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Development of a Particulate Matter and Carbon Monoxide Detector

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Abstract: *Air pollution is inarguably a common tragedy in the today's world: a resultant effect of industrialization and civilization. This work considered two of the most common domestic air pollutants – particulate matter (PM) and carbon monoxide (CO). This developed device is able to detect the presence of these two pollutants in the atmosphere, and trigger an alarm when the levels of these pollutants is above the safe level with respect to the World Health Organization (WHO) standards. NOVA SDS011 and MQ135 were used as the particulate matter and carbon monoxide sensors respectively, 20 x 4 Liquid Crystal Display (LCD) was used as the display unit, and a buzzer as the alarm device which is triggered when the pollutant level is high. The device utilizes Arduino Uno R3 as its microcontroller for controlling the operation of the device. The key contribution to knowledge of this work is the design of a low-cost, portable and modern pollutant detector that can be traditionally deployed in either closed or open environments. On testing the device under different conditions for 500 seconds per condition, the indoor PM2.5, P.M10 and CO levels ranged between 16-19 µg/m^3, 43-80 µg/m^3 and 0.6-1.3 parts per million (PPM) respectively. The outdoor PM2.5, PM10 and CO levels were between 17-23 µg/m^3, 19-62 µg/m^3 and 0.3-0.6 PPM respectively. These levels are considered reasonable enough compared to World Health Organization safe limits of below 25 µg/m^3, below 54 µg/m^3 and 9 PPM for the PM2.5, PM10 and CO respectively. The device was further exposed to the combustion of fuels and to a dusty environment to read very unsafe limits. This work helped to develop a cost-efficient pollution detector; even as optimal operating efficiency was retained.*

Keywords: *Air Pollution, Particulate Matter, Carbon monoxide, Particulate Matter and Carbon Monoxide Detector, Cost-efficient.*

1. INTRODUCTION

Air pollution as an everyday life multi-facet phenomenon has been an area of great interest for research [21]. Air pollution can be categorized into two classes - the outdoor and indoor air pollution. The outdoor air pollution, also known as ambient air pollution is simply the case of having the atmosphere contaminated outside a confinement, while the indoor category is within a confinement. Annual deaths as a result of exposure to outdoor air pollution is estimated to be 4.2 million, while estimated mortality rate as a result of exposure to indoor air pollution from unclean cooking stoves and fuels fumes is 3.8million. Air pollution, especially the outdoor air pollution has over the years resulted into a number of deadly diseases – Schematic heart diseases, pneumonia, chronic respiratory defects, strokes, asthma etc. [13]. About 91% of the entire world's population reside in locations where there is the violation of the air quality standards given by the World Health Organization [13]. From a recent European Environment Agency (EEA) report, air pollution is recorded to be the major cause of diseases and untimely deaths in Europe [8]. More than 500,000 premature deaths are recorded annually due to inadequate air quality and related adverse effects [8]. According to an annual report released by the Health Effects Institute (HEI) in 2016, the state of the air quality in Nigeria has the highest linkage of fatalities in Africa and the 4th highest in the entire world (the first three being Afghanistan with 406, Pakistan with 207 and India with 207); with 150 deaths out of 100,000 people attributed to air pollution. Nigeria and a minimum of 10 other countries are among the deadliest places on earth with higher outdoor air pollution death rates emanating from a number of environmental hazards coupled with man-made pollution sources like vehicle emissions, generator fumes, crop burning etc. [3]. Air pollution is not only harmful to man, but it also has vivid adverse effects on the ecosystem as a whole [4].

Atmospheric pollution detectors are used as both indoor and outdoor devices that use sensors as their central components to detect, and to measure the deposits of air pollutants in the surroundings. These detectors on measuring the air quality (AQ) of the surroundings read out the results to the users and they also give warning when the AQ is inadequate or hazardous to human health with respect to some given standards [20]. The rate of air pollution (or concentration of air pollutants) of a place is traditionally monitored using the stationary air pollution monitoring systems. These systems are recognized to be very accurate, precise and have a wide range of air pollutants that they can detect and monitor [27]. The advancement in technology has brought about the availability of smart, cheaper and more sensitive sensors for general and special purposes. The recent low-cost sensors make it possible to monitor air pollution with much greater spatial resolution. These low-cost sensors are available for many pollutant gases, such as the electrochemical sensors for oxides of nitrogen, carbon monoxide, oxides of sulfur, ozone etc. These gas sensors are made of semiconductors, and have been optimized for more than three decades giving them a high sensitivity for certain gas detection, a fast response time, a small size, low cost compared to other types of sensors, and ease of use in electronic systems which make them attractive and cheap to consumers [6]. Low-cost sensors which are able to measure particulate matter (PM) concentrations are also available, where mass concentration is typically based on the amount of light scattered by the airborne particles [2]. To measure gaseous air pollutants, one of these following classes of sensors is used: electronic circuitry (electrochemical - EC) sensors, aerometric (metal oxide - MO) sensors, and non-dispersive infra-red (NDIR) sensors [5, 10]. The sensors for measuring the concentration of atmospheric particles like the PM can belong to any of these classes of sensors: smart optical particles counters (OPCs), capacitive solid-state sensors, and particle spectrometers. Each of these sensors operate based on algorithms unique to them with respect to their specific functions. The development of these cheap smart sensors has given room for a wider range of domestic uses, other than just the industrial applications. Some of these modest applications include: the possibility for the inhabitants of an area to be familiar with the air quality of their vicinity, the measurement of pollutants levels in a home, personal measurement of the air quality of any place at any time using these sensors [5]. This work aimed to develop a readily available, cheap and mobile particulate matter and carbon monoxide detector (PCD), which can be used anywhere, any time (both indoor and outdoor) to monitor the atmospheric concentrations of these two domestic air pollutants – PM (PM2.5 and PM10) and CO. The PM2.5 talks about the particulate matter with diameter of 2.5 µm or less, while the PM10 refers to the particulate matter with the diameter of 10 µm or less.

According to the United States Environmental Protection Agency [24], the six most common air pollutants are: particulate matter, carbon-monoxide, sulfur dioxide, nitrogen dioxide, ozone and lead.
Table 1 shows the adverse effects of these six most common air pollutants on human health as given by the United States Environmental Protection Agency (US EPA).

Table 1: The adverse effects of the six most common air pollutants [25]

S/N	Pollutants	Adverse Effects on Human Health
1.	Particulate Matter (PM)	Premature death, asthma, decreased lung function growth, respiratory defects.
2.	Carbon Monoxide (CO)	Poor transportation of oxygen by blood cells to body tissues and organs like the heart, anaemia, asthma in children diabetes, death for long-term exposure.
3.	Nitrogen Dioxide (NO_2)	Respiratory defects, worsens existing heart diseases, bronchitis, premature death.
4.	Sulphur Dioxide (SO_2)	Breathing difficulties, chest tightness, worsens asthma condition.
5.	Ozone (O_3)	Bad breathing, chest pain, cough, damage of lungs as a result of long-term exposure.
6.	Lead (Pb)	Lowered intelligence quotient (IQ), behavioural defects.

To avoid or reduce the spread of the adverse effects that these common air pollutants have on especially the human health, low-cost pollution detectors should be made available for both indoor and outdoor purposes [17]. Also, government policies that will enforce the use of these detectors to mitigate the adverse effects caused by air pollutants should be encouraged.

A number of works have been done on air pollution detectors and on low-cost pollutant sensors using different materials to produce cost-effective pollutant sensors with targeted pollutants and different modes of operation. Spinelle et al. [23], in their review concerning volatile organic compounds (VOCs) sensors/devices - using benzene as their case study, stated that most of the small commercial VOCs sensors operate based on one of the six principles they presented (i.e. Photo-ionization detectors, electrochemical, portable or micro-gas chromatograph, metal oxide, optical and electronic noses sensors). They made use of the data given by sensors manufacturers and some previous literatures to deduce the overall view and state of some VOCs sensors, with respect to their advantages and setbacks. It was ascertained from the review, that only the Aeroqual virtual metrology (VM) semiconductor, and some other two Photo-ionization detectors (PID) sensors from Mocon Baseline and Alphasense did well with respect to the limit of detection, in measuring benzene in outdoor (ambient) air surroundings. Mead et al. [14] showed in their paper that low-cost electrochemical sensors that are used for the measurement of gaseous air pollutants at the parts per million (PPM), can be reconfigured to detect and measure the pollutants at a higher resolution of parts per billion (PPB). Both static (stationary) and handheld mobile detectors were examined in determining the air quality of Cambridge, United Kingdom surroundings. They concluded that an urban area such as Cambridge will need more than just the stationary pollution detectors to really ascertain the level of air quality there. Also, pollution detectors with higher resolution will do justice to accurate measurement of air quality level in such areas. Singh et al. [20] proposed the need for an indoor air quality monitoring system (IAQMS) that will be capable of identifying indoor air pollutants sources by the use of machine learning algorithms (supervised), specifically K-nearest neighbour (KNN), multilayer perceptron (MLP), and linear discrimination analysis (LDA). The proposed system on testing, successfully classified some five (5) indoor air pollutants sources when independently examined using the three (3) aforementioned algorithms. The system was limited to classifying these sources when only a maximum of two sources are mixed i.e. introduced at the same time to the indoor environment. More emphasis has been laid on the need to monitor the outdoor (ambient) air, whereas most people spend more of their time inside than in the outside [19]. Hence, both the indoor and outdoor environments need a close air quality monitoring.

Cao & Thompson [7] developed a portable field device for the monitoring of PM2.5 concentration with respect to the individual's exposure to outdoor air. A calibrated DN7C3CA006 dust sensor was used as it was able to read to a detection limit of 9 μgm^{-3} for the period of 60 seconds, indicating its ability and of course the developed device to read very fine particles we get exposed to in our day to day living. The device was tested by individuals residing in Lubbock and Atlanta (Both in the United States), and it was observed that the highest mass concentrations of P.M2.5 were gotten during cooking activities, road transportation, applying cosmetics, visiting restrooms, and cleaning activities. Caubel et al. [9] attempted to solve the problem of not having a low-cost sensor to measure black carbon, (which is a key constituent of particulate matter pollutant) by designing the Aerosol Black Carbon Detectors (ABCD). Their work showed the efforts made to lower the sensitivity of the ABCD to changes in the surroundings temperature, to better the measurement performance of the detectors in a just any (random) environment. A hand-held device for the regulation of CO_x emitted by vehicles was developed by Divan [11], using the MQ-7 sensor (for detection and measurement of CO_x). The device was built such that the emitted CO_x level will read on the vehicle's dashboard and an alarm will be triggered through a buzzer when the standard set limit of CO_x emission is exceeded by the vehicle; this will lead to the halting of the vehicle after a short while. Vehicles cannot but emit gaseous pollutants which can be dangerous to the immediate environment if the emission rate is not controlled [12]. A pollution control circuit was modelled by Kulkarni & Teja [12] to monitor and regulate the vehicles pollutants. Smoke and temperature sensors, a GSM and GPS devices were all incorporated into the control circuit and connected to a central controller. A vehicle connected to this control circuit will be made to stop and send a SMS to the number linked to the setup when a set pollutants emission level is exceeded. The vehicle position on stopping is read by the GPS devices attached to the circuit. The key contribution to knowledge of this work is the design of a low-cost, portable and modern air pollutant detector that can be domestically deployed in either closed or open environments.

The introductory part of this work shows an overview of air pollution effects, low-cost sensors situation and some past related works on pollutants detection; section 2 talks about the methods, processes and materials used in this work. The section 3 shows the results and observations deduced from the work; while section 4 gives recommendation and conclusions meted from the work.

2. METHODS AND MATERIALS

The particulate matter and carbon monoxide detector (PCD) device was built with the Arduino Uno R3 being its microcontroller programmed in C+ + on the Arduino Integrated Development Environment (IDE). The sensors and other peripherals that were connected to this microcontroller include: NOVA SDS011 4(particulate matter sensor), MQ135 (carbon monoxide sensor) gas sensor, power supply, the display unit (LCD 20 x 4) and the buzzer as the alarm device. The core components of this device are the two sensors used. A thorough backend research was conducted to come up with the sensors used as a highly sensitive, low-power consuming and low-cost device was aimed.

The stages involved in developing the PCD are:

i. the careful selection of the two sensors for the detection and measurement of the targeted pollutants (i.e. PM and CO), using price to resolution template to get low-cost but very reliable sensors
ii. the addition of the SDS011 library file to the Arduino IDE library file, and then programming the SDS011 sensor
iii. the addition of the MQ135 library file to the Arduino IDE library file, and then calibrating the MQ135 sensor
iv. the integration of the sensors, LCD, buzzer and power supply to the microcontroller
v. casing the integrated device
vi. Indoor and outdoor testing of the device for performance evaluation purposes.

The device can therefore be divided into three main parts:

i. The microcontroller (ARDUINO UNO R3)
ii. The output unit: Liquid Crystal Display (LCD 20 x 4) and the buzzer.
iii. The sensors (NOVA SDS011 and MQ135)

2.1 Sensors Implementation

The MQ135 gas sensor generates an analog output of the CO level in the atmosphere, therefore its output pin was connected to the Analog port (A0) of the Arduino Microcontroller. The SDS011 PM sensor is a digital device with its own inbuilt microprocessor (8-bit) and its output is in digital form; so, the receiver and transmitter pins of this sensor is connected to the TX and RX port of the digital ports on the Arduino Microcontroller board respectively. The outputs of these sensors (SDS011 and MQ135) will be monitored by the Arduino Microcontroller at regular intervals and the output values will be displayed on the LCD in Parts Per Million (PPM) for the PM and in μgm^{-3} for the CO. Whenever the output of these sensors (i.e. the pollutants concentration) exceeds the allowable exposure in the surrounding atmosphere, the Arduino will trigger the alarm to warn the inhabitants of the impending danger. Sufficient knowledge about the sensors used for this device was established before their implementation. The NOVA FITNESS SDS011 sensor and the MQ135 have different operating principles.

2.2 NOVA fitness sensor SDS011

The NOVA SDS011 sensor works on the principle of optical analyzing sensors, using high-energy laser [16]. The SDS011 sensor library was not available in the Arduino IDE, therefore the first thing that was done was to get the library file and add it to Arduino library files (.h extension files). After updating the library, SDS011 can now be controlled by Arduino. After this, the Arduino was programmed such that it could control the sensor (SDS011) for the detection and measurement of PM2.5 and PM10 on connection as shown in Figure 1. Table 2 shows how the pins of the SDS011 sensor were connected to the microcontroller. This sensor didn't need any calibration process as it has already been automatically designed to accurately read PM values by the manufacturer.

Table 2: SDS011 and Arduino relationship

SDS011 ports	Arduino ports
TX	0 (RX)
RX	1 (TX)
GND	GND
VCC	5V
2.5μm	Not connected

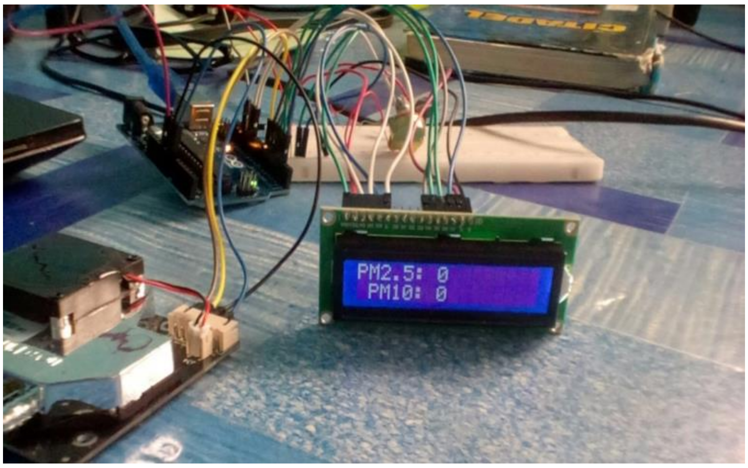

Figure 1: PM sensor and Arduino setup

2.3 MQ135 Gas Sensor

The MQ135 gas sensor displayed in Figure 2, works on the principle of heating semiconductor. Heating semiconductor gas sensor is made up of a metal-oxide (tin dioxide – SnO_2 in the case of MQ135 sensor) sensing layer which is capable of detecting gases. The mass concentration of such detected gases is measured by measuring the change in the electrical conductivity and or resistivity of the sensitive layer [1]. The target gas concentration for an electrochemical sensor is calculated thus:

$$C_x = \frac{1}{M} \times (V_{gas} - V_{gas\,0}) \quad (1)$$

where C_x is the gas concentration; M is the sensor calibration factor found on the sensor's sticker; V_{gas} is the output voltage signal and $V_{gas\,0}$ is the output voltage gas signal in a pure air environment.

$$V_{gas\,0} = V_{ref} + V_{offset} \quad (2)$$

where V_{ref} is the output voltage reference signal, and V_{offset} is a voltage offset factor which is often negligible [22].

Figure 2: MQ135 Gas Sensor [1]

Just like for the SDS011 sensor, the MQ135 sensor library was not available in the Arduino IDE, therefore the sensor library file was added to the Arduino library files (.h extension files). After updating the library, MQ135 could now be controlled by the Arduino. The next step was calibration of the sensor; this was done for a period of 12hrs in an indoor air atmosphere and in outdoor air atmosphere for additional 30 minutes. The method employed for this calibration process was to expose the metallic part of the sensor to burning papers (being a source of CO) for the indoor; and then to clean air for the outdoor. These CO and clean air concentrations were unmeasured. The sensor circuitry was designed and simulated on Proteus Virtual System Modelling (VSM) as shown in Figure 3. The components used in the design include: an Arduino Uno R3, MQ135 gas sensor, 10K potentiometer, 20x4 LCD, 5V power supply and jumper cables.

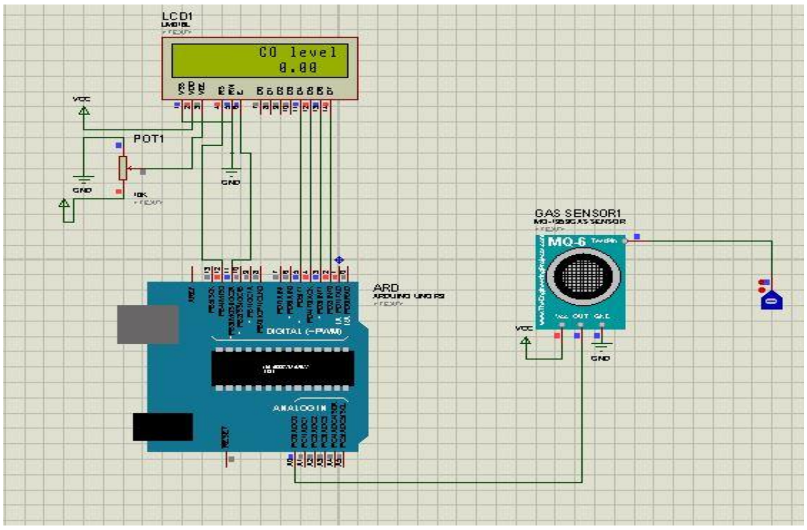

Figure 3: MQ135, Arduino and LCD circuit schematic on proteus VSM [15]

On calibrating the MQ135 sensor as shown in Figure 4, the Rzero value (379.13) was determined which was added to the header file (.h extension file) in the MQ135 library files and the read operation code was uploaded into the microcontroller (i.e., the Arduino). After the implementation of the two sensors, all the other detachable components that make up the device were assembled and cased as shown in Figures 5-7.

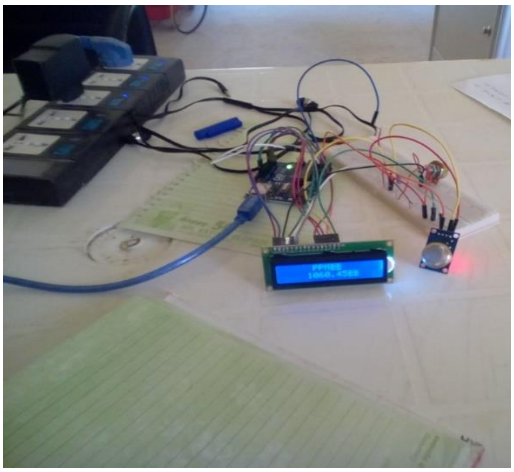

Figure 4: MQ135 calibration process

Figure 5: Assembling the components

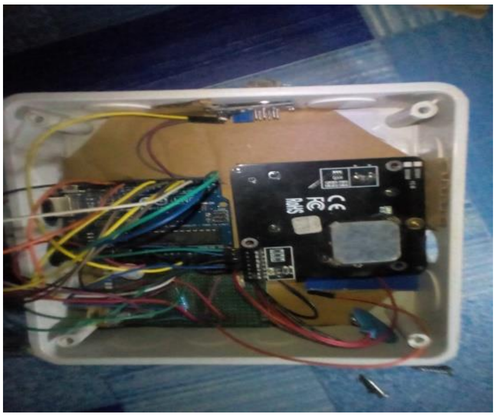

Figure 6: PCD’s panel interface

Figure 7: The developed PCD

More so, the total power consumption was estimated as shown in Table 3, to be sure our power supply was sufficient, or the device could shutdown unexpectedly. It is also useful to know if the device was to be operated on rechargeable batteries, knowing that the power consumption will determine the estimated operating time.

Table 3: Power requirement estimations

Components	**Current (mA)**	**Voltage (V)**	**Power (W)**
Arduino UNO	40.00	5.00	0.2000
SDS011	77.00	5.00	0.3850
MQ135	40.00	5.00	0.2000
20 x 4 LCD	40.00	5.00	0.2000
Piezo Buzzer	20.00	5.00	0.2000
Total	217.00	5.00	1.1850

3. RESULTS AND DISCUSSION

The device was tested under a series of six (5) conditions to validate its operation and also to compare various results of its output under different circumstances. The device was tested within the hostel rooms in Ikole-Ekiti to check for the indoor CO and PM levels under normal condition, dusty condition for PM measurement, and then cooking condition for CO measurement. Furthermore, for outdoor test, the device was exposed to the air along the highway just in front of the Ikole Campus. These conditions read thus:

1. Particulate matter indoor test: the device was used to measure the indoor PM level for a period of five hundred seconds (500s) and the plot on the Arduino IDE serial plotter is shown in Figure 8. Figure 8 shows that the PM2.5 level here was within the range of 16 to 19 µgm^{-3}, while the PM10 value was within the range of 43 to 80 µgm^{-3} throughout the cycle (which are considerably safe according the WHO’s standard for PM daily limit). The WHO’s standard daily limits for PM2.5 and PM10 are below 25 µgm^{-3} and below 54 µgm^{-3} respectively. The white area just beneath the blue area in Figure 8 connotes the PM2.5 level measurements while the blue area shows the PM10 level measurement. This color representation is also applicable to Figures 9 and 10
2. Particulate matter outdoor test: the device was also tested in the outdoor environment and the Arduino IDE serial plotter output was also derived as shown in Figure 9. From the output of the plotter in Figure 9, the outdoor plot of PM for the 500 seconds was within 19 to 62 µgm^{-3} for PM10 and 17 to 23 µgm^{-3} for PM2.5. These PM levels of the outdoor environment was okay due to low activities in the neighborhood and also low movement of particles due to low moment of vehicles and other related activities
3. The PM operation was also tested in a dusty room, to observe the difference in the particulate matter nature due to the presence of dust in the atmosphere which was generated from sweeping. It is seen as shown in Figure 10 that there was a sudden rise in the values of both PM10 and PM2.5 as a result of the large amount of dust particles suspended in the air from the sweeping activity.

4. MQ135 indoor test: the MQ135 operation was also tested in indoor air and the output was monitored still with the Arduino IDE serial plotter for 500 seconds as seen in Figure 11. The output of the serial monitor showed low CO content in the atmosphere of 0.6 to 1.3 PPM, (compared to the WHO's 9 PPM standard) making the indoor air of the location safe. Another test was carried out for the MQ135 indoor test where pollutant level in the atmosphere was increased by the combustion of some fuels (papers), the MQ135 output was observed on the Arduino IDE serial plotter and it was observed that the level of CO in the atmosphere increased during and immediately just after the combustion, and the value of CO exposure on the plot reduced in the surrounding as viewed on the plotter a while after the process ceased.
5. MQ 135 outdoor air test: the device was again exposed to the outdoor air of the environment and it was likewise monitored using the Arduino IDE Serial plotter. The outdoor air was also safe; the plot in Figure 12 shows that the overall output to be within 0.3 to 0.6 PPM is less than the WHO daily limit for CO exposures.
6. From the tests carried out with this developed PCD, it was revealed that due to poor indoor air flow compared to outdoor, there are more pollutants retained in the indoor air compared to the outdoor air. This proves that movement of the suspended particles and CO in indoor air (relative to the outdoor air) remain in the household for longer period of time and in most cases takes longer time to spread and escape from the house depending on the type of ventilation in the house. Furthermore, it was also deduced that the continuous movement of air in the outdoor environment allows pollutants to spread easily and quickly, making the pollutants level in the surrounding low compared to indoor space. Compared to Usikalu et al. [26] whose results were expressed in volts, the developed PCD was able to measure CO in PPM which is the best and simplest way to express CO concentration in air. Also, the MQ135 sensor used in this work compared to the TGS 2442 used by Usikalu et al. [26] is able to detect more than just the CO for future modification and usage. The results compared to Reza [18] and Usikalu [6] showed the possibility of synergizing the measurements of the CO and PM using very sensitive, durable but low-cost sensors on just a single device.

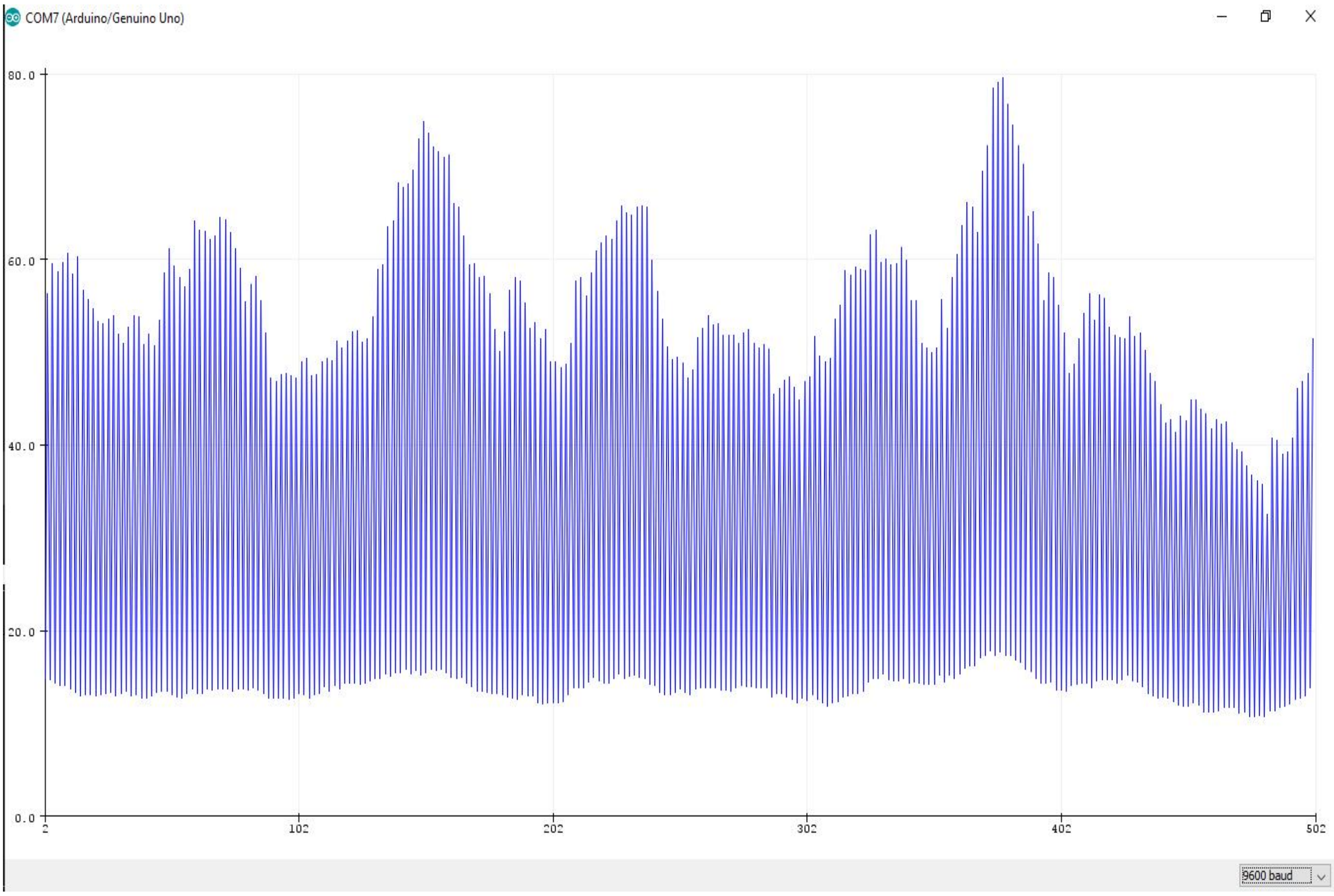

Figure 8: Indoor PM level chart

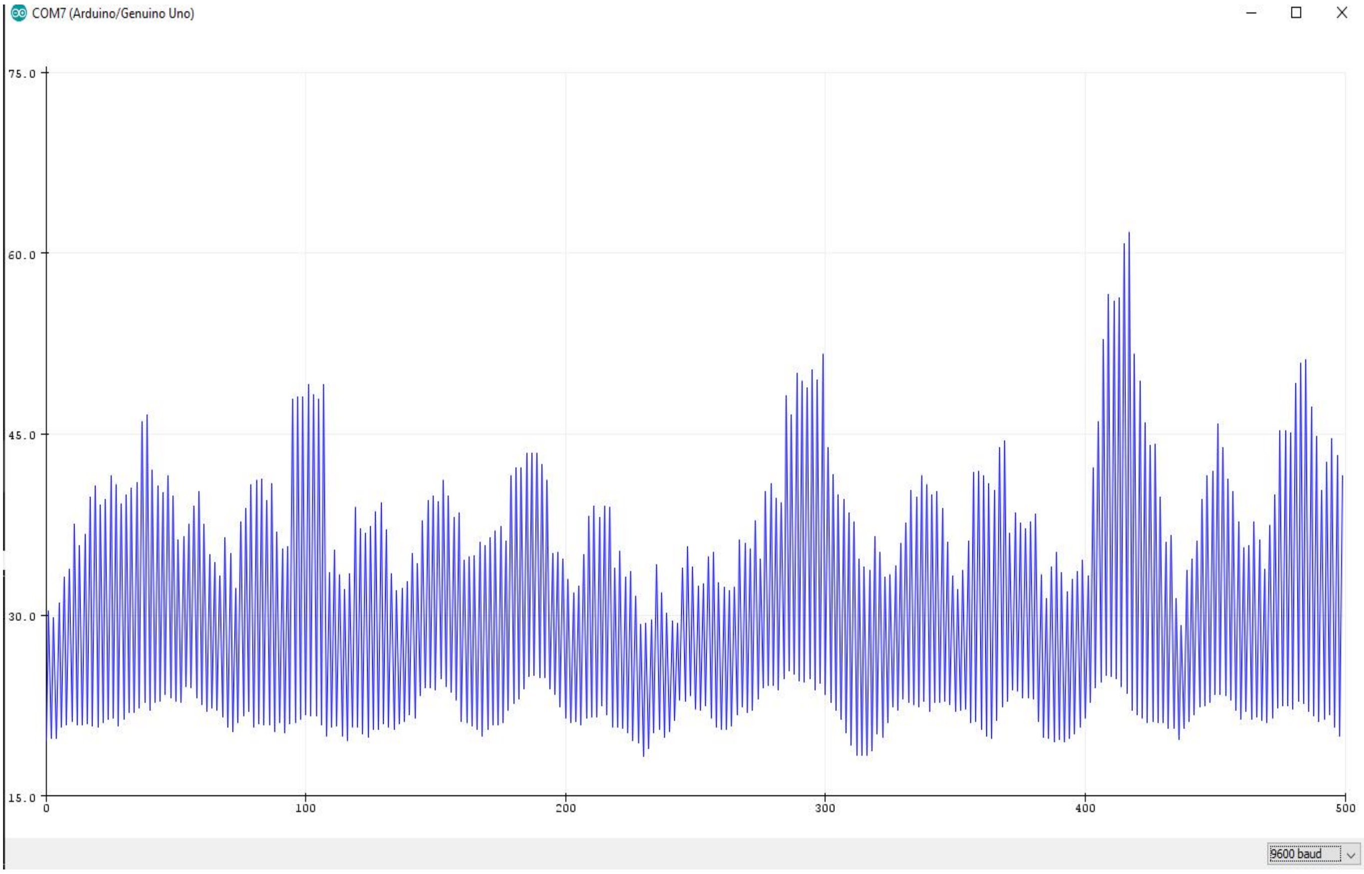

Figure 9: Outdoor PM level chart

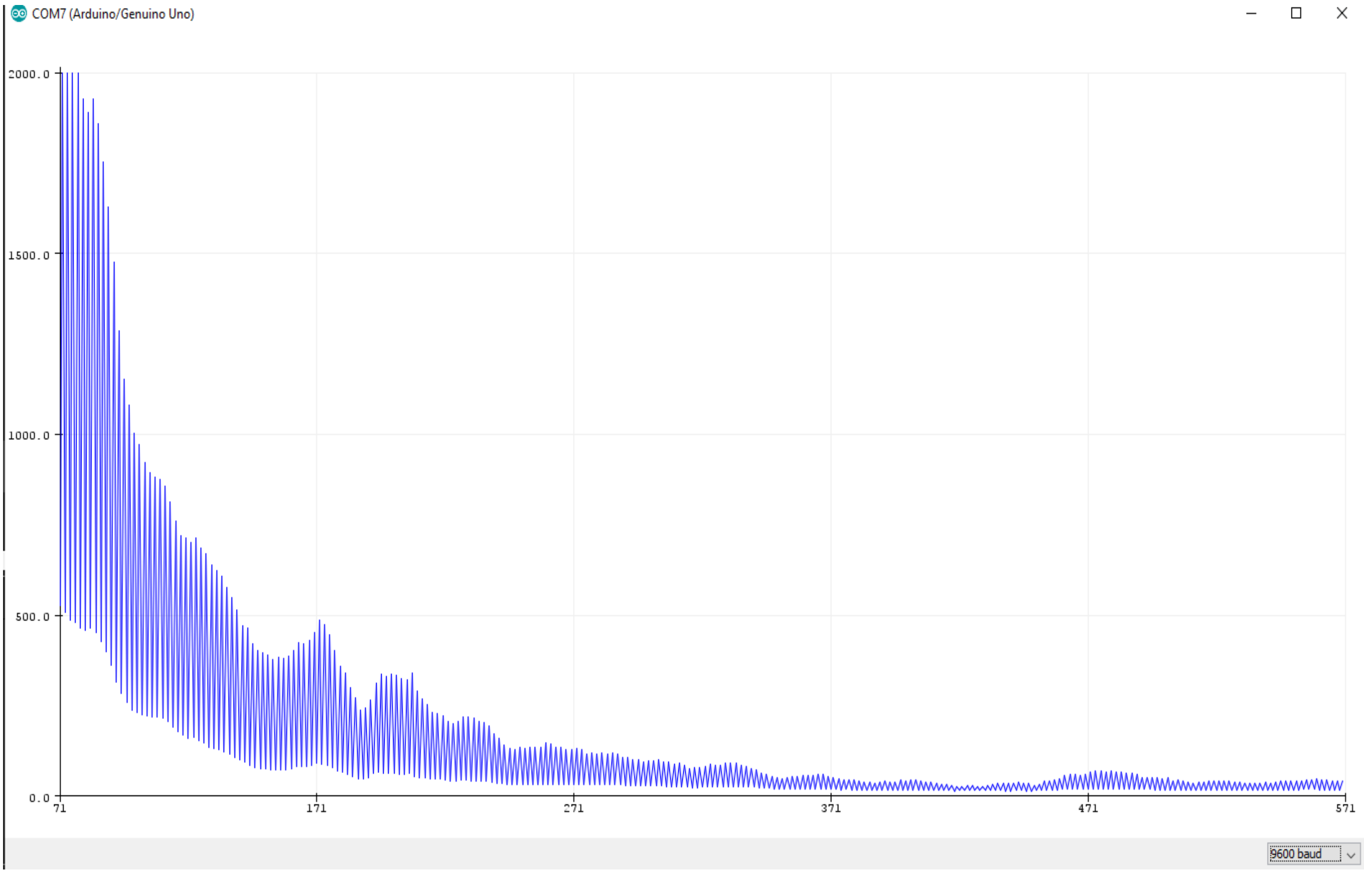

Figure 10: PM level chart in a dusty environment

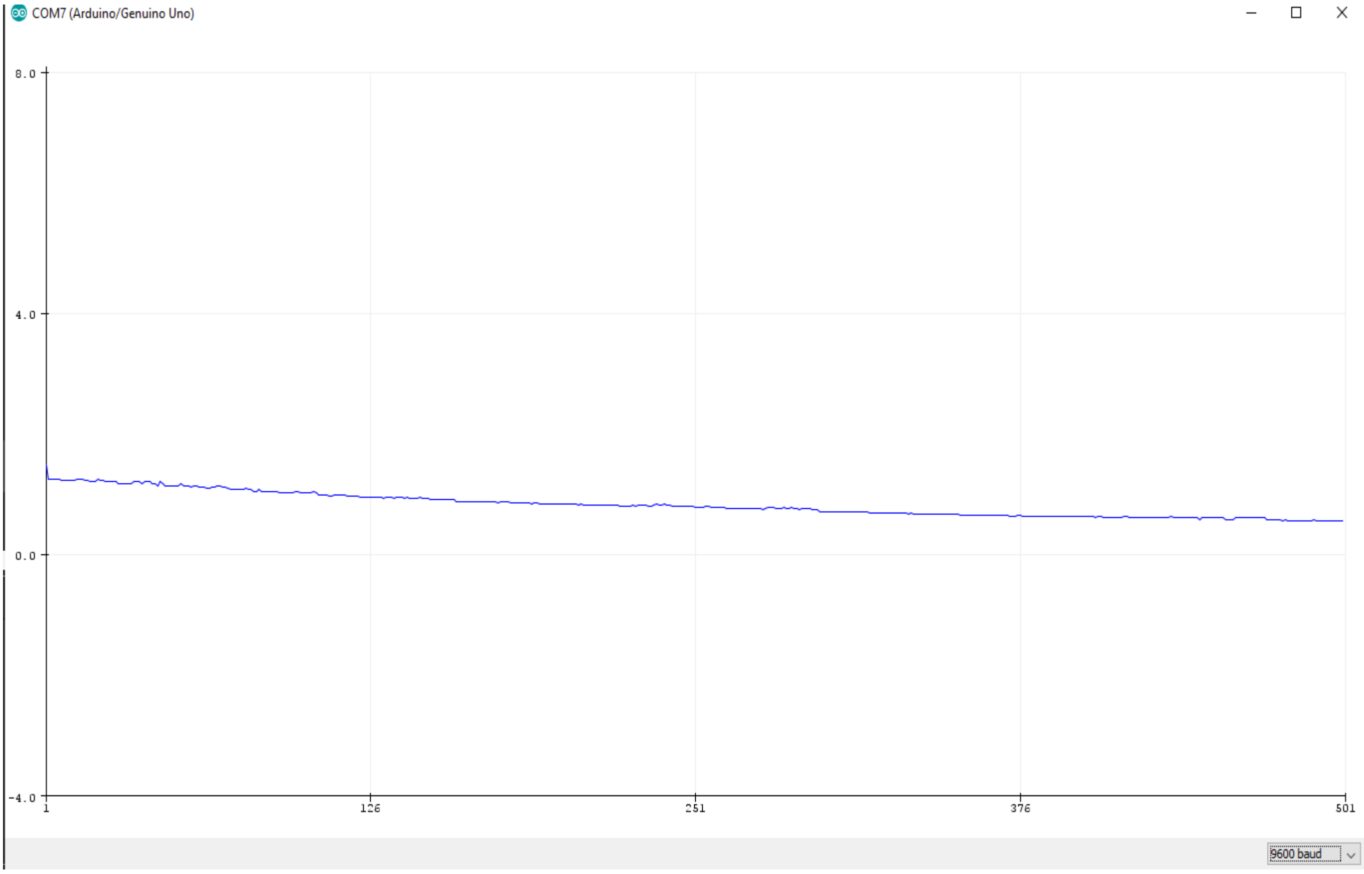

Figure 11: Indoor CO chart

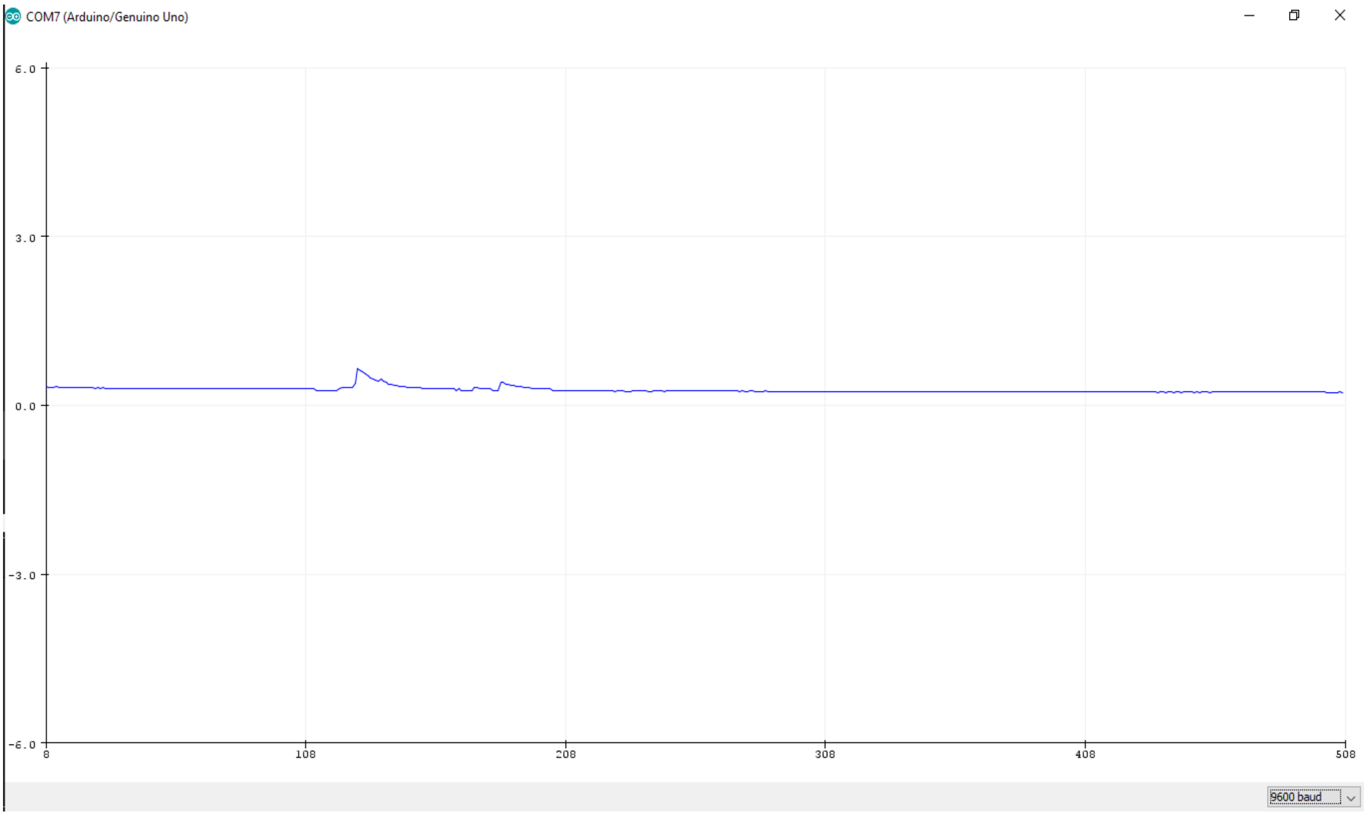

Figure 12: Outdoor CO level chart

4. CONCLUSION AND RECOMMENDATION

The low-cost Particulate Matter and Carbon Monoxide Detector (PCD) was successfully developed with NOVA SDS011 as PM Sensor, and the MQ135 as the CO sensor. The 20 x 4 LCD was used as the display unit, buzzer as the alarm device and the Arduino Uno R3 as the central microcontroller which was programmed via the Arduino IDE. The device was tested under six (6) different conditions during which certain observations were made. The pollutants concentration in the indoor air is higher than outdoor air of the environment due to poor aeration in the houses. Some common house chores such as sweeping tends to be a major source of PM in the house, while combustion happens to be the major source of CO generation in the homes. It is recommended that, to reduce the adverse effect of pollution in Nigeria, the government should enforce pollution control policies and as well monitor the pollution exposure in our urban cities so as to reduce the impending catastrophe that is being caused in the communities, especially urban centers. Similar devices like this PCD is recommended to be domestically used for this purpose in our homes and communities. The key contribution to knowledge of this work to build a low-cost, portable and modern pollutant detector that can be deployed in either indoor or outdoor environments was successfully meted. This work promotes better air quality management by providing accessible solutions to the pressing issue of air pollution.

REFERENCES

[1] Abbas, F. N., Abdalrdha, Z. K., Saadoon, M. M., & Abud, E. N. (2020). Capable of gas sensor MQ-135 to monitor the air quality with arduino uno. *International Journal of Engineering Research and Technology, 13*(10), 2955-2959. https://doi.org/10.37624/IJERT/13.10.2020.2955-2959

[2] Al Barake, Z., Breuil, P., Redon, N., Pijolat, C., Locoge, N. & Viricelle, J. P. (2017). Development of a normalized multi-sensors system for low cost on-line atmospheric pollution detection. *Sensors and Actuators B: Chemical*, *241*, 1235-1243. https://doi.org/10.1016/j.snb.2016.10.006

[3] Alege, P. O., Adediran, O. S., & Ogundipe, A. A. (2016). Pollutant emissions, energy consumption, and economic growth in Nigeria. *International Journal of Energy Economics and Policy*, *Econjournals*, *6*(2), 202-207.

[4] Atani, M. (2024). Air Pollution: Africa invisible silent killer. UN environment. https://www.unenvironment.org/news-and-stories/story/air-pollution-africas-invisible-silent-killer-1

[5] Broday, D. M. (2017). Wireless distributed environmental sensor networks for air pollution measurement - The promise and current reality. *Sensors*, *17*(10). https://doi.org/10.3390/s17102263

[6] Buček, P., Maršolek, P., & Bílek, J. (2021). Low-cost sensors for air quality monitoring - The current state of the technology and a use overview. *Chemistry, Didactics, Ecology, Metrology Journal*, *26*(1-2), 41-54. https://doi: 10.2478/cdem-2021-0003

[7] Cao, T., & Thompson, J. E. (2017). Portable, ambient pm2.5 sensor for human and/or animal exposure studies. *Analytical Letters*, *50*(4), 712-723. https://doi.org/10.1080/00032719.2016.1190736

[8] Carvalho, H. (2019). Air pollution-related deaths in Europe: Time for action. *Journal of global health*, *9*(2), 1-4, https://doi:10.7189/jogh.09.020308

[9] Caubel, J. J., Cados, T. E., & Kirchstetter, T. W. (2018). A new black carbon sensor for dense air quality monitoring networks. *Sensors*, *18*(3). 1-18, https://doi:10.3390/s18030738

[10] Dhall, S., Mehta, B. R., Tyagi, A. K., & Sood, K. (2021). A review on environmental gas sensors: materials and technologies. *Sensors International*, *2*. 1-10, https://doi.org/10.1016/j.sintl.2021.100121

[11] Divan, T. (2014). *Hand-held device for detection of air pollutants in vehicles* (unpublished master dissertation). Rastrasanta Tukadoji Maharaj Nagpur University, India.

[12] Kulkarni, A., & Teja, T. R. (2014). Automated system for air pollution detection and control in vehicles. *International Journal of Advanced Research in Electrical, 3*(9), 5, 12196-12200

[13] Kunecki, P., Franus, W., & Wdowin, M. (2020). Statistical study and physicochemical characterization of particulate matter in the context of Kraków, Poland. *Atmospheric Pollution Research Journals*, *11*(3), 520-530. https://doi.org/10.1016/j.apr.2019.12.001

[14] Mead, M. I., Popoola, O. A., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., McLeod, M. W., Hodgson, T. F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell J. R., Jones, R. L. (2013). The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, *70(1)*, 186-203. https://doi.org/10.1016/j.atmosenv.2012.11.060

[15] Najmurrokhman, A., Kusnandar, A., Syaripudin, A., & Munir, A. (2019). Development of human machine interface for supporting the disaster mitigation system in the city using wireless sensor network. *Journal of Physics: Conference Series*, *1280*(2). 1-8, https://doi:10.1088/1742-6596/1280/2/022032

[16] Nguye, N. H., Nguye, H. X., Le, T. B., & Vu, C. D. (2021). Evaluating low-cost commercially available sensors for air quality monitoring and application of sensor calibration methods for improving accuracy. *Open Journal of Air Pollution*, *10(1)*, 1-17. https://doi.org/10.4236/ojap.2021.101001

[17] Rawat, N., & Kumar, P. (2022). Interventions for improving indoor and outdoor air quality in and around schools. *Science of the Total Environment*, *858*(5), 1-24, https://doi.org/10.1016/j.scitotenv.2022.159813

[18] Reza, D. (2019). Carbon monoxide sensor based on non-dispersive infrared principle. *Journal of Physics: Conference Series*. https://doi:10.1088/1742-6596/1201/1/012012

[19] Saad, S. M., Andrew A. M., Shakaff, A. Y., Dzahir, M. A., Hussein, M., Mohamad, M., & Ahmad, Z. A. (2017). Pollutant recognition based on supervised machine learning for indoor air quality monitoring systems. *Applied Science, 7*(8), 1-21, https://doi.org/10.3390/app7080823
[20] Singh, D., Dahiya, M., Kumar, R., & Nanda, C. (2021). A review on sensors and systems for air quality assessment monitoring and management. *Journal of Environmental Management, 289*(7). doi:10.1016/j.jenvman.2021.112510
[21] Singh, S. P., & Sharma, M. K. (2018). Impact of air pollution on global environment. *Science Technical and Medicine Journals, 7*(1), 23-32, https://doi:10.37591/rrjoe.v7i1.816.
[22] Spec Sensors (2016): Ultra-low power analog sensor module for respiratory irritants. https://www.spec sensors.com
[23] Spinelle, L., Gerboles, M., Kok, G., Persijn, S., & Sauerwald, T. (2017). Review of portable and low-cost sensors for the ambient air monitoring of benzene and other volatile organic compounds. *Sensors Journal, 17*(7). https://doi:10.3390/s17071520
[24] US EPA (2024): Criteria air pollutants. https://www.epa.gov/criteria air-pollutants.
[25] US EPA (2015): Criteria air pollutants.https://www.epa.gov/sites/default/files/2015-10/ace3_criteria_air_pollutants
[26] Usikalu, M. R., Umoren, I., Ndubuisi, A. O., & Olawole O. F. (2019). Design and construction of carbon monoxide detector. *International Journal of Civil Engineering and Technology, 1*(3), 464-469.
[27] Ye, Y., & Geng, P. (2023). A review of air pollution monitoring technology for ports. *Applied Science Journals, 13*(8), 1-15, https://doi.org/10.3390/app13085049