Research Article

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

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ABSTRACT

Indoor air quality (IAQ) in educational environments significantly impacts student health and aca- demic performance. 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 com- mercially 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 VOCs levels in real-time. 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; IoT; Indoor Air Quality; Carbon Dioxide Monitoring; Volatile Organic Compounds; Arduino

INTRODUCTION

Several studies have shown that in recent years, indoor air pollution has been one of the top risks to public health (1-3). 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 (2). IAQ is more likely to affect the health of individuals, when compared to outdoor air quality, as individuals spend nearly 90% of their time indoors (3). The indoor concentrations of many pollutants that compose the IAQ are often higher than those found outdoors (4).

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 (3). Additionally, IAQ poses a risk in office buildings where millions work, as poor IAQ has a significant detrimental effect on workers'

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productivity in these settings (3, 5). Pollutants of IAQ, such as combustion products and volatile organic compounds (VOCs), can cause disease, disability, and mortality in extreme cases (4). 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 (4). Those who are allergic may be at a higher risk of experiencing respiratory illnesses (6). Moreover, a connection has been established between indoor environmental factors that affect indoor air quality (IAQ) and the respiratory condition of asthma (7).

In indoor environments, VOCs such as formaldehyde, benzene, and acetone, released from products such as paints, solvents, and varnishes, are associated with poor health conditions (6, 4). Sensory irritation as well, under specific environmental conditions, can be caused by some VOCs in the air (7). Elevated carbon dioxide (CO_2) levels are a sound indicator of poor IAQ, and are used as guidelines for the IAQ of school buildings (8). These compounds potentially irritate the nose, eyes, and throat, and result in symptoms of nausea, headache, dizziness, and fatigue (2).

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 (9). 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 (10). 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 (3).

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 (11).

The existing IAQMS are not yet adequate to perform a thorough IAQ assessment. Some IAQMS focus heavily on the aesthetics while ignoring functionality (10). A research paper highlights a study con- ducted 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 (10). 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 the 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.

METHODS AND MATERIALS

Hardware Components

Arduino Uno R3. The Arduino Uno 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 Arduino powers a breadboard and through it, the multiple components of the setup through the VCC (voltage common collector) and GND (ground) pins. The Arduino microcontroller itself is versatile in accepting power; for this setup, it is powered through the USB connector.

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.

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 0-10,000 ppm (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 (12), 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 a small dependency on temperature and humidity as seen in its datasheets. As shown in Fig. 2 (12), there is a miniscule dependency on temperature and humidity, meaning that the sensor readings will not fluctuate greatly with changes in the temperature and humidity of the environment.

SGP40 (Sensirion) VOCs Sensor. The SGP40 VOCs 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 materi- als. 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 80% (Fig. 3) (13).

ESP-01S Wi-Fi module. The ESP-01S Wi-Fi 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 VOCs readings) to the dashboard for remote monitoring (14).

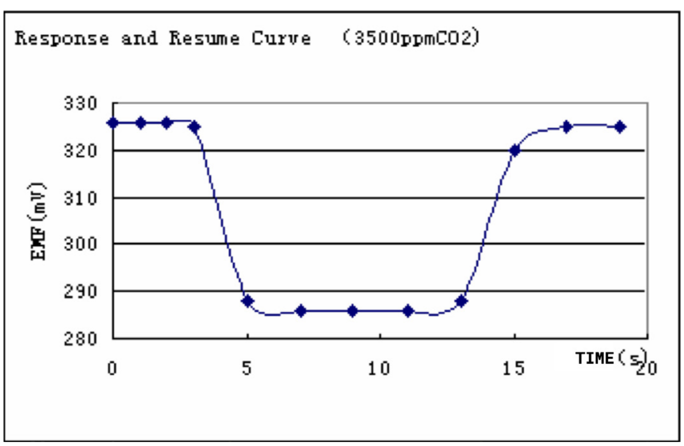

Figure 1. Response and Resume curve of MG811 CO_2 Sensor, displaying the 20-second period needed for the sensor to complete its reaction (12).

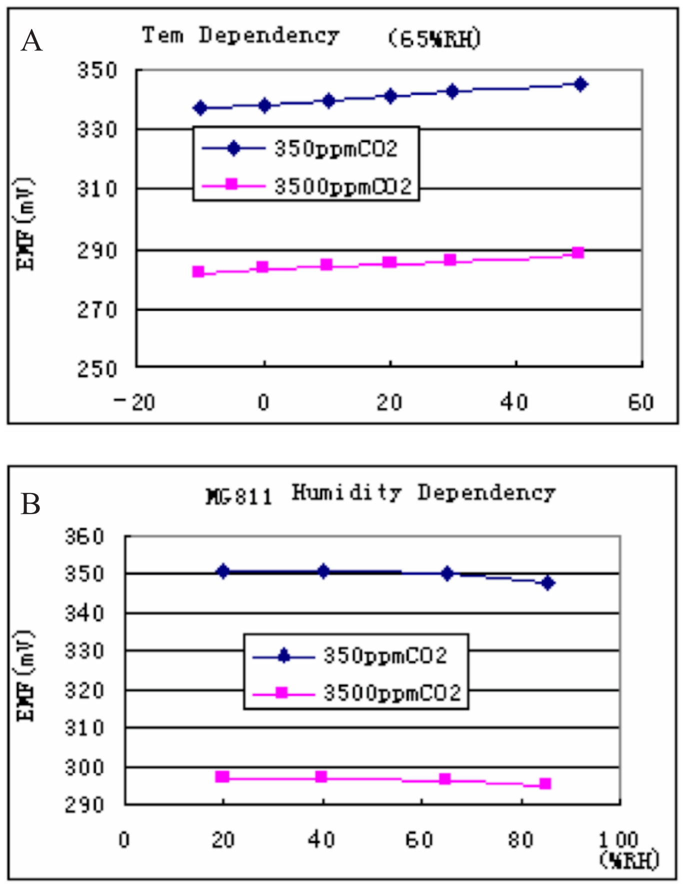

Figure 2. Graphs of (A) the effect of temperature on the output voltage reading of the MG811 sensor and (B) the effect of humidity on the output voltage reading of the MG811 sensor (12).

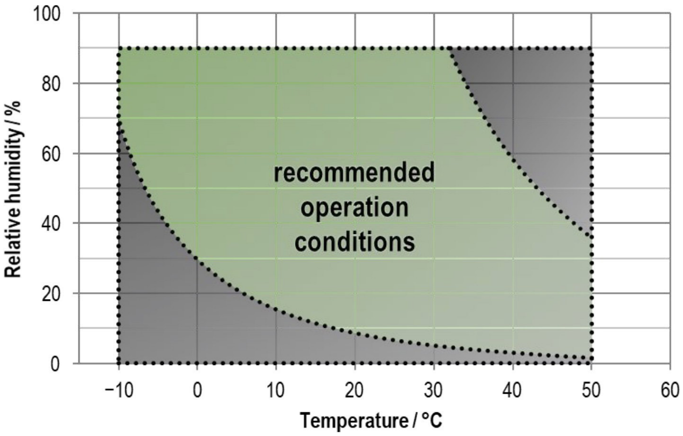

Figure 3. Graph of Temperature and Relative Humidities for optimal operation of SGP40 sensor (13).

DS3231 RTC Module. The DS3231 RTC (Real-time clock) is a component that serves to store accurate time 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.

MicroSD Card Module. The microSD 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), VOCs on a relative intensity scale, with 100 being average, and time in an hour, minute, second format.

Overview of System Hardware Components (Table 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 and shown in Fig. 4 and Fig. 5:

Arduino had the USB cable connected through the USB jack onboard. Arduino's 3.3V pin is con- nected 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 compo- nents can directly connect to the breadboard's ground. To power the MG811,

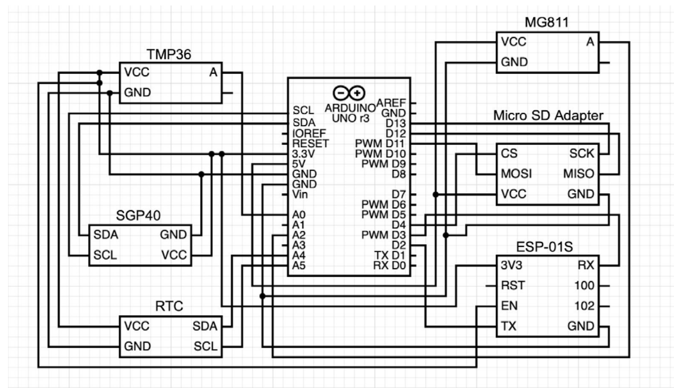

Figure 4. A circuit diagram of the proposed IAQMS. The arduino UNO board is connected to a temperature sensor (TMP36), a CO_2 sensor (MG811), a VOCs sensor (SGP40), a Wi-Fi module (ESP-01S), a clock module (DS3231), and a microSD card adapter (17).

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
MicroSD Card Module	Enables microcontroller to interface with the microSD card for data collection during monitoring of parameters

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 microSD 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.

System Diagram. The components of the system are shown in Fig. 5.

Calibration

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 (15). This resulted in an approximate outdoor air quality of 430 ppm, similar to the MG811 sensor reading of less than 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.

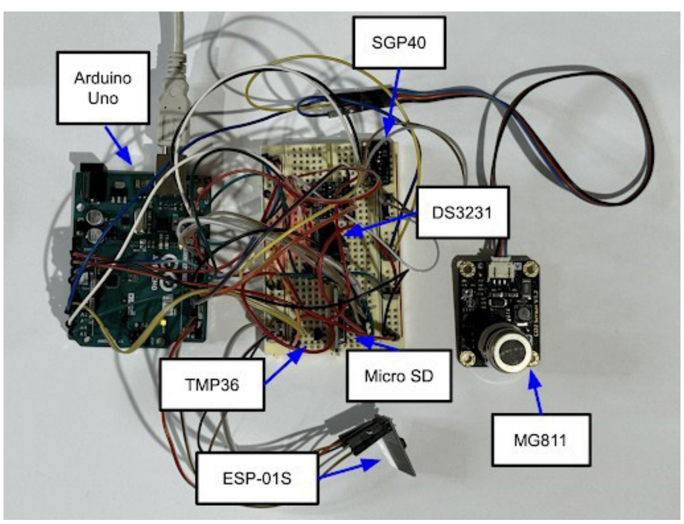

Figure 5. The proposed system with the components labeled.

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 VOCs 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 VOCs sensor, to monitor its reactions (Fig. 6). The second and third sets of three lines indicate when the acetone solution was sprayed in the area above the VOCs sensor. Similar spikes can be seen in both the second and third sets of spikes, where the VOCs 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 VOCs level in its surroundings.

Software

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 cali- bration and initialization. Temperature, CO_2, VOC, and time data are stored on the SD card at 20-second intervals.

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 ESP-01S Wi-Fi module (16). It was chosen for this project because it allows for remote monitoring by uploading sensor data (temperature, CO_2, and VOCs 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 ESP-01S, which sends the data over Wi-Fi to the ThingSpeak dashboard to display the collected values over time in an easy-to-read manner.

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 VOCs 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 was placed in multiple locations. The setup was specifically placed on a cart with wheels for easy maneuvering. The setup was 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 microSD card was removed from the adapter, connected to a reader, and connected to a laptop to open the data file. The data in the file was then graphed to allow for visual analysis of the compound 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 ESP-01S module was used. This component was versatile and allows for simple integration with the Arduino Uno. The program was updated to send data to the ESP-01S module. The ThingSpeak IoT platform was used to display the data passed from the ESP-01S to the internet.

RESULTS

VOCs Calibration

Below is the resulting graph of the VOCs calibration, establishing that the SGP40 is able to pick up distinct changes to the relative VOCs levels in its surroundings (Figure 6).

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 purple line over the CO_2, VOC, and temperature graphs (Fig. 7). After the change in environment, VOCs 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. The temperature level increased from 26°C to 36°C over the time interval.

Previously Collected Data

Before ESP-01S integration, previous representative test data was collected in school classrooms to observe the response of the sensors. Below are graphs of such data collected.

CO_2. CO_2 was measured over time beginning from halfway through a chorus period where students were singing (Fig. 8). 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.

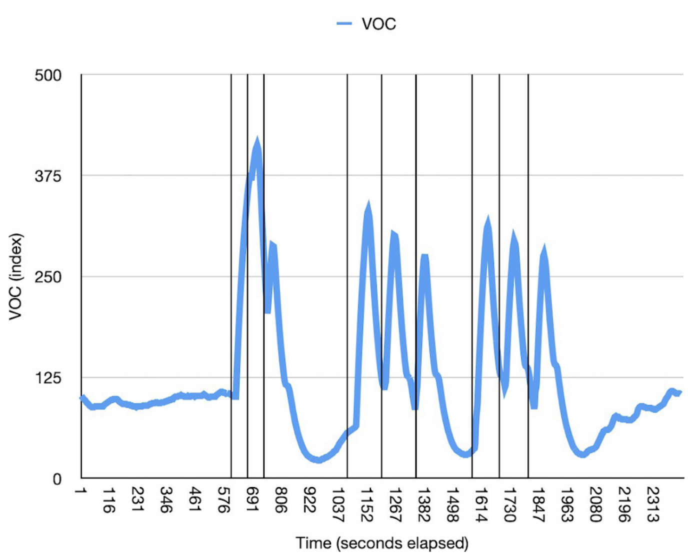

Figure 6. Graph of data from acetone spray experiment at different intervals showing SGP40's responsiveness.

VOC. VOCs were measured over time in a classroom (Fig. 9). This sample data displays the initialization period of the SGP40 VOCs sensor in the beginning of a round of data collection. This graph shows the plateau of VOCs levels.

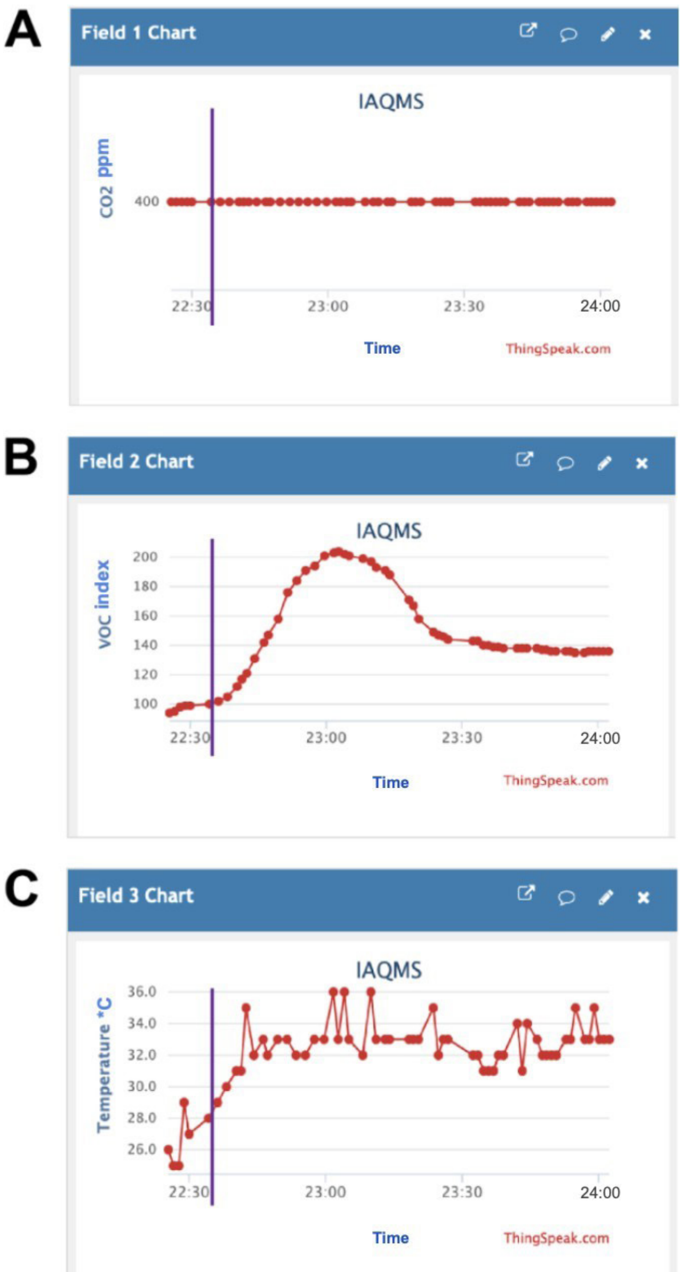

Figure 7. A representative data sample from the ThingSpeak dashboard, including CO_2 data (A), VOCs data (B), and temperature data (C) over time. The vertical purple line indicates changing the location to a room with a higher temperature (16).

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.

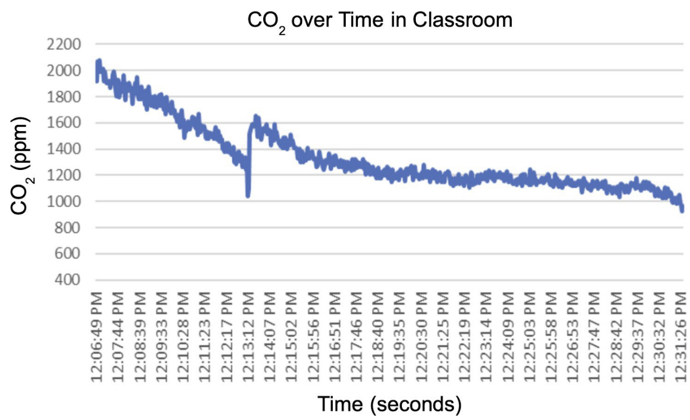

Figure 8. Representative CO2 measurement obtained in a classroom.

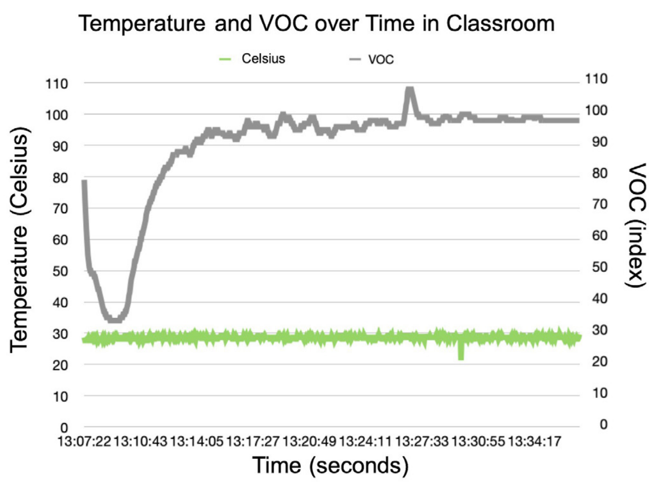

Figure 9. Representative VOCs measurement obtained in a classroom. The gray line represents the VOCs index recorded over time, and the green line shows temperature in Celsius.

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 provide more precise, real-time data and function reliably across large school buildings. By further refining the monitoring system, it could 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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DECLARATION OF CONFLICT OF INTERESTS

The author declares that there are no conflicts of interest regarding the publication of this article.

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