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Revitalizing IoT-based air quality monitoring system for major cities in Indonesia

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Abstract

An IoT-based air quality monitoring system is a technology that integrates with the internet to monitor and measure numerous air quality metrics in real-time. CO levels, dust particle levels, temperature, and humidity are the air quality characteristics that must be monitored. The air quality monitoring system in its current state requires further development, such as challenges to acquiring accurate and real-time data and difficulty in accessing reliable information. Poor air quality causes various health problems, respiratory, vision, heart disease, and even cancer. The development of air pollution producers continues to increase along with the number of oil-fueled vehicles, industries operated using petroleum-fueled engines, power plants that use energy from coal, gas and petroleum. This study presents an IoT-based air quality parameter monitoring system solution that is connected with the Blynk platform and can be accessible in real time, in an effort to assist the SDGs program, which is mandated by the global community through the UN. The research technique employed is Analysis, Design, Development, Implementation, and Evaluation. The study successfully presented an IoT-based air quality monitoring system connected with the Blynk platform, which showed great accuracy in measurement 94.34% (CO), 81.15% (dust), 99.14% (temperature), and 96.84% (humidity). These results advance urban air quality monitoring and inform sustainable technology development, contributing to environmental and health-related SDGs.

Keywords:
ADDIE Analysis;
Air Quality Monitoring;
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Public Health;
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INTRODUCTION

In recent decades, air quality has emerged as an increasingly critical environmental concern [1]. Technological advancements in the 5.0 era, along with an increase in population, industrial expansion, and other human activities, have produced an increase in air pollution in many locations throughout the world [2]. This can cause a decrease in air quality which contains air pollutants such as fine particles, dangerous chemicals and gas emissions which have serious impacts on health problems, including respiratory problems, vision problems, heart disease and even cancel [3][4]. Air quality monitoring is very necessary as information about whether the air is healthy or contains dangers, this will increase awareness of the need to monitor air quality levels and take steps to overcome them [5][6].

Much research has been conducted to build effective and integrated monitoring systems in order to overcome air quality issues [7][8]. This study provides a low-cost air quality monitoring system based on the ESP32 microcontroller, drawing on several discoveries from earlier research on air quality monitoring systems [9]. This system measures pollutant concentrations in the air using a variety of sensors. The acquired data is subsequently transferred to a cloud-based server, where it is presented in real time and utilized to generate alerts and notifications. However, in this study, the system devised was not as precise as some of the other systems available. The sensors utilized are not calibrated, and the data is not processed using any algorithm to improve accuracy. Next, this paper offers a WSN system for air quality monitoring that uses multiple sensors to assess pollutant concentrations in air [10]. The collected data is subsequently transferred to a central server, where it is presented in real time. This system is scalable and may be used to monitor air quality in a variety of settings, including big cities, small towns, and rural locations. However, the disadvantage of this research is that it is unable to add additional installed sensors without changing the existing network [11].

Significant swings in air pollution levels have occurred, particularly in Bandung, one of Indonesia's most populated cities, with documented PM2.5 levels changing greatly. Individuals who are susceptible to airborne contaminants, such as youngsters, the elderly, and those with specific medical problems, may suffer significant health consequences as a result of these pollution levels. Air pollution in Bandung is mostly caused by pollutants from motor vehicles, industries, and construction [12]. This shows the importance of this research in developing solutions to improve air quality monitoring and management in big cities like Bandung.

CO levels, dust particle levels, temperature, and humidity are all air quality characteristics that need to be monitored [13]. However, the air quality monitoring system in present settings still has various shortcomings, such as hurdles to acquiring accurate and real-time data and problems with accessing precise and accurate information [14]. This research presents an air quality monitoring system solution with measurable parameters, notably CO levels, dust particle levels, temperature, and humidity based on the Internet of Things that is connected with the Blynk platform and can be useful in real-time and correctly. This research is a real attempt to assist the Sustainable Development Goals (SDGs), an agenda required by the global community through the United Nations. This research encompasses multiple themes from the vision and goal of the SDG agenda, including excellent health and well-being (point 3); industry, technologies, and infrastructure (point 9); sustainable cities and communities (point 11); climate action (point 13); and life on land (point 15).

In addressing the challenges of air quality monitoring, past research has identified several limitations in existing air quality monitoring systems, including limitations in scale, cost, and accuracy [15]. Highlighted that conventional air quality monitoring systems are often limited by fixed infrastructure that is expensive and difficult to expand to new regions [16]. Adding that many existing systems lack in providing real-time data, which is critical for rapid response to changing air conditions [17]. These conclusions emphasize the need for more flexible, cost-effective, and accurate solutions, which can be implemented in a variety of urban environments.

Given these restrictions, this study intends to build and implement an IoT-based air quality monitoring system that not only overcomes cost and scalability limits, but also enhances the accuracy and availability of real-time data. The suggested system, which uses the ESP32 microcontroller and the Blynk platform, provides an easy-to-implement and extendable framework for more comprehensive and rapid air quality monitoring. The primary goal of this study is to show how an innovative system design may significantly enhance air quality monitoring, therefore enabling data-driven choices for public health and environmental policy.

METHOD

Method Research

This study's research technique is the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) model, a systematic methodology generally acknowledged for its efficiency in developing technical tools as presented in Figure 1 [18]. This strategy stresses iterative feedback and continual improvement, which are critical in the context of designing an IoT-based air quality monitoring system.

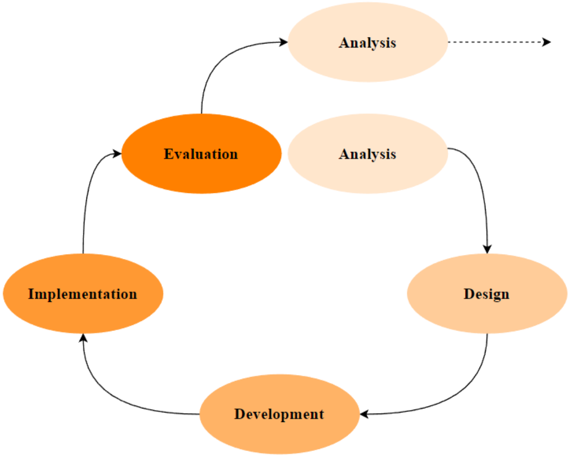

Figure 1. Research Method

This initial phase includes a thorough assessment of current literature on air quality monitoring systems. Sources such as peer-reviewed articles, authoritative books, and technical reports were meticulously selected based on their relevance, currency, and scientific contribution to the topic. The analysis focused on identifying the need for innovative solutions capable of overcoming the limitations of existing systems, particularly in terms of real-time data accuracy and accessibility [19].

The design phase aimed to create a scalable and cost-effective system with a user-friendly interface. To achieve this, we developed a system architecture that integrates various components such as sensors for CO, dust particulates, temperature, and humidity levels. The design process also included the creation of block diagrams to visually represent the system's workflow and component interactions [20].

In the development phase, the design was transformed into a functional prototype. The system was constructed utilizing the ESP32 microcontroller and coupled with the Blynk platform to ensure real-time data transfer and processing. Throughout this stage, the team addressed numerous challenges, including sensor calibration and data integrity assurance.

The fully developed system was then implemented in a real-world urban setting to monitor air quality. This phase involved not only the physical installation of the system but also the configuration of software and network connections to facilitate seamless data transmission and accessibility for end-users.

The final phase involved a rigorous evaluation of the system's performance. Accuracy was assessed by comparing sensor readings with standard measurement instruments, and the system's responsiveness was tested under various environmental conditions. The review procedure was critical in identifying areas for improvement and verifying the system's preparedness for broad deployment [21].

Bibliometric Analysis Research

In this study, bibliometric analysis was performed to assess the position of the research to be carried out based on the findings of prior studies and to examine the innovation that develops from this research [22][23]. VOSviewer provides for the display and mapping of prior research using data from the Scopus database as shown in Figure 2. To understand the progress of research connected to this issue, we analyzed 200 publications from 2015-2023 with the main topic of "Air Quality Monitoring System" from the Scopus database [24][25]. Figure 3 depicts one of the clusters, specifically the first cluster using the keyword "Air Quality Monitoring System" as the major focus of this study.

To further understand the innovation and improvements presented by this study, we conducted a comparison analysis that highlighted the distinguishing aspects and developments of our IoT-based air quality monitoring system. Unlike previous systems that frequently rely on complicated and costly infrastructure, our solution utilizes the ESP32 microcontroller, which is known for its strong performance and cost effectiveness, paired with the Blynk platform for an easy user interface.

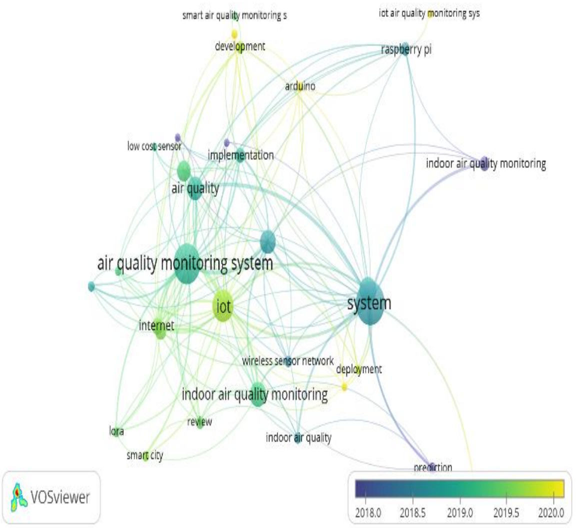

Figure 2. Shows the visualization results using VOSViewer for the primary topic Air Quality Monitoring

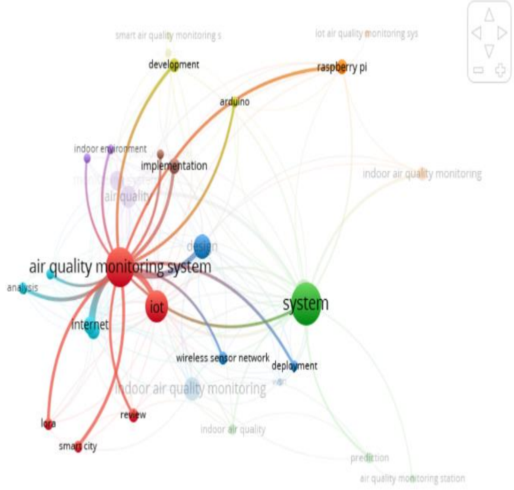

Figure 3. Visualization results using VOSViewer with the primary subject first cluster

This integration not only significantly reduces the overall system cost but also simplifies installation and maintenance, making it highly accessible for urban areas in developing countries.

Our system's adaptive algorithm for real-time data processing and calibration is a remarkable breakthrough that solves one of the main issues in air quality monitoring: the fluctuation of ambient variables. Furthermore, our system introduces a modular design, allowing for seamless integration of additional sensors to monitor a broader range of pollutants, without necessitating significant modifications to the existing setup. This flexibility is pivotal for adapting to the evolving urban pollution landscape and regulatory requirements.

In summary, the enhancements and innovations of our air quality monitoring system lie in its cost-effectiveness, scalability, and advanced data processing capabilities. These attributes represent a significant leap forward in democratizing air quality monitoring, making it more accessible and effective for communities worldwide, especially in resource-constrained settings.

Process Sensor Characterization

Many devices or tools use basic electrical principles in their operation, and almost all data collection, transmission, and analysis systems depend on electronic devices. In this case, monitoring air quality requires measuring CO levels, dust particulates, temperature and humidity remotely and recording them, requiring a sensor or transducer to be installed at the location you want to observe, and this device converts what is measured into electrical voltage. appropriate. This voltage is then sent to the receiving station, where it is displayed in a suitable manner. Each step in this process involves the use of electrical devices.

While the datasheet provides the basic characteristics of the sensor, direct field testing is required to validate its performance under real conditions, which often differ from laboratory conditions. Sensor characterization in the field ensures data accuracy and reliability for air quality monitoring applications, which are critical in decision-making related to public health and environmental policy. Therefore, this sensor characterization process not only follows datasheet standards but also involves empirical testing to evaluate sensor performance under varying environmental conditions [26].

Sensor characterisation was performed on all three sensors utilized in this study. This characterisation uses sensor data from the MQ-2, GP2Y1010AU0F, and DHT22 sensors.

The MQ-2 sensor measures CO levels in the air by converting the 10-bit ADC data received by the ESP32 analog input pin to a concentration measurement in ppm units. The first step is to determine the output voltage from the MQ-2 sensor using (1) [27].

$$V_{RL} = \frac{Sensor\ Value\ x\ 3.3\ v}{1023} \tag{1}$$

Convert the output voltage of the MQ-2 sensor into ppm units, by looking at the graph of the relationship between the output voltage and parts per million (ppm) on the MQ-2 sensor.

Based on Figure 4, to get the ppm value on the MQ-2 sensor, it is obtained using (2) [28].

$$CO\ (ppm) = 3.027 * \ e^{(1.0698 * V_{RL})} \tag{2}$$

The GP2Y1010AU0F sensor, used to measure the level of dust particulates, is connected to the microcontroller analog pin to be converted into a 10 bit ADC value according (2) obtained (3).

$$V_o\ (Volt) = \frac{value\ sensor \times 3.3\ V}{1023} \tag{3}$$

The resulting output voltage is then converted to dust units (mg/m^3) by referring to the sensor calibration graph in Figure 5 and (5) [29].

$$particulate\ dust\ \left({}^{mg}/{}_{m^3}\right) = 0.17 * \ Voltage\ (Volt) - 0.1 \tag{5}$$

The DHT22 sensor is used to monitor temperature and humidity levels in an area. This sensor's output includes 8 bits of integer humidity data, 8 bits of humidity decimal data, 8 bits of temperature integer data, and 8 bits of temperature fractional data. Figure 6 shows the digital signal produced on the DHT22 sensor.

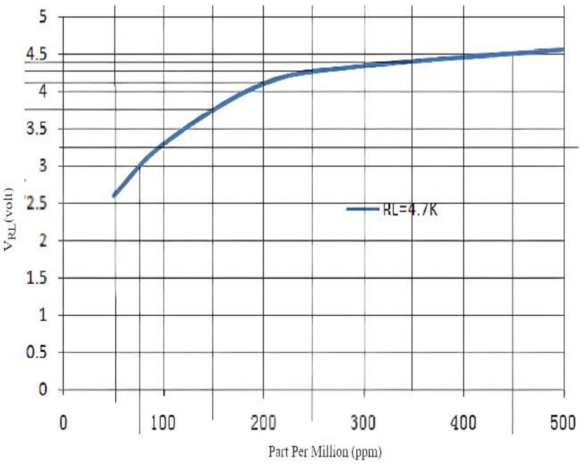

Figure 4. Relation VRL with part per million (ppm)

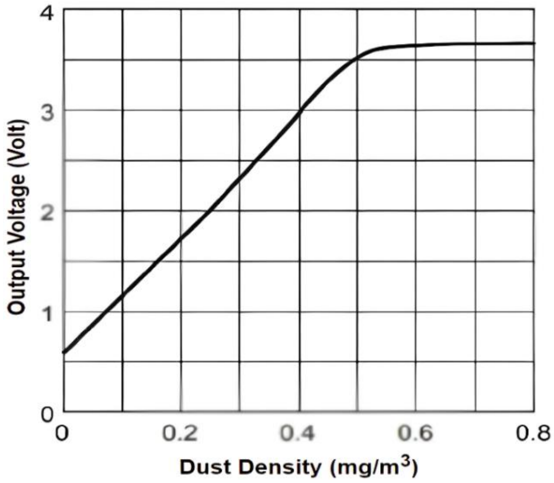

Figure 5. Graph V_O to mg/m^3

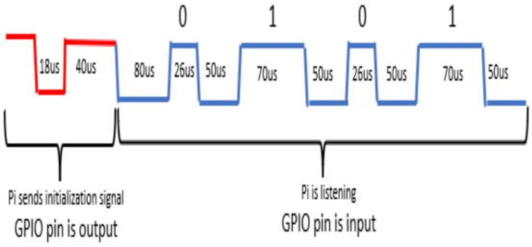

Figure 6. Digital output signal from DHT22 sensor

To convert the output from the output voltage value produced by the DHT22 sensor, the following (6) is obtained [30].

$$V_o\ (Volt) = \frac{value\ sensor \times 3.3\ V}{255} \tag{6}$$

The properties of each sensor employed are required to evaluate performance, including accuracy. The initial round of testing is designed to determine the amount of sensor accuracy [31]. In the context of measurement, precision is a crucial factor that might influence the quality of the instrument being built. Tests are conducted by comparing the sensor to standard instruments. The results of this comparison will generate an error value determined using (7).

$$Error = \left| \frac{standard\ value - test\ value}{standard\ value} \right| \tag{7}$$

The sensor must then be tested to determine its accuracy with each use. This test is performed to determine the extent to which the sensor can deliver consistent data on a certain scale in repeated measurements [32]. This precision test is carried out by calculating the standard deviation of each sensor tested.

$$\sigma = \frac{\sqrt{\sum_{i=1}^{n}(x_i - x)}}{(n-1)} \tag{8}$$

Architecture System

In designing an effective air quality monitoring system, several important components must be considered so that it can meet the needs for optimal use [33]. Figure 7 is a representation of the designed system architecture.

The air quality monitoring system includes numerous key components, including the use of sensors as air quality measuring parameters to collect data, as well as the use of the ESP32 microcontroller to analyze the data collected from each sensor in real time [34]. Then internet access also becomes a crucial component. By connecting the system to the internet, the data acquired and processed is then saved on the Blynk cloud service, where the data may be later shown to consumers via the device [35].

Flowchart System

The system process flow or flowchart for the planned air quality monitoring system tool. This flowchart is a visual depiction of the actions that the system takes to monitor and create the appropriate air quality information data [36]. Figure 8 shows the system flowchart.

The flowchart depicted can elucidate the functioning of the devised air quality monitoring tools. The procedure begins with the tool's activation and preparation for the device that will be used, whether it is a personal computer or smartphone. Following that, each critical variable for air quality monitoring is initialized, followed by the configuration of communication settings on the Blynk platform, which includes setting up the API, SSID, and password to guarantee the tools' real-time integration with Blynk application.

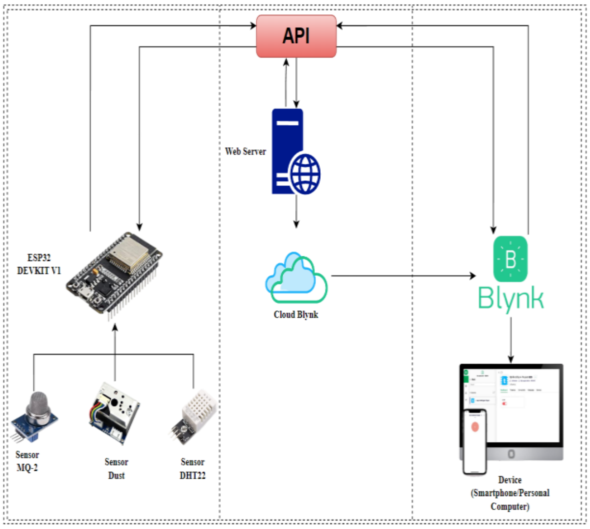

Figure 7. Architecture System

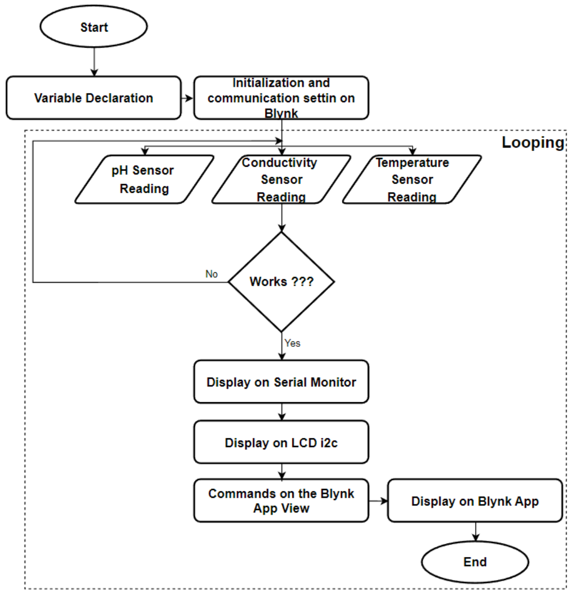

Figure 8. Flowchart System Prototype

The system employs three sensor components, including the MQ-2 sensor for CO level detection, a dust sensor for particulate matter (PM) assessment, and the DHT22 sensor for temperature and humidity measurements. These sensors survey the environment and relay the data to the ESP32 microcontroller, which interprets the values generated [37][38].

The "Works?" decision point in the flowchart serves as a crucial verification stage, where the system determines if the sensor readings are within acceptable ranges. This step ensures data accuracy before presentation. Should the data fail to meet the set standards, corrective actions such as sensor recalibration or adjustments to the processing algorithms are undertaken. Once validated, the accurate sensor readings are displayed on an i2c LCD screen and transmitted to the Blynk platform. Through the Blynk application, users can access comprehensible and actionable air quality information.

RESULTS AND DISCUSSION

Block Diagram System

This study generated a block diagram of an air quality monitoring system. The block diagram consists of three basic blocks: input, process, and output. Each block has a particular function [39][40]. The block diagram design can be seen in Figure 9 which is interconnected between input, process and output blocks to produce one output.

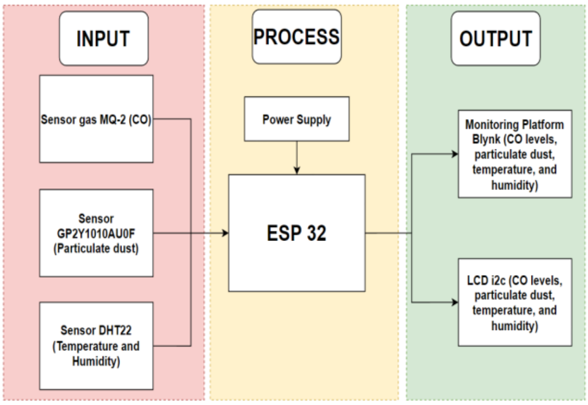

Figure 9. Block Diagram System

Hardware System Design

On the tools air quality monitoring system, its operation requires a 3.3 – 5 volt DC voltage source using USB Type-CF. Figure 10 shows a circuit schematic tool planned.

Prototype Design Specification

The tool is developed to meet particular requirements for the combination of sensors used to detect the relevant air quality metrics. The study's characteristics were CO levels, dust particles, temperature, and humidity. Figure 11 shows a tool that has been planned.

This prototype integrates numerous sensors and their components to create an air quality monitoring system, can be seen in Figure 11. Component (1) shows an arrow with an ESP32 microcontroller as the main processor that takes sensor input, interprets data, and transfers it for display and recording. Component (2) is a temperature and humidity sensor that measures environmental temperature and humidity levels.

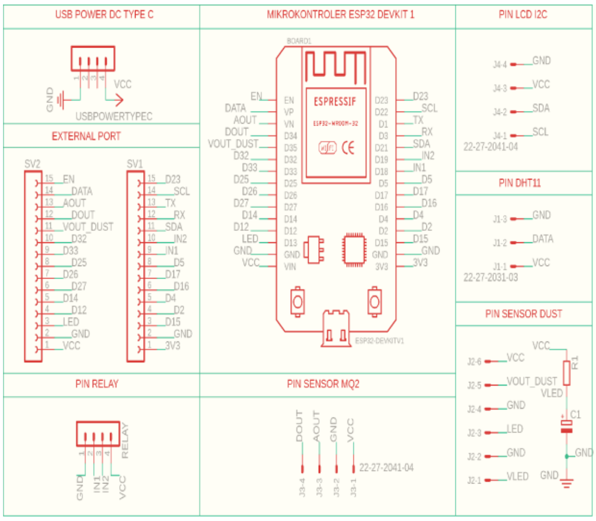

Figure 10. Schematic tool designed

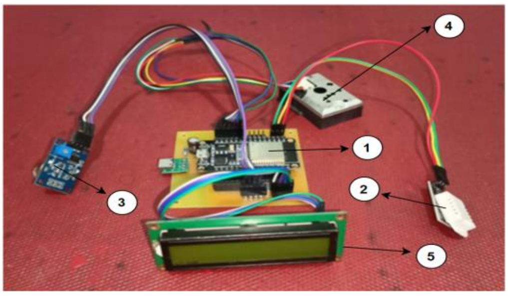

Figure 11. Prototype Design Air Quality Monitoring System

Component (3) is the MQ-2 CO sensor, which detects the level of CO in the air and sends data to the microcontroller. Component (4) is a dust particle sensor that determines the concentration of dust particles in the air. While component (5), an LCD displaying real-time air quality values for instant observation. Table 1 provides a quick reference to the key specifications of the air quality monitoring system prototype. The table lists dimensions, operational ranges for air quality, temperature, humidity, power requirements, and sensitivity levels for the pollutants detected by the prototype, ensuring clarity on its functional parameters and design.

Sensor Analysis

Testing of sensor characteristics carried out in this research focused on testing the accuracy of the three sensors used. The method used to calculate accuracy is repetition [41]. Condition testing is carried out when conditions detect interference with the three sensors used [42]. The data obtained from each sensor was obtained by testing repeatedly until 10 data were obtained from each sensor. Table 2 provides the test results for all sensors. Based on the data summarized in Table 2, all sensors used when carrying out accuracy tests have good accuracy in detecting conditions.

Table 1. Prototype Design Specifications

Specification	Description
Board measures	7 cm by 7 cm
Air quality ranges	from 200 to 10000 ppm
Temperature range	--40°C to 80°C with precision of ±0.5°C
Humidity range	0% to 100% with accuracy of ±2%
Power Supply	5V / 500mA
Sensitivity	500 ppm (CO levels) and 0.5V/(0.1 mg/m^3)

Table 2. Measured Sensor Characteristic

Sensor	Average Error	Accuracy (%)	Standard Deviation
CO levels	0.06	94.34%	175.48
Particulate dust	0.26	81.15%	801.76
Temperature	0.01	99.14%	0.32
Humidity	0.03	96.84%	2.18

Data from Observation

Data collected from these three sensors may be monitored and analyzed using the Blynk platform and the parameters employed, which include CO levels, dust particles, temperature, and humidity in the air. Figure 12 shows a depiction of the Blynk platform that has been created.

Testing is carried out by repeated testing under different conditions, where the first condition is under normal conditions (sterile air) and the second condition is when a disturbance is detected (non-sterile air). The purpose of observing this data is to see the changes that occur from time to time obtained through testing 10 times in two different conditions. Figure 13-Figure 16 depicted the results obtained from the observation data that has been carried out. Figure 13 traces CO levels, where detecting conditions reveal a consistent increase over time. Dust particle variations are captured in Figure 14, with detection conditions showing intermittent spikes, suggestive of air quality degradation. Temperature data in Figure 15 indicates a modest fluctuation under detecting conditions, pointing to potential environmental impacts on thermal stability. Lastly, Figure 16 plots humidity levels, which display more pronounced changes with detected air disturbances, underscoring the prototype's responsiveness to varying air quality conditions.

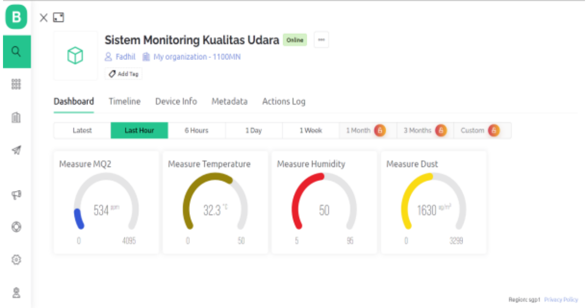

Figure 12. Dashboard Monitoring on the Blynk Platform

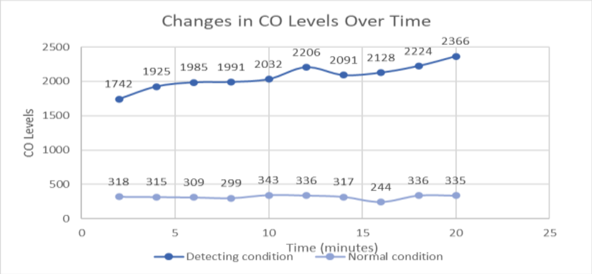

Figure 13. Observation data for CO levels over time

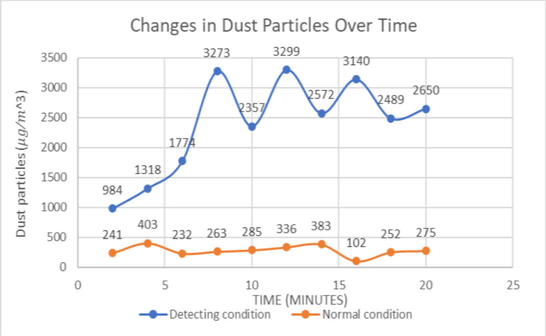

Figure 14. Observation data for dust particles over time

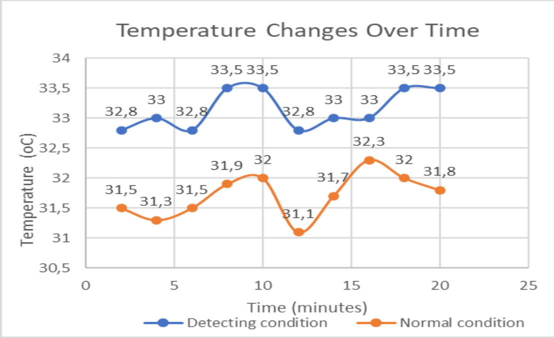

Figure 15. Temperature observation data over time

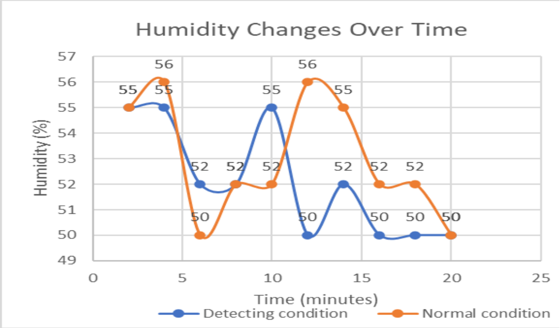

Figure 16. Humidity observation data over time

Comparison with the Air Quality Index (AQI) from the United States Environmental Protection Agency (EPA) was performed using the prototype's data on CO levels and dust particles, as detailed in Table 3. This table aligns the prototype's readings with the EPA's AQI categories. An AQI of 0-50 correlates with 'Good' air quality, indicating CO levels up to 0.1 PPM and dust concentrations up to 75 mg/m^3, which pose minimal risk. AQI values of 51-100 are 'Moderate'; 101-150 are considered 'Unhealthy for sensitive groups' with increasing concentrations of pollutants.

Table 3. Index of Parameters Measured on the Prototype

Value of Index AQI EPA's (PPM)	CO Concentration Range (PPM)	Dust Particles Range (mg/m^3)	Level of Concern
0 – 50	0.1	0 – 75	Good
51 – 100	0.5 – 5	75 – 150	Moderate
101 – 150	5 – 15	150 – 300	Unhealthy for sensitive groups
151 – 200	100 – 200	300 – 1050	Unhealthy
201 – 300	5000	1050 – 3000	Very Unhealthy
301 than higher	7000	3000 than higher	Hazardous

For AQI values of 151-200, the air quality is deemed 'Unhealthy'; 201-300 is 'Very Unhealthy'; and an AQI over 301 signifies 'Hazardous' conditions with serious health implications. The EPA's AQI provides a framework for assessing the health risks associated with the air quality measured by the prototype [43].

Data Transmission Test

System testing is performed by designing a tool that employs three separate sensors, each of which is attached to a specially constructed board. This test, which connects the Blynk platform to the NodeMCU ESP32 as a microcontroller capable of connecting to Wi-Fi on the user's device, measures the latency between the user, the server, and the installed sensors [44]. Aside from this, it is also used to measure server response on the monitoring display provided on the Blynk platform with a specified internet speed range.

The "Data Transmission Test" part in Table 4 demonstrates how Wi-Fi internet speed and user internet speed affect system latency. These findings are critical for better understanding the real-time functioning of an IoT-based air quality monitoring system. To offer a larger perspective and demonstrate the relevance of our research, we compare our results to similar past studies.

An IoT-based air quality monitoring system was found to have an average delay of 2 seconds at comparable internet speeds [45]. Similarly, a study reported an average delay of 1.8 seconds under similar network conditions [46]. Compared to these findings, our system shows significant improvement in response time, with the lowest delay reaching 0.8 seconds under optimized conditions. This suggests that optimizations in the system design and integration with the Blynk platform contribute to higher data transmission efficiency.

Table 4. Data Transfer of the Prototype on the Blynk Platform

WiFi internet speed (MBps)	User internet speed (MBps)	Delay time (s)
21 – 30	11 – 15	0.8
11 – 20	6 – 10	1
0 – 10	0 – 5	1.5

Furthermore, the improvements in delay that we achieved not only increase the reliability of the system in providing real-time data but also open up possibilities for wider implementation in environmental monitoring applications that require fast response. As such, our findings make a significant contribution to the improvement of air quality monitoring technology, underscoring the importance of data transmission efficiency in IoT-based system design.

CONCLUSION

This study successfully built and deployed an IoT-based air quality monitoring system that integrates with the Blynk platform, providing an effective and unique solution for real-time air quality monitoring. The system is capable of monitoring essential air quality parameters such as CO, particle dust, temperature, and humidity with specifications including a range of CO levels from 200 to 10000 ppm, temperature range that can be detected from -40°C to 80°C, detectable humidity range from 0% to 100%. With a high level of accuracy in detecting air quality conditions (CO: 94.34%, dust: 81.15%, temperature: 99.14%, humidity: 96.84%), the system enables accurate and reliable data collection, assisting in making informed decisions to address air pollution and protect public health. These findings emphasize the importance of advanced air quality monitoring technologies in understanding and addressing environmental and health challenges. In addition, this study offers a foundation for further development, including the addition of sensors for additional air quality parameters, supporting ongoing efforts in green technology and public health. These results contribute to the broader goal of achieving sustainable development and public well-being.

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REFERENCES

[1] J. Huang *et al.*, “A Crowdsource-Based Sensing System for Monitoring Fine-Grained Air Quality in Urban Environments,” *IEEE Internet Things J*, vol. 6, no. 2, pp. 3240–3247, 2019, doi: 10.1109/JIOT.2018.2881240.

[2] S. Esfahani, P. Rollins, J. P. Specht, M. Cole, and J. W. Gardner, “Smart City Battery Operated IoT Based Indoor Air Quality Monitoring System,” in *2020 IEEE SENSORS*, 2020, pp. 1–4. doi: 10.1109/SENSORS47125.2020.9278913.

[3] H. Zhang, R. Srinivasan, and V. Ganesan, “Low cost, multi-pollutant sensing system using raspberry pi for indoor air quality monitoring,” *Sustainability (Switzerland)*, vol. 13, no. 1, pp. 1–15, Jan. 2021, doi: 10.3390/su13010370.

[4] N. S. Baqer, H. A. Mohammed, and A. S. Albahri, “Development of a real-time monitoring and detection indoor air quality system for intensive care unit and emergency department,” *Signa Vitae*, vol. 19, no. 1, pp. 77–92, 2023, doi: 10.22514/sv.2022.013.

[5] 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 and Intelligent Systems*, vol. 7, no. 6, pp. 2923–2947, Dec. 2021, doi: 10.1007/s40747-021-00476-w.

[6] W.-T. Sung and S.-J. Hsiao, “Building an indoor air quality monitoring system based on the architecture of the Internet of Things,” *EURASIP J Wirel Commun Netw*, vol. 2021, no. 1, p. 153, 2021, doi: 10.1186/s13638-021-02030-1.

[7] J. González-Martín, N. J. R. Kraakman, C. Pérez, R. Lebrero, and R. Muñoz, “A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control,” *Chemosphere*, vol. 262, p. 128376, 2021, doi: 10.1016/j.chemosphere.2020.128376.

[8] P. Manikandan, B. N. K. Reddy, M. V Bhanu, G. Ramesh, and V. P. Reddy, “IoT Based Air Quality Monitoring System with Email Notification,” in *2021 6th International Conference on Communication and Electronics Systems (ICCES)*, 2021, pp. 616–620. doi: 10.1109/ICCES51350.2021.9489027.

[9] M. Taştan, “A low-cost air quality monitoring system based on Internet of Things for smart homes,” *J Ambient Intell Smart Environ*, vol. 14, no. 5, pp. 351–374, 2022, doi: 10.3233/AIS-210458.

[10] M. Godase and M. K. Bhanarkar, “WSN Node for Air Pollution Monitoring,” in *2021 6th International Conference for Convergence in Technology (I2CT)*, 2021, pp. 1–7. doi: 10.1109/I2CT51068.2021.9418058.

[11] D. N. Paithankar, A. R. Pabale, R. V. Kolhe, P. William, and P. M. Yawalkar, “Framework for implementing air quality monitoring system using LPWA-based IoT technique,” *Measurement: Sensors*, vol. 26, p. 100709, 2023, doi: 10.1016/j.measen.2023.100709.

[12] M. Adrian, P. Lestari, F. Iskandar, and M. M. Munir, “The Impact of Public Activity Restriction during COVID-19 to Air Quality in Urban Area of Bandung Measured Using Mobile Monitoring,” *Aerosol Air Qual Res*, vol. 23, no. 3, p. 220215, 2023, doi: 10.4209/aaqr.220215.

[13] É. Lutz and P. C. Coradi, “Applications of new technologies for monitoring and predicting grains quality stored: Sensors, Internet of Things, and Artificial Intelligence,” *Measurement*, vol. 188, p. 110609, 2022, doi: 10.1016/j.measurement.2021.110609.

[14] 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 (Netherlands)*, vol. 19, Aug. 2022, doi: 10.1016/j.iot.2022.100540.

[15] X. Dai, W. Shang, J. Liu, M. Xue, and C. Wang, “Achieving better indoor air quality with IoT systems for future buildings: Opportunities and challenges,” *Science of The Total Environment*, vol. 895, p. 164858, 2023, doi: 10.1016/j.scitotenv.2023.164858.

[16] S. R. Laha, B. K. Pattanayak, and S. Pattnaik, “Advancement of Environmental Monitoring System Using IoT and Sensor: A Comprehensive Analysis,” *AIMS Environ Sci*, vol. 9, no. 6, pp. 771–800, 2022, doi: 10.3934/environsci.2022044.

[17] J. Buelvas, D. Múnera, D. P. Tobón V, J. Aguirre, and N. Gaviria, “Data Quality in IoT-Based Air Quality Monitoring Systems: a Systematic Mapping Study,” *Water, Air, and Soil Pollution*, vol. 234, no. 4. Institute for Ionics, Apr. 01, 2023. doi: 10.1007/s11270-023-06127-9.

[18] J. Kustia, D. Fahrizal, and I. Surya, “Mecha-Learn: Innovative Learning Media for Mechatronics to Improve Technological in the SDGs Era,” 2024, pp. 502–510. doi: 10.2991/978-2-38476-198-2_69.

[19] J. Kustija, A. U. Afifah, D. Fahrizal, and I. Surya, “Solutions to Improve Performance of IoT-Based Air Quality Monitoring System to

Achieve The Sustainable Development Goals in Indonesian," *E3S Web of Conferences*, vol. 484, p. 03006, Feb. 2024, doi: 10.1051/e3sconf/202448403006.

[20] J. Kustija and N. D. Jayanto, "IoT Implementation for Development of Remote Laboratory (Case Study on Microscope Practice)," *REKA ELKOMIKA: Jurnal Pengabdian kepada Masyarakat*, vol. 3, no. 1, pp. 20–29, Jan. 2022, doi: 10.26760/rekaelkomika.v3i1.20-29.

[21] J. Kustija, I. Surya, and D. Fahrizal, "Electrical Energy Savings By Utilizing Internet-Based Automatic Monitoring And Control of Things," *International Journal of Engineering Applied Sciences and Technology*, vol. 7, no. 10, pp. 144–150, Feb. 2023, doi: 10.33564/IJEAST.2023.v07i10.020.

[22] J. Saini, M. Dutta, and G. Marques, "A comprehensive review on indoor air quality monitoring systems for enhanced public health," *Sustainable Environment Research*, vol. 30, no. 1. BioMed Central Ltd, 2020. doi: 10.1186/s42834-020-0047-y.

[23] A. Kumar, M. Kumari, and H. Gupta, "Design and Analysis of IoT based Air Quality Monitoring System," in *2020 International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC)*, 2020, pp. 242–245. doi: 10.1109/PARC49193.2020.236600.

[24] D. Singh, M. Dahiya, R. Kumar, and C. Nanda, "Sensors and systems for air quality assessment monitoring and management: A review," *J Environ Manage*, vol. 289, p. 112510, 2021, doi: 10.1016/j.jenvman.2021.112510.

[25] F.-C. Adochiei *et al.*, "Electronic System for Real-Time Indoor Air Quality Monitoring," in *2020 International Conference on e-Health and Bioengineering (EHB)*, 2020, pp. 1–4. doi: 10.1109/EHB50910.2020.9280192.

[26] A. Adriansyah, M. H. Budiutomo, H. Hermawan, R. I. Andriani, R. Sulistyawan, and A. U. Shamsudin, "Design of water level detection monitoring system using fusion sensor based on Internet of Things (IoT)," *SINERGI*, vol. 28, no. 1, pp. 191–198, 2024, doi: 10.22441/sinergi.2024.1.019.

[27] P. D. Potbhare, K. Bhange, G. Tembhare, R. Agrawal, S. Sorte, and P. Lokulwar, "IoT based Smart Air Pollution Monitoring System," in *2022 International Conference on Applied Artificial Intelligence and Computing (ICAAIC)*, 2022, pp. 1829–1834. doi: 10.1109/ICAAIC53929.2022.9792743.

[28] S. Listyarini, L. Warlina, and A. Sambas, "The Air Quality Monitoring Tool Based on Internet of Things to Monitor Pollution Emissions Continuously," *Environment and Ecology Research*, vol. 10, no. 6, pp. 824–829, Dec. 2022, doi: 10.13189/eer.2022.100616.

[29] M. Ghamari, C. Soltanpur, P. Rangel, W. A. Groves, and V. Kecojevic, "Laboratory and field evaluation of three low-cost particulate matter sensors," *IET Wireless Sensor Systems*, vol. 12, no. 1, pp. 21–32, Feb. 2022, doi: 10.1049/wss2.12034.

[30] Sunardi, A. Yudhana, and Furizal, "Tsukamoto Fuzzy Inference System on Internet of Things-Based for Room Temperature and Humidity Control," *IEEE Access*, vol. 11, pp. 6209–6227, 2023, doi: 10.1109/ACCESS.2023.3236183.

[31] P. Megantoro, S. A. Aldhama, G. S. Prihandana, and P. Vigneshwaran, "IoT-based weather station with air quality measurement using ESP32 for environmental aerial condition study," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 19, no. 4, pp. 1316–1325, 2021, doi: 10.12928/TELKOMNIKA.v19i4.18990.

[32] R. Chauhan, H. Kaur, and B. Alankar, "Air Quality Forecast using Convolutional Neural Network for Sustainable Development in Urban Environments," *Sustain Cities Soc*, vol. 75, p. 103239, 2021, doi: 10.1016/j.scs.2021.103239.

[33] J. Tryner *et al.*, "Design and testing of a low-cost sensor and sampling platform for indoor air quality," *Build Environ*, vol. 206, Dec. 2021, doi: 10.1016/j.buildenv.2021.108398.

[34] G. Marques, J. Saini, M. Dutta, P. K. Singh, and W. C. Hong, "Indoor air quality monitoring systems for enhanced living environments: A review toward sustainable smart cities," *Sustainability (Switzerland)*, vol. 12, no. 10, May 2020, doi: 10.3390/SU12104024.

[35] Susanto, D. Stiawan, M. Agus Syamsul Arifin, M. Y. Idris, and R. Budiarto, "Effective and efficient approach in IoT Botnet detection," *SINERGI*, vol. 28, no. 1, pp. 31–42, 2024, doi: 10.22441/sinergi.2024.1.004.

[36] J. Kuula *et al.*, "Laboratory evaluation of particle-size selectivity of optical low-cost particulate matter sensors," *Atmos Meas Tech*, vol. 13, no. 5, pp. 2413–2423, May 2020, doi: 10.5194/amt-13-2413-2020.

[37] K. B. Kumar Sai, S. Mukherjee, and H. Parveen Sultana, "Low Cost IoT Based Air Quality Monitoring Setup Using Arduino and

MQ Series Sensors with Dataset Analysis," in *Procedia Computer Science*, Elsevier B.V., 2019, pp. 322–327, doi: 10.1016/j.procs.2020.01.043.

[38] Q. Aini, U. Rahardja, D. Manongga, I. Sembiring, M. Hardini, and H. Agustian, "IoT-Based Indoor Air Quality Using Esp32," in *2022 IEEE Creative Communication and Innovative Technology (ICCIT)*, 2022, pp. 1–5. doi: 10.1109/ICCIT55355.2022.10119001.

[39] D. Wu *et al.*, "When Sharing Economy Meets IoT: Towards Fine-Grained Urban Air Quality Monitoring through Mobile Crowdsensing on Bike-Share System," *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, vol. 4, no. 2, Jun. 2020, doi: 10.1145/3397328.

[40] Q. P. Ha, S. Metia, and M. D. Phung, "Sensing Data Fusion for Enhanced Indoor Air Quality Monitoring," *IEEE Sens J*, vol. 20, no. 8, pp. 4430–4441, 2020, doi: 10.1109/JSEN.2020.2964396.

[41] H. F. Hawari, A. A. Zainal, and M. R. Ahmad, "Development of real time internet of things (IoT) based air quality monitoring system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 13, no. 3, pp. 1039–1047, Mar. 2019, doi: 10.11591/ijeecs.v13.i3.pp1039-1047.

[42] L. Angrisani *et al.*, "An Innovative Air Quality Monitoring System based on Drone and IoT Enabling Technologies," in *2019 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*, 2019, pp. 207–211. doi: 10.1109/MetroAgriFor.2019.8909245.

[43] L. D. Perlmutt and K. R. Cromar, "Comparing associations of respiratory risk for the EPA Air Quality Index and health-based air quality indices," *Atmos Environ*, vol. 202, pp. 1–7, 2019, doi: 10.1016/j.atmosenv.2019.01.011.

[44] Jaja Kustija, Irgi Surya, and Diki Fahrizal, "Design of automated power factor monitoring and repair tool for industry in real time based on Internet of Things," *International Journal of Science and Technology Research Archive*, vol. 3, no. 2, pp. 001–008, Oct. 2022, doi: 10.53771/ijstra.2022.3.2.0106.

[45] T. Blinova, S. Singh Chauhan, T. Singla, S. Bansal, A. Mittal, and V. S. Yellanki, "Performance Evaluation of IoT Sensors in Urban Air Quality Monitoring: Insights from the IoT Sensor Performance Test," *BIO Web Conf*, vol. 86, p. 01088, Jan. 2024, doi: 10.1051/bioconf/20248601088.

[46] V. Barot, V. Kapadia, and S. Pandya, "QoS enabled IoT based low cost air quality monitoring system with power consumption optimization," *Cybernetics and Information Technologies*, vol. 20, no. 2, pp. 122–140, 2020, doi: 10.2478/cait-2020-0021.