with IoT Devices	2024	Multi-sensor IoT systems with AI	Enhanced pollution alerts and management

Experimental setup

The experimental setup for this study is divided into multiple components. The hardware design involves the development of a framework for air quality monitoring. Sensors capable of detecting pollutants such as CO (Carbon Monoxide), NO2 (Nitrogen Dioxide), SO2 (Sulfur Dioxide), VOCs (Volatile Organic Compounds), and PM2.5 were selected.These sensors are integrated with microcontrollers like Raspberry Pi and Arduino using both wired (I2C, SPI) and wireless (LoRaWAN, Wi-Fi) communication interfaces. The system was designed to be deployed in various environments, including indoor, outdoor, and mobile units, , to cater to different industrial zones. Regular calibration against standard gas concentrations and testing under varying environmental conditions ensured the accuracy and reliability of the sensors.



The software design incorporates preprocessing algorithms to filter noise and normalize the collected data for consistency. Data is transmitted to cloud platforms such as AWS IoT and Azure IoT Hub, ensuring seamless storage and analysis. Real-time alerts are generated when pollutant levels breach predefined thresholds. The output is visualized through real-time dashboards and heatmaps that display trends and provide actionable insights. Predictive models, including CNN and LSTM, were employed for forecasting pollutant concentrations, while Random Forest was used to calculate and classify the Air Quality Index (AQI).

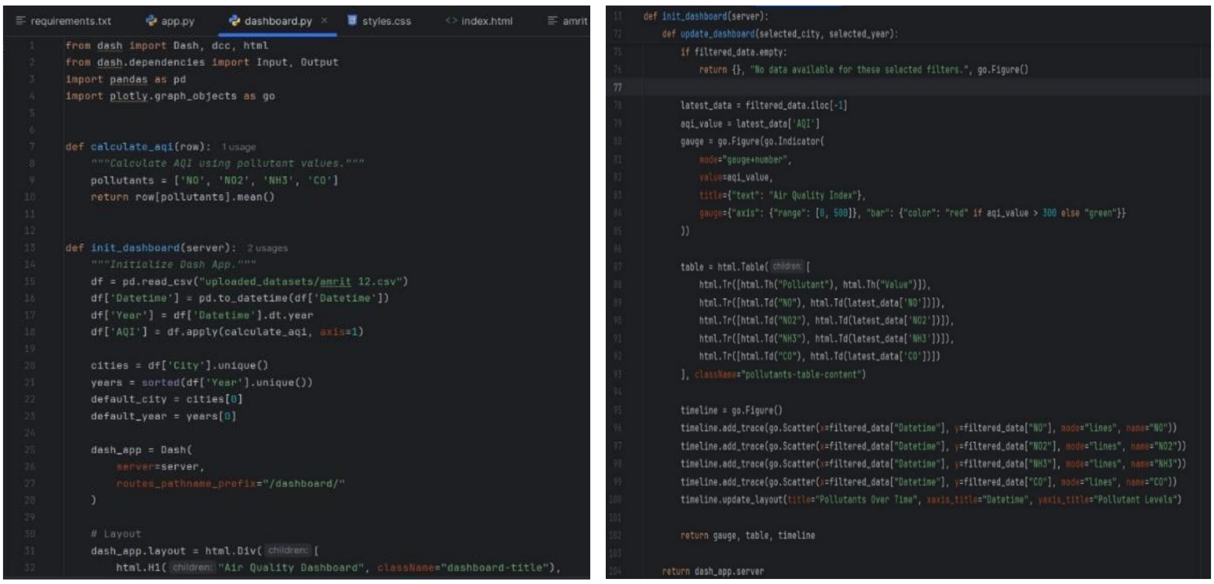


Fig 2: Code Snippets

```html
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0">
    <title>air quality data </title>
    <link rel="stylesheet" href="{{ url_for('static', filename='styles.css') }}">
</head>
<body>

    <!-- Embed Dash app -->
    <iframe src="/dashboard/" width="100%" height="600" style="border:none;"></iframe>
</body>
</html>
```

```python
from flask import Flask, render_template
from dashboard import init_dashboard

# Initialize Flask app
app = Flask(__name__)

# Initialize the Dash app inside Flask
app = init_dashboard(app)

# Home route for rendering the HTML page
@app.route("/")
def index():
    return render_template("index.html")

# Run Flask app
if __name__ == "__main__":
    app.run(debug=True)
```

Fig 3: Code Snippets

The system interface includes a user-friendly dashboard that provides real-time pollutant levels and historical trends. Visualization tools, such as heatmaps and statistical trend analysis, enable users to gain a comprehensive understanding of air quality. Interactive alerts, delivered through LEDs, buzzers, or mobile apps, notify users of hazardous conditions promptly.

Fig 4: Dashboard Tabs

The dataset for this study is of the AQI of Amritsar and comprises real-time air quality data collected using advanced sensors. The monitored pollutants include PM2.5, NO2, SO2, VOCs, and CO. Data was sampled at regular intervals, such as hourly, and stored locally via SD cards or onboard memory. Cloud-based storage was utilized for large-scale analysis. Preprocessing steps included noise filtering to eliminate irregularities and data fusion to compute a comprehensive AQI.

A comparative analysis with similar research highlights the strengths and improvements of the proposed system. A notable study by Waheb A. Jabbar et al. (2022) implemented a LoRaWAN-based IoT system for outdoor air quality monitoring, utilizing NO2, SO2, CO, and PM2.5 sensors integrated with ThingSpeak dashboards. While the study demonstrated scalability, cost-efficiency, and robust data transmission, the proposed system advances these features by integrating predictive analytics using CNN and LSTM models. Additionally, it offers an enhanced user dashboard with real-time visualizations, historical analysis, and the capability to monitor both indoor and outdoor environments. The proposed system thus outperforms prior work in predictive accuracy and actionable insights, providing a significant step forward in real-time air quality monitoring.

Discussion

The reviewed studies emphasize the transformative role of IoT and AI in monitoring air quality across diverse settings, including urban, industrial, and indoor environments. Integration of low cost sensors with IoT infrastructures is a common theme, and applications are being developed to measure inorganics (PM2.5, CO2, NOx, and VOCs). The flexibility of these systems allows them to be applied to a range of situations, ranging in scale from wide area urban monitoring to spatial and temporal targeted industrial pollution control.

One of the most important mining in most papers is the use of machine learning (ML) algorithms to perform predictive analytics. For instance, Banciu et al. (2020) also used random forest models to predict AQI and successfully obtain high accuracy by AQI prediction. In a similar way, Ayele and Mehta (2018) applied LSTM networks for predicting pollution concentrations, demonstrating the convergence between IoT and AI. These advancements enable proactive measures, such as activating exhaust systems before air quality deteriorates, as demonstrated in Ramadan et al. (2024).

Some studies, Tapashetti and Vegiraju (2020) to be noted among them, emphasize the need for real-time visualization of the data and the interactions with the user. Systems like “Oxygen Tocsin” (Jabbar et al., 2020) and “AirProp” (Ng and Dahari, 2020) integrate IoT with mobile applications, enabling immediate alerts for hazardous conditions. This not only empowers users to take timely action but also raises public awareness about air pollution’s health impacts.

Hinder remains in particular areas, such as sensor calibration, network trustworthiness, and data confidentiality. Many studies, such as those by Srivastava et al. (2019) and Kamble et al. (2020) raise these challenges and refine IoT frameworks for reliability and scalability. The integration of LoRaWAN in Jabbar et al. (2020) and Zigbee in Han et al. (2019) exemplifies innovations to enhance communication efficiency.

Although the field has advanced, there remains a need for comprehensive and integrated solutions that incorporate multiple pollutant measurements alongside renewable energy such as solar or wind power for long term sustainable systems. Future directions should focus on multi-source data integration, expanding the scope of AI algorithms for anomaly detection, and improving system robustness for diverse environments.

Conclusion and Future Work

The development of an IoT-enabled real-time air quality monitoring system is a significant step toward addressing the pressing issue of industrial air pollution. This project will combine IoT technology with robust environmental monitoring practices to create a scalable, efficient, and cost-effective solution for industrial zones. By integrating advanced sensors, cloud-based analytics, and real-time alert mechanisms, the proposed system enables continuous monitoring of critical pollutants like PM2.5, NO_2, and SO_2, ensuring timely responses to hazardous air quality condnitions. The system's ability to transmit data in real time to a cloud platform will not only supports visualization and historical analysis but also facilitates compliance with environmental regulations and enhances operational decision-making. This will empower industries to proactively manage emissions, minimize environmental impact, and improve worker safety. Furthermore, the deployment of power-efficient technologies such as Raspberry PI 5 microprocessor and Arduino Uno microcontrollers and renewable energy sources like solar panels ensures the system's sustainability, even in remote or large-scale industrial zones. By addressing challenges such as delayed pollutant tracking and limited spatial coverage of traditional monitoring methods, this project highlights the potential of IoT to revolutionize environmental management. The adoption of this solution can lead to significant improvements in public health, regulatory adherence, and industrial sustainability. Moreover, the incorporation of predictive analytics and scalable network designs provides a foundation for future enhancements, ensuring that this system remains adaptable to evolving environmental and industrial demands.

In conclusion, this IoT-enabled system sets a benchmark in real-time air quality monitoring, demonstrating how technological innovation can align with environmental stewardship to create a healthier and more sustainable industrial ecosystem. By empowering industries with real-time data and analytical tools, this system not only addresses the immediate need for effective air quality management but also inspires a broader movement towards sustainable industrial practices and enhanced environmental protection.

Table 1: Expected Outcomes

Outcome	**Description**
Real-Time Monitoring	Continuous tracking of air quality.
Timely alerts	Immediate notifications for pollution spikes
Regulatory Compliance	Reliable data supports compliance with environmental regulations
Sustainable Operations	Solar-Powered system ensures long-term functionality

Contribution of the Study

This study contributes significantly by integrating IoT with advanced sensor technology, cloud platforms, and predictive analytics to create a comprehensive air quality monitoring solution. It empowers stakeholders, including industries, regulators, and communities, by providing actionable insights through real-time data and automated alerts. The system emphasizes sustainability by incorporating renewable energy sources, such as solar panels, ensuring long-term, environmentally friendly operations. Its modular design allows scalability, making it suitable for deployment across diverse industrial settings, from small manufacturing units to large industrial zones. Furthermore, the generated data supports policymakers in enforcing environmental regulations and promoting sustainable industrial practices.

References

[1] W. A. Jabbar, T. Subramaniam, A. E. Ong, M. I. Shu'Ib, W. Wu, and M. A. De Oliveira, "LORAWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring," *Internet of Things*, vol. 19, p. 100540, 2022. doi: 10.1016/j.iot.2022.100540.

[2] Y. Zhu, S. A. Al-Ahmed, M. Z. Shakir, and J. I. Olszewska, "LSTM-Based IoT-Enabled CO2 Steady-State Forecasting for Indoor Air Quality Monitoring," *Electronics*, vol. 12, no. 1, p. 107, 2022. doi: 10.3390/electronics12010107.

[3] L. García, A. Garcia-Sanchez, R. Asorey-Cacheda, J. Garcia-Haro, and C. Zúñiga-Cañón, "Smart Air Quality Monitoring IoT-Based Infrastructure for Industrial Environments," *Sensors*, vol. 22, no. 23, p. 9221, 2022. doi: 10.3390/s22239221.

[4] M. Taştan, "A Low-Cost Air Quality Monitoring System Based on Internet of Things for Smart Homes," *Journal of Ambient Intelligence and Smart Environments*, vol. 14, no. 5, pp. 351–374, 2022. doi: 10.3233/ais-210458.

[5] A. Palamar, M. Karpinski, M. Palamar, H. Osukhivska, and M. Mytnyk, "Remote Air Pollution Monitoring System Based on Internet of Things," in *Proc. 2022 Int. Conf. IoT and Smart Environments*, 2022.

[6] A. H. Kelechi et al., "Design of a Low-Cost Air Quality Monitoring System Using Arduino and ThingSpeak," *Computers, Materials & Continua*, vol. 70, no. 1, pp. 151–169, 2021. doi: 10.32604/cmc.2022.019431.

[7] K. A., S. M., and E. N., "IoT Enabled Cloud-Based Application for Air Quality Monitoring System-'O2 TOCSIN,'" in *Proc. IEEE*, 2021. doi: 10.4108/eai.7-12-2021.2314720.

[8] J. N. Shrote and J. A. Pawar, "Smart Air Pollution Monitoring System Using IoT and Raspberry Pi," *BioGecko Journal*, vol. 12, no. 2, pp. 1746–1753, 2023.

[9] U. K. Lilhore et al., "Design and Implementation of an ML and IoT-Based Adaptive Traffic-Management System for Smart Cities," *Sensors*, vol. 22, no. 8, p. 2908, 2022. doi: 10.3390/s22082908.

[10] T. P. Truong, D. T. Nguyen, and P. V. Truong, "Design and Deployment of an IoT-Based Air Quality Monitoring System," *Int. J. Environ. Sci. Dev.*, vol. 12, no. 5, pp. 139–145, 2021. doi: 10.18178/ijesd.2021.12.5.1331.

[11] C. B. V., M. A. Y. H., D. K. S., C. P. R. V., and P. I. Dodawad, "A Raspberry-Pi Based Embedded System to Monitor Air and Sound Pollution Using IoT," *Int. J. Innov. Res. Electr., Electron., Instrum. Control Eng.*, vol. 9, no. 7, pp. 92–97, 2021.

[12] N. M. K. Kamble et al., "IoT-Based Air Pollution Monitoring System Using Raspberry Pi," *Int. J. Adv. Res. Sci. Commun. Technol.*, pp. 332–336, 2022. doi: 10.48175/ijarsct-5032.

[13] S. A. Dhumal, M. R. Mule, S. S. Pawar, and S. B. Lande, "Performance Evaluation of IoT-Based Air Pollution Monitoring System: A Review," *Int. Res. J. Modernization Eng. Technol. Sci.*, vol. 6, no. 10, pp. 173–183, 2024.

[14] D. Wall, P. McCullagh, I. Cleland, and R. Bond, "Development of an Internet of Things Solution to Monitor and Analyse Indoor Air Quality," *Internet of Things*, vol. 14, p. 100392, 2021. doi: 10.1016/j.iot.2021.100392.

[15] G. Mani, J. K. Viswanadhapalli, and P. Sriramalakshmi, "AI-Powered IoT-Based Real-Time Air Pollution Monitoring and Forecasting," *J. Phys. Conf. Ser.*, vol. 2115, no. 1, p. 012016, 2021. doi: 10.1088/1742-6596/2115/1/012016.

[16] B. Thiyaneswaran, P. Elayaraja, P. Srinivasan, S. Kumarganesh, and K. Anguraj, "IoT-Based Air Quality Measurement and Alert System for Steel, Material and Copper Processing Industries," *Mater. Today Proc.*, vol. 81, pp. 127–132, 2021. doi: 10.1016/j.matpr.2021.02.696.

[17] J. Saini, M. Dutta, and G. Marques, "Sensors for Indoor Air Quality Monitoring and Assessment Through Internet of Things: A Systematic Review," *Int. J. Environ. Res. Public Health*, vol. 17, no. 14, p. 4942, 2020. doi: 10.3390/ijerph17144942.

[18] A. S. Moursi, N. El-Fishawy, S. Djahel, and M. A. Shouman, "An IoT-Enabled System for Enhanced Air Quality Monitoring and Prediction on the Edge," *Complex Intell. Syst.*, vol. 7, no. 6, pp. 2923–2947, 2021. doi: 10.1007/s40747-021-00476-w.

[19] J. Saini, M. Dutta, and G. Marques, "Sensors for Indoor Air Quality Monitoring and Assessment Through Internet of Things: A Systematic Review," *Int. J. Environ. Res. Public Health*, vol. 17, no. 14, p. 4942, 2020. doi: 10.3390/ijerph17144942.

[20] C. Balasubramaniyan and D. Manivannan, "IoT Enabled Air Quality Monitoring System (AQMS) Using Raspberry Pi," *Indian J. Sci. Technol.*, vol. 9, no. 39, 2016. doi: 10.17485/ijst/2016/v9i39/90414.

[21] A. Tapashetti, D. Vegiraju, and T. Ogunfunmi, "IoT-Enabled Air Quality Monitoring Device: A Low-Cost Smart Health Solution," in *Proc. IEEE GHTC*, 2016. doi: 10.1109/ghtc.2016.7857352.

[22] D. S. Simbeye, "Industrial Air Pollution Monitoring System Based on Wireless Sensor Networks," *Scitech Res. Org.*, vol. 6, no. 2, pp. 612–624, 2017.

[23] N. A. Zakaria, Z. Zainal, N. Harum, L. Chen, N. Saleh, and F. Azni, "Wireless Internet of Things-Based Air Quality Device for Smart Pollution Monitoring," *Int. J. Adv. Comput. Sci. Appl.*, vol. 9, no. 11, 2018. doi: 10.14569/ijacsa.2018.091110.

[24] K. O. Okokpujie, E. Noma-Osaghae, M. Odusami, S. N. John, and O. Oluga, "A Smart Air Pollution Monitoring System," *Scopus*, 2018.

[25] T. W. Ayele and R. Mehta, "Air Pollution Monitoring and Prediction Using IoT," in *Proc. IEEE ICICCT*, 2018, pp. 1741–1745. doi: 10.1109/icicct.2018.8473272.

[26] O. Elijah, T. A. Rahman, I. Orikumhi, C. Y. Leow, and M. N. Hindia, "An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges," *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3758–3773, 2018. doi: 10.1109/jiot.2018.2844296.

[27] C. Srivastava, S. Singh, and A. P. Singh, "IoT-Enabled Air Monitoring System," in *Advances in Intelligent Systems and Computing*, 2019, pp. 173–180. doi: 10.1007/978-981-13-6095-4_13.

[28] Q. Han, P. Liu, H. Zhang, and Z. Cai, "A Wireless Sensor Network for Monitoring Environmental Quality in the Manufacturing Industry," *IEEE Access*, vol. 7, pp. 78108–78119, 2019. doi: 10.1109/access.2019.2920838.

[29] R. Rawal, "Air Quality Monitoring System," *Int. J. Comput. Sci. Eng.*, vol. 9, no. 1, pp. 1–9, 2019. doi: 10.13140/RG.2.2.20471.37282.

[30] K. B. K. Sai, S. R. Subbareddy, and A. K. Luhach, "IoT-Based Air Quality Monitoring System Using MQ135 and MQ7 with Machine Learning Analysis," *Scalable Comput. Pract. Exp.*, vol. 20, no. 4, pp. 599–606, 2019. doi: 10.12694/scpe. v20i4.1561.

[31] S. Ramalingam, K. Baskaran, and D. Kalaiarasan, "IoT Enabled Smart Industrial Pollution Monitoring and Control System Using Raspberry Pi with BLYNK Server," in *Proc. IEEE ICCES*, 2019, pp. 2030–2034. doi: 10.1109/icces45898.2019.9002430.

[32] W. J. Ng and Z. Dahari, "Enhancement of Real-Time IoT-Based Air Quality Monitoring System," *Int. J. Power Electron. Drive Syst.*, vol. 11, no. 1, pp. 390–397, 2020. doi: 10.11591/ijpeds.v11.i1.pp390-397.

[33] T. Glass, S. Ali, B. Parr, J. Potgieter, and F. Alam, "IoT Enabled Low-Cost Air Quality Sensor," in *Proc. IEEE SAS*, 2020, pp. 1–6. doi: 10.1109/sas48726.2020.9220079.

[34] H. Karnati, "IoT-Based Air Quality Monitoring System with Machine Learning for Accurate and Real-Time Data Analysis," *arXiv preprint arXiv:2307.00580*, 2023. doi: 10.48550/arXiv.2307.00580.

[35] M. N. A. Ramadan, M. a. H. Ali, S. Y. Khoo, M. Alkhedher, and M. Alherbawi, "Real-Time IoT-Powered AI System for Monitoring and Forecasting of Air Pollution in Industrial Environment," *Ecotoxicol. Environ. Saf.*, vol. 283, p. 116856, 2024. doi: 10.1016/j.ecoenv.2024.116856.

[36] C. Banciu, A. Florea, and R. Bogdan, "Monitoring and Predicting Air Quality with IoT Devices," *Processes*, vol. 12, no. 9, p. 1961, 2024. doi: 10.3390/pr12091961.