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Monitoring Indoor Air Quality Using Low-Cost IoT

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Abstract

Measuring air quality in some regions under non-ideal circumstances is still a challenge. In many third-world countries, acquiring expensive air quality testing equipment is beyond capacity. Monitoring non-healthy environments in such regions is vital, so we implemented a low-cost IoT indoor air quality tester. The system comprises attached field instrument sensors and a WiFi-to-cloud monitoring unit. The sensing unit includes Arduino UNO attached to MQ-7, CCS811, and MQ-137 sensors to measure carbon monoxide (CO), carbon dioxide (CO_2), and the total volatile organic compounds (TVOCs), and NH_3, respectively. The sensors also include the DHT11 to measure temperature (T) and relative humidity (RH). To collect data from distributed field sensing devices and monitor it on the ThingSpeak website, an NRF24l01+ wireless model is connected to each data logger and the central data collector ESP32. The proposed low-cost system was operated in one of the higher education buildings of the Middle Technical University, measuring the concentrations of the most common air quality factors (CO, CO_2, NH_3, TVOC, RH, and T).

Publisher: Middle Technical University

Keywords: Air Quality; Arduino; IoT; Online Monitoring; ThingSpeak.

1. Introduction

Air quality is a vital environmental factor that has a direct influence on human health and performance, particularly for vulnerable persons known as special groups (SG), such as children, pregnant women, seniors (65 and older), and those with cardiovascular and respiratory problems (e.g. asthma). The backdrop of the development was the 2020 pandemic. Poorly ventilated indoor spaces have become a significant focus as people have learned more about how diseases spread. Measuring air quality and keeping it clean will be necessary for people with breathing problems long after the pandemic. Most people in academic facilities spend most of their day indoors; therefore, monitoring indoor air quality is essential for public health [1, 2]. Diseases such as sick-building syndrome, multiple chemical sensitivity, and vertigo are approximately one thousand times more likely to be caused by indoor air pollutants. Indoor air quality management is essential because it can prevent exposure through proactive precautions [3].

Recent efforts have been pursued to reduce exposure to air contamination, including developing low-cost air quality measuring devices for some less fortunate communities in third-world countries' schools and universities [4–7]. In [8], several environmental factors, including temperature, humidity, light, noise level, carbon monoxide (CO), and amide (NO_2), were demonstrated for an environmental monitoring system that utilised Raspberry Pi and MICS-4514 sensors to permit both indoor and outdoor testing. In a proposed system for detecting environmental contamination, various environmental detectors were used to identify temperature, humidity, ambient light, gas sensors, and particulate matter [9].

All of the data measured by the system using the STM32f4xx and Sharp GP2Y1010 for PM and the TGS5342 for CO are stored in the system's internal memory and on a server connected to the internet via the Wi-Fi network. Another indoor air quality system [10], known as an integrated environmental monitoring system (IEMS), was proposed, using ATmega328AVR controller, DHT22 temperature sensor, Sharp GP2Y1010AU0F dust sensor, and UVM-30A UV sensors. In another study [11], the authors proposed using an Internet of Things (IoT)-based indoor environmental quality (IEQ) assessment system built with Arduino Uno modules and inexpensive sensors such as the DHT22. In [12], the authors proposed an IoT system that measures only indoor CO_2, even though CO_2 is not the only prevalent indoor air pollutant. Multiple gases, including CO_2, NO_2, ethanol, methane, and propane, were detected using an alternative IoT-based system for real-time IAQ surveillance utilising ESP8266 as the controller and MICS-6814 sensors as the detection unit. Multiple gases, including CO_2, NO_2, ethanol, methane, and propane, were detected using an alternative IoT-based system for real-time IAQ surveillance utilising ESP8266 as the controller and MICS-6814 sensors as the detection unit is entirely wireless [13]. The authors of a separate study demonstrated an IoT-based system for real-time PM surveillance using an ESP8266 controller and the open-source IoT platform ThingSpeak to record the readings of inexpensive sensors. Dust

Nomenclature & Symbols			
NO_2	Amide	LCD	Liquid Crystal Display
NH_3	Ammonia	MOX	Metal Oxide
EPA	Environmental Protection Agency	NTC	Negative Temperature Coefficient
eCO_2	Equivalent CO_2	PM	Particulate Matter
IEMS	Environmental Monitoring System	SVOC	Semi VOC
CO	Carbon Monoxide	SG	Special Groups
CO_2	Carbon Dioxide	TVOCs	Total Volatile Organic Compounds
IEQ	Indoor Environmental Quality	VOCs	Volatile Organic Compounds
IoT	Internet of Things	WHO	World Health Organization

sensor PMS 5003 transmits system measurement data to users via the Wi-Fi module WEMOS D1 [14]. In [15], the authors utilised an ESP-32 Controller along with GP2Y1010AU, MH-Z14, MICS-4514, and DHT22 sensors at a total cost of $100. The authors of [16] utilised ESP32 with a Bosch BME680 sensor to detect gases and alcohol at a comparable cost. This article proposes an IoT system that monitors CO, CO_2, total volatile organic compounds (TVOCs), ammonia NH_3, temperature, and relative humidity. The significant contribution of the proposed study is proposing a very low-cost real-time air quality monitoring system tailored for general indoor public buildings. The remainder of this article is organised as follows: Section 2 presents the theory about air quality parameters, healthy and non-health levels, and the most common sources of indoor air pollution. Section 3 explains the monitored air pollutants and used hardware and lists the cost of the items. The Section also highlights practical calibration and usage procedures for each sensor, and Section 4 concludes the article.

2. Background

Air quality is usually categorized as good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous. Air quality is generally measured in volatile organic compounds (VOCs) and particulate matter (PM). Indoor air quality (IAQ) is usually concerned with total VOC (TVOC) alongside other environmental factors, such as relative humidity, temperature, ventilation, and general cleanliness. The most common indoor air pollutants are volatile organic compounds (VOCs). VOCs are simply gases emitted from solids or liquids. VOCs are carbon-based chemicals with high vapor pressure rates: 70 Pa at room temperature, boiling points below 260°C at atmospheric pressure, or organic compounds with relative volatility pressure 10 Pa at 20°C. VOCs usually have low water solubility; thus, humidity slightly affects them. VOCs include many common substances such as ethylene glycol, acetone, acetaldehyde, benzene, xylene, methyl chloride, styrene, formaldehyde, heptane, hexane, isopropyl alcohol, methyl ethyl ketone, ethyl acetate, toluene, naphthalene, monomethyl ether, and carbon tetrachloride. They can be among many indoor materials, such as air freshener, perfume, glue, solvent, varnish, paint, laundry detergent, dry cleaning fluid, laundry softener, scented candles, bug repellent, pesticides, wood, kerosene, smoking tobacco, perfume, hair spray, soap, floor wax, lacquer, textile, and from copying/printing machines. People are more prone to inhale VOCs when sleeping due to inadequate bedroom ventilation and closer proximity to VOC-emitting mattresses and pillows. Long-term exposure to high amounts can affect the kidneys, neurological system, and liver. Some VOCs, like formaldehyde, can even cause cancer. Less excessive exposure to VOCs may cause respiratory infection with symptoms including a runny nose, sore throat, and cough. Lighter exposures can still cause headaches, dizziness, nausea, eye/nose/throat/skin irritation, loss of coordination, exhaustion, other health issues, and poor work performance.

TVOC is the collective indoor air pollution measure for the evaporated organic substances within a space volume; in general, each of those pollutants has a vapor pressure over 133.32 Pa at room temperature and a 50°C-250°C boiling point. Some institutes classify TVOC based on boiling temperatures into: semi-VOC (SVOC), like diisononyl phthalate; volatile VOC, like benzene; and very VOC (VVOC), like formaldehyde.

Indoor paint largely contributes to TVOCs; in some cases, the paint VOC might be two to five times more than its influence outside. Recently, a giant Japanese polymers and coating producer, Toyochem, has produced a low-odor and low-VOC adhesive (EXK21-046) for enclosed spaces such as vehicles and buildings to reduce its TVOC by 10 % [17]. Paint-producing companies usually advertise low-odor, eco, VOC-free, non-VOC, or zero-VOC paints. TVOC indication does not distinguish between toxic and less dangerous compounds. TVOC levels below 300 $\mu g/m^3$ are usually considered not a problem for non-toxic pollutants. However, that also depends on the people's age, health, number, and type of indoor activities. In Europe, preschool classrooms (for 3–5-year-old children) are recommended to have a TVOC of less than 200 µg/m3; however, many rooms usually exceed this by three to four times, especially by the end of the school day [18]. TVOC can be easily measured using a photo-ionizing detector and reduced by proper ventilation. On an international scale, there are no global IAQ standards; This article refers to the United States Environmental Protection Agency (EPA) regulations when discussing IAQ for schools and higher education institutes.

Particulate matter (PM), also known as particle pollution, is another parameter for measuring pollution; it refers to the mixture of solid particles and liquid particulates in the air. PM is the most prevalent indicator of air quality, and these contaminants have both short- and long-term health effects. Air quality is measured using two types of particulate matter: particles with a diameter of less than 2.5 µm (PM2.5) and particles with a diameter of less than 10 µm (PM10). PM2.5 particles are hazardous because they can penetrate deeper into the cardiopulmonary system due to their small size. The World Health Organization (WHO) suggests that the average annual PM2.5 concentration should not exceed 10 µg/m3, and the PM10 concentration should not exceed 20 µg/m3. The annual average PM2.5 concentration in Iraq is approximately 62 µg/m3. Iraq's poor air quality is primarily attributable to vehicle emissions, power generators, and explosions at oil and gas refineries [19]; therefore, air quality measures indicate many unhealthy days, especially between October and May [20]. Those months also make the academic year in Iraq.

On the other hand, climatic temperatures are more acceptable in these months. Some air quality standards use the volume rate of pollutant particles to air particles in terms of parts per million (ppm) or parts per billion (ppb); these equal 0.0001% and 0.0000001%, respectively. It should be kept in mind that the volumes of various substances may vary with atmospheric temperature and pressure at different rates, causing the ppm/ppb rates to fluctuate. On the other hand, some air quality charts may list a pollutant concentration as a rate of mass per volume, such as milligrams or micrograms per cubic meter or litre, which commonly appear as mg/m^3, $\mu g/m^3$, mg/L, or µg/L, respectively. The IAQ guidelines are not only related to TVOC; it is also concerned about temperature and humidity, ventilation, and general cleanliness. Dirt and moisture would allow warmth, moulds, and other biological contaminants to thrive. Insects, vermin, rodents, and head lice thrive in unsanitary conditions, and improper use of pesticides exacerbates the IAQ challenges.

3. Experimental Setup

In this study, we monitor a couple of air quality factors on a campus in Baghdad city, utilizing low-cost Arduino sensors (MQ-7, CCS811, and MQ-137) to monitor CO, CO_2, and NH_3, respectively. We ordered the required items from Alibaba as in Table 1. The sensors used are as follows:

- MQ-7 is a carbon monoxide gas sensor that usually comes attached to an interfacing board. MQ-7 can measure a CO concentration of 20-2000 ppm, a working temperature range of 20°C-50°C, and relative humidity up to 90%. Noting that the oxygen concentration can affect the measuring accuracy, its typical value should be over 2%.MQ-7 standard working conditions are 5.0 V, 65% ± 5% humidity, and 20°C ± 2°C temperature. The sensor comprises a microscopic Al_2O_3 ceramic tube, a tin dioxide (SnO_2) sensitive layer, a measuring electrode, and a heater; these components are held together by a plastic and stainless-steel net coating. The heater provides sensitive components with the required operating conditions. The bundled MQ-7 contains six pins: four collect signals and two pass the heating current. The resistivity of MQ-7 varies based on the gas type and concentration. As a result, sensitivity must be modified while using these components. We suggest calibrating the detector for 200 ppm CO in air and load resistance (R_l) of roughly 10 kΩ. The calibration procedure requires a 48-hour pre-heat phase during which the sensor must be connected to the application circuit and powered on.
- MQ-137 is a gas sensor for Ammonia (NH_3); it is highly sensitive to NH3 gas but can also detect organic amines such as Trimethylamine and Cholamine. MQ-137 has a detection range up to 5500 ppm for NH3 gas. The detecting element is SnO_2, which has a greater resistivity in clean air; nevertheless, NH3 reduces the sensor's resistance. The MQ-137 best works on 5 ∓ 0.1 V, within 65 % ∓ 5 % humidity, and 20^o C ∓ 2^o C temperature. The sensor must first be calibrated before considering its readings. It should be powered up for over 24 hours to achieve a one-time burn-in process. Next, the MQ-137 must be exposed to fresh air, preferably within 65 % ∓ 5 % humidity, and 20^o C ∓ 2^o C. This preparation process helps know the sensor's offset baseline and enhances sensitivity, stability, and reliability. Furthermore, we must warm the MQ-137 for at least 20 seconds to get steady data. The MQ-137 gas sensor comprises a sense resistor (R_S) that inversely varies based on the gas concentration. The sensitivity of the MQ-137 gas sensor is adjusted via an external 10 kΩ to 100 kΩ load resistor (R_L); the greater the value, the more sensitive the sensor becomes. We used WebPlotDigitizer [21], an open-source fitting website, to calibrate the sensor outcomes.
- DHT11 is a temperature and humidity sensor assembly with calibrated digital signal output that offers reliability and outstanding long-term stability by combining temperature and humidity sensing technology with a novel digital signal collecting approach [22]. This sensor uses a resistive hygrometer element and a negative temperature coefficient (NTC) temperature measuring element to provide quality, rapid response, interference resistance, and cost savings. It is connected to a high-performance 8-bit microprocessor. The DHT11 is particularly precise regarding humidity calibration since every element has undergone meticulous calibration in the lab. In the one-time programmable (OTP) memory, calibration coefficients are stored as programs for use by the sensor's internal signal detection mechanism. The serial interface with a single wire simplifies system integration. Due to its compact dimensions, low power utilization, and signal transmission of up to 20 meters, it is the best choice for various applications, even the most demanding ones. The ability to connect is straightforward, and consumer-specific products can be provided.
- The CCS811 is a metal oxide (MOX) sensor designed to detect a variety of VOCs. The CCS811 is built on the exclusive micro hot-disk technology of ams [23], enabling a very reliable gas sensor solution, extremely quick cycle times, and considerable average power consumption savings. The CCS811 item supports sophisticated algorithms that provide equivalent total volatile organic compounds (eTVOC). The CCS811 provides various modes. It also supports an idle mode that prolongs battery life in portable applications.

Table 1. Bill of materials

Component	Quantity	Unit Cost	Total Cost
UNO R3	1	7$	7$
ESP-32	1	15$	15$
20x4 LCD	1	3.2$	3.2$
SD Shield	1	0.25$	0.25$
NRF24L01+	2	1.5$	3$
CCS811	1	24.25$	24.25$
MQ-7	1	1.27$	1.27$
Junction Box	2	0.33$	0.66$
	Total		54.63 $

The eTVOC concentration (ppb) and equivalent CO_2 (eCO_2) concentration (ppm) were measured in modes 1, 2, and 3. Mode 1 has the most considerable operating current, leading to a fast response when a gas is present. Mode 3 has the lowest average operating current, leading to a slower presence. When switching from one sensor operating mode to another with a lower sample rate, the sensor must be in mode 0 (inactive) for at least 10 minutes before the mode change. (for example, mode 1 to mode 3). When the operating mode of the sensor changes to a new mode with a higher sample rate, there is no need to delay before activating the new mode. (e.g., from mode 3 to mode 1). Mode 4 is utilized when an external host system must perform algorithms on unprocessed data; a new data sample is provided every 250 milliseconds. Mode 4 is recommended for end-of-line testing to reduce testing time [24]. Mode timings are typically within a 2% tolerance due to the precision of the internal system clock. The CCS811 has an eCO_2 output range of 400 ppm to 29206 ppm. The CCS811 may produce eTVOC in the range of 0 ppb to 32768 ppb. The CCS811's resistance and sensitivity performance vary at the beginning of usage. In the first 48 hours of operation, the resistance changed the most. After operating in modes 1-3 for 60 minutes, the CCS811 manages the cut-off time, allowing eCO_2 and eTVOC values to be utilized from the initial power-on. Period of stabilization (Run-In), a trial phase is needed for the sensor to obtain adequate stability after starting a run (Burn-In) before monitoring VOCs for a lengthy period. Before getting reliable readings, CCS811 should run for 20 minutes before setting the sensor in one of the fourth modes. The sensor's output is the sensitive layer's R_S resistance. Metal oxide sensors do not, however, provide definitive information. Sensor to sensor (manufacturing variant), use case to use case, and R_S resistance changes with time. The sensor output is normalized to help with this issue; the baseline refers to the R_A value. R_A is continually maintained in the program and cannot be calculated by a single calibration. Basic correction is the name of this procedure. The minimal amount of time to apply a baseline correction is 24 hours since it is normal for air quality in a typical area to change. After the gadget has been turned on for the first time, automatic baseline correction is activated. Moreover, the BASELINE register in CCS811 can manually save and restore a prior baseline [25]. It used the NRF24L01+ module to transmit data from the data logger unit to the ThingSpeak website[26] through an ESP32 development board. NRF24L01+ uses GFSK modulation and operates in the global 2.4 GHz ISM frequency band; the data transfer rate is configurable to 250 kbps, 1 Mbps, or 2 Mbps. The four items mentioned above, with an Arduino Uno controller and an LCD were enclosed in a plastic enclosure, as shown in Fig. 1. There is no central air conditioning, just typical closed-system split units. The lab has no flame, food, or vacuum fan. It utilized the proposed setup to monitor the indoor air quality parameters (CO, CO_2, NH_3, relative humidity, temperature, and TVOC). The measurements were inside a lab in one of the higher education premises in Al-Zafraniya area in Baghdad, with dimensions of 13.4 m in length, 6.6 m in width, and 3.75 m in height over the working week (Oct. 17-Oct. 21, 2022). The average number of occupants in the lab (students and staff) was around 30. Fig. 1 shows the enclosure used for the data logger and the wireless units, Fig. 2 illustrates the Sensing, processing, and communication units, and Fig. 3 illustrates the wiring diagram of the hardware devices.

Fig. 1. Enclosure used for the data logger and the wireless units

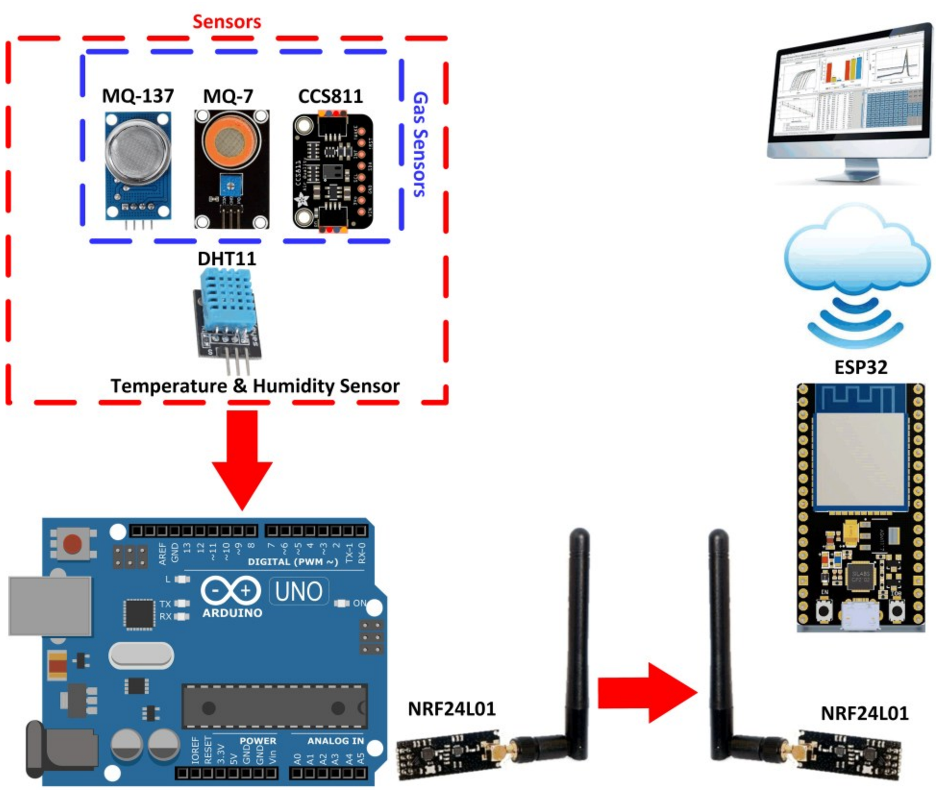

Fig. 2. Sensing, processing, and communication units

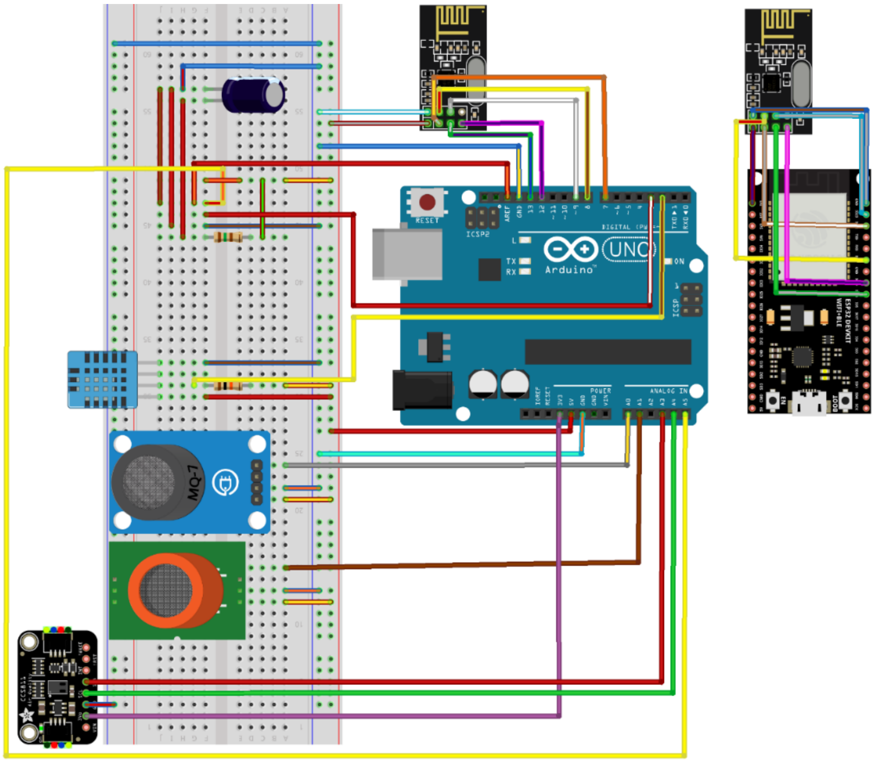

Fig. 3. Wiring diagram of the hardware devices

4. Results and Discussion

The data logger records the air quality parameters (CO, CO_2, NH_3, relative humidity, temperature, and TVOC), storing the data on a solid-state memory card. The local data logger system simultaneously transmits the data through an NRF24L01+ module to the remote monitoring ESP32 to the cloud linker unit, which can simultaneously collect the readings from more than one data logger unit. The proposed system provides flexibility in fitting the measured readings of each sensor to match the multi-gas detector Microtector II G460, which we referred to as a benchmark. The most common indoor air quality parameters (CO, CO_2, NH_3, relative humidity, temperature, and TVOC) were measured in Al-Zafraniya, which is the place of the Institute of Technology-Baghdad, Middle Technical University and among the industrial areas in Baghdad, Iraq. The area is adjacent to Al-Daura Refinery, the General Company for the Vegetarian Oils Industry, the Baghdad South Gas Power Plant, and Al-Rustamiya Wastewater Treatment Plant. The Al-Zafraniya area is home to many sources of air pollution, such as factories and workshops; however, the area contains many higher educational campuses affiliated with Middle Technical University; therefore, we chose to measure the air quality in these premises. The measurements were done in a regular lab for electronic circuits academic experiments, so there is no exposure to chemicals. It is clear from the data collected over one week that on Thursday, although no classes commenced in that lab, one of the lab technicians was heavily smoking, which made clear indications, primarily through the TVOC parameter. This result adds importance to this parameter to impose non-smoking restrictions on such premises. We found that indoor air quality parameters (CO, CO2, NH3, relative humidity, temperature, and TVOC) had the highest pollution rates on some working days with the heaviest class occupation. Interestingly, no lessons commenced on the last day of the working week, and the smoking by one of the staff members was reflected in the results, especially on the TVOC chart. Despite the warning posters, smoking indoors is standard on these premises. We displayed the measurements as they were, reserving integrity. Fig.4 shows a snapshot of the datalogger LCD displaying CO_2, CO, and NH_3; pressing a display button within the datalogger switches the display, displaying humidity and temperature, as shown in Fig. 5. It retrieved the one working week of data from the memory card, imported it into the Excel program, and plotted the CO, CO_2, NH_3, TVOC, RH, and temperature measurements in histograms shown in Figs. 6-11, respectively.

Fig. 4. LCD displaying CO2, CO, and NH3

Fig. 5. LCD displaying humidity and temperature

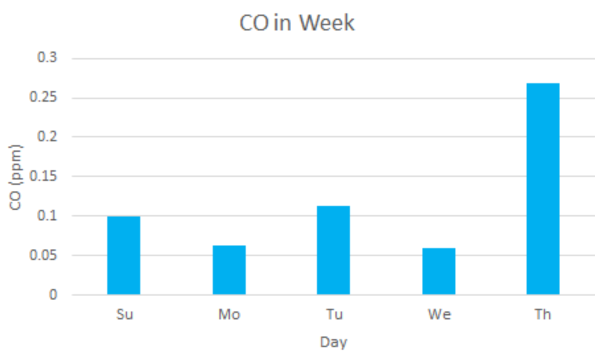

Fig. 6. CO monitoring for five working days

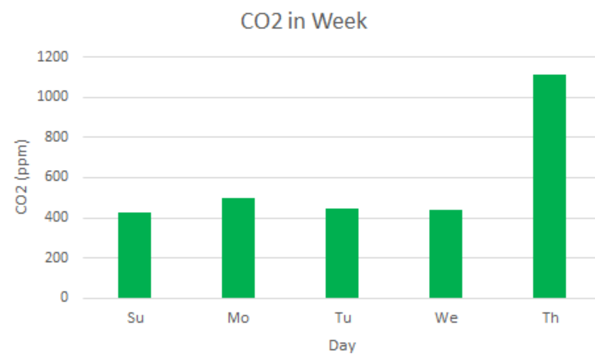

Fig. 7. CO_2 monitoring for five working days

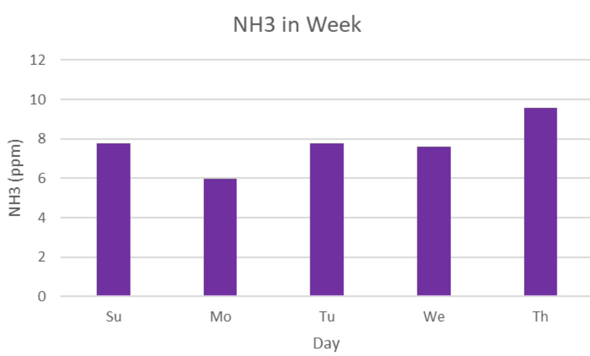

Fig. 8. NH_3 monitoring for five working days

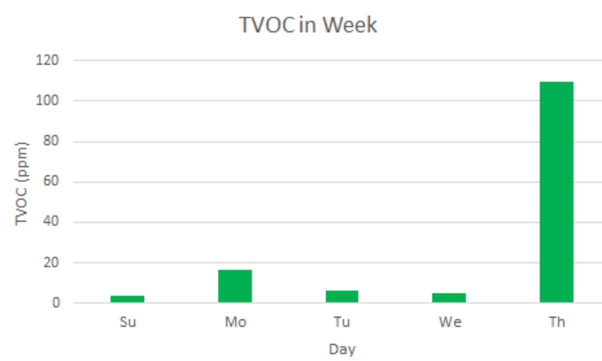

Fig. 9. TVOC monitoring for five working days

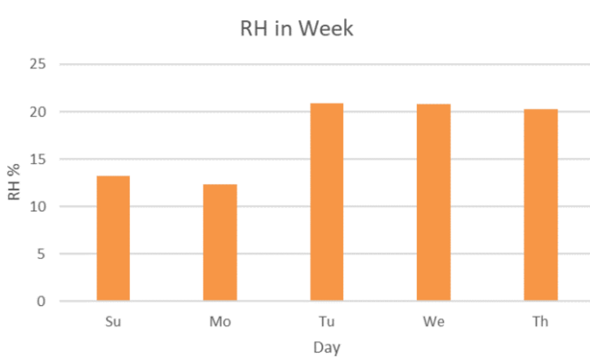

Fig. 10. RH monitoring for five working days

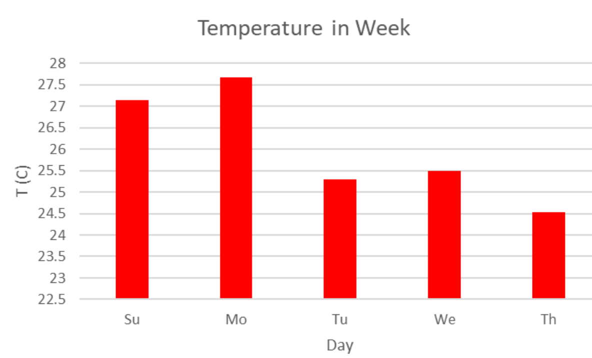

Fig. 11. RH monitoring for five working days

It utilized the ThingSpeak website to instantly monitor the CO, CO_2, NH_3, TVOC, RH, and temperature measurements, as shown in Figs. 12-17, respectively.

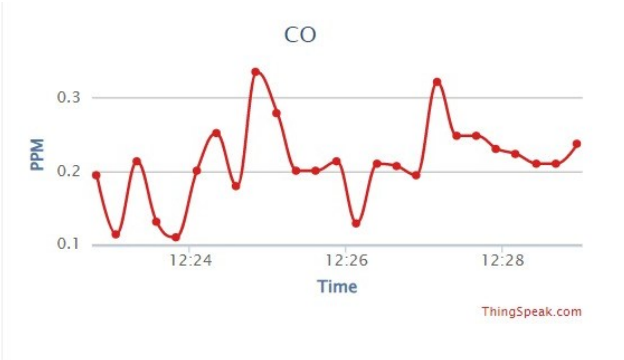

Fig. 12. CO online monitoring

Fig. 13. CO_2 online monitoring

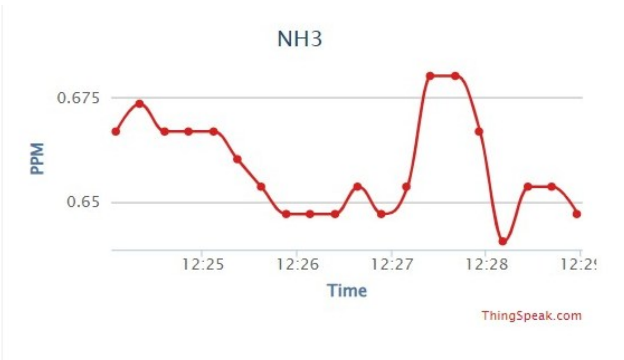

Fig. 14. NH_3 online monitoring

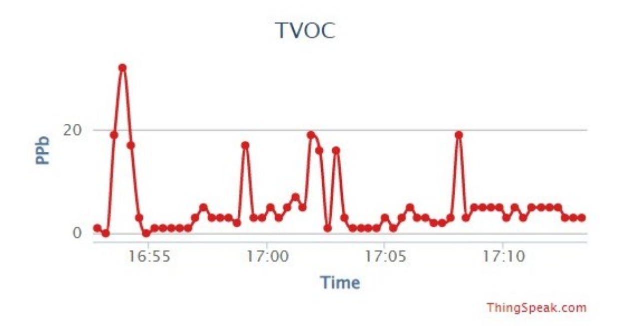

Fig. 15. TVOC online monitoring

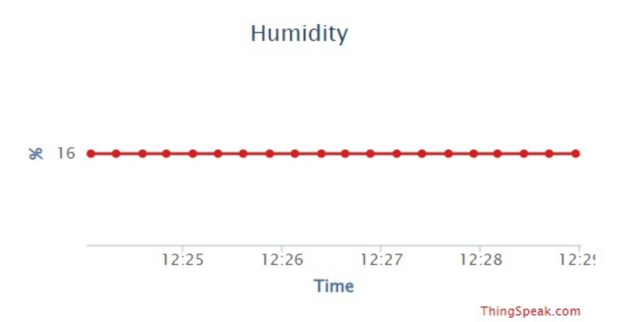

Fig. 16. RH online monitoring

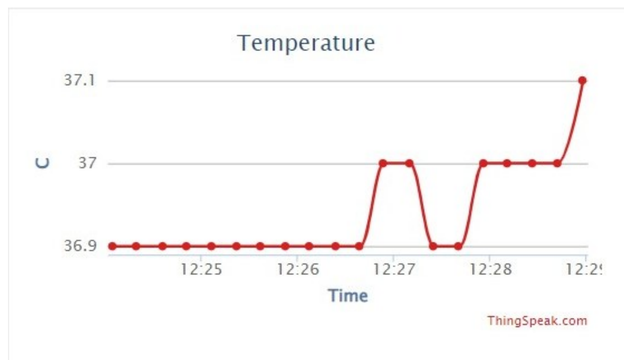

Fig. 17. Temperature online monitoring

5. Conclusion

This research utilized low-cost approaches using publicly available microcontrollers and sensors to monitor indoor air quality parameters. The applied low-cost experimental setup is handy, especially for third-world countries where commercial air quality meters are out of reach. The results showed consistency as the parameters varied according to the occupancy of the class and went low when the lab had no students. We measured the CO, CO_2, and NH_3 concentrations, temperatures, and relative humidity; the proposed system allows online monitoring through ThingSpeak. The proposed system costs around 55 USD, making it a low-cost commercial air quality measuring alternative.

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