

## Design and Implementation of a Microcontroller-Based Air Filter System with Android Application Interface

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**Abstract** – Indoor air quality is a crucial factor influencing occupants' health and comfort. Various issues, including dust particles, excessive humidity, hazardous gases, and inadequate lighting conditions, can significantly reduce indoor air quality. However, most existing air filter systems still lack real-time monitoring and remote control capabilities. Therefore, this study aims to develop a microcontroller-based air filter system using ESP32 integrated with an Android application via Wi-Fi connectivity. The proposed system utilizes a DHT22 sensor to measure temperature and humidity, a GP2Y1010AU0F sensor to detect dust particles, an MQ-135 sensor to detect harmful gases and unpleasant odors, and a BH1750 sensor to measure light intensity. All sensor data are processed by the ESP32 microcontroller and displayed through an Android application developed using Android Studio, allowing users to monitor indoor air quality conditions in real time. System testing was conducted under several indoor air quality scenarios, including variations in humidity and dust concentration levels. The results demonstrate that the system operates accurately, responsively, and in real time in monitoring indoor air quality. Furthermore, the system can be remotely controlled through the Android application. This system is expected to improve indoor air quality while providing positive impacts on environmental health and comfort.

**Keywords** – Indoor air quality; ESP32 microcontroller; Air filtering system; Real-time monitoring; Internet of Things.

### I. INTRODUCTION

INDOOR air quality is one of the most critical environmental factors because it fundamentally influences human health, comfort, and productivity through multiple interrelated parameters [1, 2]. Numerous studies have demonstrated that environmental factors such as temperature, humidity, particulate matter concentration, the presence of hazardous gases, and lighting intensity directly affect both physiological and psychological conditions of indoor occupants [3, 4].

Previous research consistently emphasizes that indoor environmental quality encompasses thermal comfort, air quality, acoustic conditions, and visual comfort [5, 6]. Indoor pollutants may cause adverse health effects ranging from reduced concentration levels to more severe physiological responses [7, 8]. The scientific community increasingly recognizes that indoor environmental parameters are complex and multidimensional, significantly influencing human well-being [9].

Long-term exposure to indoor air pollutants, including fine particulate matter and toxic gases, has been associated with respiratory disorders, eye irritation, and decreased work productivity [10]. Therefore, maintaining indoor air quality has become increasingly important, particularly in residential buildings, offices, and enclosed public spaces.

Modern air purification systems have evolved rapidly from passive dust filtration devices into intelligent monitoring platforms capable of providing real-time indoor air quality information. Several studies have proposed Internet of Things (IoT)-based solutions that extend beyond conventional filtration by integrating multi-sensor data acquisition and intelligent data processing [11–13]. These advanced systems utilize environmental sensors, including temperature, humidity, and particulate sensors, and in some cases implement machine learning techniques not only to filter air but also to actively monitor and communicate air quality conditions to users [11, 14].

For instance, Chang *et al.* developed a smart air quality monitoring system capable of sending alert notifications to mobile applications when air quality deteriorates [15]. Similarly, Poulouse *et al.* proposed an

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automated air filtration system that activates filtration mechanisms based on real-time sensor data and machine learning-based decision models [11]. These research efforts collectively demonstrate the potential to transform air purification systems from passive devices into intelligent and user-responsive platforms supporting real-time monitoring and adaptive control [16, 17].

Despite these advancements, conventional air filters generally lack real-time monitoring capabilities, preventing users from rapidly identifying changes in indoor air quality and forcing them to rely on manual inspection or fixed operational schedules [18, 19]. Kong *et al.* reported that existing air quality monitoring systems are unable to “rapidly capture air quality fluctuations occurring minute by minute” [18]. Likewise, Pei *et al.* found that many air filters are “installed and operated with limited performance monitoring systems,” reducing user awareness of filtration effectiveness [19].

To overcome these limitations, several studies have introduced IoT-based solutions for indoor air quality monitoring and control. Jo *et al.* developed an IoT platform enabling users to monitor air quality “anytime and anywhere” using network-connected devices [20]. Meanwhile, Sung *et al.* introduced a smart air monitoring system integrated with smartphones, providing real-time air quality information with measurement accuracy reaching  $\pm 4\%$  for major pollutants [21]. These technological innovations represent significant progress in overcoming the fundamental limitations of conventional air monitoring systems and demonstrate the feasibility of real-time, user-oriented indoor air quality supervision using IoT technologies [22, 23].

With the rapid advancement of microcontroller technology, environmental sensing devices, and wireless communication systems, IoT has emerged as a promising approach for developing intelligent, integrated, and accessible indoor air quality monitoring systems. IoT-based systems allow sensor data to be transmitted in real time to servers or mobile applications for visualization and analysis [24]. Microcontrollers such as ESP32, which include integrated Wi-Fi modules, are widely adopted as main controllers in environmental monitoring systems due to their low cost, low power consumption, and high compatibility with various sensors [25].

Various environmental sensors can be integrated to represent indoor air quality conditions comprehensively. The DHT22 sensor is commonly used to measure temperature and humidity, the GP2Y1010AU0F sensor is used for dust particle detection, the MQ-135 sensor is used to detect hazardous gases and unpleasant odors, and the BH1750 sensor is used to measure

light intensity. This multi-sensor integration approach enables a more accurate and representative assessment of indoor air quality compared to systems relying on a single environmental parameter [26].

Several previous studies have investigated the use of environmental sensors and microcontrollers for IoT-based indoor air quality monitoring. These studies indicate that low-cost IoT systems are capable of performing real-time air quality monitoring with acceptable accuracy [27]. However, most existing systems are limited to monitoring functions only and do not provide direct integration with air filtration mechanisms or remote control capabilities through Android-based applications. Furthermore, relatively few studies have combined multi-parameter indoor air quality monitoring with automated air filtration systems that can be remotely controlled in real time through mobile devices.

Several recent studies have investigated IoT-based air quality monitoring and air purification systems using multi-sensor integration and automated control mechanisms. These studies demonstrate significant improvements in real-time environmental monitoring capabilities and intelligent air purification strategies. The present study extends previous research by integrating real-time multi-parameter monitoring with Android-based remote visualization and filtration control mechanisms, providing improved system accessibility and user interaction within indoor environmental monitoring applications. Based on these research gaps, this study proposes the design and implementation of an ESP32-based air filtration system integrated with an Android application. The proposed system performs real-time indoor air quality monitoring based on temperature, humidity, dust concentration, gas concentration, and light intensity parameters. Sensor measurement data are transmitted via Wi-Fi to an Android application developed using Android Studio, allowing users to monitor indoor air conditions directly and remotely control the air filtration system.

The main contributions of this research include: (1) the design of a microcontroller-based air filtration system with multi-parameter indoor air quality monitoring, (2) integration with an Android application enabling real-time monitoring and remote control, and (3) experimental performance evaluation under various environmental conditions to assess system accuracy, responsiveness, and reliability. The developed system is expected to provide a practical and efficient solution for improving indoor air quality while supporting the implementation of IoT-based smart home environments.

## II. RESEARCH METHODS

This study employs a system design and implementation methodology to develop a microcontroller-based air filtration system integrated with an Android application. The methodology consists of several major stages, including hardware design, software development, system integration, system performance testing, and data analysis.

This structured methodological approach is intended to ensure that each stage, from initial design to system testing, can be systematically evaluated. Consequently, the effectiveness, reliability, and responsiveness of the developed system can be objectively measured based on experimental testing results. The system architecture in this study consists of two main components, namely hardware and software.

### i. Hardware

The hardware subsystem consists of several primary components as follows:

1. **ESP32 Microcontroller** The ESP32 microcontroller is used as the main control unit to acquire data from all sensors, process the data, and transmit measurement results to the database via Wi-Fi connectivity.
2. **Air Quality Sensors** The sensors used in this study include:
  - (a) GP2Y1010AU0F sensor for detecting dust particle concentration.
  - (b) MQ-135 sensor for detecting hazardous gases and unpleasant odors.
  - (c) DHT22 sensor for measuring temperature and humidity.
  - (d) BH1750 sensor for measuring light intensity.
3. **Air Filtration and Fan System** The air filter and fan are used to continuously intake and filter indoor air. The fan operation is controlled by the microcontroller to adjust filtration performance according to the detected air quality conditions.

### ii. Software

The software subsystem consists of the following main components:

1. **Microcontroller Program** The Arduino IDE is used to develop and upload firmware to the ESP32 microcontroller. The program is responsible for reading sensor data, processing the data, and transmitting measurement results to the database in real time.
2. **Android Application** Android Studio is used to develop the Android application, which functions

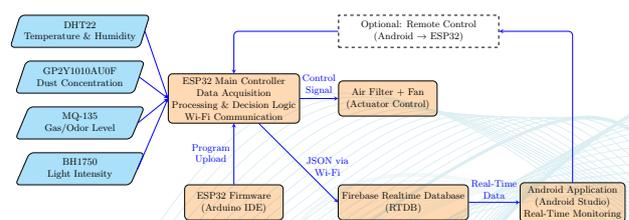
as the user interface. The application displays real-time air quality data and enables users to remotely monitor indoor air conditions.

3. **Firestore Database** Firestore Realtime Database is used to store measurement data transmitted from the ESP32 microcontroller. The communication architecture of the proposed system is designed using a cloud-based client-server model to enable real-time environmental monitoring. In this architecture, the ESP32 microcontroller functions as the primary data acquisition unit and transmits sensor measurements periodically through Wi-Fi connectivity to the Firestore Realtime Database. The Firestore platform acts as a cloud storage server that enables real-time synchronization of environmental data with the Android application, which serves as the user interface for monitoring indoor air quality conditions, as illustrated in Fig. 1. This cloud-based communication framework improves system scalability, data accessibility, and monitoring reliability. Moreover, such architecture allows flexible deployment of the monitoring system in various indoor environments without requiring significant hardware modification. The use of cloud-based IoT communication has been widely adopted in environmental monitoring systems due to its ability to support distributed sensing and real-time data visualization. The database is periodically updated and accessed by the Android application for real-time visualization.

### iii. System Flowchart

The system flowchart illustrates the overall operational workflow, starting from sensor data acquisition, data processing by the ESP32 microcontroller, transmission of data to the Firestore database via Wi-Fi connectivity, and visualization of data through the Android application.

The air filtration control mechanism implemented in this study is based on a rule-based decision system. Environmental parameters, including dust concentration, hazardous gas level, temperature, humidity, and light intensity, are periodically evaluated by the ESP32

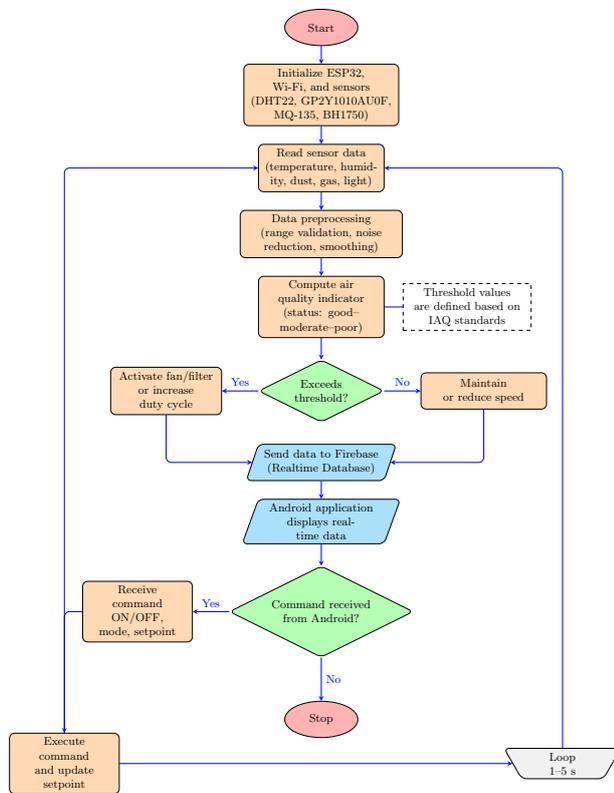


**Figure 1:** Block diagram of the ESP32-based air filtration system integrated with Firestore Realtime Database and an Android application.

microcontroller. The measured values are compared with predefined threshold values representing indoor air quality standards.

When one or more environmental parameters exceed the predefined threshold limits, the system automatically activates the air filtration fan or adjusts the fan duty cycle to improve air circulation and filtration effectiveness. This rule-based control strategy provides stable system responsiveness and reliable environmental adaptation. Such control mechanisms are commonly applied in environmental monitoring applications due to their simplicity, reliability, and rapid response to environmental changes.

Additionally, the flowchart describes the control mechanism of the fan and air filtration unit based on the detected indoor air quality conditions, as illustrated in Fig. 2.



**Figure 2:** Flowchart of the microcontroller-based air filtration system

#### iv. Research Procedure

The research procedure in this study was carried out through several sequential stages. The initial stage involved a literature review focusing on microcontroller technology, air quality sensors, air filtration systems, database technologies, and system integration based on Android and Internet of Things (IoT) concepts. This stage aimed to provide a theoretical foundation and technical references for system development.

The next stage involved hardware design, which included selecting appropriate sensors, configuring the ESP32 microcontroller, determining suitable actuators, and designing the supporting electrical circuit. This stage was conducted to ensure that the developed hardware system could operate reliably and efficiently.

Following the hardware design stage, software development was performed. This stage included programming the ESP32 firmware using Arduino IDE, configuring Firebase as a real-time database, and developing the Android application using Android Studio as a user interface for monitoring indoor air quality.

After both hardware and software components were completed, system integration was carried out to ensure proper communication between sensors, microcontroller, database, and Android application. This stage was essential to verify the overall functionality of the system.

Finally, system testing was conducted to evaluate the performance of indoor air quality monitoring. The sensor data obtained during testing were analyzed to assess system effectiveness. The analysis focused on changes in indoor air quality parameters, system response to environmental variations, and consistency between sensor measurement results and data displayed in the Android application.

To obtain representative values of environmental parameters during testing, statistical averaging was applied. The arithmetic mean of sensor readings is calculated as expressed in (1):

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad (1)$$

where  $X_i$  represents individual sensor readings and  $n$  represents the total number of measurements. This averaging method was applied to obtain representative values of temperature, humidity, dust concentration, gas concentration, and light intensity during each testing session. The averaged values were later used as reference parameters in Section III to evaluate system stability and environmental variations.

The hardware used in this study consisted of several main components. The ESP32 Dev Module microcontroller was employed as the primary processing unit, operating at 3.3 V with a clock frequency of up to 240 MHz and integrated Wi-Fi 802.11 b/g/n connectivity. The DHT22 sensor was utilized to measure temperature within the range of  $-40$ – $80^\circ\text{C}$  with an accuracy of  $\pm 0.5^\circ\text{C}$  and humidity within the range of 0–100%RH. Dust particle concentration was detected using the GP2Y1010AU0F dust sensor, which operates at 5 V. Hazardous gases including  $\text{NH}_3$ ,  $\text{NO}_x$ , alcohol vapor, benzene, and  $\text{CO}_2$  were monitored using the

MQ-135 gas sensor. Light intensity was measured using the BH1750 light sensor with a measurement range of 1–65,535 lux and I<sup>2</sup>C communication interface. The air filtration mechanism consisted of a 12 V DC fan combined with a fiber-based or HEPA air filter unit.

The software used in this research included Arduino IDE for ESP32 firmware development, Android Studio for Android application development, and Firebase Realtime Database for storing and synchronizing sensor data.

The indoor air quality parameters monitored in this study included room temperature (°C), relative humidity (%RH), dust particle concentration, gas concentration, and light intensity (lux).

The performance of the developed system was evaluated based on system response time, data transmission reliability, sensor measurement accuracy, and air filtration control responsiveness.

System testing was conducted under several indoor environmental conditions, including normal indoor air conditions, increased dust concentration, increased humidity levels, presence of hazardous gases, and remote connectivity and monitoring evaluation.

The experimental testing procedure was conducted through several sequential stages. The initial stage involved device preparation and testing environment setup, including hardware assembly, firmware uploading to the ESP32 microcontroller, Wi-Fi and Firebase configuration, Android application installation and verification, and preparation of the testing room under normal indoor air conditions.

The next stage involved initial sensor calibration. The DHT22 sensor was calibrated using reference thermometer and hygrometer instruments. Baseline values of the GP2Y1010AU0F dust sensor were determined. The MQ-135 gas sensor underwent a preheating process for approximately  $\pm 24$  hours to stabilize sensor readings. The BH1750 light sensor was verified using a calibrated lux meter.

Following calibration, normal air condition testing was conducted by activating the system for approximately 10–15 minutes while periodically recording sensor data and verifying data transmission through Firebase and the Android application interface.

Subsequent testing stages included dust concentration increase testing through gradual introduction of artificial dust and observation of air filtration system responses. To quantify filtration effectiveness, pollutant reduction efficiency is evaluated using (2):

$$\eta = \frac{C_{initial} - C_{final}}{C_{initial}} \times 100\% \quad (2)$$

where  $C_{initial}$  represents pollutant concentration before filtration and  $C_{final}$  represents concentration after filtration. This equation was used to analyze the reduction

trend of particulate matter and gaseous pollutants discussed in Section III.

Humidity increase testing was conducted using a humidifier to observe system responses to environmental humidity variations. Gas presence testing was performed by simulating hazardous gases or unpleasant odors while monitoring MQ-135 sensor responses and air filtration performance. Light intensity testing was carried out by adjusting indoor lighting conditions and recording BH1750 sensor measurements.

Connectivity and remote monitoring testing was performed by evaluating Wi-Fi data transmission, sending control commands through the Android application, and measuring system response delay.

The final stage involved data recording and processing. Sensor data were stored in Firebase Realtime Database, exported into tabular format, visualized in graphical form, and analyzed to evaluate sensor accuracy, system response time, and data transmission reliability.

To evaluate measurement stability and sensor consistency, the standard deviation of sensor readings was calculated using (3):

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^2} \quad (3)$$

Lower standard deviation values indicate stable environmental monitoring conditions and reliable sensor performance.

Furthermore, to integrate environmental parameters with different measurement scales, normalization was applied using min-max normalization as shown in (4):

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (4)$$

The normalized parameters were then aggregated into an indoor air quality index calculated using weighted summation expressed in (5):

$$IAQ = \sum_{k=1}^m w_k X_{norm,k} \quad (5)$$

where  $w_k$  represents weighting coefficients and  $m$  represents the number of environmental parameters. The IAQ index was used as a decision reference for evaluating indoor air quality status and determining filtration control responses. The computed IAQ values were subsequently analyzed in Section III to evaluate system responsiveness and air purification effectiveness.

### III. RESULTS AND DISCUSSION

This section presents the experimental results of the developed air filtration system and discusses system

effectiveness, sensor performance, and system integration with the Android application developed using Android Studio. The testing process monitored several indoor air quality parameters, including dust concentration ( $\mu\text{g}/\text{m}^3$ ), hazardous gas concentration (ppm), temperature ( $^{\circ}\text{C}$ ), humidity (%RH), and light intensity (lux). Indoor air quality measurements were conducted through three periodic measurement sessions to evaluate sensor stability and consistency.

*i. Periodic Measurement I*

Table 1 presents the results of the first periodic measurement. The recorded temperature ranged from 28.60 to 28.70  $^{\circ}\text{C}$  with an average value of 28.67  $^{\circ}\text{C}$ . The humidity level ranged from 84.4 to 85.0 %RH with an average of 84.63 %RH. Dust concentration varied between 1.3 and 6.2  $\mu\text{g}/\text{m}^3$ , with an average value of 2.60  $\mu\text{g}/\text{m}^3$ . The light intensity remained relatively constant at 6.6 lux, while gas concentration ranged from 210 to 660 ppm with an average of 480.83 ppm.

**Table 1:** Results of Periodic Measurement I

No	Temperature ( $^{\circ}\text{C}$ )	Humidity (%)	Dust ( $\mu\text{g}/\text{m}^3$ )	Light (lux)	Gas (ppm)
1	28.70	85.0	1.5	6.6	480
2	28.70	84.9	2.2	6.6	620
3	28.70	84.6	3.1	6.6	465
4	28.70	84.5	6.2	6.6	660
5	28.60	84.4	1.3	6.6	450
6	28.60	84.4	1.3	6.6	210
<b>Average</b>	28.67	84.63	2.60	6.60	480.83

data transmitted from the ESP32 microcontroller. The measured temperature was 28.6  $^{\circ}\text{C}$  and categorized as “Moderate”. The temperature graph shows a stable pattern within the range of 28.6–28.7  $^{\circ}\text{C}$ , followed by a slight decrease toward the end of the observation period. This indicates that the indoor temperature remained stable with minimal fluctuations during testing.

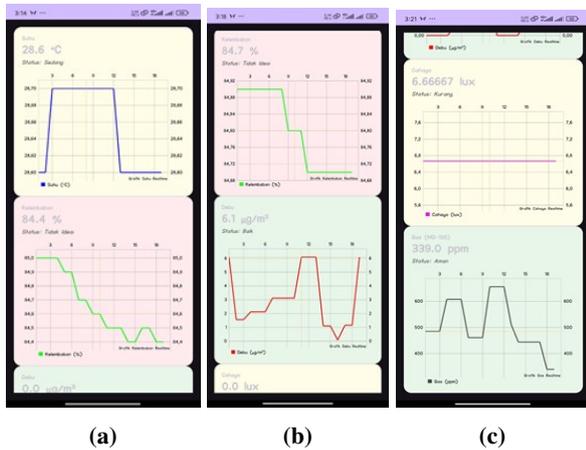
The humidity parameter showed a measured value of 84.4 %RH, categorized as “Not Ideal”. The humidity graph shows a gradual decrease from approximately 85.0 %RH to 84.4 %RH. Although a slight reduction was observed, humidity levels remained relatively high and did not reach the recommended comfort range. These results confirm that the system was able to continuously and reliably acquire and display temperature and humidity data in real time through the Android application interface.

The stability of the temperature graph indicates that the air filtration system had no significant effect on indoor temperature variation during testing. The small fluctuation (approximately 0.1  $^{\circ}\text{C}$ ) demonstrates both environmental stability and consistent DHT22 sensor performance. In contrast, the gradual decrease in humidity suggests that the air filtration and air circulation produced by the fan slightly influenced indoor humidity conditions, although the effect remained limited. From a system integration perspective, the Android application successfully displayed real-time data visualization in both numerical and graphical forms, indicating reliable communication among sensors, ESP32 microcontroller, Firebase Realtime Database, and the Android application.

Overall, the results confirm that the developed system successfully performed stable and responsive real-time monitoring of temperature and humidity. However, the limited reduction in humidity indicates the need for future development of humidity control modules to enable automatic air conditioning functionality.

Based on Figure 3(b), the Android application successfully displayed real-time humidity and dust concentration data transmitted from the ESP32 microcontroller. The measured humidity value was 84.7 %RH, categorized as “Not Ideal”. The humidity graph shows a gradual downward trend, although the overall humidity level remained high.

For the dust parameter, the measured value reached 6.1  $\mu\text{g}/\text{m}^3$ , categorized as “Good”. The dust concentration graph shows noticeable fluctuations, initially around 5  $\mu\text{g}/\text{m}^3$ , decreasing to approximately 2  $\mu\text{g}/\text{m}^3$ , and increasing again to above 6  $\mu\text{g}/\text{m}^3$  at the end of the observation period. These fluctuations indicate variations in airborne particle concentration during testing, potentially influenced by human activity, airflow dynamics, or external environmental factors.



**Figure 3:** Android application interface showing real-time indoor air quality monitoring: (a) temperature and humidity, (b) humidity and dust concentration, and (c) light intensity and gas concentration.

Figure 3(a), Figure 3(b), and Figure 3(c) respectively present the Android application interface displaying temperature and humidity data, dust concentration data, and light intensity and gas concentration data during the first periodic measurement.

Based on Figure 3(a), the Android application successfully displayed real-time temperature and humidity

From a system performance perspective, the Android application successfully visualized humidity and dust concentration data in real time. This confirms reliable communication between sensors, ESP32 microcontroller, Firebase database, and the Android application. Although dust concentration remained within acceptable limits, humidity levels remained above recommended comfort thresholds, indicating the need for adaptive humidity control and enhanced filtration mechanisms in future system development.

Based on Figure 3(c), the Android application successfully displayed real-time light intensity and gas concentration data transmitted from the ESP32 microcontroller. The measured light intensity was 6.67 lux, categorized as “Low”. The light intensity graph shows a nearly horizontal and stable trend, indicating consistent lighting conditions throughout the observation period.

For the gas parameter, the measured value was 339.0 ppm, categorized as “Safe”. The gas concentration graph shows significant fluctuations, with values exceeding 600 ppm at several intervals before decreasing to approximately 350 ppm toward the end of the observation period. These variations indicate temporary changes in indoor gas concentration, possibly influenced by human activity, odor sources, or ventilation changes.

The stable light intensity suggests that indoor lighting conditions remained constant and relatively low, which is consistent with closed-room environments with limited natural lighting. Meanwhile, the fluctuating gas concentration demonstrates the system’s ability to detect dynamic environmental changes. From a system integration standpoint, the Android application successfully visualized real-time gas and light intensity data, confirming stable data communication across the entire system architecture.

Overall, the results confirm that the developed system successfully performed reliable real-time monitoring of light intensity and gas concentration. However, the low lighting condition and fluctuating gas levels indicate potential areas for system improvement, including automated lighting control and adaptive air filtration mechanisms.

## ii. Periodic Measurement II

The results of the second periodic measurement are presented in Table 2. The recorded temperature ranged from 28.05 to 28.30 °C with an average value of 28.14 °C. Humidity slightly increased, with an average value of 85.75 %RH. Dust concentration decreased significantly, ranging from 0.18 to 1.80  $\mu\text{g}/\text{m}^3$  with an average of 0.76  $\mu\text{g}/\text{m}^3$ . Light intensity ranged from

5.83 to 6.60 lux with an average value of 6.47 lux. Gas concentration decreased to a range of 230–550 ppm with an average value of 347.50 ppm.

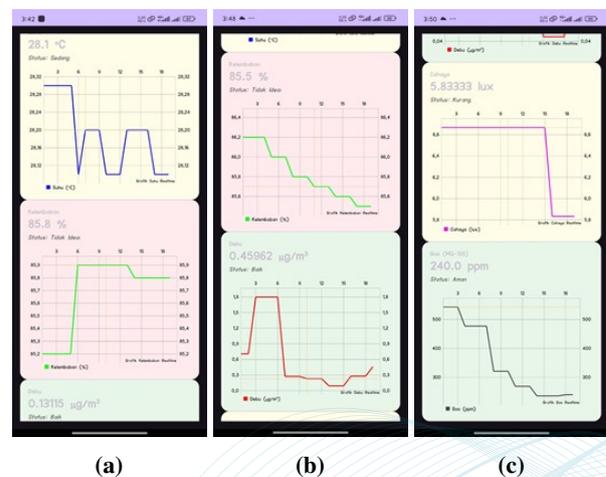
**Table 2:** Results of Periodic Measurement II

No	Temperature (°C)	Humidity (%)	Dust ( $\mu\text{g}/\text{m}^3$ )	Light (lux)	Gas (ppm)
1	28.30	85.2	1.80	6.6	550
2	28.05	85.9	1.80	6.6	475
3	28.20	85.9	0.25	6.6	325
4	28.05	85.9	0.25	6.6	265
5	28.20	85.8	0.18	6.6	230
6	28.05	85.8	0.28	5.83	240
<b>Average</b>	28.14	85.75	0.76	6.47	347.50

Based on Table 2 and Figure 4(a), the indoor temperature remained stable within a narrow range, indicating that the operation of the air filtration system did not significantly affect thermal conditions. The humidity level remained relatively high and stable, suggesting that the air filtration and air circulation mechanisms provided limited impact on reducing indoor humidity. This indicates that the developed system primarily functions as an air purification system rather than a humidity control system.

For the dust parameter, significant reduction was observed during testing. As shown in Figure 4(b), dust concentration decreased from approximately 1.80  $\mu\text{g}/\text{m}^3$  to values as low as 0.18–0.28  $\mu\text{g}/\text{m}^3$ . This trend confirms that the air filtration mechanism effectively removes airborne particulate matter. The measured dust levels were categorized as “Good,” indicating safe indoor air quality conditions with respect to particulate concentration.

Light intensity values remained low and stable, ranging from 5.83 to 6.60 lux, as shown in Figure 4(c). The stable trend indicates that indoor lighting conditions remained unchanged during testing. The recorded



**Figure 4:** Indoor air quality monitoring results during Periodic Measurement II displayed in the Android application: (a) temperature and humidity, (b) dust concentration, and (c) light intensity and gas concentration.

**Table 3:** Results of Periodic Measurement III

No	Temperature (°C)	Humidity (%)	Dust ( $\mu\text{g}/\text{m}^3$ )	Light (lux)	Gas (ppm)
1	28.30	83.2	0.18	7.5	298
2	28.30	83.3	0.05	8.3	292
3	28.30	83.2	0.09	9.2	290
4	28.30	83.3	0.90	9.2	291
5	28.30	83.3	0.90	8.3	293
6	28.30	83.2	0.017	8.3	294
<b>Average</b>	28.30	83.25	0.356	8.46	293.00

light levels fall under the “Low” category, suggesting insufficient illumination for typical indoor comfort standards. This condition is commonly associated with enclosed rooms with limited natural lighting.

Gas concentration showed a noticeable decreasing trend during testing. As illustrated in Figure 4(c), gas levels decreased from approximately 550 ppm to around 230–240 ppm toward the end of the observation period. This indicates that the developed air filtration system contributed to reducing gas concentration and unpleasant odors inside the room. The final gas levels were categorized as “Safe,” indicating acceptable indoor air quality conditions in terms of gaseous pollutants.

Comparison between the numerical values presented in Table 2 and the graphical data displayed in Figure 4 confirms consistent and reliable data communication among sensors, ESP32 microcontroller, Firebase Realtime Database, and the Android application. The system successfully provided accurate and responsive real-time visualization of indoor air quality parameters.

Overall, the second periodic measurement demonstrates that the developed air filtration system performed most effectively in reducing dust and gas concentrations. The significant reduction in particulate and gas levels confirms the effectiveness of the filtration and air circulation mechanisms in improving indoor air quality.

In contrast, temperature and humidity parameters showed minimal variation. The stable temperature indicates that the system does not significantly influence thermal conditions, while consistently high humidity levels suggest that additional humidity control modules are required for comprehensive air quality conditioning.

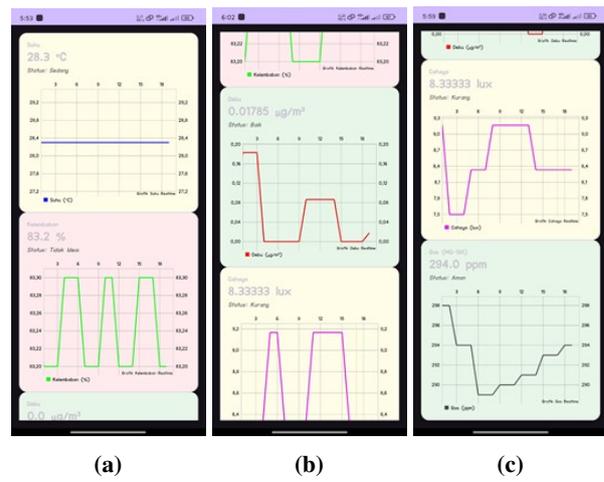
Furthermore, the low and stable light intensity indicates that the system does not influence indoor lighting conditions. However, low lighting conditions are often associated with high humidity levels in enclosed environments with limited ventilation and natural light exposure.

Overall, the results confirm that the proposed microcontroller-based air filtration system successfully performs real-time air quality monitoring and purification, particularly for particulate and gaseous pollutants. Future system improvements may include humidity control modules and adaptive lighting support to en-

hance overall environmental comfort.

### iii. Periodic Measurement III

Table 3 presents the results of the third periodic measurement. The recorded temperature remained stable at 28.30 °C, while humidity ranged from 83.2 to 83.3 %RH with an average value of 83.25 %RH. Dust concentration ranged from 0.017 to 0.90  $\mu\text{g}/\text{m}^3$  with an average of 0.356  $\mu\text{g}/\text{m}^3$ . Light intensity increased within the range of 7.5–9.2 lux with an average value of 8.46 lux. Gas concentration remained stable between 290 and 298 ppm with an average value of 293 ppm.



**Figure 5:** Indoor air quality monitoring results during Periodic Measurement III displayed in the Android application: (a) temperature and humidity, (b) dust concentration, and (c) light intensity and gas concentration.

Based on Table 3 and Figure 5(a)–(c), the developed air filtration system successfully performed consistent real-time indoor air quality monitoring during the third periodic measurement.

The temperature parameter remained highly stable around 28.30 °C. The temperature graph in Figure 5(a) shows an almost horizontal pattern, indicating constant indoor thermal conditions and confirming that the air filtration system does not significantly influence room temperature.

Humidity values ranged from 83.2 to 83.3 %RH with minor fluctuations. Although slight variations occurred due to sensor response or air circulation, humidity remained within the “Not Ideal” category. This indicates that the current system is not designed to actively control indoor humidity levels.

For the dust parameter, concentrations ranged from 0.017 to 0.90  $\mu\text{g}/\text{m}^3$  with a significant overall reduction trend. The dust graph in Figure 5(b) shows a noticeable decrease from higher initial values to near-zero levels before slightly increasing toward the end

of the observation period. These results confirm the effectiveness of the filtration mechanism in reducing airborne particulate matter. The measured dust levels remained within the “Good” air quality category.

Light intensity ranged from 7.5 to 9.2 lux, as shown in Figure 5(c). Moderate fluctuations were observed, indicating minor changes in indoor lighting conditions. However, the overall lighting level remained categorized as “Low,” suggesting that the room illumination does not meet typical indoor comfort standards.

Gas concentration remained stable between 290 and 298 ppm. The gas graph in Figure 5(c) shows an initial decrease followed by a slight increase toward the end of the observation period. This indicates that the air filtration system effectively maintains gas concentration at a low and stable level. The recorded gas levels were categorized as “Safe,” indicating acceptable indoor air quality.

Compared with previous measurements, the third periodic measurement demonstrates the most stable overall system performance. The reduced average dust concentration of  $0.356 \mu\text{g}/\text{m}^3$  and low average gas concentration of 293 ppm confirm the effectiveness of the filtration and air circulation mechanisms in improving indoor air quality.

Conversely, temperature and humidity parameters showed minimal variation. This confirms that the system functions primarily as an air purification system rather than a full environmental conditioning system. The system does not actively regulate thermal or humidity conditions.

The low lighting levels observed are consistent with enclosed environments that have limited natural lighting and ventilation. Furthermore, the consistency between numerical data in Table 3 and real-time graphical visualization in Figure 5 confirms reliable data communication among sensors, ESP32 microcontroller, Firebase Realtime Database, and the Android application.

Overall, the results confirm that the proposed microcontroller-based air filtration system successfully performs real-time indoor air quality monitoring and purification, particularly in reducing particulate and gaseous pollutants. However, additional humidity control modules and improved lighting systems are recommended to enhance overall environmental comfort.

#### iv. Average Indoor Air Quality Results

Table 4 presents the average values of each indoor air quality parameter obtained from the three periodic measurements.

Based on the periodic measurement results, the average values of each indoor air quality parameter were

obtained. As shown in Table 4, temperature remained relatively stable within the range of 28.14–28.67 °C. This indicates that the air filtration system does not significantly influence indoor thermal conditions.

Humidity values ranged from 83% to 86%RH, indicating that the air filtration system also has limited impact on reducing indoor humidity levels. Light intensity remained relatively low and stable within the range of 6–9 lux, indicating that testing was conducted under low indoor lighting conditions.

The most significant improvements were observed in dust and gas concentration parameters. Dust concentration decreased from  $2.60 \mu\text{g}/\text{m}^3$  during the first measurement to  $0.76 \mu\text{g}/\text{m}^3$  in the second measurement and further decreased to  $0.356 \mu\text{g}/\text{m}^3$  in the third measurement. This trend confirms that the air filtration system effectively removes airborne particulate matter.

**Table 4:** Average Indoor Air Quality Measurement Results

Parameter	Measurement I	Measurement II	Measurement III
Temperature (°C)	28.67	28.14	28.30
Humidity (%)	84.63	85.75	83.25
Dust ( $\mu\text{g}/\text{m}^3$ )	2.60	0.76	0.356
Light (lux)	6.60	6.47	8.46
Gas (ppm)	480.83	347.50	293.00

To provide a more comprehensive evaluation of system performance, the measured indoor air quality parameters were compared with recommended indoor environmental quality standards reported in previous scientific studies. Such comparative evaluation provides scientific justification regarding environmental safety and comfort levels. The observed reductions in particulate matter concentration and gas levels indicate that the proposed air filtration system effectively contributes to maintaining indoor air quality within acceptable environmental comfort and health ranges.

Similarly, gas concentration decreased from 480.83 ppm in the first measurement to 347.50 ppm in the second measurement and further decreased to 293 ppm in the third measurement. These results indicate that the developed system contributes significantly to reducing gaseous pollutants and unpleasant odors in indoor environments.

Power consumption represents an important performance parameter in IoT-based monitoring systems. The developed system utilizes an ESP32 microcontroller, which is recognized for its low power consumption characteristics and support for energy-efficient operating modes. The integration of low-power environmental sensors and controlled fan operation contributes to reducing overall system energy consumption. Evaluating power consumption provides important insight into system sustainability and supports the feasibility of long-term environmental monitoring implementation.

This study still has several limitations that need to be considered. The Android application developed in this research is currently limited to monitoring functionality and does not yet support direct control of the air filtration system. In addition, sensor data are stored temporarily in Firebase and may be overwritten by new data, which limits the ability to perform long-term analysis. Furthermore, system testing was conducted in a room with limited size, which may not fully represent various environmental and extreme air quality conditions. One important limitation of cloud-based IoT monitoring systems is the dependence on stable network connectivity. Temporary network disruptions may affect data transmission continuity and real-time monitoring performance. Future system development may incorporate local data buffering mechanisms that allow temporary storage of sensor data during network interruptions, followed by automatic data synchronization once network connectivity is restored. This approach is widely implemented in IoT monitoring systems to improve system reliability and operational stability.

Future research is expected to improve the system by developing a database capable of storing long-term historical sensor data. The addition of remote control features in the Android application is also recommended to enhance system usability and functionality. Further testing should be conducted in larger indoor environments and under extreme air quality conditions to evaluate system performance more comprehensively. Additionally, the development of automatic humidity control modules is recommended to improve overall environmental comfort and system performance.

#### IV. CONCLUSION

Based on the design, implementation, and experimental evaluation of the microcontroller-based air filtration system integrated with an Android application, it can be concluded that the developed system successfully achieved the objectives of this study. The system is capable of performing real-time indoor air quality monitoring based on temperature, humidity, dust particle concentration, gas concentration, and light intensity parameters.

Experimental results indicate that temperature and humidity remained relatively stable during system operation, suggesting that the air filtration system does not significantly influence indoor thermal conditions. In contrast, dust and gas concentrations demonstrated consistent reduction trends across periodic measurements. The average dust concentration decreased from  $2.60 \mu\text{g}/\text{m}^3$  to  $0.356 \mu\text{g}/\text{m}^3$ , while gas concentration decreased from 480.83 ppm to 293 ppm. These results confirm that the developed air filtration system

effectively improves indoor air quality.

Furthermore, the integration between the ESP32 microcontroller, environmental sensors, Firebase Real-time Database, and the Android application developed using Android Studio operated reliably. Sensor data were successfully transmitted and visualized in real time with stable system responsiveness, enabling users to remotely monitor indoor air quality conditions.

Overall, the proposed microcontroller-based air filtration system demonstrates reliable, accurate, and responsive real-time indoor air quality monitoring capabilities. The system shows strong potential as a practical solution for improving indoor environmental quality and supporting the implementation of Internet of Things (IoT)-based smart home technologies.

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