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Enhancing Patients Outcomes and Infection Control through Smart Indoor Air Quality Monitoring Systems

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Abstract

Air pollution poses a critical threat to public health and environmental sustainability globally, and Nigeria is no exception. Despite significant economic growth and urban development, Nigeria faces substantial air quality challenges, particularly in urban centers. While outdoor air pollution has received considerable attention, the issue of indoor air quality remains underexplored yet equally critical. This study aims to develop a reliable, cost-effective, and user-friendly solution for continuous monitoring and reporting of indoor air quality, accessible from anywhere via a web interface. Addressing the urgent need for effective indoor air quality monitoring in urban hospitals, the research focuses on designing and implementing a smart indoor air quality monitoring system using Arduino technology. Employing an Arduino Uno, ESP8266 Wi-Fi module, and MQ135 gas sensor, the system collects real-time air quality data, transmits it to the ThingSpeak cloud platform, and visualizes it through a user-friendly web interface. This project offers a cost-effective, portable, and reliable solution for monitoring indoor air quality, aiming to mitigate health risks and promote a healthier living environment.

Keywords

Artificial Intelligence, Air Pollution, Infection Control, Data Transmission, Data Acquisition, Sensors

1. Introduction

More than one-third of the people in Nigeria, a developing nation with a population of over 191 million, live in impoverished conditions in places with poor environmental standards. According to Tran *et al.*, [1], medical facilities built within such suburbs frequently have inadequate ventilation and poor indoor air quality, which exacerbates the spread of airborne illnesses and other health problems. Low-income inhabitants of traditional, unplanned urban areas are especially affected by this circumstance [2]. Numerous researches related to patient's outcome and infection control have been emphasized by earlier studies to investigate indoor air quality in residential buildings [2] [3]. Similar health risks resulting from indoor air pollution have been noted in other developing nations [1]. According to numerous researchers, the majority of illnesses associated with environmental factors are mostly caused by exposure to indoor air pollution [3] [4]. At the moment, worries about energy use, sustainable building techniques, and outdoor air quality frequently cast a shadow over indoor air quality [3]. However, there is mounting proof that lower Indoor air quality is associated with greater rates of disease and mortality [5]. Indoor air quality (IAQ) is a vital component of public health, especially considering that individuals who are sick spend a majority of their time indoors in hospital wards [1]. Poor IAQ is associated with a wide range of adverse health effects, from respiratory issues and cardiovascular diseases to chronic obstructive pulmonary disease and these can affect patient's outcome [6].

This research is motivated by the critical need to comprehensively understand the sources, impacts, and mitigation strategies for indoor air pollution in medical facilities in Abuja municipality. By exploring the effectiveness of current monitoring systems, evaluating health outcomes, and proposing evidence-based interventions, this study aims to fill a significant gap in environmental health research and policy in Nigeria. Enhancing air quality can reduce healthcare costs, improve productivity, and contribute to a higher quality of life for all residents. This study is focused on creating a Smart Indoor Air Quality Monitor using Arduino technology. The goal is to provide a solution that is affordable, accessible, and user-friendly for monitoring and improving indoor air quality. The project aims to create a sensor array that can accurately measure various indoor air quality parameters, including VOCs, particulate matter, NH_3, NO_x, benzene, smoke, alcohol, and CO_2. The design and assembly of the array prioritizes compatibility with Arduino technology [7]. In addition, the project entails developing software for streamlined data collection and processing, enabling seamless real-time monitoring. An emphasis is placed on creating an interface that is easy to use and understand for interpreting air quality data. Additionally, efforts are made to establish connectivity options for remote monitoring and sharing of data. Through the attainment of these objectives, the research aims to offer a pragmatic and innovative solution to the deficiencies found in existing indoor air quality monitoring systems. This will ultimately contribute to the promotion of healthier and safer indoor environments.

2. Related Work

Indoor air pollution has emerged as a significant public health issue, particularly in healthcare settings where vulnerable populations are at heightened risk [8]. This literature review compares and contrasts existing studies on the impact of indoor air pollution on patient outcomes and infection control practices within hospitals. By examining various research findings, methodologies, and conclusions, this review aims to highlight commonalities and differences in the literature, providing a comprehensive understanding of how indoor air quality affects patient health and infection rates.

2.1. Impact of Indoor Air Pollution on Patient Outcomes

A consensus exists across multiple studies that indoor air pollution significantly impacts patient outcomes, particularly in terms of respiratory and cardiovascular health [9]. Research consistently shows that pollutants such as particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) contribute to the exacerbation of chronic conditions and acute health episodes [2]. For instance, Kim *et al.* [10] found a direct correlation between elevated levels of PM2.5 in hospitals and increased hospital admissions for asthma and COPD. Similarly, Zhang and Srinivasan, [11] linked prolonged exposure to high indoor pollution levels with higher mortality rates among patients with pre-existing conditions. However, differences in study design and population focus have resulted in varying degrees of outcomes. For example, studies like that of Park *et al.* [8] emphasize the vulnerability of specific populations such as pregnant women and children, showing a strong association between indoor air pollution and adverse pregnancy outcomes like preterm birth and low birth weight. In contrast, Kumar *et al.*, [12] highlight the neurological impacts, noting cognitive decline and exacerbation of mental health disorders due to prolonged exposure. These variations underline the necessity of considering demographic and health status diversity when assessing the impact of indoor air pollution on patient outcomes [7].

2.2. Air Pollution and Infection Control in Healthcare Settings

The role of indoor air quality in infection control within healthcare environments is another critical area of focus. Research indicates that poor indoor air quality can exacerbate the spread of airborne pathogens, compromising infection control measures [4]. Saini, *et al.*, [2] demonstrated that higher levels of indoor air pollutants were associated with increased hospital-acquired infections (HAIs), particularly respiratory infections. Airborne particulate matter can carry bacteria, viruses, and fungi, enhancing their transmission in poorly ventilated areas [1].

Contrasting studies reveal different perspectives on how specific pollutants influence infection rates. Park *et al.*, [8] pointed out that pollutants like NO_2 and VOCs impair immune responses, thereby increasing susceptibility to infections among patients. In intensive care units (ICUs) and operating rooms, where infection control is paramount, these pollutants can have particularly severe consequences [4]. Conversely, some studies argue that while pollutants do contribute to HAIs, the primary issue lies in the inadequacy of ventilation and filtration systems rather than the pollutants themselves [9]. This suggests that improving infrastructure might mitigate some of the pollution-related infection risks, emphasizing the complexity of managing indoor air quality in healthcare settings.

2.3. Interventions and Strategies for Improving Indoor Air Quality

Effective interventions to mitigate the effects of indoor air pollution on patient outcomes and infection control are a common theme in the literature [3] [5]. High-efficiency particulate air (HEPA) filters and ultraviolet germicidal irradiation (UVGI) are widely recognized as effective technologies for reducing airborne pollutants and pathogens. Megahed *et al*., [9] demonstrated that HEPA filters in hospital ventilation systems significantly reduced airborne particle and pathogen concentrations, thereby decreasing HAIs. Comparative analysis of intervention strategies reveals a diversity of approaches and emphases. While some studies focus on technological solutions like advanced filtration and UVGI, others highlight the importance of ventilation improvements [7] [8]. For example, mechanical ventilation systems with controlled airflows and regular maintenance of HVAC systems are essential strategies noted across various studies [9] [10]. Moreover, some research stresses the importance of source control measures, such as using low-emission building materials and reducing the use of volatile chemicals within healthcare facilities [3] [7]. This multifaceted approach indicates that a combination of technological, structural, and policy-based interventions is necessary for effectively managing indoor air quality in healthcare settings.

Numerous studies consistently affirms that indoor air pollution adversely affects patient outcomes and complicates infection control in healthcare environments [2] [8]. However, variations in study design, population focus, and methodological approaches lead to differing emphases and conclusions. While some research underscores the direct health impacts of specific pollutants, others point to the broader issues of ventilation and infrastructure inadequacies [10]. Effective interventions range from advanced filtration technologies to comprehensive ventilation improvements and source control measures, highlighting the need for a multifaceted strategy to address indoor air pollution in hospitals [3]. Research has shown that improving indoor air quality requires a holistic approach that incorporates the latest technology, infrastructure upgrades, and stringent regulations [1]. Ongoing research is crucial to improve and customize these tactics to meet the individual requirements of various healthcare environments. Addressing indoor air pollution is essential for protecting patient health, improving infection control, and creating a safer and better hospital environment [3].

3. Method

This section provides a comprehensive overview of the methodological approach adopted in the design, development, and implementation of the smart indoor air quality monitoring system using Arduino [13]. The design methodology for the smart indoor air quality monitoring system is outlined, detailing the systematic approach taken to develop, implement, and validate the system. The methodology encompasses the stages of design, data collection, data consolidation, statistical analysis, software development, and testing and validation [14]. Each stage is elaborated with specific processes, tools, and techniques to ensure a robust and reliable outcome.

3.1. Sources of Data Collection

Data collection for the indoor air quality monitoring system involves multiple sources to ensure comprehensive and accurate data acquisition. The primary source is the MQ135 gas sensor, which continuously monitors air quality by detecting various pollutants such as CO_2, ammonia, benzene, and smoke [6]. This sensor outputs analog signals proportional to the concentration of these gases, which are then read and processed by the Arduino Uno microcontroller. Additionally, the system can integrate data from local weather stations and external air quality monitoring networks to contextualize indoor readings. This integration helps in understanding the influence of outdoor conditions on indoor air quality. Furthermore, user interactions with the web application provide another data layer, offering insights into how real-time and historical data is accessed and utilized [15]. This multi-source approach ensures that the monitoring system captures a holistic view of air quality, facilitating accurate analysis and effective interventions.

3.2. Data Cleaning and Preprocessing

The data was cleaned and preprocessed to eliminate anomalies and noise, ensuring data integrity. This process included normalization and standardization to facilitate accurate analysis and comparison, essential for deriving meaningful insights [16]. A real-time dashboard featuring graphs and indicators was developed to display current air quality metrics, while Historical Data Analysis allows users to observe trends and patterns over time through interactive charts [17]. There is the option to download CSV files of historical data for further analysis. The web application was deployed on Vercel for scalability and performance, with the codebase hosted on GitHub for version control and collaborative development. The design and development of the indoor air quality monitoring system involved several key steps. The system aims to monitor indoor air quality by measuring gas concentrations using an MQ135 gas sensor connected to an Arduino Uno, which processes the sensor data and transmits it to an ESP8266 Wi-Fi module [14]. The system architecture for the smart indoor air quality monitoring project is robust, scalable, and modular, enabling accurate real-time monitoring and analysis. It encompasses hardware components, software systems, communication protocols, and cloud-based data management and visualization [16]. This detailed system architecture ensures seamless integration and efficient operation of all components, providing a reliable solution for indoor air quality monitoring.

3.3. System Design and Development

The design entails the creation of a system that combines an Arduino Uno, an ESP8266 Wi-Fi module, and a MQ135 gas sensor to oversee and assess the quality of the air [12]. The system retrieves air quality data from the MQ135 sensor, which is capable of detecting pollutants such as CO_2, ammonia, and benzene. This data is then transmitted over the ESP8266 module to the ThingSpeak cloud platform. The Arduino Uno, selected for its user-friendly interface and interoperability, executes firmware to collect sensor data, while the ESP8266 manages Wi-Fi networking and data transmission. The ThingSpeak API gathers and stores the data, which is then shown on a web application. The portable system is specifically engineered for deployment in diverse indoor medical facilities and locations in Abuja, such as hospitals, residences, offices, and schools, in order to assess its efficacy and dependability. By continuously collecting and transmitting data to ThingSpeak, it is possible to monitor air quality in real-time. The web application provides current air quality readings and historical trends, and also allows users to download the data in CSV format.

3.4. System Architecture Description

The system specification includes the need for real-time data transmission, web accessibility, an intuitive interface, dependable data storage, and secure data transmission [17]. Additionally, the system is designed to handle real-time data processing and provide visual representations such as graphs and charts. The development roadmap is organized into different phases, including planning and requirements analysis, system design, hardware development, software development, testing and validation, and deployment and documentation. The system architecture shown in **Figure 1** incorporates the Arduino Uno microcontroller, MQ135 gas sensor, ESP8266 Wi-Fi module, and ThingSpeak cloud platform, guaranteeing smooth data transmission from the sensor to the cloud for instant monitoring and analysis.

4. Results and Findings

The outcome of this work aimed to contribute to the advancements in real-time air quality assessment and management. By integrating components such as the MQ135 gas sensor, Arduino Uno microcontroller, and ESP8266 Wi-Fi module, the system effectively measures and transmits air quality data, ensuring continuous monitoring [12]. The implementation of ThingSpeak for data storage and visualization, coupled with a web application interface, facilitates user-friendly

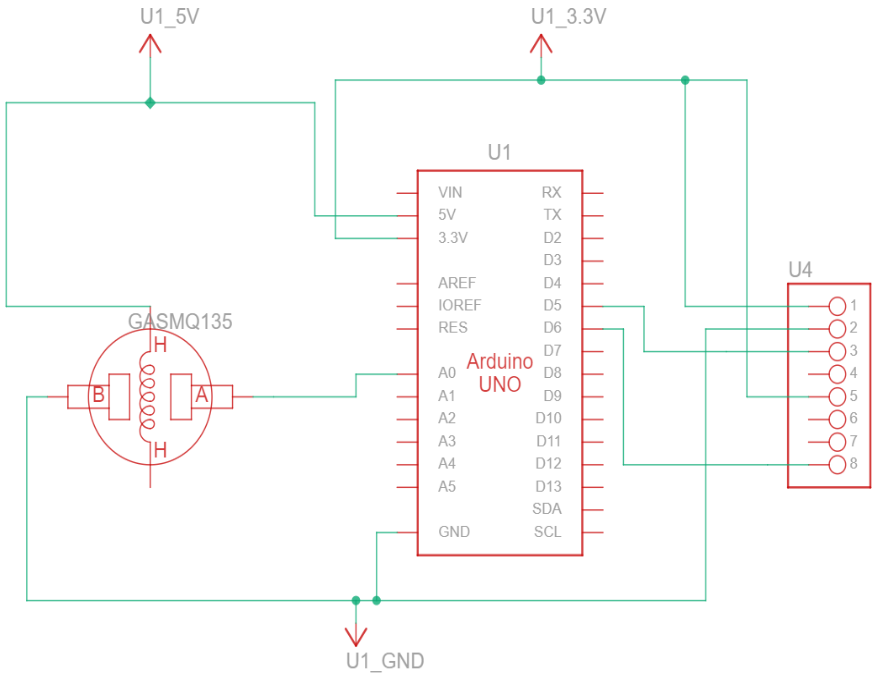

Figure 1. AQ monitor circuit schematic view.

access to both real-time and historical data, enabling comprehensive analysis and proactive air quality management. Additionally, the modular architecture of the system allows for scalable and flexible adaptations, including the addition of new sensors or communication modules, thus broadening its application scope.

Error detection and recovery mechanisms embedded within the system firmware further bolster reliability, making the system robust against data anomalies and communication failures [6]. These findings underscore the system's efficacy in providing a reliable, scalable, and secure solution for indoor air quality monitoring, highlighting its potential for widespread use in diverse environments such as hospitals, homes, offices, and schools.

4.1. System Design and Algorithms

Firstly, the MQ135 gas sensor, which outputs an analog voltage varying with gas concentration, was integrated and connected to the Arduino Uno's analog input pins (**Figure 2**). The Arduino Uno, mounted with the sensor, reads these analog signals, converts them to digital values, and processes the data to determine air quality levels. Using the Arduino IDE, the microcontroller was programmed to read sensor data, perform necessary calculations, and prepare the data for transmission. The ESP8266 Wi-Fi module was then integrated to enable data communication by establishing a Wi-Fi connection to the local network and transmitting sensor data to the ThingSpeak cloud platform via HTTP POST requests. This setup facilitates real-time monitoring of air quality data. Additionally, data from local weather stations and air quality monitoring networks were integrated to contextualize indoor readings.

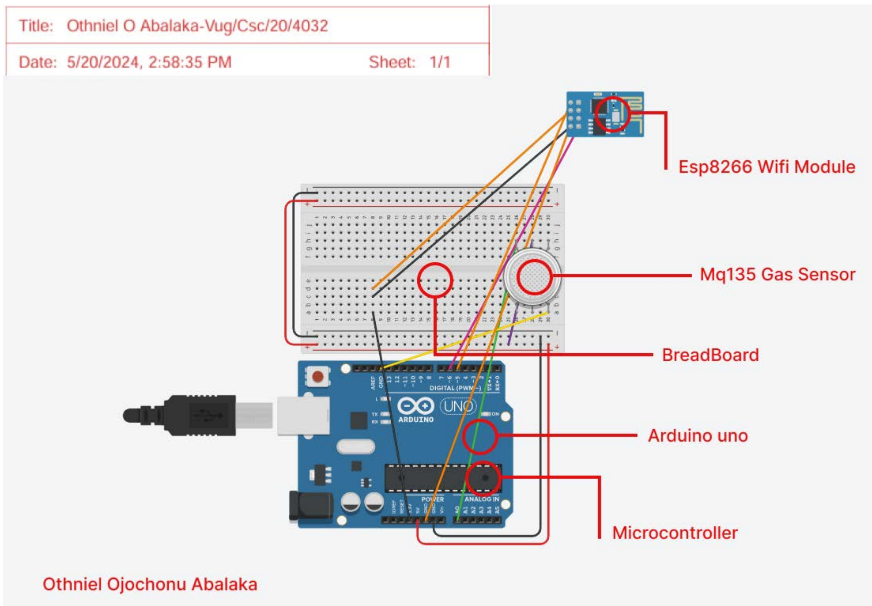

Figure 2. The ESP8266 Wi-Fi module and Circuit Diagram.

The system collects real-time data from the MQ135 sensor every 30 seconds using the Arduino Uno and transmits it to ThingSpeak via the ESP8266 Wi-Fi module. ThingSpeak was chosen for its structured storage and easy retrieval capabilities, with data logging mechanisms implemented to ensure data persistence and accessibility for reliable monitoring [13]. The completed device build is shown in **Figure 3**.

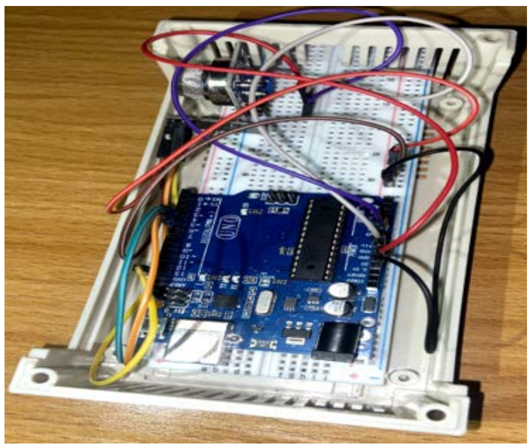

Figure 3. Completed device build.

4.2. Data Acquisition and Communication Workflow

The data acquisition procedure began with the integration of the MQ135 sensor for continuous air quality monitoring. The sensor transmitted analog signals to the Arduino Uno, where the data was processed and converted to a suitable format for transmission. Next, a data communication protocol was established, utilizing serial communication to send the processed data from the Arduino

Uno to the ESP8266 module. The ESP8266 module then established a Wi-Fi connection to transmit the data via HTTP POST requests to the ThingSpeak API. Once ThingSpeak received the data, it processed it, performed the necessary calculations, and promptly updated the real-time dashboard for analysis and visualization as shown in **Figure 4**. A web application was developed to retrieve both historical and real-time data from ThingSpeak, featuring an intuitive user interface for easy air quality monitoring and data extraction (**Figure 5**). Data security was ensured through API key authentication for access management and HTTPS encryption for data transmission. Additionally, routine backups of ThingSpeak data were implemented for data preservation, and error detection and recovery mechanisms in the firmware of both the Arduino and ESP8266 ensured system reliability. The modular architecture of the system allows for seamless integration of additional communication modules or sensors, enhancing its scalability and adaptability.

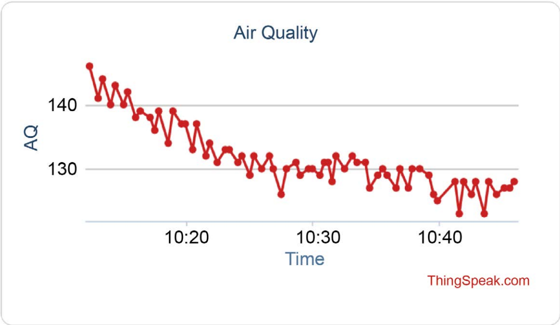

Figure 4. Air quality chart.

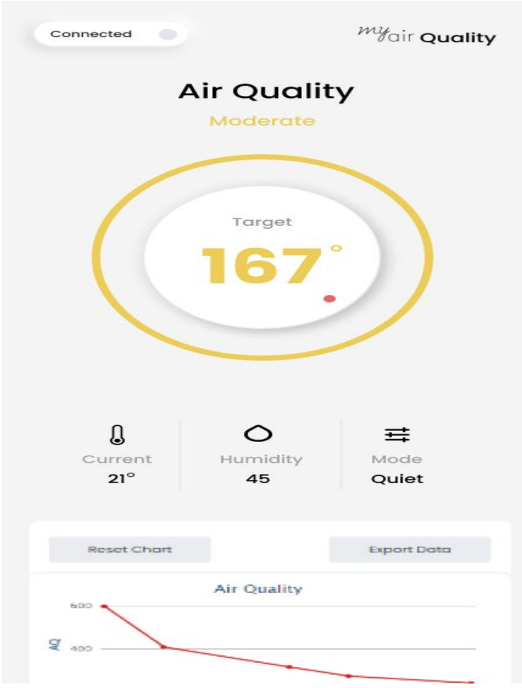

Figure 5. Air quality user interface.

By utilizing readily available and inexpensive components such as the Arduino Uno, ESP8266 Wi-Fi module, and MQ135 gas sensor, this research offers an economical solution for indoor air quality monitoring, making it accessible to a broad audience including medical facilities, households, schools, and small businesses [11]. Integration with the ThingSpeak cloud platform enables real-time data collection, storage, and visualization, allowing users to access their data anytime, anywhere, through a web interface. This makes air quality information readily available and actionable. The development of an intuitive web application enhances user experience by providing clear visualizations of air quality data, including real-time graphs, historical data charts, and options to download data for further analysis [12]. The modular design of the system allows for easy scaling and customization, enabling users to add more sensors or modify the system to meet specific needs, making it adaptable for various applications and environments. Designed to be energy-efficient and operate silently, the system can be deployed in various indoor settings without causing disturbances or significantly impacting energy consumption.

5. Discussion

The integration of Smart Indoor Air Quality Monitoring Systems in healthcare settings has a profound impact on patient outcomes and infection control, albeit in different ways. Regarding patient outcomes, these systems play a crucial role in improving health by constantly monitoring and controlling indoor air pollutants, including volatile organic compounds (VOCs), particulate matter (PM), and carbon dioxide (CO_2). Research consistently shows that indoor air quality has a significant impact on respiratory conditions, cardiovascular diseases, and cognitive functions. With the help of real-time data and historical trends, smart monitoring systems allow for timely interventions to address indoor pollutants. These interventions can include improving ventilation or using air purifiers, which can greatly reduce the negative health effects caused by these pollutants. In addition, having access to and being able to analyze extensive air quality data enables healthcare providers to customize environmental adjustments for vulnerable patients, such as those with asthma or chronic obstructive pulmonary disease (COPD), resulting in better patient outcomes.

On the other hand, Smart Indoor Air Quality Monitoring Systems greatly enhance infection control by effectively identifying and responding to conditions that promote the growth of pathogens. High levels of humidity, dust, and microbial contaminants in the air can contribute to the spread of airborne infections in healthcare facilities. Through the careful management of indoor air quality, these systems effectively minimize the risk of hospital-acquired infections (HAIs) by regulating environmental factors that can facilitate the survival and transmission of pathogens. In addition, sophisticated monitoring systems have the capability to seamlessly integrate with current building management systems, enabling automated responses like adjusting airflow or activating air filtration units in response to elevated pollutant levels. Although the enhancements in patient outcomes may not be immediately apparent, the infection control measures implemented by these systems have the immediate and tangible advantage of reducing the transmission of infectious diseases. This proactive approach prioritizes the safety of patients and healthcare workers, resulting in lower infection rates and a safer healthcare environment. Therefore, the benefits of smart monitoring systems in healthcare settings are evident in both patient outcomes and infection control. However, it is important to note that these benefits vary in terms of mechanisms and immediacy. This emphasizes the diverse value of technological advancements in the professional healthcare field.

6. Conclusions

Smart Indoor Air Quality Monitoring Systems utilizing an Arduino Uno, ESP8266 Wi-Fi module, and MQ135 gas sensor represent a cost-effective and customizable alternative to commercial systems. The implementation leverages on the Arduino platform's flexibility and the ESP8266's connectivity to offer real-time monitoring and remote data access via mobile apps or cloud platforms. The MQ135 sensor detects a range of harmful gases such as CO_2, ammonia, and benzene, providing essential insights into indoor air quality. Unlike traditional systems, which often feature limited sensor types and basic displays, this Arduino-based approach can be expanded with additional sensors (e.g., PM2.5, VOCs) and integrated with home automation systems for comprehensive monitoring. However, existing commercial systems typically offer more advanced features such as AI-driven data analysis, user-friendly interfaces, and seamless integration with other smart home devices. They are designed for ease of use, with plug-and-play installation and minimal maintenance, whereas the Arduino setup requires technical knowledge for assembly, programming, and troubleshooting. Despite these differences, the Arduino-based system offers a budget-friendly and highly customizable solution for users seeking to monitor and improve their indoor air quality.

The smart indoor air quality monitoring system developed in this project offers an affordable, portable, and reliable solution for tracking indoor air quality. Utilizing Arduino and cloud-based data services, it provides real-time insights that help users make informed decisions to improve their indoor environment. Further research can explore the correlation between indoor and outdoor air quality to develop more effective mitigation strategies, and studies on the health impacts of indoor air pollution, especially in vulnerable populations, can underscore the importance of monitoring. Future enhancements include integrating machine learning algorithms for predictive analytics and anomaly detection, and expanding coverage by deploying additional units in multiple locations to provide a comprehensive view of indoor air quality across diverse environments.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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