Clean Air, Clear Minds: A Real-Time Carbon Dioxide and Volatile Organic Compounds Monitoring System for Classrooms

Aneira Vundecode, Omar Tawakol
Smithtown High School West, United States
Illinois Institute of Technology, United States
The University of Chicago, United States

Abstract

Indoor air quality (IAQ) in educational environments significantly impacts student health and productivity. This research presents an electronic system for monitoring IAQ, focusing on detecting carbon dioxide (CO_2) and volatile organic compounds (VOCs) using a microcontroller-based prototype. Inspired by previous research linking poor IAQ with student performance, this system was developed to measure and analyze these parameters for use in educational facilities. The proposed system utilizes commercially available Arduino-based sensors and components, enabling real-time data collection and analysis. Preliminary results indicate that the system detects changes in CO_2 and VOC levels in realtime. The system was designed to wirelessly send real-time sensor readings to an online dashboard, which allows for sharing the data to the cloud. The data can be internally shared with the members of an institution to allow for intervention if necessary. This research emphasizes sensor calibration and validation, ensuring the system's readiness for real-world classroom settings, and offering a practical solution to improve IAQ in educational environments.

Keywords: Air quality management, microcontroller, real-time monitoring

1. Introduction

Several studies have shown that in recent years, indoor air pollution has been one of the top risks to public health (Sadrizadeh et al., 2022). Although its effects are often overlooked, indoor air quality (IAQ) can have a negative impact on the well-being of hundreds of millions of people inside residential and commercial buildings. For example, IAQ is the second major factor for the relatively high mortality rate in India, resulting in upwards of 1.3 million deaths annually (Saini et al., 2020). IAQ is more likely to affect the health of individuals, when compared to outdoor indoor quality (OAQ), as individuals spend nearly 90% of their time indoors (Mannan & Al-Ghamdi, 2021). The indoor concentrations of many pollutants that compose the IAQ are often higher than those found in OAQ (Jones, 1999).

IAQ research includes a broad range of locations in which it is being monitored, as it can affect multiple groups of people. For example, as children are more susceptible to indoor pollutants than adults are, IAQ is a concern for schools and educational facilities (Mannan & Al-Ghamdi, 2021). Additionally, IAQ poses a risk in office buildings where millions work, as poor IAQ has a significant detrimental effect on workers' productivity in these settings (Mannan & Al-Ghamdi, 2021). Pollutants of IAQ, such as combustion products and VOCs (volatile organic compounds), can cause disease, disability, and mortality in extreme cases (Jones, 1999). A major concern of IAQ is its contribution to student or employee health, performance and productivity, and illness-based absenteeism, or the action of being absent, as a result of illness. IAQ, with a combination of other factors, such as an individual's allergic susceptibility to certain air contaminants, their physical and psychological health, and the concentration of the air contaminants, can determine the degree to which the individual is affected (Jones, 1999). Those who are allergic may be at a higher risk of experiencing respiratory illnesses (Annesi-Maesano et al., 2013). Moreover, a connection has been established between indoor environmental factors that affect indoor air quality (IAQ) and the respiratory condition of asthma (Richardson et al., 2005).

In indoor environments, volatile organic compounds such as formaldehyde, benzene, and acetone, released from products such as paints, solvents, and varnishes, are associated with poor health conditions (Rosén & Richardson, 1999), (Jones, 1999). Sensory irritation as well, under specific environmental conditions, can be caused by some VOCs in the air (Wolkoff, 2013). Elevated carbon dioxide (CO_2) levels are a valid indicator of poor IAQ, and are used as guidelines for the IAQ of school buildings (Chatzidiakou et al., 2015). These compounds potentially irritate the nose, eyes, and throat, and result in symptoms of nausea, headache, dizziness, and tiredness (Saini et al., 2020). Multiple effects on students and workers can be discerned as caused in part by contaminants and pollutants as part of CO_2 and VOCs that impact IAQ. Unobtrusive monitoring of IAQ parameters can make significant progress to bettering IAQ in schools (Grimsrud et al., 2006).

In order to measure indoor air quality to minimize impacts on health, several electrical systems have been deployed to monitor the relative levels of compounds that impact air quality, namely CO_2 and VOCs. Creating these systems allows users to understand the levels of pollutants in an indoor environment, as well as potentially aid in decreasing the adverse effects of these pollutants (Chojer et al., 2020). It is important to note that a multitude of factors impact air quality, including but not limited to wind, airflow, size, and the number of people in the room. Some of these IAQ Monitoring systems (IAQMS) are tuned towards monitoring IAQ in homes. This application of the IAQMS involves multiple individual sensors placed in various areas of the house, including the kitchen where gasses are released, and collecting the total inputs from these sensors in real-time, providing IAQ results (Mannan & Al-Ghamdi, 2021).

Studies aimed at measuring IAQ parameters in schools using the Arduino microcontroller, tend to take a different approach, using a single system that records the levels of different compounds that affect IAQ and transmitting the data to a centralized server (Adochiei et al., 2020).

The existing IAQMS are not yet adequate to perform a thorough IAQ assessment. Some IAQMS focus heavily on the aesthetics while ignoring functionality (Chojer et al., 2020). A research paper highlights a study conducted where IAQMS were evaluated for specific calibration and performance of sensors, and it was found that out of 35 systems, only 16 included calibration and or validation of the sensors (Chojer et al., 2020). Proper validation of the functionality of the sensors is necessary to assess the performance of any IAQMS. Moreover, even fewer studies were done using a separate established reference test instrument to verify the accuracy and precision of measurements. This highlights the need for IAQMS that are validated externally.

The proposed system herein strives to implement proper sensor calibration and validation of the measurements being recorded by each sensor by cross-referencing with a state-of-the-art commercial sensor. A real-time monitoring system such as this one allows users to see results of the respective levels of CO_2 and VOCs in a user-friendly manner. That would serve to address the issues associated with poor IAQ in the respect of students in classrooms.

2. Methods

2.1 Hardware components

2.1.1 Arduino Uno R3

The *Arduino R3* microcontroller was selected to create the setup as it has a wide range of sensor capabilities, supporting the usage of the multiple sensors and components used in the setup while providing ample power and voltage regulation onboard. The *Arduino* IDE (Integrated Development Environment) is user-friendly, making it easy to upload the program to the *Arduino*. Its 14 digital I/O pins and 6 Analog Input pins ensure ample connectivity to multiple components. Additionally, the *R3* is perfect for educational and innovative use purposes such as for this setup. The various installable libraries and open-source codes enable users to create projects suitable for their needs as well as access a multitude of support on online web forums. The *Aruduino* powers a breadboard and through it, the multiple components of the setup through the VCC and GND (ground) pins. The *Arduino* itself is versatile in accepting power; for this setup it is powered through the USB connector.

2.1.2 TMP36:

The *TMP36* temperature sensor was selected to create this setup due to its cost-effectiveness as well as its impressive accuracy of +/- 2°C, ranging from -40°C to 125°C. The code to calculate the temperature measurement of the system was manipulated to provide temperature reading in Celsius. This sensor is easily integrated with the *Arduino* using a simple breadboard. *TMP36* has a simple 3-pin structure, accepting power through VCC, returning it through GND, and outputting temperature readings through analog output pin.

2.1.3 MG811 (SEN0159-DFRobot) CO_2 Sensor:

The *MG811* CO_2 sensor was selected to create this setup as it is highly sensitive to carbon dioxide levels, a key air quality impactor that was being observed. *MG811* provides accurate CO_2 readings after a 5-10 minute initialization period each time the setup is powered. It provides an analog output that is read by the analog input pins on the *Arduino*, allowing for straightforward data collection. With a wide range from 0-10,000ppm (parts per million), the *MG811* was suitable for this project, monitoring air quality in different levels throughout the educational facility. The *MG811* provides 3 pins, accepting power through VCC, returning it through GND, and outputting CO_2 readings through analog output pin. As shown in Fig. 1 by the Response and Resume curve, the *MG811* takes approximately 20 seconds to complete its electrochemical reaction, and so readings are taken every 20 seconds. It has small dependency on temperature and humidity as seen in its datasheets. As shown in Fig. 2A and Fig. 2B, there is a very small dependency on temperature and humidity, meaning that the sensor readings will not fluctuate greatly with changes in the temperature and humidity of the environment.

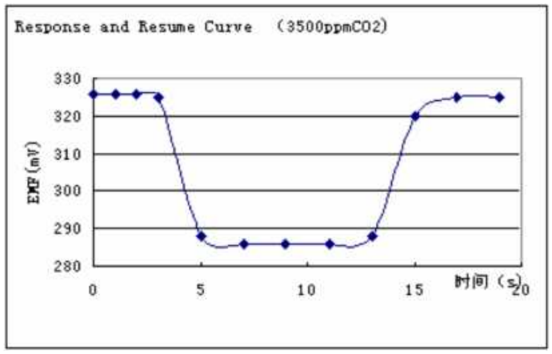
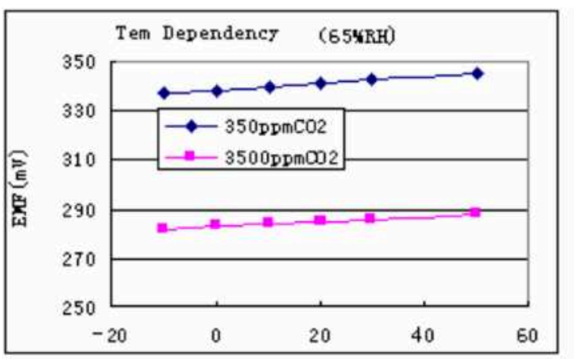


Figure 1. Screenshotted Response and Resume curve of MG811 CO_2 Sensor, displaying the 20-second period needed for the sensor to fully complete its reaction. Image taken from MG811 datasheet.

A.



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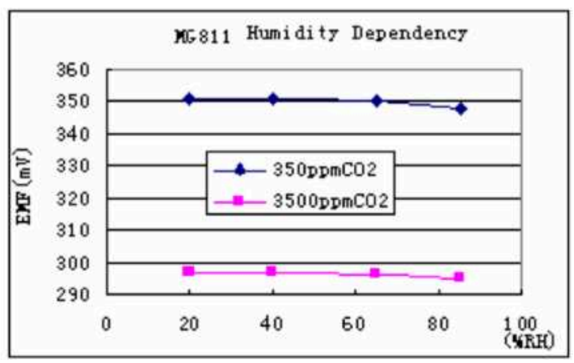

Figure 2. Screenshotted graphs of the effect of temperature on the output voltage reading of the MG811 sensor (A). The effect of humidity on the output voltage reading of the MG811 sensor (B), Image taken from MG811 datasheets.

2.1.4 SGP40 (Sensirion) VOC Sensor:

The *SGP40* VOC sensor was selected because of its high sensitivity to a range of VOCs, including formaldehyde, ethanol, acetone, and other compounds that are common in household and industrial cleaning supplies, solvents, paints, building materials, etc. *SGP40* is able to record changes in the relative intensity of indoor VOC, giving it value for recording long-term VOC, as required by the proposed system. The considered average value of the sensor is a reading of 100. *SGP40* takes approximately 5-10 minutes to initialize. Its thin, lightweight frame contributes to the goal of the portability of the system. This sensor works best in temperatures of -10°C to 50°C, and relative humidities of 0% to 18%.

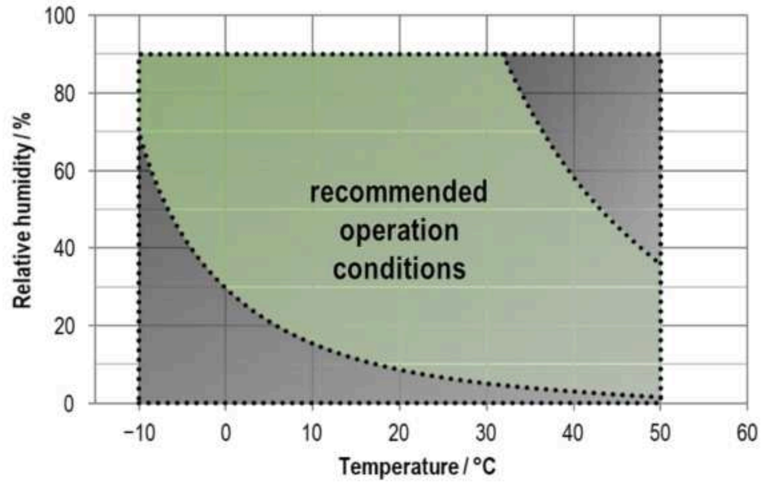

Figure 3. Screenshotted graph of Temperature and Relative Humidities for optimal operation of SGP40 sensor. Image taken from SGP40 datasheet.

2.1.5 ESP01 Wi-fi module:

The ESP01 Wifi module allows microcontrollers, such as the *Arduino Uno*, to connect to the internet via Wi-Fi. This module is based on the ESP8266 chip, enabling wireless data transmission to cloud services, IoT platforms, or local networks. It communicates with the Arduino through serial communication (TX/RX) and is programmed to send sensor data (such as temperature, CO_2 levels, and VOC readings) to the dashboard for remote monitoring.

2.1.6 DS3231 RTC Module:

The *DS3231* RTC (Real-time clock) is a component that serves to store accurate time, down to the second while the setup is being run. Its lithium battery allows it to store accurate time and date information even when not powered through the setup.

2.1.7 Micro SD Card Module:

The micro SD card module is an essential component of the setup, storing all data outputted from *TMP36*, *MG811*, *SGP40*, and *DS3231*, respectively, temperature in °C (Celsius), CO_2 in ppm (parts per million), VOC on a relative intensity scale, with 100 being average, and time in an hour, minute, second format.

2.2 Overview of System Hardware Components

Table 1. System components

Component	Description
Arduino Uno	An established microcontroller that serves as the brain, which allows for the simple integration of multiple sensors
TMP36	Straightforward temperature sensor providing output of temperature in °C, suitable for temperature monitoring
MG811	A CO_2 sensor that provides analog voltage output proportional to the concentration of CO_2 in the air, appropriate for monitoring purposes
SGP40	Digital gas sensor that provides intensity readings of VOCs in the environment
ESP01	A compact Wi-Fi module that connects microcontrollers to Wi-Fi networks, enabling wireless data transmission and remote monitoring
DS3231	A highly accurate clock that keeps time and date down to the second
Micro SD Card Module	Enables microcontroller to interface with the micro SD card for data collection during monitoring of parameters

2.2.1 ***System Schematic*:**

The setup consists of the sensors and components connected to a breadboard, programmed to the *Arduino*, all connected via common jumper wires. Beginning with the *Arduino*, the established connections are as stated:

Arduino had the USB cable connected through the USB jack onboard. *Arduino's* 3.3V pin is connected to the breadboard's power rail, allowing other components to connect to the rail to draw power. One of the *Arduino*'s two ground pins is connected to the sister power rail on the breadboard so other components can directly connect to the breadboard's ground. To power the *MG811,* the 5V pin is connected to the opposite power rail on the breadboard, and the remaining ground pin is connected to the sister power rail as well. The power pin for *MG811* is connected directly to this power rail, allowing it to take in the necessary 5V for optimal functionality. *MG811* ground is connected to the ground power rail to ensure proper voltage flow. Analog pin is connected to *Arduino* A2 (analog in pin #2). For all other sensors and components, the first power rail was used to power the VCC pins, and the ground rail was used to receive the GND pins. *SGP40* was soldered to the breadboard to ensure connectivity. SCL pin is connected to *Arduino* SCL, and SDA pin is connected to *Arduino* SDL. *The TMP36* analog pin is connected to *Arduino* A0. The *RTC* SCL pin is connected to *Arduino* A5, and the SDA pin is connected to A4. The micro SD card module CS pin is connected to *Arduino* digital pin 4, the SCK pin to digital 13, the MOSI pin to digital 11, and the MISO pin to digital 12. These were the specifications of the established connections of the setup.

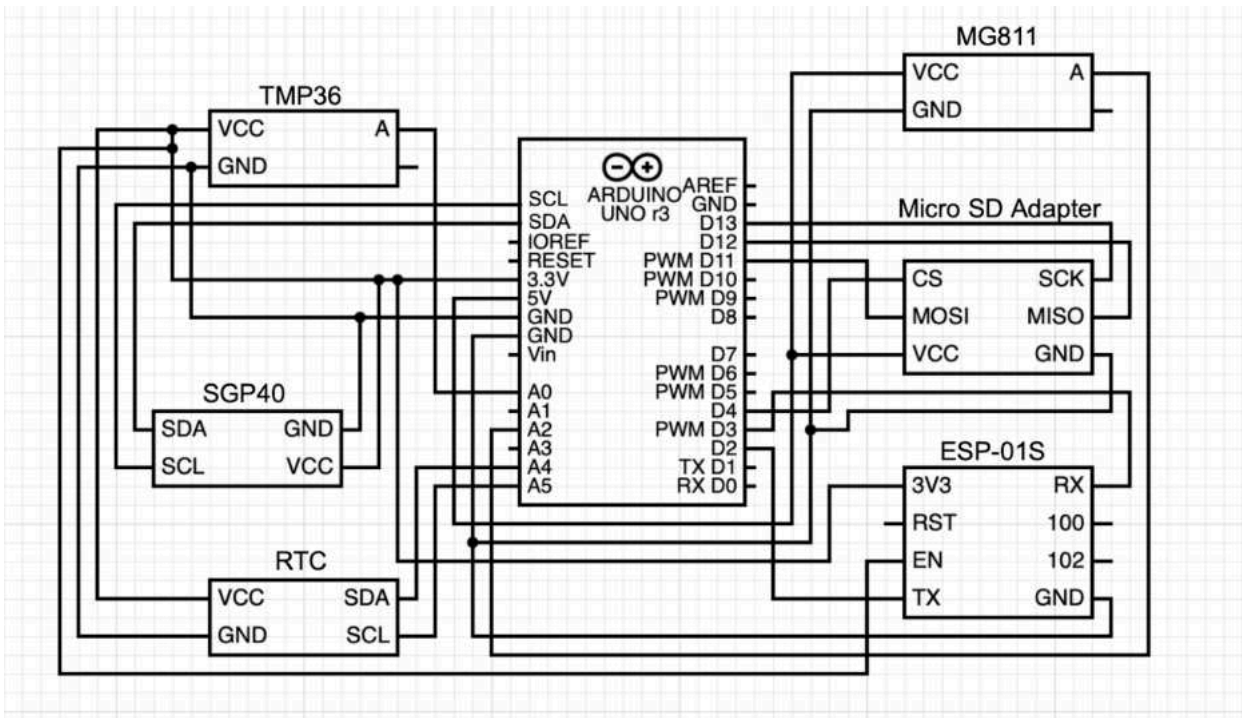

Figure 4. A circuit diagram of the proposed IAQMS. The arduino UNO board is connected to a temperature sensor (TMP36), a CO_2 sensor (MG811), a VOC sensor (SGP40), a Wifi module (ESP-01S), a clock module (DS3231), and a micro SD card adapter. Created by student researcher via Circuit-Diagram.org.

2.2.2 *System Diagram*:

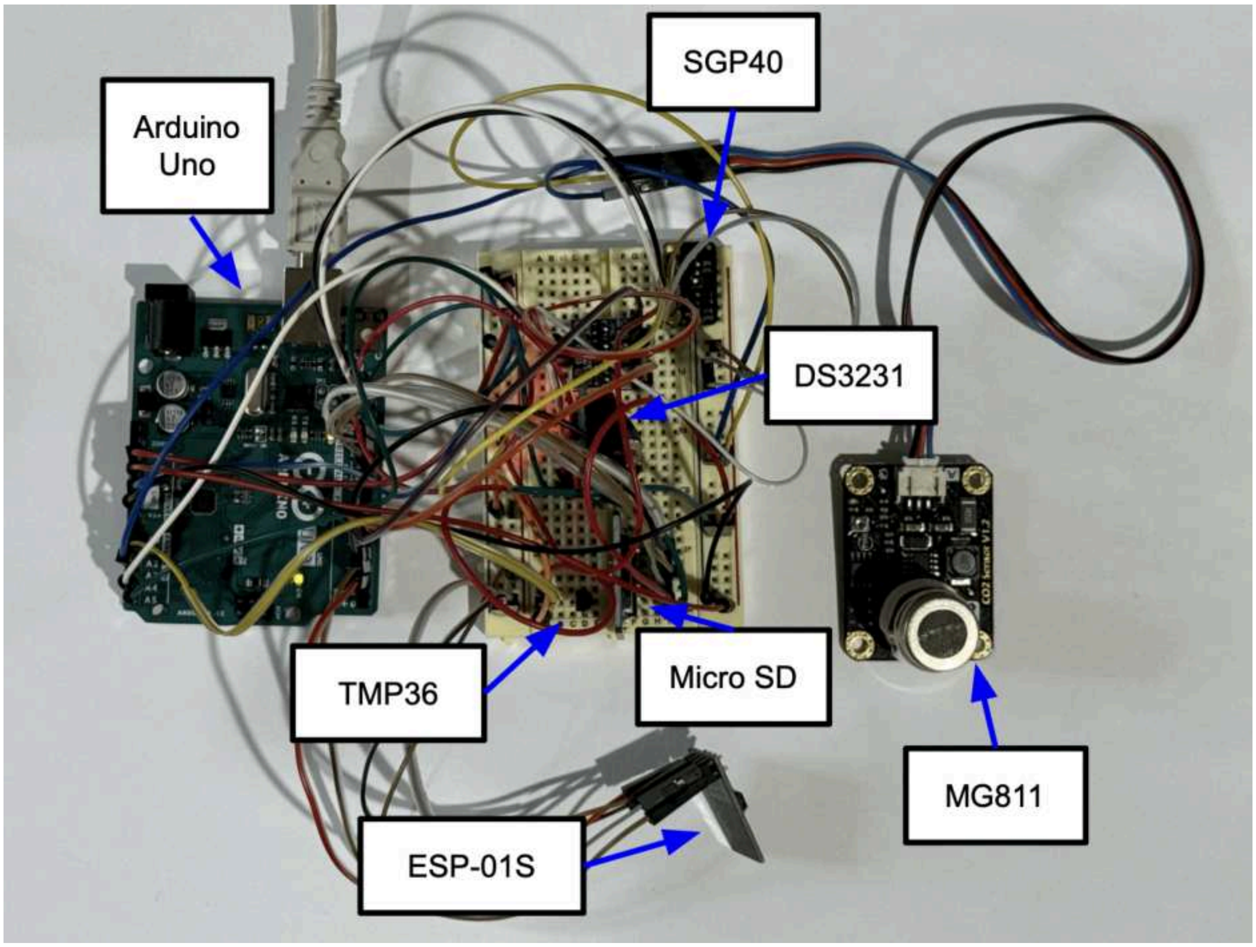

Figure 5. The proposed system with the components labeled. Created by student researcher.

2.3 Calibration

2.3.1. CO_2 calibration in outdoor environment

To ensure proper calibration of the system, the Vernier sensor first had to be properly calibrated. To do this, the system was placed in clean outside air, which has a typical CO_2 level of 400 ppm, and then the calibration of the device was set to 400 ppm through the Vernier Graphing Analysis monitoring software. This resulted in an approximate outdoor air quality of 430 ppm, similar to the MG811 sensor reading of <400 ppm or ~400 ppm. The MG811 sensor was recalibrated as well in an outdoor environment so it calculates a reading of around 400 ppm, similar to the Vernier sensor.

2.3.2. CO_2 calibration in typical indoor conditions

To collect an additional calibration data point for the MG811 and Vernier sensor (with the Vernier sensor being the reference), both sensors were placed in an indoor environment, after both being calibrated to 400 ppm in outside air quality conditions. When both sensors were brought inside, they initially fluctuated, then both stabilized to approximately 600 ppm. This signifies that the MG811 sensor is properly calibrated to the vernier sensor (an industry standard).

To ensure the SGP40 VOC sensor is working accordingly, an experiment was carried out. This entailed spraying acetone a varying number of sprays at fixed intervals a certain distance away from the VOC sensor, to monitor its reactions (see Fig. 8). The second and third sets of three lines indicate when the acetone solution was sprayed in the area above the VOC sensor. Similar spikes can be seen in both the second and third sets of spikes, where the VOC index hits approximately 350 before settling to 105 then repeating this action at each spray of the solution. This validates the ability of the SGP40 to pick up sudden changes in the relative VOC level in its surroundings.

2.4 Software

2.4.1 *Arduino IDE*:

The master program was created by manipulating online source code for each respective sensor and component on the *Arduino* IDE, using open-source libraries. The code allows for a 10-second initialization period to power on the components, and additional time delay can be added to ensure optimal sensor calibration and initialization. Temperature, CO_2, VOC, and time data are stored on the SD card at 20-second intervals.

2.4.2 ThingSpeak:

The *ThingSpeak* software is an IoT analytics platform that allows for the collection, analysis, and visualization of real-time data sent from the Arduino via the ESP01 Wi-Fi module. It was chosen for this project because it allows for remote monitoring by uploading sensor data (temperature, CO_2, and VOC levels) to an online dashboard, where the data can be accessed and visualized from anywhere with an internet connection in a user-friendly manner. It was also used for data storage and analysis, making it easier to identify trends or patterns in the sensor readings over time. At set time intervals, such as 15 seconds, CO_2, VOC, and temperature data is sent to the ESP01, which sends the data over Wi-Fi to the ThingSpeak dashboard to display the collected values over time in an easy-to-read manner. Below are images of data collected from the setup displayed on the ThingSpeak dashboard.

2.5 System Verification

The first part of this study included creating the IAQMS by using 3 sensors and 2 extra components with an Arduino breadboard. The 3 sensors and components, SEN0159 CO_2 sensor, SGP40 VOC sensor, TMP36 temperature sensor DS3231 RTC, and a microSD card adapter, record temperature, CO_2, VOC, and time data on a microSD card which can then be analyzed. Next, the system was checked for optimal calibration by comparing measured values to those achieved by more established industrial sensors. The second part of the study included placing the system in select different locations to monitor the changes in CO_2 and VOCs over time, repeating trials to ensure accuracy. This gathered data was then analyzed to draw conclusions regarding the efficiency of the system, as well as to address any seemingly concerning IAQ levels in the recorded areas.

The setup is placed in multiple locations. The setup is specifically placed on a cart with wheels for easy maneuvering. The setup is accompanied by a laptop on which the program resides, connected by a USB cable. The setup was angled in such a way that the protruding *MG811* and *SGP40* are towards the edge of the cart, to pick up the most accurate readings. The setup was run for at least 30 minutes each time data was collected. After collecting the data, the micro SD card is removed from the adapter, connected to a reader, and connected to a laptop to open the data file. The data in the file is then graphed to allow for visual analysis of the compounds trends over time to create generalizations about the air quality trends in the locations captured. To allow for calibration time which causes fluctuations in data, the first five minutes of the data are removed.

To allow school administrators to use the system, a Wi-fi transmitting component was introduced that enables real-time display of sensor data and trends in a user-friendly online dashboard. To do this, the ESP8266 - 01 module was used. This component is versatile and allows for simple integration with the Arduino Uno. The program was updated to send data to the ESP01 module. The ThingSpeak IoT platform is used to display the data passed from the ESP01 to the Internet.

3. Results

3.1 VOC Calibration

Below is the resulting graph of the VOC calibration, establishing that the SGP40 is able to pick up distinct changes to the relative VOCs levels in its surroundings.

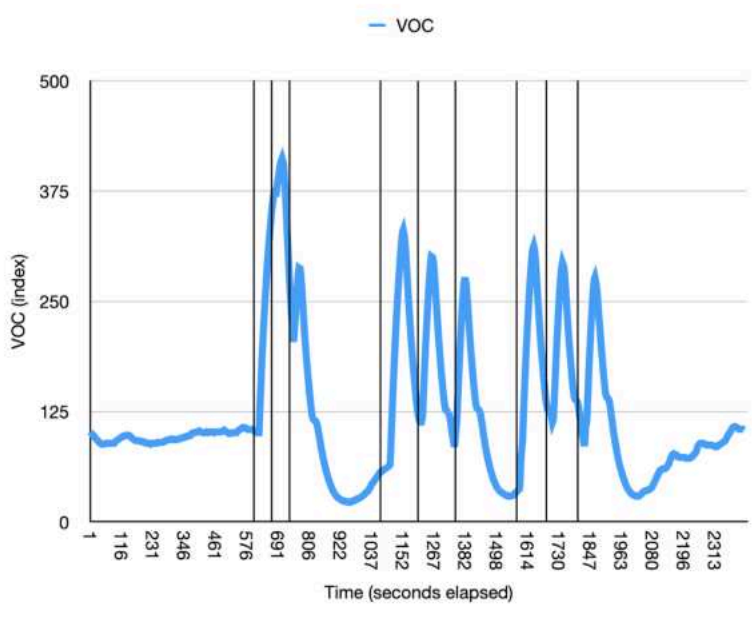

Figure 8. Graph of data from acetone spray experiment at different intervals showing SGP40's responsiveness. Created by student researcher.

3.2 Dashboard Display

The ThingSpeak dashboard receives CO_2, VOC, and temperature data every 15 seconds, and plots it on respective graphs for each value recorded. The setup was started and brought into a heated room at the time stamp 22:34, denoted by a solid vertical black line over the CO_2, VOC, and temperature graphs (See Fig. 10). After the change in environment, VOC levels increased from 100 to 200, likely due to the change in temperature in the environment. This value then decreases over the next hour, settling at a reading of 140.

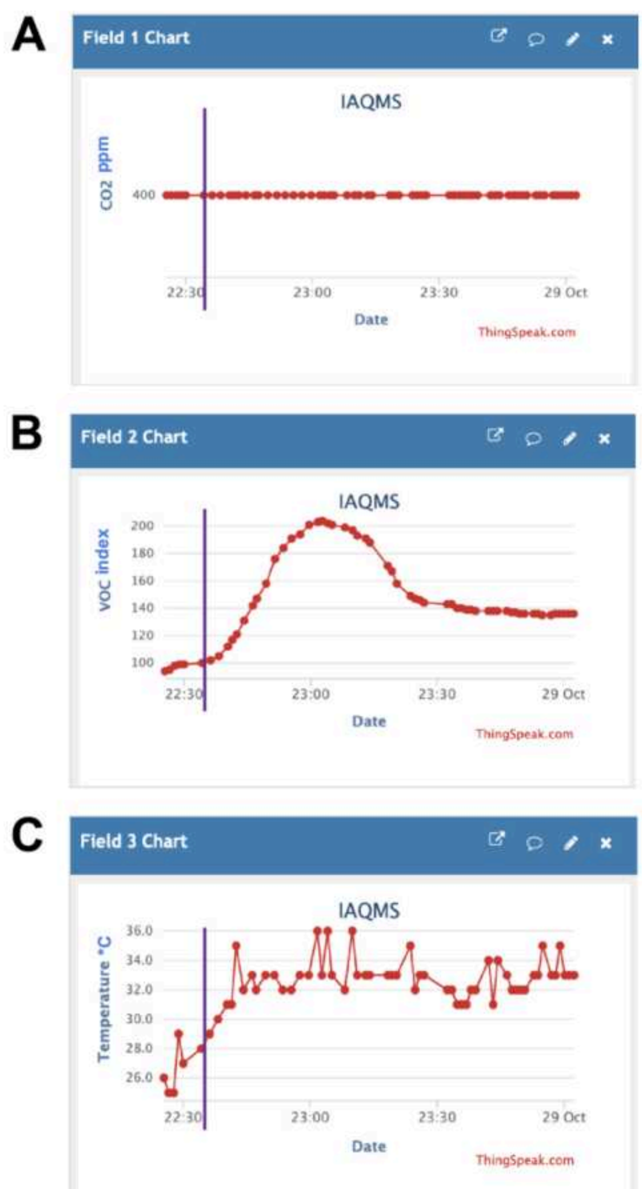

Figure 9. A representative data sample from the ThingSpeak dashboard, including CO_2 data (A), VOC data (B), and temperature data (C) over time. The vertical purple line indicates changing the location to a room with a higher temperature. Created by student researcher.

3.3 Previously collected data

Before ESP01 integration, previous representative test data was collected in school classrooms to observe the response of the sensors. Below are graphs of such data collected.

3.3.1. CO_2:

CO_2 was measured over time beginning from halfway through a chorus period where students were singing (See Fig. 10). In this graph, it is seen that CO_2 decreases as students conclude singing from 2,100 ppm to 1,000 ppm by the end of the period. This decrease is needed to ensure there is no prolonged exposure to CO_2 levels higher than that point.

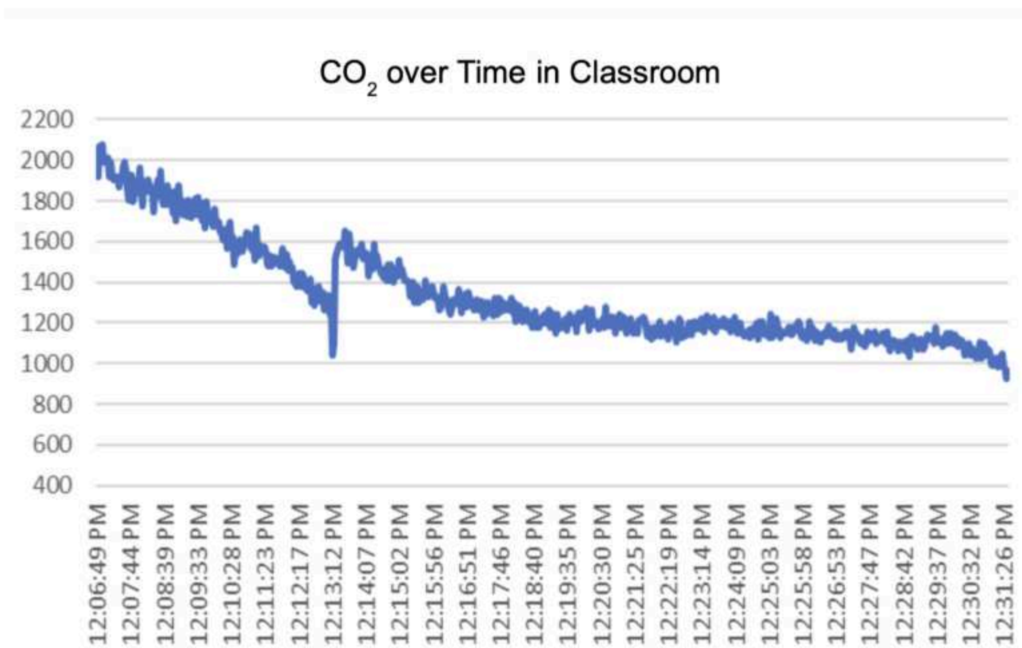

Figure 10. Representative CO_2 measurement obtained in a classroom. Created by student researcher.

3.3.2. VOC:

VOC was measured over time in a science classroom (See Fig. 11). This sample data displays the initialization period of the SGP40 VOC sensor in the beginning of a round of data collection. This graph shows the plateau of VOC levels.

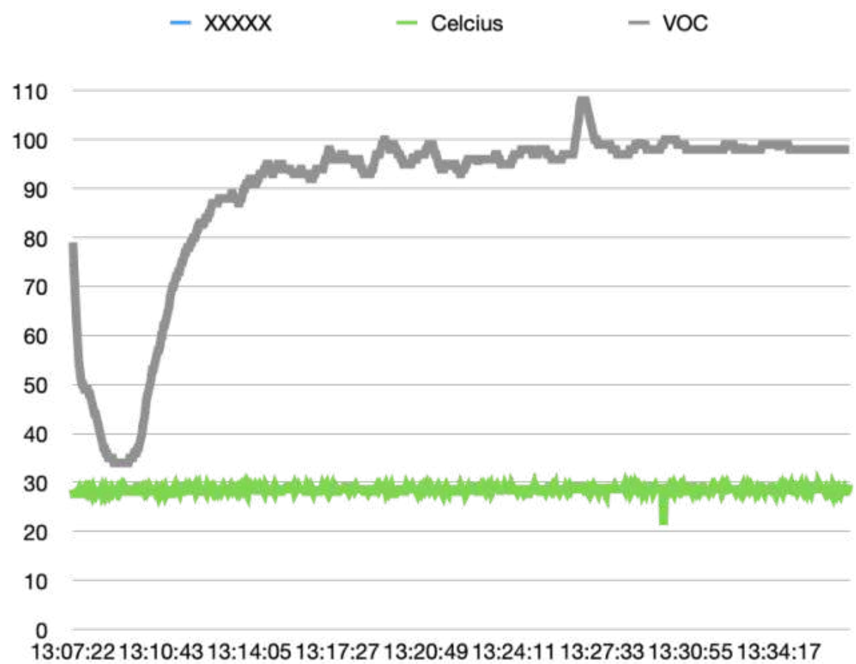

Figure 11. Representative VOC measurement obtained in a classroom. The gray line represents the VOC index recorded over time, while the green line shows temperature in Celcius. Created by student researcher.

4. Discussion

This paper successfully created a real-time, calibrated indoor air quality monitoring system (IAQMS), appropriate for use in school environments. Through thorough calibration against the Vernier sensor, the system can pick up changes in CO_2, VOC, and temperature in an indoor environment. This allows school administrators to take preventative action if needed, and ensure that students and staff are in clean indoor environments. Through a combination of multiple sensors and real-time monitoring, the IAQMS offers a practical solution to monitoring key impacts of indoor air quality. This research highlights the potential of the IAQMS as a tool that can help support healthier, more productive learning spaces in school.

Some difficulties were encountered when developing the system. For example, the MG811 posed an issue when it was not receiving sufficient voltage, and its calibration had to be redone due to incorrect reaction voltage calculations in the program. The MG811 is less sensitive than the Vernier sensor, and so establishing a reference point for calibration was also difficult, but was eventually achieved by calibrating the sensor in typical outdoor and indoor conditions. The ESP-01S was initially troublesome to integrate into the program to send the data to the dashboard. Additionally, due to time constraints, data to be displayed on the real-time dashboard was not yet collected.

Future directions for this research include enhancing sensor calibration by introducing a known ppm concentration of CO_2, optimizing system portability by utilizing a portable battery as the voltage source, and integrating artificial intelligence for data interpretation and feedback. Improvements in sensor accuracy and internet connectivity would enable the system to prove more precise, real-time data and function more reliably across large school buildings. By further refining the monitoring system, it holds the potential to serve as a valuable tool for school administrators in assessing and mitigating IAQ concerns, ultimately contributing to the overall well-being and academic performance of students.

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6. Bibliography

Adochiei, F.-C., Nicolescu, Ş.-T., Adochiei, I.-R., Seritan, G.-C., Enache, B.-A., Argatu, F.-C., & Costin, D. (2020). Electronic System for Real-Time Indoor Air Quality Monitoring. *2020 International Conference on E-Health and Bioengineering (EHB)*, 1–4. https://doi.org/10.1109/EHB50910.2020.9280192

Annesi-Maesano, I., Baiz, N., Banerjee, S., Rudnai, P., Rive, S., & the SINPHONIE Group. (2013). Indoor Air Quality and Sources in Schools and Related Health Effects. *Journal of Toxicology and Environmental Health, Part B*, *16*(8), 491–550. https://doi.org/10.1080/10937404.2013.853609

Chatzidiakou, L., Mumovic, D., & Summerfield, A. (2015). Is CO_2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO_2 levels, ventilation rates and selected indoor pollutants. *Building Services Engineering Research and Technology*, *36*(2), 129–161. https://doi.org/10.1177/0143624414566244

Chojer, H., Branco, P. T. B. S., Martins, F. G., Alvim-Ferraz, M. C. M., & Sousa, S. I. V. (2020). Development of low-cost indoor air quality monitoring devices: Recent advancements. *The Science of the Total Environment*, *727*, 138385. https://doi.org/10.1016/j.scitotenv.2020.138385

Circuit Diagram Web Editor. (n.d.). Retrieved October 30, 2024, from https://www.circuit-diagram.org/editor/

does esp01 connect to arduino breadboard? - Google Search. (n.d.). Retrieved October 4, 2024, from https://www.google.com/search?client=safari&rls=en&q=does+esp01+connect+to+arduino+breadboard%3F&ie=UTF-8&oe=UTF-8#fpstate=ive&vld=cid:849a2e8c,vid:uA1Ah-0IyMc,st:86

Esp_01_connections.png 1,034×708 pixels. (n.d.). Retrieved October 14, 2024, from https://dpl6hyzg28thp.cloudfront.net/media/esp_01_connections.png

ESP8266 programming with Arduino UNO - IotCircuitHub. (2020, December 3). https://iotcircuithub.com/esp8266-programming-arduino/

Go Direct® CO_2 Gas Sensor User Manual. (n.d.-a). Vernier. Retrieved October 4, 2024, from https://www.vernier.com/manuals/gdx-co2/

Go Direct® CO_2 Gas Sensor User Manual. (n.d.-b). Vernier. Retrieved October 3, 2024, from https://www.vernier.com/manuals/gdx-co2/#

Grimsrud, D., Bridges, B., & Schulte, R. (2006). Continuous measurements of air quality parameters in schools. *Building Research & Information*, *34*(5), 447–458. https://doi.org/10.1080/09613210600808880

IAQMS - ThingSpeak IoT. (n.d.). Retrieved October 27, 2024, from https://thingspeak.mathworks.com/channels/2704798/private_show

981a1c460385a2f2d769e26f53dd45e4fb03c212.png 681×399 pixels. (n.d.). Retrieved October 14, 2024, from https://dpl6hyzg28thp.cloudfront.net/media/981a1c460385a2f2d769e26f53dd45e4fb03c212.png

Jones, A. P. (1999). Indoor air quality and health. *Atmospheric Environment*, *33*(28), 4535–4564. https://doi.org/10.1016/S1352-2310(99)00272-1

Mannan, M., & Al-Ghamdi, S. G. (2021). Indoor Air Quality in Buildings: A Comprehensive Review on the Factors Influencing Air Pollution in Residential and Commercial Structure. *International Journal of Environmental Research and Public Health*, *18*(6), Article 6. https://doi.org/10.3390/ijerph18063276

Richardson, G., Eick, S., & Jones, R. (2005). How is the indoor environment related to asthma?: Literature review. *Journal of Advanced Nursing*, *52*(3), 328–339. https://doi.org/10.1111/j.1365-2648.2005.03591.x

Rosén, K. G., & Richardson, G. (1999). Would removing indoor air particulates in children's environments reduce rate of absenteeism—A hypothesis. *Science of The Total Environment*, *234*(1), 87–93. https://doi.org/10.1016/S0048-9697(99)00266-1

Sadrizadeh, S., Yao, R., Yuan, F., Awbi, H., Bahnfleth, W., Bi, Y., Cao, G., Croitoru, C., de Dear, R., Haghighat, F., Kumar, P., Malayeri, M., Nasiri, F., Ruud, M., Sadeghian, P., Wargocki, P., Xiong, J., Yu, W., & Li, B. (2022). Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment. *Journal of Building Engineering*, *57*, 104908. https://doi.org/10.1016/j.jobe.2022.104908

Saini, J., Dutta, M., & Marques, G. (2020). A comprehensive review on indoor air quality monitoring systems for enhanced public health. *Sustainable Environment Research*, *30*(1), 6. https://doi.org/10.1186/s42834-020-0047-y

TakumiIto. (n.d.). *ThingSpeak Using ESP8266*. Instructables. Retrieved October 4, 2024, from https://www.instructables.com/ThingSpeak-Using-ESP8266/

Wolkoff, P. (2013). Indoor air pollutants in office environments: Assessment of comfort, health, and performance. *International Journal of Hygiene and Environmental Health*, *216*(4), 371–394. https://doi.org/10.1016/j.ijheh.2012.08.001

Wyon, D. P. (2004). The effects of indoor air quality on performance and productivity: The effects of IAQ on performance and productivity. *Indoor Air*, *14*, 92–101. https://doi.org/10.1111/j.1600-0668.2004.00278.x