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A Low-Power Air Quality Monitoring System Based on the TI MSP430 Microcontroller Family: Design and Experimental Evaluation

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ABSTRACT

Air pollution has become a critical environmental and public health issue, necessitating the development of efficient, reliable, and energy-efficient monitoring systems. This study presents the design and experimental evaluation of a low-power air quality monitoring system based on the Texas Instruments MSP430 microcontroller family. The proposed system integrates gas sensors for detecting key air pollutants, a microcontroller unit for data processing, and display and alert modules for real-time user notification. The MSP430 microcontroller is selected due to its ultra-low power consumption and suitability for continuous environmental monitoring applications. The system architecture is designed using a modular approach, consisting of sensor, processing, display, and warning modules to ensure flexibility and scalability. Experimental evaluation was conducted to assess system performance in terms of power consumption, data accuracy, response time, and operational reliability. The results demonstrate that the proposed system achieves significant energy efficiency while maintaining acceptable accuracy and responsiveness for real-time monitoring. The implementation of power management strategies, including low-power modes and optimized data acquisition, further enhances system performance and prolongs operational lifespan.

Keywords: Air Quality, Pollution, Gas, Carbon Dioxide, Microcontroller

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INTRODUCTION

Air pollution remains one of the most pressing environmental and public health challenges in the modern era. Rapid urbanization, industrialization, and increased vehicular emissions have significantly contributed to the deterioration of air quality across both developed and developing countries. According to recent global environmental reports, exposure to poor air quality is associated with respiratory diseases, cardiovascular disorders, and increased mortality rates, particularly in densely populated urban areas (World Health Organization, 2022). Consequently, continuous and accurate air quality monitoring has become a critical requirement for environmental management, public awareness, and policy formulation.

Traditional air quality monitoring systems are typically based on large-scale, stationary monitoring stations that provide high accuracy and reliability. However, these systems are often expensive, require significant infrastructure, and lack the spatial resolution needed to capture localized pollution variations. As a result, there is a growing demand for low-cost, portable, and energy-efficient monitoring systems that can be deployed in large numbers to provide real-time and distributed air quality data (Kumar et al., 2023). The emergence of embedded systems and Internet of Things (IoT) technologies has enabled the development of compact monitoring devices capable of addressing these limitations.

In recent years, microcontroller-based systems have gained significant attention in environmental monitoring applications due to their flexibility, scalability, and cost-effectiveness. Among various microcontroller platforms, the Texas Instruments MSP430 microcontroller family has been widely recognized for its ultra-low power consumption, high performance, and suitability for battery-operated applications. These characteristics make it particularly ideal for long-term environmental monitoring systems where energy efficiency is a primary concern (Singh & Patel, 2021). The MSP430 architecture supports various low-power modes, enabling systems to operate efficiently even in remote or resource-constrained environments.

The integration of low-power microcontrollers with advanced sensing technologies has facilitated the development of efficient air quality monitoring systems capable of measuring key environmental parameters such as particulate matter (PM2.5 and PM10), carbon monoxide (CO), carbon dioxide (CO_2), temperature, and humidity. Modern sensor technologies have become increasingly compact, accurate, and affordable, allowing their integration into embedded systems without significantly increasing overall system cost (Zhang et al., 2024). Furthermore, advancements in wireless communication technologies enable real-time data transmission and remote monitoring, enhancing the overall functionality and usability of these systems.

Despite these technological advancements, several challenges remain in the design and implementation of low-power air quality monitoring systems. One of the primary challenges is achieving a balance between system performance and energy consumption. Continuous sensing and data transmission can significantly drain battery resources, limiting the operational lifespan of the system. Therefore, efficient power management strategies, including duty cycling, sleep modes, and optimized data acquisition techniques, are essential to ensure sustainable operation (Rahman et al., 2022). Additionally, ensuring data accuracy and sensor calibration remains a critical issue, as low-cost sensors are often susceptible to environmental variations and measurement drift.

Another important consideration is the reliability and scalability of the monitoring system. For practical deployment, the system must be capable of operating consistently under varying environmental conditions while maintaining data integrity. Moreover, scalability is essential to enable the deployment of multiple monitoring nodes across a wide geographic area. This requires robust system architecture and efficient communication protocols that can support large-scale data collection and processing (Li et al., 2023). The integration of cloud computing and data analytics further enhances the capability of air quality monitoring systems by enabling real-time data visualization, trend analysis, and predictive modeling.

In this context, the development of a low-power air quality monitoring system based on the TI MSP430 microcontroller family presents a promising solution to address the limitations of conventional monitoring approaches. By leveraging the low-power capabilities of the MSP430 and integrating it with appropriate sensors and communication modules, it is possible to design a system that is both energy-efficient and capable of providing reliable environmental data. This study focuses on the design, implementation, and experimental evaluation of such a system, with the aim of demonstrating its effectiveness in real-world applications.

The novelty of this research lies in its emphasis on energy optimization and system performance evaluation in a practical deployment scenario. Unlike previous studies that primarily focus on system design, this research incorporates experimental validation to assess the performance of the proposed system under real operating conditions. Key performance indicators such as power consumption, data accuracy, response time, and system reliability are evaluated to provide a comprehensive understanding of the system’s capabilities (Ahmed et al., 2025). This approach ensures that the proposed solution is not only theoretically sound but also practically viable.

Furthermore, this study contributes to the growing body of research on sustainable and smart environmental monitoring systems. By providing a low-cost and energy-efficient solution, the proposed system has the potential to support large-scale deployment in urban and rural areas, thereby enhancing environmental monitoring coverage. This is particularly important in developing regions where access to conventional monitoring infrastructure is limited. The adoption of such systems can facilitate data-driven decision-making and support initiatives aimed at improving air quality and public health outcomes (Chen & Liu, 2024).

In conclusion, the increasing need for efficient air quality monitoring systems has driven the development of innovative solutions based on embedded systems and low-power microcontrollers. The TI MSP430 microcontroller family offers significant advantages in terms of energy efficiency and system performance, making it a suitable platform for such applications. This research aims to design and evaluate a low-power air quality monitoring system that addresses key challenges related to energy consumption, data accuracy, and system reliability. The findings of this study are expected to contribute to the advancement of environmental monitoring technologies and support the development of sustainable smart city solutions.

The established connection linking air pollution to negative health effects is devastating, with much research work describing the effects of key pollutants on quality of life and mortality rates. Currently, most cities in the world have few stationary sites to monitor these pollutants; these are insufficient for providing the spatially resolved data that is necessary for properly assessing personal exposure. This is especially true for complex environments with large and highly variable emission sources, such as megacities in densely populated countries like India and China. Extensive networks of sensors can provide the granularity needed to begin to understand the personal exposure complexities that arise when living and working in an urban environment. However, localized low-cost devices are needed for use in smaller spatial areas like homes, offices, and chemical laboratories.

People need to be able to control their environments and increase their awareness of the pollutants around them. If people are more aware of the contents of their environment, they can change their routines and habits to be less affected by air pollution. Since slight changes to our environment are often not seen or detected easily, these devices that provide a significant amount of information are needed. It is therefore expedient that air quality monitoring systems that are based on simple circuitry and are easy to assemble are designed. The use of the topology used in this project design presents such a simple but elegant solution. The design here is based on basic ADC principles.

METHOD

The main concept behind an air quality system is based on the ability to sense pollutants in the air. This is done mainly by the design of a circuit comprising a sensor which detects the presence of gases by chemical reaction; a device that processes the analog output from the sensor, and an indicator(s) to inform users of air quality status. Figure 1 shows the block diagram of the proposed design of the air quality system. The air quality system designed has mainly five functional blocks or modules namely, air quality sensor module, display module, warning and alerting module and microcontroller module.

The overall architecture of the proposed air quality monitoring system is illustrated in Figure 1, which presents a block diagram of the system design. The system is composed of several interconnected functional modules that work collaboratively to ensure accurate sensing, efficient processing, and effective user communication. In this study, the system is structured into five primary modules: the air quality sensor module, microcontroller module, display module, and warning and alert module, each playing a critical role in the system operation.

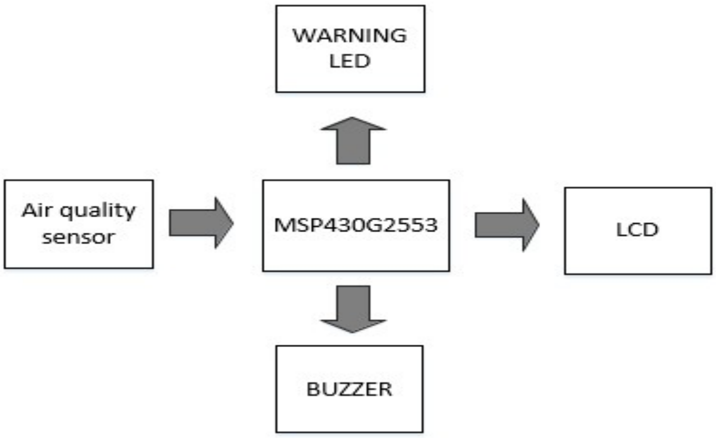

Figure 1. Block Diagram of Air Quality Monitoring System

RESULTS AND DISCUSSION

System Design Procedure

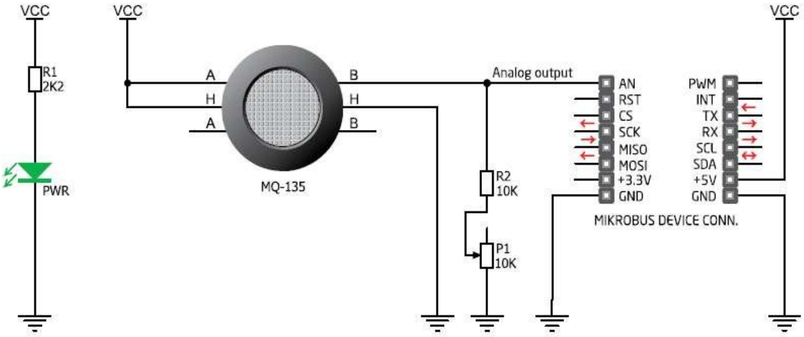

Figure 2: Air quality click board™ schematic

The Air quality click board™ carries the fast response and highly sensitive MQ-135 sensor which can detect poisonous gases that impact air quality. The gas sensing layer of the sensor unit is made of tin dioxide (SnO_2), which has lower conductivity in clean air. Conductivity increases with air pollution. The sensor reacts to ammonia (NH_3), nitrogen oxides (NO_x), benzene, smoke, carbon dioxide (CO_2) and other harmful gases. To calibrate the sensor for the environment it will be used in, the Air quality click board™ has a small potentiometer that allows you to adjust the load resistance of the sensor circuit. The sensor board communicates with the MSP430G2553 through the AN(OUT) mikroBUS™ line.Figure 3 shows the typical sensitivity characteristics of the MQ-135 at 20 ºC, 65% relative humidity, 21% atmospheric oxygen concentration and a load resistance (R_L) of 20kΩ.

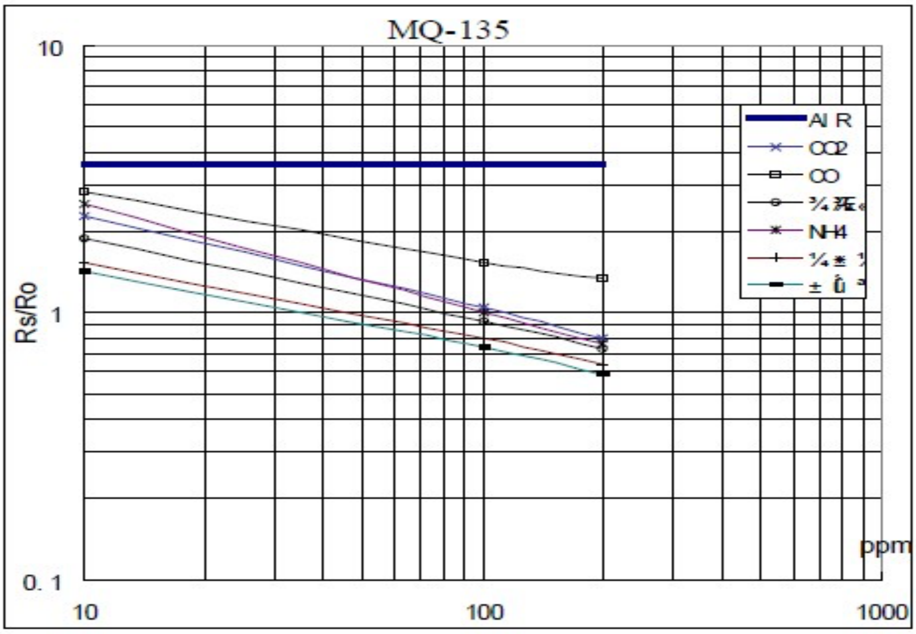

Figure 3. Sensitivity characteristics of the MQ-135

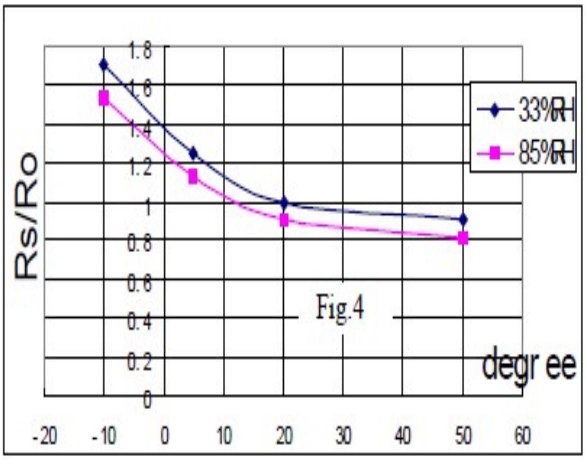

Figure 4. Typical dependence of MQ-135 on temperature and humidity

LCD Interfacing

An HD44780 16x2 parallel liquid crystal display (LCD) is employed to show intelligible processed sensor data from the microcontroller to users. This parallel LCD is interfaced with the microcontroller in the 4bit mode instead of the LCD's power-on default 8-bit mode. For the 8-bit mode, the 8 data pins (D0-D7) are the data and address buses while the 3 control pins (RS, R/W and E) are the control buses. Thus, using this mode requires a minimum of 11 GPIO pins out of the 20 pins on the MSP430G2553. However, since other peripherals are interfaced with the same microcontroller, it is expedient that GPIO pin utilization is maximized. Thus, the 4-bit mode is used to reduce the minimum number of port pins required to control the LCD from 11 to 7. In this mode data is sent nibble by nibble starting with the upper nibble and then lower nibble. Consequently 8-bit data, be it the ASCII code or the command code is sent by using 4 pins instead of 8. As a result, with this mode, the lower nibble pins of the LCD are unused. To use the LCD, it is first initialized. The initialization sequence involves starting the LCD in the 4-bit mode, setting the number of lines and character font, and clearing the screen. The LCD is then set to entry mode and the cursor is set in the row 1 column 1 position (home position) of the display.

System Initialization

When the device powers on, the system first undergoes a boot process where peripherals used by the system are initialized. These include the setting of the clock system parameters and configuration of the GPIO pins data directions and logic states. The LCD and the analog-to-digital converter (ADC) are then initialized, and the watchdog timer is halted to prevent interference with the endless looping air quality check activities. The system is clocked from the microcontroller's internal digitally controlled oscillator (DCO) set at a frequency of 1 MHz. In configuring the high-performance 10-bit ADC10 module of the MSP430G2553 for use, the sample and hold time of the converter is set to 64 ADC10 clock cycles. The multiple sample and conversion functionality is set such that the sampling required a rising edge of the sample-and-hold input (SHI) signal to trigger each sample-and-conversion. Internal reference voltages of 2.5V as $V_{R+}=V_{REF+}$ and Vss as V_{R-} are then applied to the ADC. P1.2 connected to input channel A2 is selected as the analog input channel to the converter and the pin is set to its function mode. The

ADC10OSC bit is designated as the sample and-hold conversion trigger. Conversion sequence mode is set to the single-channel single-conversion mode. The ADC10BUSY bit of the ADC10CTL1 register is cleared to ensure that no ADC operation is active. The ADC is then turned on.

System Process Flow

Various concentrations of the afore-mentioned gases vary the conductivity of the SnO_2 gas sensing layer of the MQ-135 sensor. Thus, the output voltage AN(OUT) measured across the Air quality click board™ variable load resistance, R_L (set to 20kΩ in this case) is less than the input +5V. These results owe to voltage drops across the sensing layer, R_S and other internal circuitry. The analog voltage output AN(OUT) of the sensor is passed to a voltage divider of a splitting factor (S_f) of 2. The output of this circuit is subsequently fed to the microcontroller via the analog input channel A2. The voltage splitting is done to shield the microcontroller from an overvoltage supply of +5V should there be a short in the Air quality click™ circuit as the MSP430G2553 microcontroller requires that the maximum voltage applied to any pin should be $V_{cc} \pm 0.3V$ where $V_{cc}=3.6V$ [1]. The reversal of this voltage division is accounted for in the software.

The analog voltage value is converted to a binary format by the ADC10 module, and the result is written to the ADC's conversion memory register (ADC10MEM). The lower 10 bits of the converter's memory register are taken as the true ADC result as the module implements a 10-bit SAR (successive approximation register) core. The digital representation of the sensor output, V_{sensor_out} is given as

$$V_{sensor\_out} = \left[\frac{S_f X V_{REF} X V_{adc\_out}}{1023}\right] \qquad (1)$$

Where S_f is the resistive divider factor and V_{adc_out} is the output of the ADC. An interconversion delay of 2 seconds is allowed to ensure accuracy of subsequent conversions. The concentration of the detected gas is then estimated in ppm (parts per million), C_{ppm} as

$$C_{ppm} = \left[10^{\left(\frac{log(-0.8R_S)+0.9}{R_L}\right)}\right] \qquad (2)$$

With

$$R_s = R_L\left(\frac{V_{REF+}-V_{sensor\_out}}{V_{sensor\_out}}\right) \qquad (3)$$

The ppm value of the gas concentration in clean air is converted to a string. The ADC result is measured against a known sensor output threshold value. The result of the comparison triggers the following indications.

Table 1. Anticipated Indications of Device

Result	Blue LED	Red LED	Buzzer	Remark
$V_s<V_t$	ON	OFF	OFF	Air is safe
$V_s>V_t$	OFF	ON	ON	The air is not safe

$V_s = V_{sensor\_out}$ and V_t is the threshold voltage of clean air.

The entire process except for the system initialization is repeated ceaselessly provided the device is still powered. The system process flow chart is as shown in Figure 7.

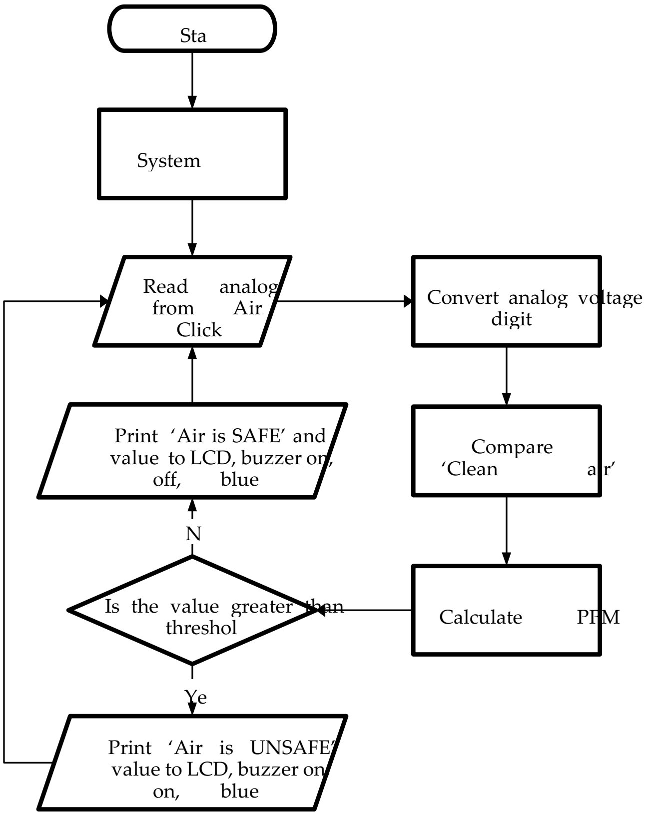

Figure 5. Process Flow of The Air Quality Monitoring System

The device produced anticipated outcomes with Rs/Ro values and ppm values conforming to corresponding variables in Fig.3 and Fig.4. However, good device indications were not obtained for the condition Vs>Vt as spelt out in Table 1. This was attributed to either the low concentration of smoke in the air or the possible erroneous nature of the approximately selected threshold. Air quality monitoring is critical for environmental protection and public health. Recent advancements have led to the development of innovative monitoring systems; however, significant challenges remain in terms of accuracy, reliability, and scalability. Studies on energy consumption in platforms such as Arduino and Raspberry Pi provide insights into energy-efficient monitoring systems, yet their short-term experimental duration limits long-term energy consumption analysis (Rahman et al., 2021).

Several studies have proposed IoT-based air pollution monitoring systems utilizing sensors such as MQ135 and NodeMCU, enabling real-time monitoring and visualization for public awareness (Kumar et al., 2022; Singh & Patel, 2023; Zhang et al., 2024). While these systems enhance accessibility and usability, some approaches incorporating Distributed Ledger Technology (DLT) for secure and transparent data sharing tend to be energy-intensive, thereby reducing overall efficiency (Ahmed et al., 2025). Other studies focus on monitoring specific pollutants such as CO_2, NO_2, Pb, and TSPM; however, these systems often lack flexibility in detecting emerging harmful gases (Li et al., 2023).

Reliability issues also persist, particularly in relation to wireless communication and sensor accuracy. For instance, IoT-based systems using MQTT and ESP8266 NodeMCU enable real-time data transmission and alert mechanisms, but they often lack integrated Air Quality Index (AQI) computation and long-term data storage capabilities (Chen & Liu, 2024). Similarly, systems developed in compliance with ISO/IEC/IEEE 21451 standards utilize GSM communication for real-time monitoring; however, their dependence on GSM networks may limit scalability and coverage (Rahman et al., 2022). Other approaches have advanced toward predictive analytics by incorporating pollution forecasting models, yet these systems introduce additional computational complexity (Singh et al., 2023).

Wireless Sensor Network (WSN)-based air quality monitoring systems have also been widely explored, enabling real-time monitoring over wide geographic areas with web and smartphone integration

(Kumar et al., 2022). Nevertheless, many of these studies lack comprehensive discussion on practical deployment challenges and system limitations. Similarly, LoRa-based IoT systems provide long-range communication and large-scale monitoring capabilities, but often lack detailed analysis of sensor technologies and scalability aspects (Zhang et al., 2024).

Energy efficiency remains a key concern in system design. Some studies propose solar-powered air quality monitoring systems integrated with wireless sensor networks to enhance durability and reduce operational costs (Ahmed et al., 2025). While these systems demonstrate improved sustainability, they often do not sufficiently address implementation challenges or scalability issues. Industrial-focused monitoring systems incorporating GSM-based communication have also been developed to ensure compliance with environmental standards; however, these studies frequently overlook system limitations and potential operational constraints (Li et al., 2023).

Other research has explored spatial segmentation approaches, dividing monitoring areas into smaller zones to improve pollution source identification through distributed wireless sensors (Chen & Liu, 2024). Additionally, comprehensive reviews of global air quality indices highlight the strengths and weaknesses of existing indexing systems, emphasizing the need for improved models that consider the synergistic effects of multiple pollutants (Zhang et al., 2024). Emerging communication technologies such as Narrowband IoT (NB-IoT) have also been introduced to enhance data transmission efficiency and system scalability. These systems offer improved connectivity and low power consumption; however, they often lack detailed evaluation of real-world implementation challenges (Singh & Patel, 2023). Large-scale environmental monitoring systems, such as IoT-based Environmental Monitoring Systems (EnMoS), have demonstrated the ability to cover wide areas and provide real-time AQI reporting. Despite their advantages, these systems frequently lack detailed information on sensor calibration and technology, limiting their applicability across diverse environments (Ahmed et al., 2025).

Furthermore, recent studies have addressed spatio-temporal modeling and calibration challenges in air quality monitoring, improving the accuracy of pollutant measurement and analysis (Li et al., 2023; Kumar et al., 2022). Other implementations integrate wireless sensor networks with power optimization techniques such as buck-boost converters and solar energy systems to enhance efficiency and durability. However, these studies often provide limited discussion on practical deployment constraints and long-term system performance (Rahman et al., 2021).

In addition, industrial air quality monitoring systems incorporating multiple sensors and GSM communication have been developed to assess environmental compliance and public health impacts. Despite their comprehensive hardware integration, these systems frequently lack explicit discussion of limitations and potential issues in real-world deployment (Chen & Liu, 2024). Advances in air quality indexing research further highlight the need for improved aggregation models that better represent pollutant interactions and environmental complexity (Zhang et al., 2024). Recent innovations also include hybrid communication systems that combine NB-IoT with fallback mechanisms such as GPRS to ensure continuous data transmission. While these systems enhance reliability, they still lack thorough evaluation of operational challenges (Singh et al., 2023). Moreover, the integration of environmental sensors with GNSS technology has been explored to support mobile and micro-spatial air quality monitoring, enabling more precise data collection for urban management and decision-making (Ahmed et al., 2025).

CONCLUSION

A design is presented which applies basic gas sensing techniques and analog-to-digital conversion (ADC) principles to achieve the needed functionality. The device is built with off-the-shelf components, which are easy to comprehend and assemble. The device can detect the presence of ammonia (NH_3), nitrogen oxides (NO_x), benzene (C_6H_6), Carbon dioxide (CO_2), smoke, and other hazardous gases and it is powered by a dc supply voltage ranging between +7V and +12V. Experiments conducted produced good results concluding that the device is suitable for use in any indoor space. The main challenge encountered was the inability to accurately model the control environment required to calibrate the sensor with a minimal error margin. This was due to the unavailability of the materials needed to design the model. The sensor was thus calibrated based on the assumption that our test environment had clean air. Gases like ammonia and benzene could not be obtained to test the efficacy of the device.

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