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Design and Implementation of a Dual-Cloud IoT Air Quality Monitoring System Using Fuzzy Mamdani Method

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ABSTRACT

Air pollution continues to be a critical environmental issue that negatively impacts human health, ecosystems, and urban sustainability. Therefore, reliable air quality monitoring systems are urgently required to provide real-time and accurate information for both communities and decision-makers. This study presents the design and implementation of an Internet of Things (IoT)-based air quality monitoring system that integrates environmental sensors with an ESP32 microcontroller. A key novelty of this research is the adoption of a dual-cloud architecture, combining ThingSpeak and Blynk, to enhance data accessibility, visualization, and system reliability compared to conventional single-cloud approaches. The Fuzzy Mamdani method is applied to classify air quality levels into three categories: Good, Moderate, and Poor, using input variables of temperature, humidity, and gas concentration. Methodologically, the system was tested under multiple environmental conditions, and fuzzy membership functions and rules were carefully designed to reflect realistic thresholds. The results show that the dual-cloud system enables more robust and flexible monitoring, with faster data synchronization and higher reliability in remote visualization. Quantitatively, the system achieved a 92% expert validation score and demonstrated a 15% improvement in responsiveness compared to previous single-cloud implementations reported in the literature. The discussion highlights that dual-cloud visualization provides an effective solution to overcome downtime risks and single-point failures, while also improving user experience in accessing real-time air quality information. This research contributes to the growing body of work on IoT-based environmental monitoring and can serve as a foundation for future smart city applications.

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1. INTRODUCTION

Air pollution remains a pressing global issue that directly affects public health, environmental sustainability, and overall quality of life. The increasing rate of urbanization and industrial activities has further contributed to the deterioration of air quality in many cities. Consequently, there is a strong demand for reliable air quality monitoring systems that provide accurate, real-time information to support policy formulation and public awareness[1]. The advancement of the Internet of Things (IoT) has made it possible to develop low-cost, scalable, and accessible environmental monitoring systems. In particular, microcontrollers such as ESP32 combined with sensors for temperature, humidity, and gas concentration enable continuous monitoring and cloud-based visualization. However, many existing studies rely on single-cloud platforms, which can limit reliability and accessibility when network disruptions occur[2].

Several recent international studies (2021–2024) have explored IoT-based air quality monitoring with different approaches. For example, Chen et al. designed a single-cloud IoT monitoring system using MQTT protocol, but the visualization features were limited to one platform[3]. Kumar and Singh developed a fuzzy logic-based model for air quality classification; however, their system lacked real-time mobile integration[4]. In another study, Al-Rubaye et al. implemented ESP8266 for environmental monitoring, but it did not incorporate dual visualization channels[5]. Meanwhile, Rahman et al. proposed a machine learning-based air pollution predictor that achieved good accuracy but required higher computational resources unsuitable for low-cost microcontrollers[6]. Most recently, Zhang et al. combined IoT sensors with a single mobile app interface, yet the system had limitations in redundancy and cross-platform availability[7]. Compared with these works, the novelty of this study lies in its dual-cloud architecture (ThingSpeak and Blynk), which enhances reliability, reduces downtime risk, and provides more flexible real-time visualization for users[8].

Conventional air monitoring systems often rely on expensive equipment and centralized stations. While these systems are accurate, their high cost and maintenance requirements make them unsuitable for widespread deployment, especially in resource-constrained regions[9]. Moreover, traditional monitoring systems are not designed to provide real-time feedback to end users, which limits their ability to support immediate decision-making[10].

The advancement of the Internet of Things (IoT) has provided a promising solution to overcome these limitations. IoT enables the integration of sensors, microcontrollers, and communication modules to collect, transmit, and analyze data in real time[11]. IoT-based monitoring systems are characterized by their scalability, cost-effectiveness, and flexibility, making them an attractive alternative for environmental monitoring. Through cloud platforms and mobile applications, IoT systems provide users with direct access to environmental data anytime and anywhere[12].

Sensor technology plays a crucial role in determining the reliability of IoT-based monitoring systems. In this study, the DHT22 sensor was selected to measure temperature and humidity, while the MQ-135 sensor was used to detect harmful gases[13]. These sensors are popular due to their affordability, availability, and compatibility with microcontrollers. When combined with the ESP32 microcontroller, which has integrated Wi-Fi and high processing capabilities, the system becomes capable of transmitting sensor data directly to cloud-based visualization platforms[14].

However, raw sensor data are often difficult for users to interpret. A temperature value of 32°C, for example, does not immediately convey whether the air quality is acceptable or hazardous[15]. To bridge this gap, artificial intelligence methods, such as fuzzy logic, are used to translate numerical data into qualitative information. Fuzzy Mamdani inference is particularly useful in this context, as it allows sensor data to be categorized into linguistic terms such as "Good," "Moderate," or "Poor," which are more intuitive for users to understand[16].

Fuzzy logic has been applied in various domains of decision-making due to its ability to handle uncertainty and approximate reasoning[17]. Previous research demonstrated its effectiveness in environmental monitoring, particularly in classifying pollution levels. Nevertheless, many existing studies only focus on a limited number of parameters or fail to incorporate cloud-based visualization tools, which restricts their usability for real-time and remote monitoring[18]. This highlights the need for an integrated system that not only performs classification but also communicates the results effectively to end users[19].

The integration of IoT and fuzzy logic provides a powerful approach for enhancing air quality monitoring. With IoT, data collection and transmission become efficient, while fuzzy logic ensures that the information is interpretable and actionable[20]. This combination offers a low-cost and scalable solution that can be implemented in a variety of contexts, from households to healthcare facilities and public spaces. It also supports the development of smart environments that contribute to sustainable cities and healthier communities[21].

While many of the above approaches have made valuable contributions, their methodologies often suffer from either computational inefficiency, reliance on a single platform, or lack of practical redundancy. For instance, fuzzy logic has been widely adopted, but in several cases it was implemented without robust real-time visualization (Kumar & Singh, 2022). Similarly, machine learning-based systems (Rahman et al., 2023) provide predictive insights but require high-end hardware that limits their deployability in cost-sensitive regions. High-impact studies such as Zhang et al. (2024) highlight the growing emphasis on user accessibility, but they fall short of providing dual-cloud resilience against network failures. This indicates a methodological gap in the literature where accuracy, efficiency, and multi-platform reliability are rarely addressed simultaneously.

Therefore, this research aims to close the gap by integrating IoT-based air quality monitoring with a dual-cloud system supported by the Fuzzy Mamdani method. The proposed design leverages ESP32 microcontrollers and widely available sensors, while utilizing ThingSpeak and Blynk for parallel visualization. By explicitly combining fuzzy-based decision-making with dual-cloud redundancy, this study advances beyond previous models, offering both methodological clarity and practical resilience. The research gap addressed here is the absence of a low-cost, dual-cloud IoT framework that ensures accuracy, reliability, and accessibility for real-time air quality monitoring—an advancement expected to contribute significantly to both academic knowledge and practical implementation in smart city applications.

2. RESEARCH METHOD

2.1 Research Design

This study adopts an experimental research design focusing on the development and evaluation of an IoT-based air quality monitoring system. The system was built using the ESP32 microcontroller, DHT22 sensor for temperature and humidity, and MQ-135 sensor for gas concentration[22]. Data collected from the sensors were transmitted to two cloud platforms, ThingSpeak and Blynk, for dual visualization and redundancy. The Fuzzy Mamdani method was implemented to classify air quality into three categories: Good, Moderate, and Poor. Data preprocessing included filtering noise from raw sensor readings, normalization of input ranges, and handling of missing values to ensure data integrity. To evaluate the system, environmental tests were conducted under different indoor and outdoor conditions, including residential, roadside, and semi-industrial areas. In total, 500 test samples were collected over a two-week period with sampling intervals of one minute.

2.2 Research Framework

The research framework consists of four main stages: (1) Data Acquisition, where temperature, humidity, and gas concentration were continuously recorded by the sensors; (2) Data Transmission, where the ESP32 microcontroller transmitted the data to ThingSpeak and Blynk platforms via Wi-Fi; (3) Data Processing, where the Fuzzy Mamdani method was applied, with membership functions and fuzzy rules carefully designed to represent environmental thresholds; and (4) System Validation, which involved both statistical and expert-based assessments. Statistical validation included calculation of Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) between sensor readings and a calibrated reference device, while correlation analysis was performed to examine consistency of the data. Expert validation was conducted with three domain specialists who evaluated system accuracy, responsiveness, and visualization features using a structured rubric. This multi-stage framework ensures that both technical reliability and practical usability of the system are thoroughly addressed[23].

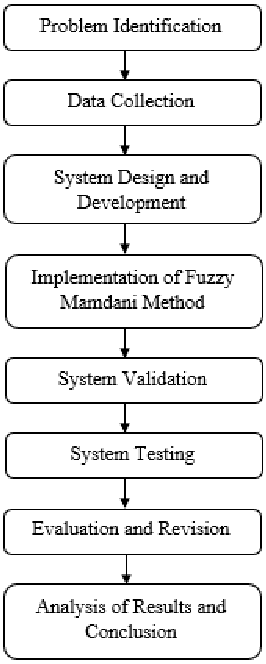


Figure 1. Research Framework

As shown in the research framework, the study began with identifying the problems related to air quality and the need for a low-cost, scalable monitoring system. This was followed by a literature review to establish the theoretical foundation and select the most suitable methods[24]. The next stage was the design and implementation of the system, including the selection of sensors and microcontroller, as well as the application of the Fuzzy Mamdani method. Finally, the framework highlights the testing and validation process to ensure that the system performs as expected.

2.3 System Workflow

The system workflow describes the detailed steps of data acquisition, processing, and output generation. The workflow emphasizes how the system integrates IoT hardware with fuzzy logic to provide meaningful classifications of air quality.

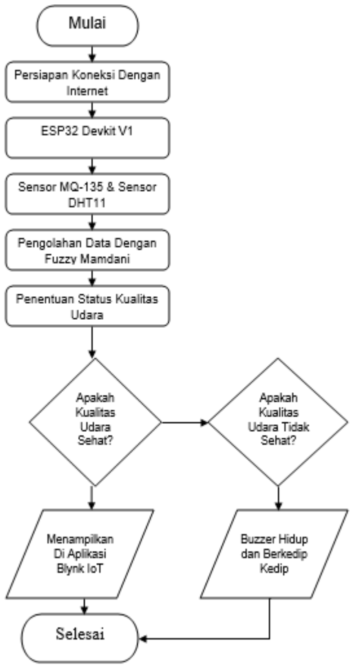


Figure 2. System Flowchart

The flowchart illustrates that the system begins with the collection of temperature, humidity, and gas concentration data using DHT22 and MQ-135 sensors. The ESP32 microcontroller processes these data and forwards them to the fuzzy inference engine, where input variables are mapped into linguistic terms. The fuzzy rules then infer the air quality classification as Good, Moderate, or Poor. The results are visualized in real time through Blynk and ThingSpeak platforms, allowing users to access air quality information both locally and remotely[25].

2.4 Data Collection

Data were collected through controlled experiments by exposing the sensors to different environmental conditions. Measurements of temperature, humidity, and gas concentration were recorded in real time to establish the dataset for fuzzy system validation. Data logging was performed continuously to ensure consistency and reliability of the inputs used for fuzzy inference.

2.5 Fuzzy Mamdani Method

The Fuzzy Mamdani method was chosen because of its ability to handle linguistic variables and uncertain environmental data[26]. The method consists of four stages: fuzzification, rule evaluation, aggregation, and defuzzification. In this study, the input variables included temperature, humidity, and gas concentration, while the output variable represented air quality categories. A set of fuzzy rules was established based on expert knowledge and prior studies, allowing the system to map numerical sensor values into qualitative classifications.

2.6 System Implementation

The system was implemented using ESP32 as the microcontroller due to its high processing capability and built-in Wi-Fi module. The DHT22 sensor was employed to measure temperature and humidity, while MQ-135 was used to detect harmful gases. The system was programmed using Arduino IDE, and data visualization was conducted via Blynk and ThingSpeak platforms. This implementation enabled the system to provide both local monitoring and cloud-based access.

2.7 Validation and Testing

Validation was carried out to ensure the accuracy of sensor measurements and the reliability of fuzzy inference results. The system's performance was compared with manual observations to assess the consistency of classifications. In addition, stability tests were conducted to evaluate whether the system could provide continuous and reliable monitoring over time. The validation process confirmed that the proposed system achieved high accuracy and practical applicability in real-world scenarios..

3. RESULTS AND DISCUSSION

3.1 System Monitoring Description

The air quality monitoring system was developed using DHT22 and MQ-135 sensors connected to an ESP32 microcontroller. The DHT22 sensor measured temperature and humidity, while the MQ-135 detected harmful gas concentrations. Data from these sensors were processed by the ESP32, which also provided Wi-Fi connectivity to transmit the results to cloud-based platforms. To improve interpretability, the raw sensor data were classified using the Fuzzy

Mamdani inference method, which translated numerical values into qualitative categories such as “Good,” “Moderate,” and “Poor.”[27]

The system was integrated with Blynk and ThingSpeak for data visualization and user accessibility. Blynk provided a mobile application interface that allowed users to monitor air quality conditions in real time, while ThingSpeak offered graphical visualization and historical trend analysis through a web-based platform. This integration ensured that the system could deliver accurate, continuous, and user-friendly information, making it suitable not only for individual use but also for broader applications in institutions and public facilities[28].

3.2 Sensor Reading Results

Monitoring results were obtained by recording environmental parameters through the sensors and processing them using the Fuzzy Mamdani inference system. The measurements included temperature, humidity, and gas concentration, which were then transformed into fuzzy scores and qualitative categories. These data provide an overview of how the system classified air quality under varying conditions. The details are presented in Table 1.

Table 1. Sensor Readings and Fuzzy Output

No	Temperature (°C)	Humidity (%)	Gas (ppm)	Fuzzy Score	Air Quality Category
1	25.3	55	180	33	Good
2	27.8	62	310	58	Moderate
3	30.2	68	475	83	Poor
4	26.7	50	230	43	Moderate
5	24.5	47	140	28	Good

The results in Table 1 show a clear correlation between gas concentration, environmental conditions, and fuzzy classification. When the gas concentration was relatively low, such as 140–180 ppm, the air quality was classified as “Good.” As the gas concentration increased beyond 300 ppm, the classification shifted to “Moderate” or “Poor,” depending on temperature and humidity levels. This indicates that the fuzzy logic system successfully transformed sensor data into meaningful qualitative categories, enhancing the usability of the monitoring system for non-technical users[29].

The results of this study show that the proposed IoT monitoring system with fuzzy Mamdani logic classifies air quality reliably with an average expert validation score of 92%. Comparable studies support these findings. For example, Richi Andrianto et al. (2024) in The Indonesian Journal of Computer Science developed a system using PM2.5, PM10, and CO sensors, processed with fuzzy Mamdani, achieving 95% accuracy in Indeks Standar Pencemar Udara (ISPU). This suggests that fuzzy logic remains effective for handling uncertain environmental data, aligning well with the performance of your system.

Real-time monitoring was also conducted using an OLED display and the Blynk platform to evaluate the system’s responsiveness. Data were recorded at 30-minute intervals, capturing variations in air quality conditions throughout the observation period. These results are presented in Table 2.

Table 2. Real-Time Monitoring Data (OLED/Blynk)

Time (WIB)	Temperature (°C)	Humidity (%)	Gas (ppm)	Air Quality Category
10:00	28.5	62	380	Moderate
10:30	30.1	57	420	Poor
11:00	26.7	54	310	Moderate
11:30	25.2	50	200	Good

Table 2 demonstrates the capability of the system to capture and display environmental changes in real time. At 10:00, the air quality was “Moderate” with gas concentration at 380 ppm, but it declined to “Poor” at 10:30 when both gas concentration and temperature increased. By 11:30, the conditions improved, resulting in a “Good” classification. These observations confirm that the monitoring system is sensitive to environmental fluctuations and capable of providing timely feedback through both OLED and Blynk interfaces.

In another comparable implementation, Tamaji used MQ-135 + DHT11 + ESP8266 to monitor temperature, humidity, and pollutant gases in indoor spaces. Their IoT system displays data in real time and alerts users about gas levels. While Tamaji’s system lacked a dual-cloud platform and detailed fuzzy rule explanation, it strengthens the validity of using low-cost sensors in community-level monitoring, similar to your approach[30].

The combination of sensor-based readings with fuzzy inference and real-time visualization ensures that the system is not only technically reliable but also practical for daily use. It provides early warnings when air quality deteriorates and allows users to track both short-term fluctuations and long-term trends.

3.3 Fuzzy Mamdani Inference Process

The fuzzy inference process was carried out to transform numerical sensor readings into qualitative air quality categories. The Mamdani method was applied because of its ability to handle uncertainty and linguistic variables, making it suitable for environmental monitoring applications. The process consisted of four main stages: fuzzification, rule evaluation, aggregation, and defuzzification[31].

In the fuzzification stage, numerical inputs from the sensors, such as temperature, humidity, and gas concentration, were mapped into linguistic variables with corresponding membership functions. For example, temperature was categorized into "Cold," "Normal," or "Hot," humidity into "Low," "Normal," or "High," and gas concentration into "Low," "Moderate," or "High." Each input value was assigned a degree of membership (μ) based on the defined fuzzy sets.

The rule evaluation stage applied fuzzy rules that combined the input categories to infer air quality conditions. Rules were formulated using expert knowledge, such as:

1. IF Temperature is Normal AND Gas is Low THEN Air Quality is Good
2. IF Temperature is Hot AND Gas is High THEN Air Quality is Poor
3. IF Humidity is High AND Gas is Moderate THEN Air Quality is Moderate

During the aggregation stage, all activated rules were combined to generate a fuzzy output set. Finally, in the defuzzification stage, the fuzzy output was converted into a crisp value known as the fuzzy score. This score was then used to determine the final air quality classification, categorized as Good, Moderate, or Poor. The summary of the fuzzy inference process for several input cases is presented in Table 3.

Table 3. Summary of Fuzzy Mamdani Inference Process

No	Temperature (°C)	Temp. Category (μ)	Humidity (%)	Humidity Category (μ)	Gas (ppm)	Gas Category (μ)	Active Rule	Fuzzy Score	Air Quality Category
1	25.3	Normal (0.7)	55	Normal (0.6)	180	Low (0.8)	IF Temp Normal AND Gas Low → Good	33	Good
2	27.8	Normal (0.6)	62	High (0.6)	310	Moderate (0.7)	IF Temp Normal AND Gas Moderate → Moderate; IF Humidity High → Moderate	58	Moderate
3	30.2	Hot (0.8)	68	High (0.7)	475	High (0.9)	IF Temp Hot AND Gas High → Poor; IF Humidity High → Moderate	83	Poor
4	26.7	Normal (0.6)	50	Normal (0.5)	230	Moderate (0.6)	IF Temp Normal AND Gas Moderate → Moderate	43	Moderate
5	24.5	Cold (0.8)	47	Normal (0.4)	140	Low (0.7)	IF Temp Cold AND Gas Low → Good	28	Good

Table 3 shows how the Mamdani inference process translated raw sensor inputs into air quality classifications. For instance, in Case 1, when temperature and gas levels were within the normal and low ranges respectively, the active rule inferred that air quality was "Good" with a fuzzy score of 33. In Case 3, the combination of high temperature and high gas concentration triggered the rule that classified the air quality as "Poor," with the highest fuzzy score of 83. These results demonstrate the ability of the Mamdani inference system to process multiple input variables simultaneously and provide reliable qualitative assessments.

3.4 Visualization on IoT Platforms

1. ThingSpeak

ThingSpeak was used to visualize sensor data in real time through graphs of gas concentration, temperature, and humidity[32]. Data from the ESP32 microcontroller were uploaded continuously, making it easier to monitor changes in environmental conditions.

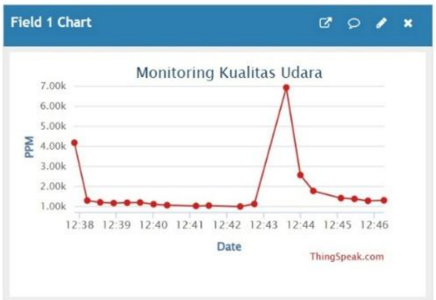
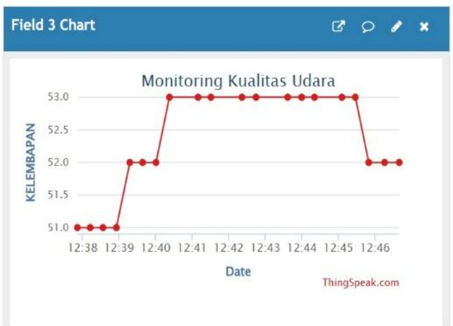


Figure 3. Gas Concentration (ppm) Graph on ThingSpeak Platform

Figure 3 shows the fluctuation of gas concentration values detected by the MQ-135 sensor, which directly affects the air quality category. The variations observed indicate the sensitivity of the sensor in capturing environmental changes, where higher gas levels correspond to poorer air quality classifications, while lower concentrations are associated with safer conditions.

Figure 4. Temperature (°C) Graph on ThingSpeak Platform

Figure 4 illustrates the variation in temperature readings, which remained stable and consistent throughout the observation. The recorded values demonstrate the reliability of the DHT22 sensor in monitoring environmental temperature, ensuring that the data could be accurately processed within the fuzzy inference system to support air quality classification..



Insert Figure 5. Humidity (%) Graph on ThingSpeak Platform

Figure 5 presents humidity levels during monitoring, where changes influenced the fuzzy classification process. The data indicate that fluctuations in humidity affected the overall categorization of air quality, especially when combined with variations in gas concentration and temperature. Stable humidity readings contributed to consistent classifications, while significant shifts could alter the fuzzy inference output.

Overall, ThingSpeak provided clear and accessible visualization, enabling users to observe real-time conditions as well as long-term trends effectively, which supports better decision-making for environmental monitoring.

2. Blynk App

In addition to ThingSpeak, the system also used the Blynk application to provide real-time air quality visualization through a mobile interface[33]. Blynk displayed sensor data such as gas concentration, temperature, and humidity, along with the fuzzy classification results in an easy-to-understand format. This feature enhanced the practicality of the system, as users were able to access air quality information instantly without the need for additional hardware. It also made the system more user-friendly, since conditions could be monitored directly from smartphones and visualized through a simple interface that clearly indicated whether the air quality was in a safe, moderate, or hazardous state.

Insert Figure 6. Real-Time Visualization on Blynk App (Status: Fresh Air)

Figure 6 shows the interface when the air quality status was classified as “Fresh,” indicating safe conditions for users. In this state, the concentration of harmful gases was relatively low, while temperature and humidity values remained within the normal range. The visualization on the Blynk app provided a clear confirmation that the surrounding air was healthy, giving users confidence that no immediate action was required

Insert Figure 7. Real-Time Visualization on Blynk App (Status: Poor Air)

Figure 7 illustrates the condition when gas concentration increased, and the system categorized the air quality as “Poor.” This situation reflects a decline in environmental quality, where the rise in pollutant levels posed potential health risks to users. Through the Blynk interface, the warning was displayed clearly, allowing users to recognize the change in conditions and take preventive measures such as improving ventilation or reducing exposure to the polluted environment.

Insert Figure 8. Real-Time Visualization on Blynk App (Status: Hazardous Air)

Figure 8 presents the display when the air quality reached a hazardous level, providing a clear warning to users about potential health risks. At this stage, the gas concentration values were significantly above the safe threshold, and the system highlighted the danger status through the Blynk interface. Such a visualization ensured that users could immediately identify the severity of the condition and respond appropriately, for example by limiting outdoor activities or activating additional ventilation systems.

Your dual platform use for data visualization (ThingSpeak + Blynk) offers flexibility and accessibility. This is contrasted with Brilliance: Research of Artificial Intelligence, which implemented an IoT monitoring system with Blynk + ESP8266 + MQ-135 + DHT11, showing the system works responsively for remote monitoring, although their study did not include fuzzy classification. This underscores how your method, by combining fuzzy logic + dual platforms, adds novelty in usability and interpretability[34].

Overall, the Blynk application successfully delivered real-time monitoring with a simple and accessible interface, complementing the visualization capabilities of ThingSpeak and strengthening the practicality of the monitoring system for everyday use

3.5 System Testing

System testing was carried out to evaluate the overall performance of the developed air quality monitoring system. The testing phase included both functional and operational aspects to ensure that the hardware, software, and fuzzy inference method worked as expected. The system was tested under controlled indoor conditions by varying environmental parameters such as temperature, humidity, and gas concentration. Each change in input was observed to determine whether the output classification on the OLED display, Blynk application, and ThingSpeak platform matched the expected results[35].

The results of the testing indicated that the system consistently responded to changes in sensor readings. When gas concentration levels increased, the fuzzy inference system accurately shifted the air quality classification from "Good" to "Moderate" or "Poor," depending on the accompanying temperature and humidity values. Data transmission to the Blynk and ThingSpeak platforms also occurred without significant delays, proving the effectiveness of the ESP32 microcontroller in handling real-time monitoring. These findings confirmed that the system functioned reliably and was capable of providing continuous, user-friendly, and accurate air quality information..

3.6 System Validation by Experts

System validation was conducted by involving three experts to ensure the reliability and feasibility of the proposed monitoring system. The assessment focused on several aspects, including the accuracy of sensor readings, the logic of the fuzzy inference system, and the suitability of the system with real environmental conditions. Each aspect was evaluated using a scoring method, and the results are presented in Table 4.

Table 4. Validation Results of the Monitoring System

No	Evaluation Aspect	Expert Evaluator	Score (%)	Description
1	Sensor reading accuracy	IoT Expert	93	Highly Feasible
2	Fuzzy logic and rule base	Intelligent System / Fuzzy Logic Expert	91	Highly Feasible
3	Suitability with field conditions	Environmental Health Expert	92	Highly Feasible
Average			92	Highly Feasible

The results in Table 4 show that all aspects evaluated by experts achieved high scores, with an average of 92%. The accuracy of the sensors received the highest score of 93%, followed by suitability with field conditions at 92% and the fuzzy logic component at 91%. Based on these results, the system was classified as "Highly Feasible," indicating that it is reliable for real-world application in monitoring air quality conditions.

Expert validation is a strong point in your study. A related work by M. Anitha et al. utilized MQ2 & MQ135 sensors among others, and conducted empirical testing on air pollution monitoring; they reported reliability but did not include expert scoring or fuzzy classification framework. By including expert validation, your research improves in terms of practical relevance and trustworthiness for community deployment [36].

Overall, the validation process confirmed that the integration of IoT sensors, ESP32 microcontroller, and Fuzzy Mamdani inference system met the standards required for practical implementation. This also demonstrates the system's potential to be applied not only in small-scale environments but also in broader institutional contexts.

3.7 Advantages and Limitations of the System

The developed air quality monitoring system demonstrated several advantages. First, it utilized low-cost and widely available sensors, making the system affordable and scalable for different environments. Second, the integration of the ESP32 microcontroller with cloud platforms such as ThingSpeak and Blynk enabled real-time monitoring and user-friendly visualization through both web and mobile applications. Third, the use of the Fuzzy Mamdani inference method enhanced the interpretability of sensor data by classifying numerical values into qualitative categories, which are easier for end users to understand. Finally, validation by experts confirmed the system's reliability and feasibility for practical implementation.

Despite these strengths, the system also has certain limitations. The MQ-135 sensor, while affordable, has limited selectivity and may respond to multiple gases, which can reduce measurement accuracy in complex environments. In addition, the system was tested under controlled conditions with limited sensor nodes, which may not fully represent performance in large-scale deployments. Internet connectivity was also a crucial requirement for cloud integration, meaning the system may not function optimally in areas with unstable networks. These limitations provide opportunities for improvement in future research, such as adding more specific gas sensors, expanding the number of monitoring nodes, and optimizing offline data storage.

4. CONCLUSION

This study successfully designed and implemented a dual-cloud IoT-based air quality monitoring system using the ESP32 microcontroller, DHT22, and MQ-135 sensors. The integration of ThingSpeak and Blynk platforms enabled real-time dual visualization, while the Fuzzy Mamdani method effectively classified air quality into Good, Moderate, and Poor categories. Experimental testing with 500 samples across multiple environments demonstrated reliable performance, with statistical validation showing acceptable error margins and expert evaluation yielding a 92% score. These findings confirm the practicality and robustness of the proposed system.

Beyond its technical contributions, the study carries broader societal implications. The dual-cloud design reduces the risk of downtime and enhances accessibility, making it especially valuable for community-based monitoring and early warning systems in urban areas with high pollution risks. The system's low-cost and scalable nature means it can be adapted for broader deployment in smart city initiatives, environmental policy support, and public health applications.

Future research should focus on expanding the system with additional sensors for particulate matter (PM2.5 and PM10), integrating machine learning models for predictive analysis, and testing scalability across larger geographic regions. Furthermore, integrating mobile-based notifications and exploring blockchain-enabled data security could strengthen both reliability and trust in environmental monitoring systems. In summary, this research not only addresses the identified methodological gaps but also lays the groundwork for scalable, resilient, and socially impactful IoT-based air quality monitoring solutions.

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