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ORIGINAL RESEARCH

Development of a real-time monitoring and detection indoor air quality system for intensive care unit and emergency department

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Abstract

To develop an Indoor Air Quality (IAQ) monitoring and detecting system based on a new Internet of Thing (IoT) sensory technology device that incorporated nine recommended indoor pollutants by the academic literature and reliable organizations, such as World Health Organization (WHO), Environmental Protection Agency (EPA), and International Organization for Standardization (ISO). The pollutants include Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Dioxide (NO_2), Ozone (O_3), Formaldehyde (HCHO), Volatile Organic Compounds (VOC), Particulate Matter 2.5 (PM2.5) as well as air humidity and temperature that are used to assess the variety of indoor pollutants and provide a new IAQ pollutants dataset. Besides, the newly developed system provides real-time air quality monitoring, reports the pollutants' data to a cloud platform *(i.e.*, ThingSpeak), and can trigger early warnings as a service when abnormalities occurred in the air quality index. The system was tested to ensure its conformance to the recommended pollutants by collaborating with surgeons and specializing in IAQ in a hospital surgical intensive care unit (SICU), emergency department (ED), and in the women's ward, which accommodate patients who are either newly born mothers (in case they need that) or who have had an operation, as well as pregnant patients who need to stay in the hospital to be under the supervision of medical care. Nine pollutants were identified and collected the pollutants dataset and their thresholds that affect the air quality within the hospital facilities and services (SICU, ED) to be used for assessing the effectiveness of the amount, concentration, and diversity of the pollutants. In the SICU, the concentrations of some pollutants were high in the beginning due to the residues of the previous surgery and because of the frequent use of sterilizers to clean and prepare the surgery room. Then, the concentrations of pollutants were moderate, but minutes after the start of the surgical, an increase in CO_2 and formaldehyde was observed, which exceeds the threshold limit because of the use of anesthetic gas and sterilization. In the women's ward, was all concentrations generally moderate except for particles matter PM2.5, and the same context with the 3rd installed location in the pharmacy of ED, most concentrations were moderate, except formaldehyde which exceeded the threshold. "CO" was the highest positive correlated and strongly correlated to "NO_2" and that was expected because CO influences the oxidation of NO to NO_2. On the contrary, the "CO" had the highest negative correlation with "VOC", and the "NO_2" had the highest negative correlation with "VOC", chemistry is part of the responsibility for the weak correlation observed between the pollutants.

Keywords

Indoor air quality; Sensors; Internet of things; Intensive care unit; Emergency department; Monitoring and detection

1. Introduction

Air pollution is one of the most prominent public health issues in the world, especially in urban areas with large population density because of the high concentration of pollution generated by hospitals and medical care units. Humans inhale approximately 14,000 litres of air to perform their daily activities [1]. According to the Air Quality Index (AQI), the quality of air is based on the concentration of pollutants present in a specified location for reporting daily air quality [2]. According to the United States Environmental Protection Agency, human exposure to indoor air pollutants may occasionally be more than 100 times higher than the levels of outdoor pollutants [3]. Indoor Air Quality (IAQ) is determined by the air pollution conditions, residence behaviour, sources and the environment infrastructure [4]. IAQ is an indicator for assessing air quality by evaluating the concentrations of pollutants in the indoor environment that directly affect air quality, such as NO_2, HCHO, O_3, CO, CO_2, PM2.5, and volatile compounds, such as paint, furniture, office equipment, trash, exhaled breath, and/or sweating. The US Environmental Protection Agency (EPA) stated that IAQ is an environmental health concern, where many public places monitor and handle air quality [5].

The environmental studies in the health care sector indicated two types of pollutants in the hospitals, namely, biological and nonbiological [6–9]. Biological pollutants include pathogenic microorganisms and airborne bio-aerosols, such as bacteria and spores of fungi, whereas nonbiological and chemical pollutants include volatile organic and inorganic compounds, such as alcohol (ethanol and isopropanol), aldehydes, detergents and consumable drugs [6]. The increasing levels of both these types pose a significant threat to environmental systems. In addition to those two, other unsafe gases, namely, sulphur dioxide (SO_2) and carbon dioxide (CO_2) affect the hospitals and partake in air quality change [10]. Consequently, the academic literature has shown increasing concerns on many primary pollutants, such as carbon monoxide (CO), ozone (O_3), sulphur dioxide (SO_2), nitric oxide (NO), nitrogen dioxide (NO_2) and a composite combination of liquid and solid droplets called particulate matters (PM) [11–13]. Moreover, Clean Air Act (CAA) indicated the significance of regularly monitoring the emission of ozone and NO_2 pollutants because the EPA scientists reported that both are considered as hazardous amongst the six common pollutants in the world (*i.e.*, carbon monoxide, lead, ground-level ozone, nitrogen dioxide, particulate matter, and sulphur dioxide) [14].

Recently, much attention has been given to the exploration of sensory and pollutant technologies in the indoor health environment [1]. Hence, pollution control using the IoT brings recent dynamic essence to the systems by continuously sensing and learning from the surroundings, it can serve the hospital environments with distinct benefits [15–18]. To avail of the actual benefits of IoT, IAQ sensor technologies should be intelligent to support hospital communities and their health facilities to analyse monitoring, detecting, and assessment techniques that utilize different pollutants to measure IAQ. Thus, integrating IAQ with sensors based on IoT technology fills in some of the knowledge gaps and it contributes to enhancing air quality strategies of hospital facilities.

The introduction of this study must address three sequential questions and layout appropriate answers to demonstrate and strengthen the obvious contribution to IAQ knowledge in hospital facilities in order to bring forth the crux of this study.

The first question that requires an appropriate answer, "***How IAQ is important for hospital facilities and Services for SICU and ED?***". Scientifically, the quality of air can deteriorate due to medical products, medications, and medical gases *i.e.*, anesthesia gas used in the SICU. In addition, asthma patients are the most common visitors to the ED, so a healthy and good IAQ should be provided. Recent research has shown clear evidence that airborne transmission plays a significant role in many nosocomial infections [19]. Air is considered the "most important carrier" of hospital contaminations, indoor environments are characterised by many as sources of pollutants, and health concerns associated with poor IAQ have become increasingly relevant in recent years especially for public health infrastructure [20, 21]. Thus, IAQ contributed to public health by conveying modern expertise to patients, hospital staff and doctors [22]; however, air quality in indoor environment is a serious concern, particularly in hospitals given the numerous residents [1]. According to the EPA, the levels of indoor air pollutants are often 2 to 5 times higher than outdoor levels, and in some cases, these levels can exceed 100 times that of outdoor levels of the same pollutants. In other words, the indoor environment can be more harmful than outdoor environment [23]. In addition, indoor air pollution is a leading risk factor for premature death. The WHO puts this figure at 4.3 million each year. Moreover, air pollution is one of the most common causes of asthma cases, affecting 91% of the world's population according to the World Health Organisation (WHO) [14]. A low IAQ can lead to ailments, such as headache, exhaustion, eye and skin irritation or long-term health effects [1]; in particular, it is a leading risk factor for premature death [24]. Hospitals rely extensively on computer technology and IoT to examine patients, cure disease, advance the science of medicine, telemedicine, and conduct the remote services of health care [25–29]. Thus, hospitals and other health care facilities have focused on monitoring pollution to reduce infections, and IAQ being one of the hot topics. For health care facilities and services, (*i.e.*, ED, Coronary Care Unit, Intensive Care Unit, Day Surgery Unit. *etc.*) especially for the patients and medical staff, the solutions to continuous monitoring the pollutants need to be addressed and developed. Thus, monitoring air quality and facilities in hospital, the detection of pollution indices exhibits its importance for healthcare environment.

In the context of a hospital, good performance in managing ventilation systems is also taken into account while controlling infections [6]. Consequently, weather conditions, as well as indoor ventilation systems, are factors that might modify IAQ, improving conditions for microbial growth and dissemination [19]. Therefore, an effective ventilation system for hospital infrastructure is important to maintain the IAQ within reasonable limits and can detect different air pollutants [30].

This fact motivated us to ask the second question, as follows: "***What is the current academic literature that designed IAQ devices based on IoT for the hospital's facilities and what is critical analysis?***".

To capture the existing state of academic knowledge about IAQ sensor technologies, it is pertinent to know the background literature clearly with their strengths and weaknesses. In these difficult circumstances, particularly with the coronavirus (COVID-19) crisis, technology alternatives are being emphasized like never before, and the need for healthcare transformation from traditional techniques to technology-driven healthcare solutions such as the IoT is being advocated to increase patient comfort, facilitate doctor decision-making and make healthcare environments safer for both patients and staff [31, 32]. In the study [33] applied IAQ monitoring and prediction solution based on the IoT sensors and machine learning capabilities, providing a platform to measure numerous indoor contaminants. However, it does not consider the hospitals and healthcare facilities, therefore, the designed device did not consider all the pollutants identified for the hospital environment. In [1] aimed to develop a low-cost device to determine the IAQ monitoring system that can measure total volatile organic compounds (TVOC), temperature and humidity used in three distinct areas (pharmacy, emergency and waiting place) in a hospital in Thailand. The study was related to the hospital environment, nevertheless, it did not identify all the common pollutants in the hospital environment and only measured the general pollutants of the indoor environment. Another study presented in [34] developed a low-cost and scalable IoT system called iDust, utilised in hospital wards to deal with lung disease, respiratory problems and asthma treatment to monitor the particulate matter (PM) in real-time and handle the early-stage air pollution problems. However, this study was concerned with one pollutant known as particulate matter (PM). The study of [3] developed low-cost IAQ monitoring wireless sensor network system by using Arduino, XBee module and micro sensor technologies for monitoring and storage data on a web portal in real time. Nonetheless, the developed device monitored temperature & humidity, carbon dioxide (CO_2), and light only disregarding the dangerous gases polluting the hospital environment.

To summarize the discussion related to the third question, it is observed that most of the literature delineated air quality monitoring devices that did not cover all types of pollutants concerning the hospital facilities and focused on only two or three pollutants [14, 35–37]. The monitoring and detection procedure for the harmful pollutants should be identified in the hospital environment at a very early stage through buzzer alarm or E-mail/ Short Message Service (SMS) to avoid heavy losses in critical places that cannot bear the presence of pollutants, particularly at surgical or emergency rooms in hospitals [15]. However, the previous studies did not consider these aspects.

In these contexts, the third question matches the second question as follows: "***Which pollutants can affect IAQ and are highly recommended in hospital facilities and services?***".

The increasing levels of pollution pose a significant threat to environmental systems. As indicated in the academic literature, the important pollutants that highly affect the IAQ in hospital facilities are discussed in a scattered way. Therefore, the current study presents the pollutants types in detail along with the latest published studies. The unsafe gases affect the hospitals and contribute to degrading air quality producing harmful gases, namely, sulphur dioxide (SO_2) which cause headaches, dizziness, restlessness, a tingling feeling in nose, difficulty in breathing, sweating, tiredness, increased heart rate, elevated blood pressure, coma, asphyxia, and convulsions *etc*. Similarly, CO_2 produces skin irritation and wears out mucous membranes of the eyes, nose, throat, and lungs. High concentrations of SO_2 can affect lung function, worsen asthma attacks, and worsen existing heart disease in sensitive groups [10]. Consequently, the academic literature has increasing concerns on many other primary pollutants [11–13], for example particulate matter, CO, benzene, formaldehyde, O_3, VOC, and NO_2 as presented in Table 1. However, no study has identified all these pollutants simultaneously in one system or device for monitoring and detecting IAQ in hospitals facilities. Thus, studies on unified numbers and types of pollutants for the hospitals environment are limited, particularly, this concept is confusing, inconsistent and detrimental to the field of IAQ studies in the health sector. Various pollutants greatly influence the air quality and cause adverse health conditions within hospital facilities. Focusing on specific pollutants and missing others leads to poor air quality, which could affect the development of health system. Resultantly, air quality guidelines should follow the global guidance on thresholds and limited to key air pollutants that pose health risks.

Moreover, the opinions and standards of relevant organisations recommend other pollutants to be taken into account in the field of IAQ for the hospital environments and this increases the complexity of the task. The WHO [38] has tightened air quality guidelines, warning that air pollution is one of the most important environmental threats to human health. They reported the most common indoor air pollutants and the health risks associated with exposure them. EPA ("Criteria Air Pollutants US EPA"), identified six common air pollutants (also known as "criteria air pollutants") that can harm health and the environment, and cause property damage. Finally, the ISO [39] also provided the standards against pollution for the surgery room in hospitals.

Therefore, this study is conducted to determine the level of satisfaction and effectiveness of IAQ in hospital facilities. The investigation of pollutants is based on the integration of recommendations carefully collected from the reliable organizations and academic literature available which helped profusely in bridging this gap. A step-by-step guide to getting more out of the common IAQ pollutants collected from the academic literature with respect to the three organisations are presented in Table 1. Besides, this congruity of information confirms that how the three organisations recommended the same common pollutants in each study. Consequently, the proposed new monitoring and detection IAQ system as a solution is discussed as demonstrated in our study framework in Fig. 1 .

This study painted the right direction for monitoring and detecting the IAQ indices based on IoT sensors technology for hospital facilities and services. The monitoring of the recommended pollutants in this paper has been accomplished by using the required sensors technology, and tested to ensure its conformance to the recommended pollutants by collaborating with surgeons and specializing in IAQ in a hospital SICU, ED, and in the women's ward, which accommodate patients who are either newly born mothers (in case they need that) or who have had an operation, as well as pregnant patients who need to stay in the hospital to be under the supervision of medical care. The detecting process is conducted by depending on pollutants thresholds to supply services in the event of exceeding the thresholds.

This study has multifaceted contributions and novelties given below:

1. It identifies and collects the nine pollutants and their thresholds that affect the air quality within the hospital facilities and services to be used for assessing the effectiveness of the amount, concentration, and diversity of the pollutants. Their identifications are recommended by a standard and reli-

TABLE 1. Common IAQ pollutants founded on literature and organization recommendation.

Common Pollutants/Parameters in SICU&ED	Used by literature studies	WHO recommendation	EPA recommendation	ISO recommendation
Temperature & Humidity	[1], [3], [10], [11], [30], [35], [40–44]	√		
Particulate Matter	[11], [24], [34], [35], [37], [41–44]	√	√	√
CO_2	[3], [10], [24], [30], [40–42], [44]			
CO	[3], [24], [36], [40]	√	√	
Benzene	[36]	√		
Formaldehyde	[40]	√		√
PAH	Not Mentioned	√		
Radon	Not Mentioned	√		√
O_3	[14], [24], [35]	√	√	
NO_2	[14], [24], [35], [42]	√	√	
SO_2	[10],[35]	√	√	
VOC	[1], [24], [40], [42], [44]			√
asbestos	Not Mentioned			√
ETO	Not Mentioned			√
Lead (Pb)	Not Mentioned		√	
Hydrogen peroxide	Not Mentioned			√

SICU: Surgical intensive care unit, ED: Emergency department, WHO: World health organization, EPA: Environmental protection agency, ISO: International organization for standardization, CO_2: Carbon dioxide, CO: Carbon monoxide,PAH: Polycyclic aromatic hydrocarbons, O_3: Ozone, NO_2: Nitrogen dioxide, SO_2: Sulfur dioxide, VOC: Volatile organic compounds, ETO: Ethylene oxide, Pb: plumbum.

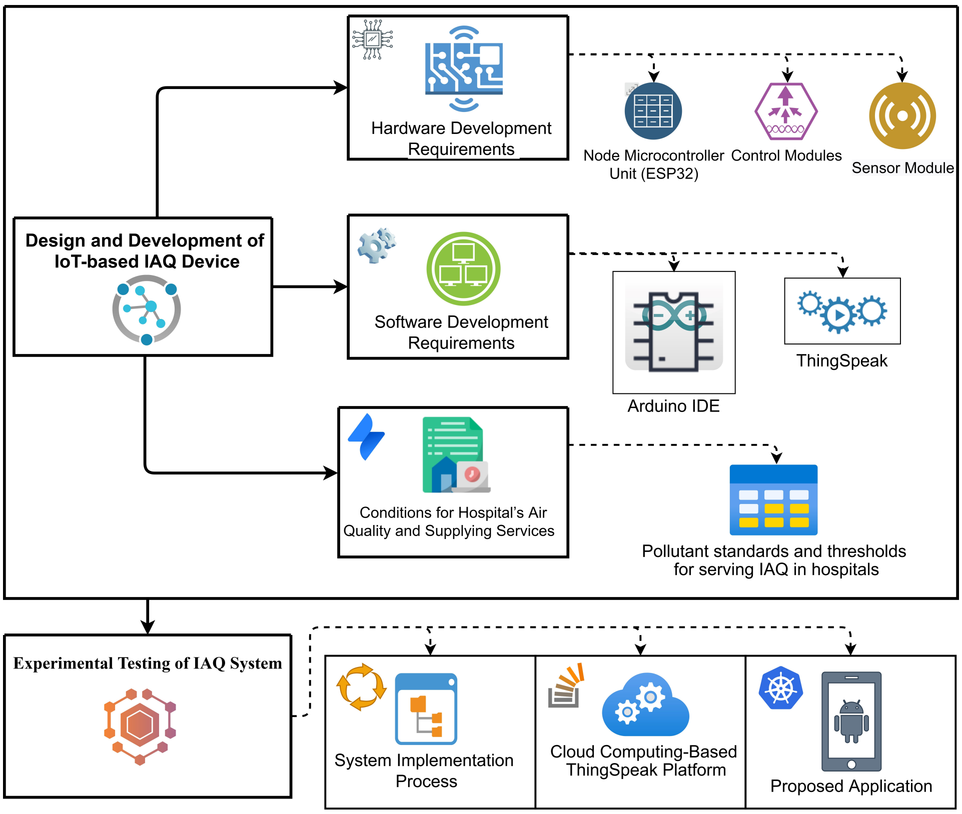

FIGURE 1. Conceptual framework for the development of a real-time monitoring and detection IAQ system.

able organizations (*i.e.*, WHO, EPA and ISO) and the academic literature.

2. It designs and develops a new IoT-based IAQ device for hospital facilities and services especially dedicated to the SICU and ED.

3. It helps implement and test a new monitoring and detection system for IAQ based on the developed IAQ device that satisfies hospital facilities. The experimental testing was achieved in real-time response, providing different types of IAQ services when the pollutions exceed the defined threshold values.

4. It applied correlation methods for pollutants dataset and present the strongly correlated and negatively correlation between pollutants.

5. Finally, it presents a real IAQ dataset for the public use by using the develop IAQ system.

2. Design and development of IoT-based IAQ device

Designing and subsequent implementation of real time IAQ monitoring system for hospitals facilities is a crucial need of the time. Several published studies report the lack of air quality control in SICU as a key factor for surgical site infections following the most common general surgery procedures [45]. The development of the IAQ for hospitals facilities is presented in this study through three sequence sections, *i.e.*, hardware development requirements; software development requirements; and conditions for hospital's air quality and supplying services. Besides, this section presents the complete technical solution to develop an IAQ monitoring system based on IoT device for hospitals facilities (*i.e.*, ED, SICU and other hospital sections). The first section (2.1), identifies and aggregates the IoT sensors and components that are developed and designed for monitoring the air quality of the hospital environment. The second section (2.2) discusses software used to code the developed device, as well as the cloud platform on which the data was uploaded. Finally, the third section (2.3) supplies the services of the proposed device that are provided in comparing the pollutants value (dataset) with their thresholds and is also detects whether any pollutant values exceed the acceptable limit from threshold.

2.1 Hardware Development Requirements

This section explains the hardware components used in the already developed device. It includes subsections node Microcontroller unit (MCU), the sensor module, and control modules. Fig. 2 shows the schematic diagram of the components used in the developed device.

As it can be seen in the Fig. 2 above, each pin of the sensor's output has been connected to the ESP32 analogy or digital pins according to the sensor data output type. In sub sections below, each component of the proposed device will be explained in details.

2.1.1 Node Microcontroller Unit (ESP32)

[1]

A low-cost ESP32 is used to handle all of the sensors and other components of the developed system. The used sensors are operated better with a 5 Volts direct current (VDC) power supply and the sensors' output voltages range from 0 to 5 volts. In addition, ESP32 is a capable SoC (System on Chip) microcontroller with integrated Wi-Fi and dual-mode Bluetooth. It is an improved chip that principally consists of two cores clocked at various speeds up to 240 MHz—a fine successor to the 8266 which was widely utilized in the studies [20, 35]. Apart from these improvements to develop the new device with the required number of sensors, ESP32 also increases the number of general purpose Input/Output (GPIO) pins from 17 to 36 and includes 4 MB of flash memory [46].

2.1.2 Sensor Modules

This section presents the seven low cost and reliable sensors used to monitor the nine IAQ pollutants in hospital's facilities. Each sensor is used to measure one pollutant; except for two sensors that can measure more than one pollutant as explained below. All of these sensors can be remotely monitored.

- GP2Y1014AU0F sensor[2]: this sensor is used to measure air particulate matter. Sharp optical dust sensor has an internal infrared diode and a phototransistor diagonally arranged. The light is projected by the diode, and the dark spots created by passing tiny particles are detected by the phototransistor.
- DHT11 sensor[3]: in order to measure humidity and air temperature in the environment, the DHT11 sensor provides a varying function of detecting two digital output pollutants (air temperature and humidity) [47].
- MiCS4514 sensor[4]: this sensor is used to measure two pollutants (CO and NO_2). This sensor consists of a metal oxide sensor (MOS) that measures output of resistance (kΩ) corresponding to the real gas concentrations. Two sensor chips with separate heaters and metal oxide layers respond to either reducing (RED) or oxidizing (OX) gases included in the MiCS-4514. The resistance of the RED sensor chip decreases in relation to CO gas, while the resistance of the OX sensor chip increases in relation to NO_2.
- MQ131 sensor[5]: it is durable, low cost, and a heating semiconductor type sensor highly sensitive to ozone pollutant. The sensitive material in this sensor is tin oxide. This sensing layer, together with an embedded heater, is built on the alumina substrate of the sensor chip. Because semiconducting oxides are sensitive to vapor and other substances, the heater needs some time to warm up.

[1] ESP32 Datasheet: https://cdn.sparkfun.com/datasheets/IoT/esp32_datasheet_en.pdf
[2] GP2Y1014AU0F Datasheet: https://www.sparkfun.com/datasheets/Sensors/gp2y1010au_e.pdf
[3] DHT11 Datasheet: https://www.mouser.com/datasheet/2/758/DHT11-Technical-Data-Sheet-Translated-Version-1143054.pdf
[4] MiCS4514 Datasheet: https://www.sgxsensortech.com/content/uploads/2014/08/0278_Datasheet-MiCS-4514.pdf
[5] MQ131 Datasheet: https://www.sensorsportal.com/DOWNLOADS/MQ131.pdf

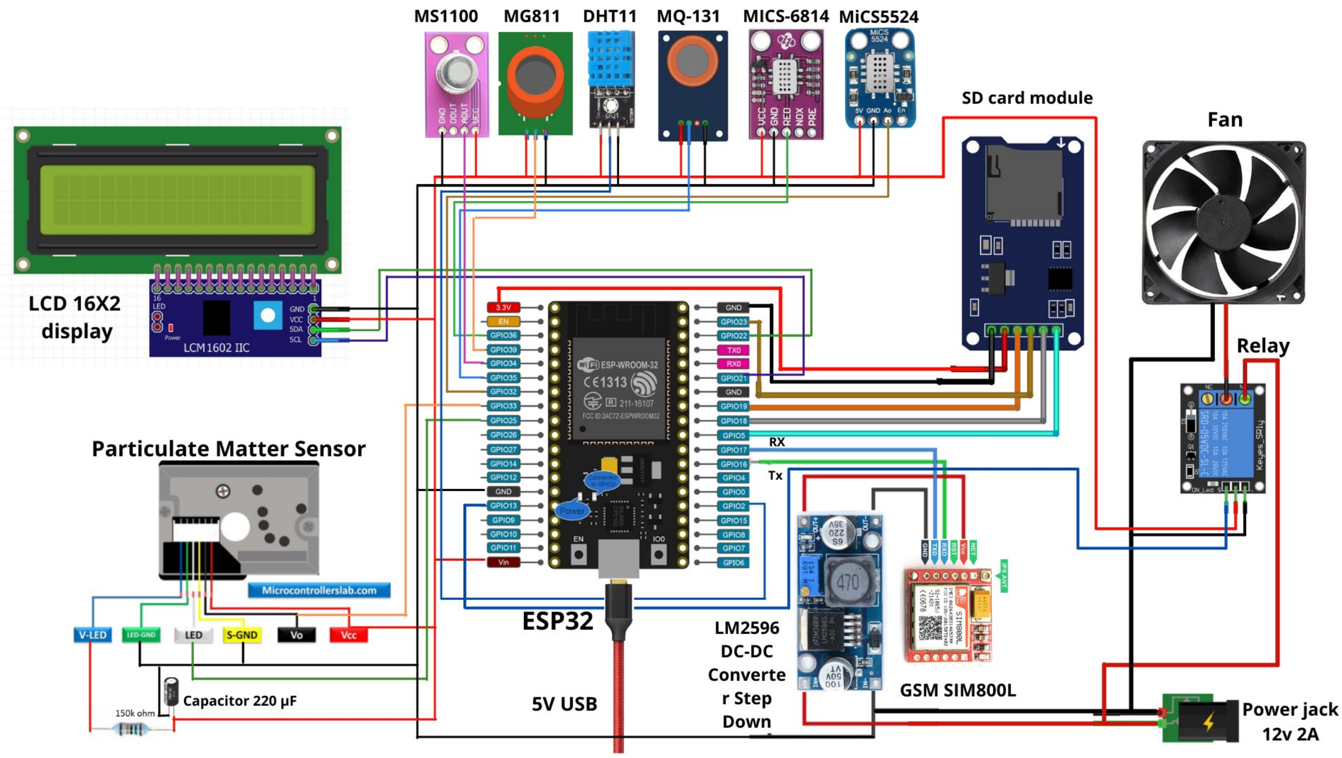

FIGURE 2. Schematic diagram of developed IoT-based IAQ device.

- MICS5524 sensor[6]: is a robust sensor for detecting indoor natural gas leaks, dedicated to volatile organic compounds (VOC). This sensor is sensitive to: CO (1 to 1000 ppm), Ammonia (1 to 500 ppm), Ethanol (10 to 500 ppm), H_2(1–1000 ppm), and Methane/Propane/Iso-Butane ($\approx$ 1000++ ppm). However, it cannot apprise about the gas it has detected; instead, it can only provide a single output (VOC).
- MG811 sensor[7]: is an electrochemical Arduino-based CO_2sensor with an integrated heating circuit that maintains the sensor's optimal operating temperature. To get the maximum performance out of the sensor, the internal power has to be increased to 6 V. It has high sensitivity and good selectivity for carbon dioxide and rapid response with durability and reliable stability. The sensors tested the concentrations of carbon dioxide in the range of 0 to 10,000 ppm.
- MS1100 sensor[8]: this sensor is mainly used for the detection of formaldehyde, with high sensitivity and stability. It is suited for detecting the gas concentration range from 0 to 1000 ppm and it includes an light-emitting diode (LED) to show if the gas concentration exceeds the zero limit [48].

2.1.3 Control Modules

This section presents the modules of the hardware accessories and other components that were used in the developed device to complete the hardware configuration of monitoring and controlling the pollution.

- GSM module[9]: The SIM800L is a small cellular module that supports general packet radio service (GPRS) transmission, as well as sending and receiving SMS. This module's low cost, small footprint and quad-band frequency support make it ideal for any project requiring long-range connectivity. After connecting the power supply, the module immediately starts up the search for a cellular network and logs in automatically. The status of the connection is shown via an onboard LED (no network coverage-fast blinking, logged in-slow blinking) [49]. By this module, the system gives a notification about the air quality when it exceeds a permissible level through SMS.
- Relay module[10]: a relay is an electrically operated switch that can be turned on or off, allowing/disrupting current flow, and is controlled with low voltage. 3.3 V is used to power relay modules, making it perfect for the used ESP32. This module was utilized to turn on and off the ventilation fan in the developed device.
- Ventilation fan: a 12-VDC fan is attached (as a proof of concept) to the relay module to be controlled by the ESP32 in case any of the detected gases is above the normal level. The system is used to make useful decisions about ventilation depending upon the threshold level of air quality parameters (see Table 1). The ventilation fan operates when any sensor value exceeds the moderate range of thresholds [50].

[6] MICS5524 Datasheet: https://cdn-shop.adafruit.com/product-files/3199/MiCS-5524.pdf
[7] MG811 Datasheet: https://sandboxelectronics.com/files/SEN-000007/MG811.pdf
[8] MS100 Datasheet: https://www.datasheet4u.com/datasheet-pdf/ETC/MS1100/pdf.php?id=813046
[9] GSM module Datasheet: https://datasheetspdf.com/pdf-file/989664/SIMCom/SIM800L/1
[10] Relay module Datasheet: https://datasheet.octopart.com/MAX4822ETP%2B-Maxim-datasheet-8430178.pdf

- LCD screen16x2: LCD module is very commonly used in most embedded projects. It is an alphanumeric LCD display module, which can show both letters and numbers. It contains 16 columns and 2 rows, resulting in a total of ($16 \times 2 = 32$) 32 characters, each of which is made up of 5×8 pixel dots. As previously illustrated in Fig. 2 , this module was used to display the levels of the pollutant (L, M, H) based on a threshold of each pollutant (See Table 1)).

- SD card module[11]: to record the data obtained from the different sensors, an SD card module is used to save the data on a memory chip, which can be used later for analyses. By using the SD card module, the risk of losing data due to loss of internet connection inside the hospital can be avoided that is not being able to be uploaded to ThingSpeak servers. Also, the "thingspeak.com" server can save data for a short period of time while the data on the memory chip can be stored up to several months.
- Step-Down Voltage Regulators[12]: when using this board, the input voltage always must be higher than the output voltage. The step-down DC/DC (direct current) conversion involves the time-division of a DC voltage. It is capable of driving a 3.0 a load with excellent line and load regulation. Its input voltage range is 4–35 V and can get an output voltage adjustable between 1.25–30 V via the trimpot on the board.

Power Supply: the developed device is meant to be operational for long working hours and the problem of electricity shortage can be an issue, so an uninterruptible power supply (UPS) is used to power up the device. The power supply can last up to 5 hours.

2.2 Software development requirements

To accomplish applying the IoT for the proposed system, software requirements need to be present and explained. This section discusses the software program that was used for coding the developed device, as well as the cloud platform on which the data was uploaded.

- Arduino IDE: the open-source Arduino software (IDE) makes the monitoring and control processes easy to write code and upload it to the board. This software can be used with any Node MCU board (*i.e.*, ESP32). Full and comprehensive instructions for installing this software on Windows, Linux, and Mac computers can be found at the Arduino website[13]. In addition, the required libraries are installed to complete the software implementation process, for example WiFi.h, HTTPClient.h, Adafruit_Sensor.h, DHT.h, and SD.h.
- ThingSpeak: This open-source IoT platform enables collecting visualizing, and analyzing the monitoring of pollutants' data that has been used in the software process of the developed system. The main component of ThingSpeak in the developed system channel is to store data sent from the used sensors. After creating a ThingSpeak channel, the pollutants' data can be published to the channel, and then it can be processed. Also, the channel can be made public which can be seen by other users or private who need the API key to view the pollutants' data.

2.3 Conditions for hospital's air quality and supplying services

The threshold of pollutants' values collected in the present study (according to Table 1) should be considered to determine whether the air quality indices exceed safety thresholds or not [24]. Therefore, this section is integrated with threshold values to ensure that the IAQ is within the acceptable range or not [3]. In addition, the detection process closely takes appropriate action after handling the monitoring context of the pollutions based on the threshold value. Accordingly, in hospital facilities, various sections (wards) should utilize the detection process in their daily work. Serious concerns about hospital facilities, such as medications, chemical compounds, volume, concentration and diversity of contaminants, exist, and each element has a special threshold limit that can affect patients and medical staff by increasing the complexity of the detection context for IAQ [6]. Thus, the acceptable and critical (poor) levels of pollutant concentrations must be determined for each ward in the hospital to support the detection process. Table 2 shows the pollutants threshold for IAQ established and extracted from the literature which depended on international standards and extracted from WHO organization guidelines in healthcare facilities [22, 24].

As shown in Table 2, each pollutant has its threshold range among three levels: "Acceptable" for the ideal value; "Moderate" for the medium danger; and "Poor" for the risky value of pollutants.

In this section, the detection and control processes are carried out when any pollutant exceeds the acceptable threshold within the workflow process (See Fig. 3). After that, the value of the pollutant is determined within any range of the threshold. If it is within the acceptable limit, the name of the pollutant will be displayed on the liquid crystal display (LCD) with "L". If the pollutant value is greater than the acceptable limit and within the highest threshold range (poor); SMS "Warring pollutant Concentration is a High !!", will be sent to the administrator, and it will display as "H" on the LCD in front of the pollutant's name, indicating that it is within the high category of pollution, and the fan will turn on. If the value of the pollutant is within the second range (Moderate), SMS "pollutant Concentration is a Medium !!" will be sent to the administrator, the fan will turn off and it will display "M" on the LCD in front of the pollutant's name.

3. Experimental Testing of IAQ System

Experimental efforts have focused on the implementation of the IoT-based IAQ monitoring and detection system. Calibration of the seven sensors used in the proposed device was utilized to determine the error value of each sensor. After the

[11] SD card Datasheet: http://datalogger.pbworks.com/w/file/fetch/89507207/Datalogger%20-%20SD%20Memory%20Reader%20Datasheet.pdf
[12] Step-Down Voltage Regulators Datasheet: https://www.onsemi.com/pdf/datasheet/lm2576-d.pdf
[13] The Arduino website is: https://www.arduino.cc

TABLE 2. Pollutant standards and thresholds for serving IAQ in hospitals.

Common Pollutants/Parameters for SICU & ED	Pollutant Threshold		
	Acceptable	Moderate	Poor quality
CO_2	400–800 ppm	800–1500 ppm	>1500 ppm
Particulate Matter	<50 mg/m^3	50–100mg/m^3	>100 mg/m^3
Temperature	21–26 °C	-	High temperature: 27–40 °C
Humidity	30–50%	<30% or 50–100%	-
VOC	0–400 ppb	400–800 ppb	>800 ppb
CO	<35 ppm	35–70 ppm	>70 ppm
NO_2	<100 ppb	100–250 ppb	> 250 ppb
Ozone	<30 ppb	30–70 ppb	>70 ppb
SO_2	0.5 ppm	0.6–0.99 ppm	1 ppm
Formaldehyde	>100 μg/m^3	-	-

SICU: Surgical intensive care unit, ED: Emergency department, CO_2: Carbon dioxide, VOC: Volatile organic compounds, CO: Carbon monoxide, NO_2: Nitrogen dioxide, SO_2: Sulfur dioxide.

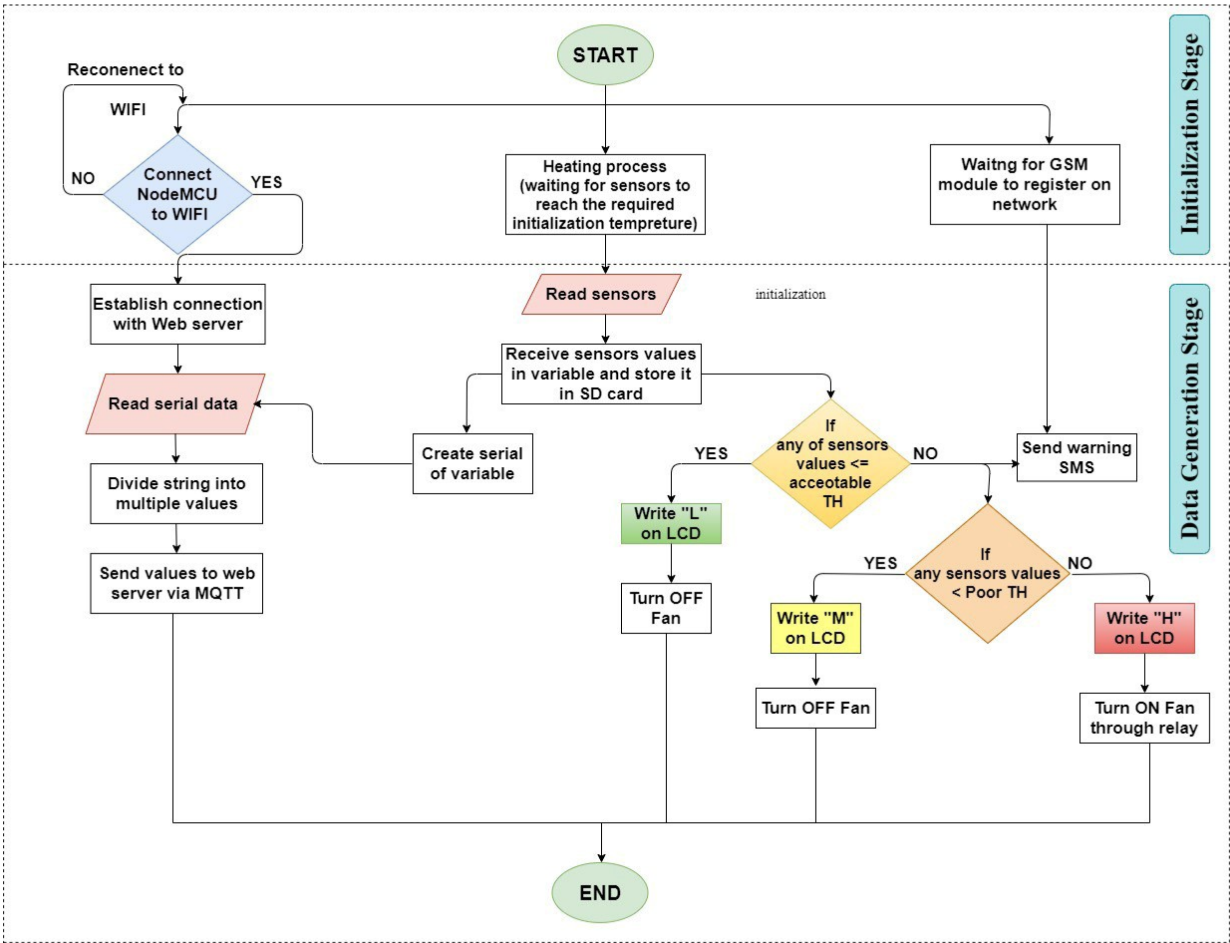

FIGURE 3. Configuration diagram for the IoT-based IAQ monitoring and detection system.

responsivity is obtained through calibration or factory specifications, the target gas concentration can be calculated with the responsivity and the current readout. The device was installed in the Al-Imamine Al-Kadhimin Medical City Hospital Baghdad, Iraq, to test the feasibility of the system in three hospital's facilities: the SICU, the women's ward, and the pharmacy of ED. The experimental testing of IAQ system started with: firstly; the system implementation process to explain how the device turning on and explain the workflow stages, secondly; cloud computing-based ThingSpeak Platform to upload and visualize pollutants data, and finally; the proposed application to monitor and control pollutions indices, and supplying the appropriate services when the pollutants exceed the threshold values.

3.1 System Implementation Process

The flow chart of the workflow process of the proposed system is explained in Fig. 3. START means turning on the device. Once the device is powered there are two kinds of stages which can be illustrated to relate the implantation process.

The first stage (initialization) takes several seconds to be carried different processes that are carried on parallelly, where the microcontroller ESP32 is connected to the Wi-Fi network, and some sensors at the beginning of their operation must complete the mandatory heating process, *i.e.*, up to MiCS4514 in which this type of sensor includes a heating circuit to achieve the best temperature. Meanwhile, the GSM is registered to the network. After the initialization stage is completed, the microcontroller ESP32 establishes a connection with the personal channel of the ThingSpeak cloud platform. The sensors start sending data for each pollutant, and these readings are stored locally on the SD card, and at the same time, data packets are sent to the server via message queuing telemetry transport (MQTT) protocol.

Simultaneously, with the second stage (the data generation stage) the data from each sensor is compared with its threshold (See Table 2). If the sensor value is within the acceptable threshold range for the pollutant, the LCD screen displayed L for this pollutant, meaning that it is within the Low value (acceptable threshold). If the reading value of the sensor is higher than the acceptable thresholds, the GSM will send a warning notification as SMS message. Also, the sensor value will be compared, if the data value of each pollutant is within the poor threshold, the relay will turn on, and then the fan operates. The LCD screen displays H for this pollutant, meaning that it is within the High threshold. But, if the reading of the pollutant value is within the moderate threshold, the LCD screen displays M for this pollutant, meaning that it is within the Moderate threshold, and at the same time the fan is turned off. Finally, the END means that the record (data row) has been completed for the nine pollutants and compared each pollutant within its threshold, by repeating all the previous steps (without going through the initialization stage).

3.2 Cloud Computing-Based ThingSpeak Platform

The cloud computing-based ThingSpeak platform was enabled after installing the IAQ device to analyze the uploaded data and to visualize the IAQ data for the system. The cloud server platform of ThingSpeak in this research is shown in Fig. 4. The data from the developed device was measured from each sensor and displayed on the platform. The platform provided a datasheet and graphs for the current set of stored data within measured times that can be extracted for review. Furthermore, the data were visualized as gauges, numeric displays, and/or graphs based on the current air quality. The graph can illustrate the visualization by changing the pollutant's value. The platform stores the air quality data in the database of the ThingSpeak server to be reviewed when needed. As a result, the manager can take necessary action to improve the air quality.

To remotely monitor air quality, a mobile application can be proposed after the ThingSpeak Platform was activated. Additionally, when the specific types of air pollutants are selected the detailed monitoring of the pollutants can be made available based on a real-time graph. However, for the current state of the proposed application, the user can be alerted through a pop-up message when the condition of the air pollutant is moderate or poor. In this case, appropriate actions should be undertaken to supply different types of services when the pollutions exceed the threshold values, indicating that IAQ is poor. Sending an alert message via Short Message Service (SMS) has been the most frequent service used so far. Nevertheless, various other services can also be provided using mobile applications for monitoring and detecting the required pollutions, as mention previously in Fig. 3 . The proposed device includes many services (sending SMS, operate ventilation fan) depending on the specific range of threshold.

4. Results and Discussion

The goal of the experiment was to perform an initial implementation of the system to monitor and detect IAQ. The proposed system wirelessly transmitted the detected data to the cloud platform, which successfully detected the condition of IAQ and displayed it via both the web and the application and supply appropriate warning services. This section presents the results and discussion of the IoT-based IAQ monitoring and detection system in the hospital facilities. Fig. 5 is shown the final design of the developed IoT-based IAQ device installed in the 1st location SICU.

The device was entered into the SICU immediately at the end of the surgery, so the first readings made on the device were the ones received during the sterilization period before the next surgery. The concentration of some pollutants was high in the beginning due to the residues of the previous surgery and because of the frequent use of sterilizers to clean and prepare the SICU. A few minutes later before the commencement of the surgery, the concentration of pollutants was moderate, nevertheless, an increase in CO_2 and Formaldehyde was observed, exceeding the threshold limit as shown in Fig. 6 .

Another installation fixed at women's ward, which consists of (three lounges: 1st, 2nd, and 3rd), each lounge consists of 10 beds, showed moderate concentrations generally, except for particles matter PM2.5 as shown in Fig. 7, vis-a-vis the concentrations at the SICU where the concentrations of ozone and humidity were lower than the former, although they did not exceed the threshold.

Similarly, the 3rd installation located in the pharmacy of ED, indicated that most concentrations were moderate, except formaldehyde, which exceeded the threshold. Fig. 8 shows the proposed device in the third location of the emergency pharmacy.

Accordingly, during the above workflow the data were transmitted to the cloud platform in which the numbers of records for the collected dataset were reaching 550 and each record represented the nine pollutants data values within a period of time ($\approx$ 15 seconds) between each record. So, each record is representing the current IAQ status in the place that the IoT-based device is located in within that period of time. Besides, the dataset was also saved locally in SD card of the developed device. The overall result of the collected IAQ dataset is

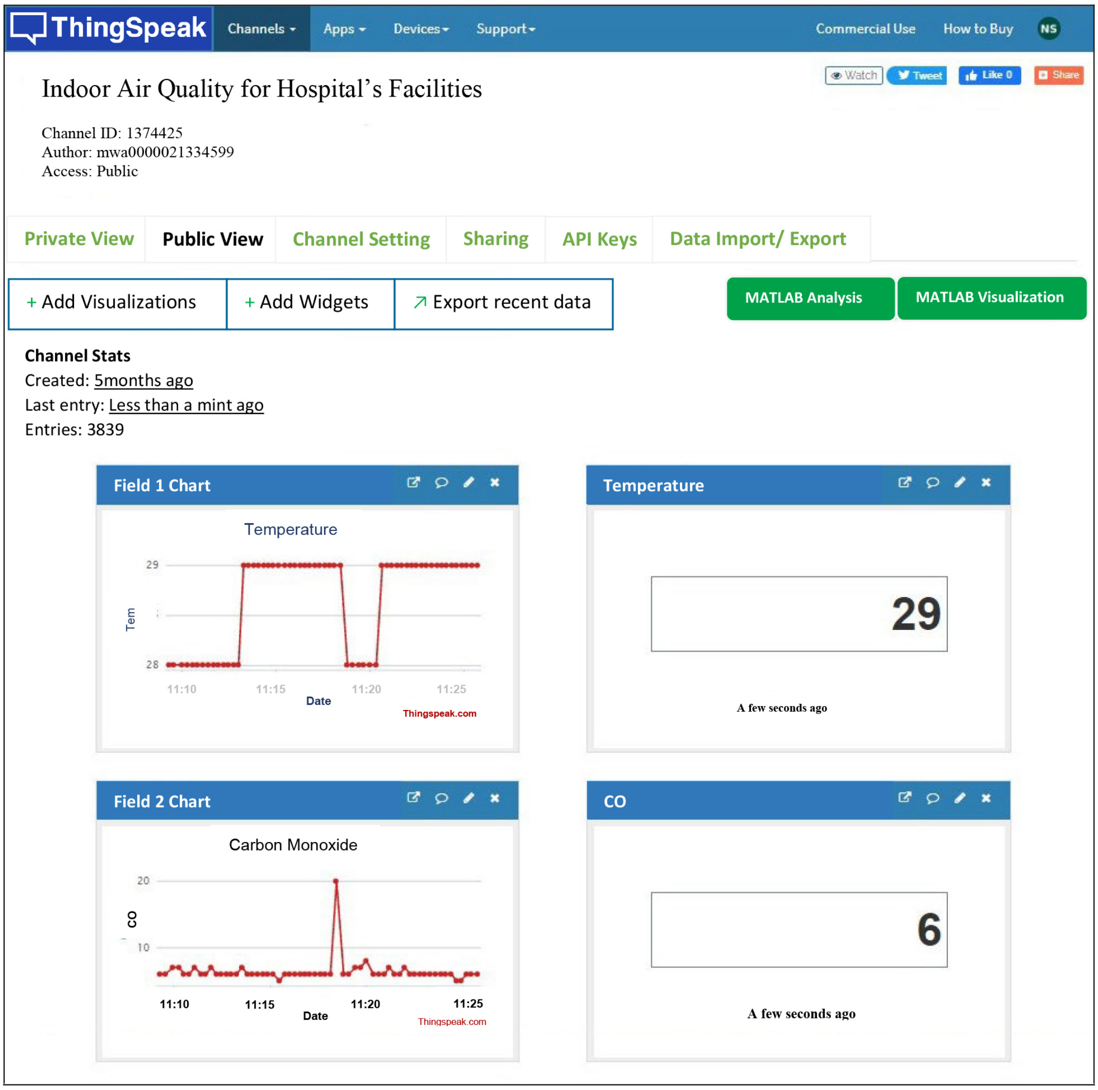

FIGURE 4. Channel of ThingSpeak cloud platform for this research.

FIGURE 5. The developed device installed in the surgery room.

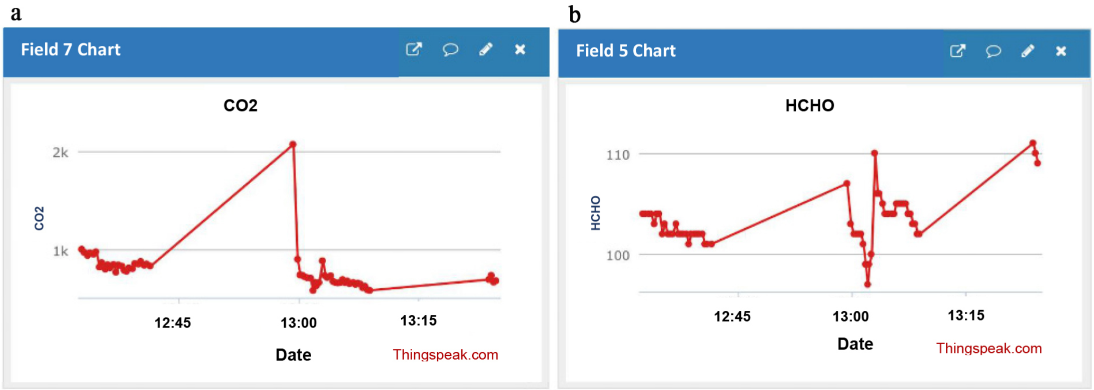

FIGURE 6. Two monitoring charts of the proposed system (CO_2), (Formaldehyde). (a) CO_2 chart from ThingSpeak Cloud platform, (b) Formaldehyde chart from ThingSpeak Cloud platform.

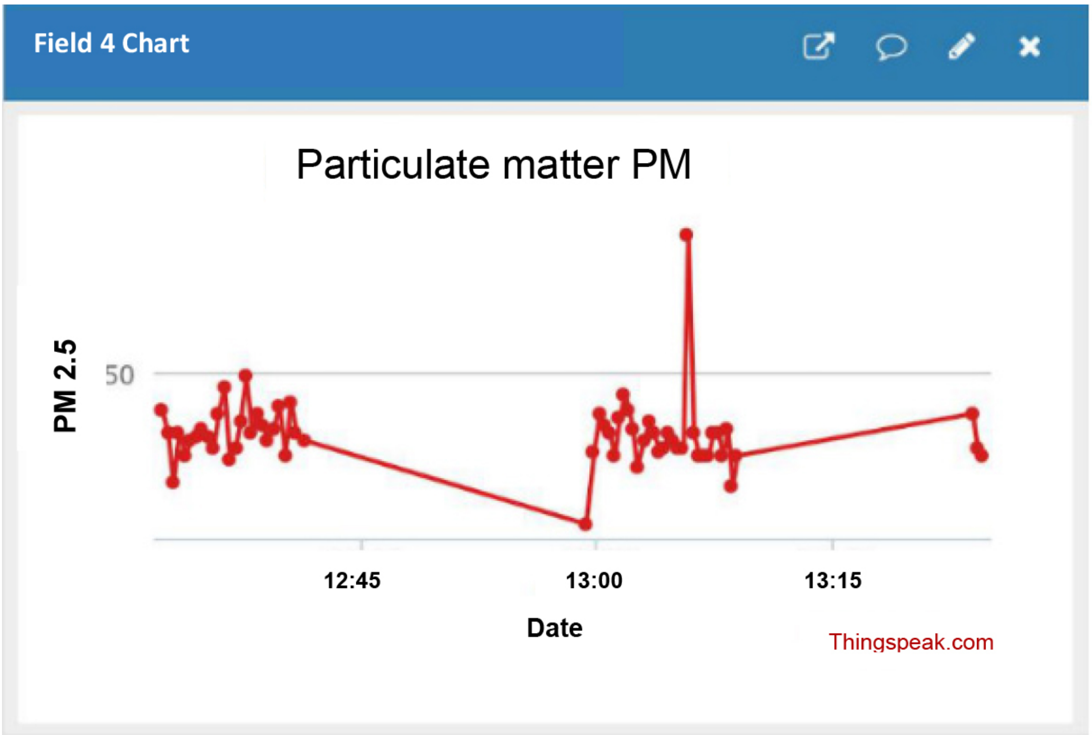

FIGURE 7. PM2.5 chart from ThingSpeak platform.

presented in the **Supplementary Table 1**.

There is variation in the pollutants data (**Supplementary Table 1**) depending on the location of the device and the condition in that location. Appropriate actions were undertaken to supply different types of services during testing the developed device because the pollutions level exceed the threshold values, indicating that IAQ is either high or moderate. Also, the proposed device would alert the administrator when pollutants rise above the acceptable threshold according to the conditions for hospital's air quality (Table 1) by sending an SMS notification. As shown in Fig. 9 , when pollutant reached the moderate range, the system notified the administrator by sending: "Concentration of pollutant n at medium level!" While, when the pollutant reached the poor range; the system notified the administrator by sending: "Warning Concentration of pollutant n at high level!".

Another solution indicated for reducing and controlling air pollution as executed in the proposed system is ventilation fan service. When the pollutants exceed the poor threshold, the proposed system provides an indicator service and turn on the ventilation fan to assist in the circulation of indoor air, eliminating stale air that can accumulate in hospital's facilities. However, ventilation fans may only be beneficial if they are properly operated, and the best way to ensure this is to program its operation through the relay (see Fig. 3). The system has been programmed when any pollutant reaches the poor threshold level to operate the relay, and thus the fan is turned on, and after the pollution level drops to the moderate or acceptable threshold, the relay turns off and the fan stops.

4.1 Correlations Analyses Results

The correlation methods have been applied to compute Spearman's correlation coefficient (r) scores for all pairs of pollutants applied only on the preprocessed real pollutants dataset

FIGURE 8. The developed device installed in emergency pharmacy.

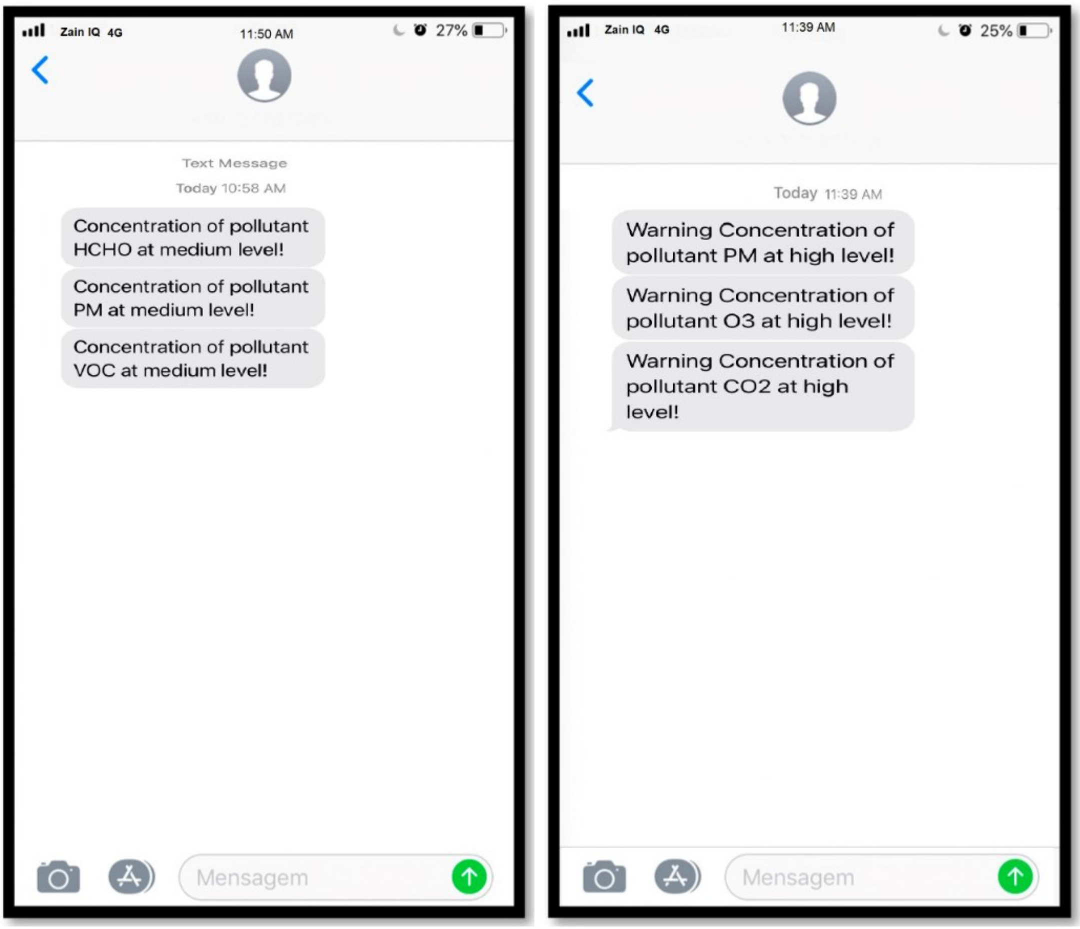

FIGURE 9. SMS notifications from the system.

TABLE 3. Correlation results for pollutants dataset.

Seq.	Pairs of Pollutants/Parameters		r value
1	CO	NO_2	+0.997
2	CO_2	NO_2	+0.926
3	CO	CO_2	+0.925
4	HCHO	O_3	+0.799
5	CO_2	Temperature	+0.772
6	NO_2	Temperature	+0.726
7	CO	Temperature	+0.717
8	Humidity	Temperature	+0.613
9	CO_2	O_3	+0.608
10	CO_2	HCHO	+0.566
11	CO	HCHO	+0.537
12	CO	O_3	+0.53
13	CO_2	Humidity	+0.52
14	HCHO	NO_2	+0.52
15	NO_2	O_3	+0.513
16	Humidity	NO_2	+0.372
17	CO	Humidity	+0.36
18	O_3	Temperature	+0.321
19	Humidity	VOC	+0.317
20	CO_2	PM	+0.289
21	CO	PM	+0.262
22	NO_2	PM	+0.259
23	CO	VOC	−0.233
24	NO_2	VOC	−0.233
25	HCHO	Temperature	+0.233
26	O_3	PM	+0.226
27	PM	Temperature	+0.184
28	HCHO	VOC	+0.156
29	HCHO	PM	+0.148
30	Humidity	O_3	+0.137
31	HCHO	Humidity	+0.131
32	Humidity	PM	+0.128
33	CO_2	VOC	−0.048
34	PM	VOC	−0.046
35	O_3	VOC	+0.041
36	Temperature	VOC	−0.014

CO: Carbon monoxide, CO_2: Carbon dioxide, HCHO: Formaldehyde, NO_2: Nitrogen dioxide, O_3: Ozone, PM: Particulate Matter, VOC: Volatile organic compounds.

which includes 550 records. In this context, the correlation sensitivity analysis can exam the impact of nine affected pollutants with each other and detect how they strongly correlated. These methods can detect monotonic relationships all pairs of pollutant. The aim of these analyses is to detect existing marked linear relationship between all pairs features [51]. Spearman's correlation coefficient method (r) [52] can be used because of its advantage to give the strength and direction of the monotonic relation between the connected features. Table 3 presents the results of the correlations with (r) values assigned for each pair of pollutant applied on pollutants dataset.

Table 3 shows that "CO" is the highest positive correlated and strongly correlated to "NO_2" with values of (+0.997) and that was expected because CO influences the oxidation of NO to NO_2. Besides, "CO_2" is also strongly related to "NO_2" with a value of (+0.926), and the "CO" is also strongly related to "CO_2" with values of (+0.925) because CO is co-emitted with CO_2 from combustion sources, leading to a significant positive correlation between them when combustion is a significant source of observed CO_2. On the contrary, the "CO" has the highest negative correlation with "VOC", and the "NO_2" has the highest negative correlation with "VOC" with the values of (−0.233). Besides, "CO_2" has a negative correlation with "VOC" with the values of (−0.048). Chemistry is part of the responsibility for the weak correlation observed between the pollutants.

5. Conclusion

According to our research results, little attention has been provided to present an IAQ system or devices that combined all important and required pollutants for hospital facilities. Thus, no dataset for IAQ considered these pollutants. The present study has gone far in characterising the monitoring of air quality either in monitoring indoor hospitals, in certain units, such as waiting area, emergency room, outpatient pharmacy, and endoscopy units. Unfortunately, no distinctive features that can supplement IAQ studies are recognised for handling precise monitoring and detecting techniques for the hospital surgery room because it is the most important unit in the hospital and is the most sensitive area to pollutants. In this case, investigation of the existing technologies, sensors, hardware, and systems for monitoring, detection, and controlling of IAQ in the hospital environment is integrated for the first time. The design and development of a new system that follows IAQ methodology phases is an essential requirement in a hospital environment and can be dedicated to different locations, such as surgery rooms, women's ward, and emergency pharmacy or any other ward. The implication of this study offered relevant information to practitioners, the healthcare sector, and environmental engineers about the processes involved in the assessment of IAQ. The impact of the implementation of the developed device is to create a large effect to enhance the IAQ in hospitals and their facilities and to provide an optimal environment for hospital occupants. The proposed system's significance can be summarized as follows:

1. Beneficial to improve health outcome: Temporary or continuous monitoring of pollution in IAQ by the proposed device, effects on health problems for hospitals and their facilities can evolve to the general health.

2. Useful to prevent accidents/gas leakages: indoor gas leakage detection is important for safety. This study contributes to detecting gas leaks at an early stage due to the accuracy of sensors used, and the activation of the detection system when pollutants exceed acceptable levels.

3. Beneficial to patients, doctors and medical staff: the perfect quality of air benefits the entire health particularly, the patients and medical staff and the rest of the crew on duty. The improvement of IAQ might minimize the average time of their residence in the hospitals.

4. Useful to environment management and improvement: a monitoring cloud system could ease building management; IoT devices assist the building manager bout inappropriate operations, ensuring that the workplace is not only safe and secure but also relaxed and efficient.

AUTHOR CONTRIBUTIONS

NSB—contributed to the planning, development and editing of the manuscript, including reading and approving the final manuscript; HAM—contributed to the development and editing of the manuscript, including reading and approving the final manuscript; ASA—contributed to the development and editing of the manuscript, including reading and approving the final manuscript; all authors have read and approved the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. A. S. Albahri is serving as one of the Editorial Board members of this journal. We declare that A. S. Albahri had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to VL.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found, in the online version, at https://oss.signavitae.com/mre-signavitae/article/1496783698353111040/attachment/SV2021103001%20Supplementary%20Table%201-layout-1.doc.

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