Intelligent Indoor Air Quality and Ventilation Management in Confined Spaces using IoT

Vishnu Simha Dussa
MSc in Electronic and Computer Engineering
Dublin City University
Dublin, Ireland
vishnu.dussa2@mail.dcu.ie

Abstract - **Optimal indoor air quality and ventilation are paramount for safeguarding human health and well-being. In addressing this critical concern, this paper introduces a comprehensive system that leverages advanced sensor technology and the Raspberry Pi microprocessor to monitor crucial indoor air parameters and implement responsive ventilation strategies. Since a significant portion of human activity occurs indoors, following energy efficiency has inadvertently presented challenges in achieving adequate ventilation. So, to handle that, this project integrates cutting-edge sensor technology, Internet of Things (IoT) principles, automation, and cloud computing to enable real-time CO_2, temperature, and humidity monitoring. Furthermore, the system's core lies in the Adafruit SCD40 sensor, seamlessly integrated with a servo motor to facilitate swift ventilation adjustments, complemented by email alerts and LED indicators that signal whenever predefined thresholds are surpassed. The system's architecture effortlessly facilitates data collection, storage, and visualization through cloud-based platforms and a mobile application. Detailed test scenarios and comparisons with other sensors demonstrate the project's effectiveness. This holistic solution effectively improves indoor air quality, enhances the comfort of occupants, and substantially contributes to the overall well-being of individuals. Moreover, the paper extends its perspective towards the system's potential for expansion and future enhancements, underscoring its role as a comprehensive approach to modern indoor environmental monitoring and management.**

Keywords - Indoor air quality Monitoring (IAQM), Air pollution, Ventilation Management, Raspberry Pi Server, Internet of things (IoT), Sensors, Hypertext Transfer Protocol (HTTP), ThingSpeak Cloud, IAQ Monitoring Application.

I. INTRODUCTION

Air quality and adequate ventilation are paramount for fostering a healthy and comfortable living environment because humans spend 90% of their time indoors [1]. In recent years, the emphasis on energy efficiency in homes has led to reducing ventilation levels and increasing the air tightness of buildings [2]. However, this practice has its drawbacks. Prolonged stays in inadequately ventilated spaces can accumulate CO_2, humidity, and pollutants, which can cause respiratory discomfort and even severe health issues. Moreover, high concentrations of CO_2 can even displace oxygen in enclosed rooms, further compromising the quality of the indoor atmosphere [3].

Poor air quality can negatively impact human cognitive ability and cause short-term health issues like fatigue, headaches and dry throat [4]. Additionally, more exposure to poor air quality can lead to long-term health consequences like chronic respiratory diseases, heart disease, and lung cancer [1]. On average, the outdoor environment contains CO_2 levels of 400 ppm, and the indoor can range from 400 to 1000 ppm. However, starting from 800 ppm, it negatively impacts humans [4]. Therefore, maintaining a balance between energy efficiency, ensuring adequate ventilation, and balancing safe CO_2 levels is vital for daily comfort and overall health.

The following section explores previous research that sets the backdrop for the study. Then, the materials and methods section elaborate on the utilization of advanced sensors, integration of responsive methods, and implementation of cloud-based data collection procedures. The results section showcases the achieved outcomes, followed by an in-depth discussion to explain, and contextualize the findings. Finally, the project's main tasks and contributions are highlighted in the Conclusion.

A. Literature Review

A website [5] from Zehnder America says that an indoor environment with excessively high or low humidity can harm human health and indoor furniture condition. Inadequate humidity can lead to discomfort, such as a sore throat and dry skin. On the other hand, high relative humidity, exceeding 70%, creates a facilitative environment for accumulating pathogens like moulds and fungi. Therefore, balancing humidity within an optimal range is essential to maintain a healthy living space while safeguarding the longevity of household items.

According to research conducted by Marie Coggins [2] on deep retrofitted homes, it was found that bedrooms tend to contain higher levels of pollutants when compared to living rooms. Additionally, a test conducted by a smart air company in a sealed room for approximately 8 hours revealed that while oxygen levels dropped by only 0.3%, CO_2 levels increased more than threefold within the 8 hours [3]. The rise of CO_2 levels may also generally depend on the occupancy level and the activities performed indoors. These increasing levels of CO_2 during night time can profoundly affect the resident's health, and it is more challenging for seniors with health issues, as they may find it hard to open windows often for fresh air due to breathing difficulties. Moreover, the awareness of high CO_2 levels may be limited. Hence, it is crucial to have solution that can take effective measures to ensure ideal CO_2, temperature, and humidity levels while advancing energy efficiency goals.

B. Research Purpose

The project's primary goal was to implement a comprehensive CO_2, temperature, and humidity monitoring system to track, analyze, and issue alerts when the indoor environment changes towards a potentially harmful state. A combination of established methodologies and innovative theories developed this effective solution, such as advanced sensor technology, principles of the Internet of Things, data analysis, automation, and cloud computing. This integrated approach formed the foundation of the endeavour to enhance indoor conditions and well-being.

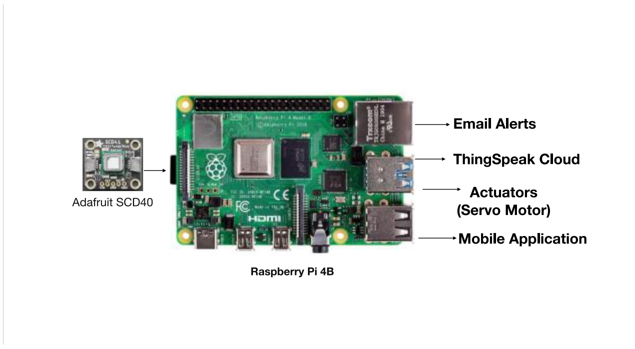

Figure 1 Project Design

The core hypothesis of this project focused on integrating current state-of-the-art sensor technology, Internet of Things connectivity, and automated systems. Combining these cutting-edge factors, the project aimed to create an indoor monitoring solution that improves air quality, efficient ventilation, and better occupant comfort. By implementing these integrated technologies, the premise that significant enhancements in indoor air quality can be achieved by monitoring CO_2, temperature, and humidity levels was indirectly examined. This, in turn, was anticipated to yield positive impacts on the health and well-being of the occupants in the indoor space. Moreover, the real-time data was expected to be seamlessly accessible through cloud and other means.

II. RELATED WORK

The scientific research community has put forth numerous systems with the goal of enhancing air quality and achieving efficient air quality monitoring. This section will emphasize the relevant previous research that aligns closely with the current project's objectives.

A Project titled “A Cost-Effective Wireless Sensor Network System for Indoor Air Quality Monitoring Applications” [1] was designed to monitor CO_2 and other air quality parameters with multiple sensors and designed to send that data to an Arduino microcontroller base station using XBee networking technology and from there, it will be sent to the cloud for storage and analysis. In this paper, they have utilised the MG-811 chemical CO_2 sensor, which requires high temperature, additional heating circuit, and power supply to get the readings and requires frequent calibration. Furthermore, it does not have any alert mechanisms, responsive actions, or a mobile application to Visualise the data.

Another project, "A Modular IoT Platform for Real-Time Indoor Air Quality Monitoring" [6], was developed to measure humidity, temperature, and six other gases. It employed ZigBee technology and established a star topology to connect with the gateway microprocessor. Significantly, adding a battery offered the advantage of data retransmission during power failure. Furthermore, the Raspberry Pi 2 was the gateway for uploading sensor readings to the Emoncms open-source web application, facilitating monitoring and visualization. However, this project did not encompass alert mechanisms, and the microprocessor was not leveraged to provide any indication or other analysis. Additionally, the employed web application lacked READ APIs for data retrieval and visualization in alternative applications.

The "Monitoring Indoor Air Quality for Enhanced Occupational Health" [7] project was also constructed using ZigBee technology. It used an Arduino Mega Microcontroller and ZigBee sensor nodes to monitor five environmental factors. ZigBee technology eased the placement of sensors in different indoor areas. Furthermore, an additional Ethernet shield was required for internet connectivity and data transfer to the cloud for the Arduino Mega microcontroller. Moreover, the system could only continuously send data to the cloud, and in the event of internet failure, data loss can occur due to the absence of local storage.

The "Indoor Environment Monitoring System Tested in a Living Lab" [8] project utilized a Raspberry Pi 3B+. The system was designed to collect data every 5 minutes, store it locally, and transmit it to the cloud for 24 hours. The sensors in this project were placed in a lab and made the tests to analyze the indoor environment and power consumption details. However, the project did not implement real-time status monitoring, alerts, and responsive actions. Additionally, the project incorporated various sensors like DHT22 and T6713 to measure temperature, humidity, and CO_2 . Notably, the CO_2 sensors utilized have a high response time and cost.

A recent project titled "Development and Assessment of an Indoor Air Quality Control IoT-Based System" [9] was introduced in 2023 to offer cost-effective solutions to vulnerable homes. The project employed an Arduino UNO microcontroller and an ESP3286 NodeMCU board for cloud data transmission. Additionally, it adopted cutting-edge technologies and followed the Test-Driven Development (TDD) process. Despite its cost-effectiveness, the project's sensors may fail in need to facilitate responsive actions more effectively. For instance, the MQ-135 sensor employed in the project was just capable of detecting CO_2 and a few other gases. However, it did not provide accurate CO_2 readings in ppm units, essential for precise decision-making based on threshold values. Furthermore, along with Arduino UNO, an additional board with Wi-Fi connectivity capabilities was required for the project to transmit data over the Internet.

Considering the limitations identified in the previous related works, the project aimed to handle them and enhance the existing air quality monitoring system by introducing several innovative features to ensure comprehensive and reliable monitoring.

The planned enhancements contain developing local indications using LEDs, emails using the internet, and other alert mechanisms to ensure that users are promptly notified of potential air quality threats. Additionally, the project entailed the design of data recording and transmission mechanisms for both local storage and the cloud. Also, it aimed to facilitate continuous monitoring and alert mechanisms even in the absence of internet connectivity. Furthermore, a local server was also planned for development to enhance the system's capabilities and intended to facilitate data storage and analysis within the premises. Moreover, the project encompassed the development of an intuitive Android application aimed at providing users with convenient access to both cloud and local server data while on the move.

The proposed system was also intended to eliminate the need for frequent calibration, thus eliminating the hassle associated with calibration processes. Through these planned enhancements, the project aimed to create a comprehensive, user-friendly, and reliable air quality monitoring solution that effectively address the shortcomings observed in existing systems.

III. Materials and Methods

Table 1 Technologies and Components Utilized in the Project

Microprocessor	Sensors and Indicator	Actuator	Connectivity	Cloud Storage and Data Visualization
Raspberry Pi 4B	Adafruit SCD40 CO_2 sensor and DHT-11 LED light	Servo Motor	Wi-Fi/HTTP	Thingspeak cloud platform. Raspberry Pi 4B as a server

In the current project, the Adafruit SCD40 sensor was utilized as a comprehensive environmental monitoring device capable of measuring CO_2, temperature, and humidity levels. The output from this sensor was integrated into a servo motor and an LED, functioning as a responsive ventilation system and an indicator that responded to predefined threshold values. When these thresholds were surpassed, the system triggered the servo motor to initiate room ventilation, thereby ensuring the preservation of optimal indoor air quality. Moreover, to test the accuracy of the SCD40 sensor, a comparative analysis was conducted using a DHT11 sensor to validate the accuracy of the collected data.

A servo motor can move its output shaft by a certain angle accurately. So, in the real world, servo motor can be linked to ventilators or windows, so that they can be moved at specific angles with the use of the servo motor. However in this project, the servo motor was added as a prototype and not connected to any ventilators.

A cloud-based approach was adopted to facilitate real-time data collection and analysis. The sensor's data was transmitted to the ThingSpeak cloud platform for remote storage, real-time graphing, and comprehensive data visualization. Its real-time data visualization tools provided the capability to create customizable graphs, charts, and gauges and offered instant insights into trends and patterns. Matlab code and its data analysis capabilities were also utilised to plot the histograms for CO_2, temperature, and humidity values based on collected data. Furthermore, it provided options to access the data through API in formats like CSV and JSON and supported integration with the Android application to view recent and historical data.

In anticipation of potential internet downtime, a redundant local data storage mechanism was established to ensure data continuity even during internet connectivity issues. Real-time data was saved concurrently into a CSV (Comma Separated Values) file on the Raspberry Pi. Additionally, by leveraging Raspberry Pi's capability, a dedicated server with the same Raspberry Pi's IP address was created to provide seamless local access to locally stored data and empower devices within the same Wi-Fi network to retrieve data through HTTP GET requests. This data was made available in CSV and JSON formats, which could be readily downloaded for offline analysis and sharing. Furthermore, an Android application was also developed to provide convenient real-time and historical data access. It was integrated with the Thingspeak API to retrieve data from the cloud and connected to the local Raspberry Pi server to provide users with a comprehensive overview of air quality and ventilation performance data.

The Android application implementation was followed based on the MVVM (Model-View-ViewModel) architecture, and the user interface was designed using the latest Jetpack compose methods and libraries. A single-screen UI was created with a few buttons that fetch data from ThingSpeak and the Raspberry Pi server and display it on the screen.

Figure 2 Recent and Historical data from Raspberry Pi Server

A few Python programs were implemented to read the CSV file and generate hourly and 24-hour data trend reports for the data collected. These programs could generate graphs containing CO_2, temperature, and humidity data trends in one graph. Temperature and Humidity trends were combined, and CO_2 trends were plotted separately for better visual understanding. A separate functionality was added to include ventilation markings on the graph whenever ventilation was required from the collected data. Furthermore, to automate graph generation in Raspberry Pi, the Linux crontab functionality was utilized to trigger Python programs at a specific time daily. After execution, the crontab commands triggered the report generation programs, generating new folders with graphs in them.

A. ThingSpeak Cloud Platform

Real-time data was presented using various formats like graphs and gauges on the ThingSpeak platform. Additionally, custom Matlab codes were implemented to generate histograms and other visual representations for the collected data to provide valuable insights into the prevalence of specific values in Temperature, Humidity, and CO_2 measurements. This strategy facilitated a deeper understanding of the distribution patterns within these key parameters.

Figure 3 Real Time Graphs of Temperature, Humidity and CO_2 values

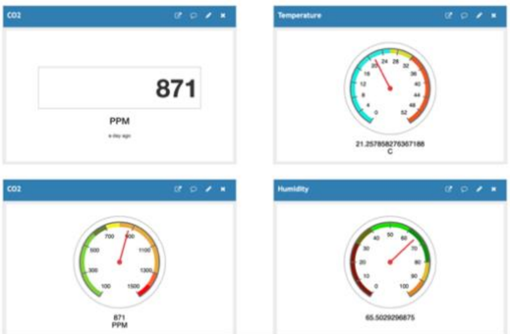

Figure 4 Real Time Gauges of Temperature, Humidity and CO_2 values

Figure 5 Histogram Analysis of Past Temperature, Humidity and CO_2 values

B. Selection of Adafruit SCD-40 sensor

The Adafruit SCD-40 CO_2 sensor was chosen for its impressive range, accuracy, and versatility, making it ideal for indoor monitoring and scientific research. Additionally, it was not used in any existing proposed systems mentioned in the literature review. Beyond CO_2, it also measures temperature and humidity, offering a comprehensive view of indoor conditions. Importantly, ranging from 400 to 2000 ppm with an accuracy of ±50 ppm + 5% of reading, it functions as an authentic CO_2 sensor utilizing photoacoustic technology and measures CO_2 concentration directly from ambient air [10].

C. Preference for Raspberry Pi over microcontrollers

The selection of the Raspberry Pi over Arduino and other microcontrollers for this project was determined by its multiple advantages that aligned seamlessly with the project's requirements. Firstly, Raspberry Pi's flexibility in supporting the Python programming language provided developers with a versatile toolbox for implementation. Additionally, Raspberry Pi has the capability to store data locally, which was a crucial feature for this project's emphasis on data preservation and offline access. Furthermore, the project's analytical capabilities were enhanced by Raspberry Pi's ability to work with sophisticated Python libraries for visualizing data. Its capacity to automate report generation using Linux crontab and facilitate remote access through VNC viewer strengthened operational efficiency and accessibility. Finally, Raspberry Pi's intrinsic qualities contributed to the project's comprehensive monitoring, control, and visualization capabilities, ultimately enhancing its overall effectiveness.

IV. RESULTS

A. Setup Placement in a Bedroom

The hardware setup was installed in a small bedroom with an area of 8.8 square meters and a volume of 19.8 cubic meters, as illustrated in Figure 6and Figure B. It was placed near a window at a height of 0.84 meters from the floor level. The decision to place it at window height level was based on the motive that this placement would measure air circulation quickly in response to changes in ventilation, such as opening or closing of windows.

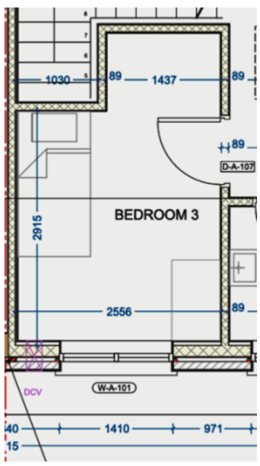

Figure 6 Tested Bedroom with Measurements

B. Test Scenario 1

After placing the hardware setup near the window, the system was evaluated under a series of test conditions and recorded the data:

- Before the test, the room was closed for a long time, and then the test was started and collected the data for 30 minutes.
- Next, the room was ventilated by opening the window for about 50 minutes, and then the window was closed.
- Finally, collected data was visualized by the Python programs developed.

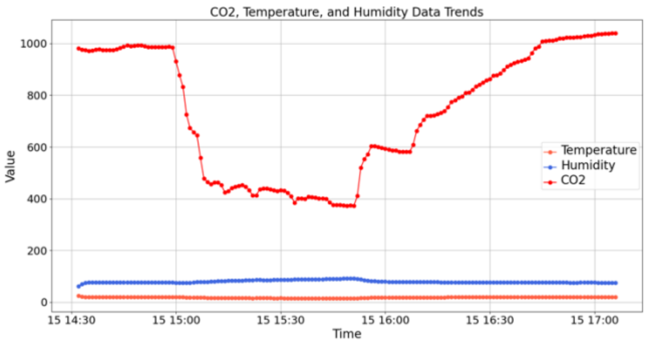

Figure 7 CO_2, Temperature and Humidity Trends for Test Scenario 1

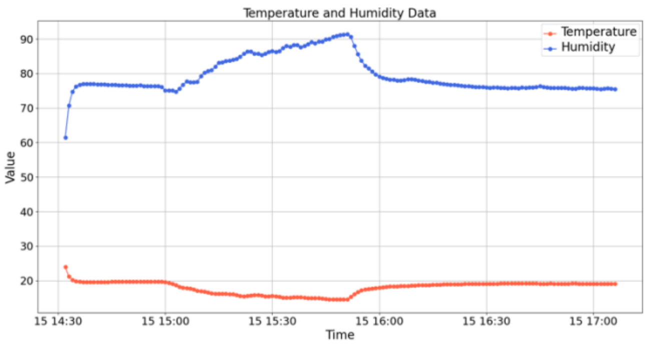

Figure 8 Temperature and Humidity Trends for Test Scenario 1

C. Test Scenario 2

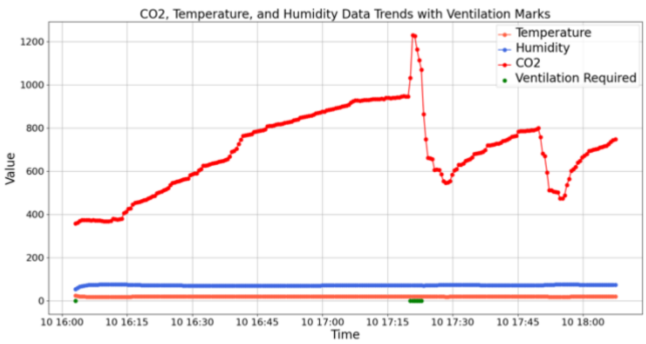

Figure 9 CO_2, Temperature and Humidity Trends for Test Scenario 2

The system was evaluated under a series of test conditions and recorded the data by following the exact sensor placement as in test scenario 1:

- Before and at the start of the test, the room was ventilated with an open window for about 10 minutes to see the temperature reading near the outdoor temperature, and then, the window was closed for more than an hour to see the high CO_2 levels.
- Once it reached above the defined threshold of 1000 ppm, the window was opened for about 15 minutes and then closed again.
- Next, data were recorded for about 20 minutes, after which the window was opened before the CO_2 levels reached above the threshold.
- Furthermore, the test was continued for 5 minutes with windows open and for 10 minutes with closed windows.
- In this test, a new Boolean field was added to the data to determine whether ventilation was required based on the defined thresholds.
- Finally, the collected data was visualized by adding ventilation marks in the graphs.

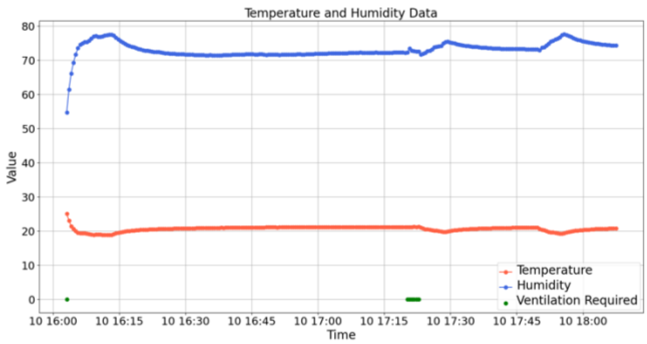

Figure 10 Temperature and Humidity Trends for Test Scenario 2

D. SCD40 and DHT11 Comparison Test

A comparative analysis was done to check the Adafruit SCD40 sensor performance compared with the DHT11 sensor. The sensor placement and the room were the same as in the above test scenarios.

The test was initiated, and data were recorded for approximately 25 minutes. Following that, the window was opened to ventilate the room for 10 minutes and then closed, ultimately allowing the setup to record for approximately ten more minutes.

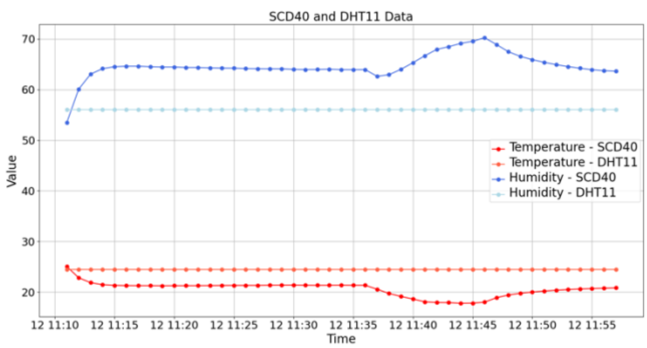

Figure 11 SCD40 and DHT11 Sensors Comparison Test

V. Discussion

A. Test Scenario 1

The tests showed a significant stabilization of CO_2 levels within the room during the ventilation interval from 15:00 to 15:45. Initially, the room exhibited high CO_2 concentrations. However, upon opening the window, the levels swiftly approached the outdoor atmosphere CO_2 levels. This observation highlights the system's effectiveness in facilitating efficient air exchange and maintaining indoor air quality.

B. Test Scenario 2

In this scenario, ventilation markings were observed on the graphs, indicating the need for ventilation due to CO_2 levels exceeding the threshold of 1000 ppm. After 17:15, when the CO_2 levels surpassed the 1000 ppm threshold, ventilation marks were plotted on the graphs until the CO_2 levels returned below the threshold. Notably, no ventilation markings appeared when the window was opened at 17:50 without exceeding the threshold. Furthermore, the CO_2 levels exhibited both gradual and rapid increases. Initially, when the room was ventilated for a long time, CO_2 levels increased gradually. However, a rapid CO_2 concentration shift occurred at 17:55 when the window was closed after a short ventilation period. The test observations highlight the significance of ventilation markings by the defined CO_2 threshold. The data also elucidated the ventilation duration's impact on CO_2 concentration dynamics and provided actionable insights for ensuring favourable indoor air quality.

C. SCD40 and DHT11 Comparison

During the comparative analysis test of Adafruit SCD40 and DHT11 sensors, when the window was opened at 11:37 for 10 minutes, the SCD40 sensor demonstrated remarkable sensitivity by promptly reflecting atmospheric changes. The noticeable sensitivity of the SCD40 sensor was displayed in its swift responsiveness to environmental aspects like temperature and humidity and led to more precise measurements than those obtained from the DHT11 sensor.

VI. Conclusion

In conclusion, the critical need for maintaining optimal indoor air quality and ventilation was effectively addressed by operating the Raspberry Pi and the Adafruit SCD40 Sensor. The indoor environment was optimized by automating responsive actions such as vent control with a servo motor. Furthermore, timely alerts and indications were proficiently issued to inform individuals of potential air quality concerns, allowing proactive measures to be taken. The generation of air quality reports was also automated by the Raspberry Pi and offered insights into the frequency of ventilation requirements. The comprehensive system, empowered by the Adafruit SCD40 sensor and advanced monitoring techniques, successfully tracked environmental parameters while demonstrating its efficiency in sustaining healthier indoor surroundings. This advancement significantly elevated comfort and overall well-being, thus making a substantial contribution to the field.

Adding a Passive Infrared (PIR) sensor to the project could be considered for future work. This sensor would detect room occupancy, and its readings could be included as an additional parameter in the data collection. This enhancement would offer valuable insights into how atmospheric variables fluctuate in the presence or absence of humans. Furthermore, leveraging machine learning prediction techniques makes it possible to formulate a predictive model based on the aggregated parameters. This predictive model could be seamlessly integrated into the existing project framework, enhancing its capabilities and functionalities.

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