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Research Article

Development of an IoT-Based Indoor Air Quality Monitoring Platform

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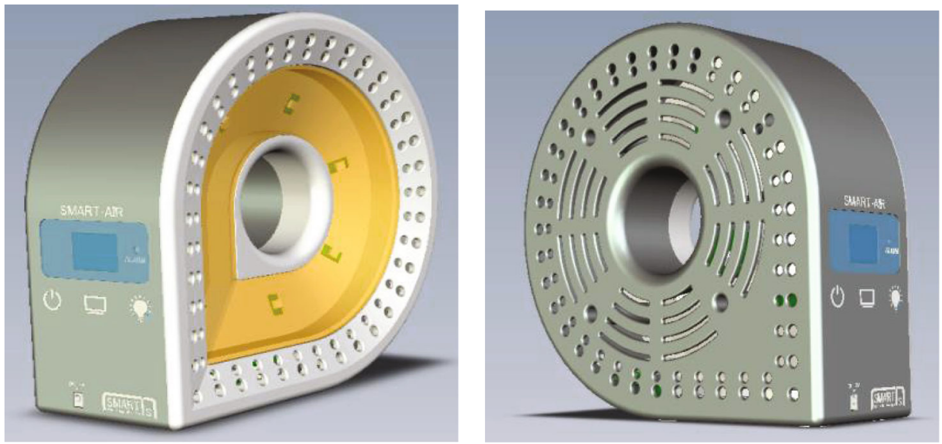
In this paper, an IoT-based indoor air quality monitoring platform, consisting of an air quality-sensing device called "Smart-Air" and a web server, is demonstrated. This platform relies on an IoT and a cloud computing technology to monitor indoor air quality in anywhere and anytime. Smart-Air has been developed based on the IoT technology to efficiently monitor the air quality and transmit the data to a web server via LTE in real time. The device is composed of a microcontroller, pollutant detection sensors, and LTE modem. In the research, the device was designed to measure a concentration of aerosol, VOC, CO, CO_2, and temperature-humidity to monitor the air quality. Then, the device was successfully tested for reliability by following the prescribed procedure from the Ministry of Environment, Korea. Also, cloud computing has been integrated into a web server for analyzing the data from the device to classify and visualize indoor air quality according to the standards from the Ministry. An application was developed to help in monitoring the air quality. Thus, approved personnel can monitor the air quality at any time and from anywhere, via either the web server or the application. The web server stores all data in the cloud to provide resources for further analysis of indoor air quality. In addition, the platform has been successfully implemented in Hanyang University of Korea to demonstrate its feasibility.

1. Introduction

Atmospheric conditions continue to deteriorate each year due to the growth of civilization and increasing unclean emissions from industries and automobiles. Although air is an indispensable resource for life, many people are indifferent to the severity of air pollution or have only recently recognized the problem [1–3]. Among various types of pollutants such as water, soil, thermal, and noise, air pollution is the most dangerous and severe, causing climate change and life-threatening diseases. According to the World Health Organization (WHO), 90 percent of the population now breathes polluted air, and air pollution is the cause of death for 7 million people every year [4, 5]. The health effects of pollution are very severe that causes stroke, lung cancer, and heart disease. Furthermore, air pollutants have a negative impact on humans and the earth's ecosystem, as observed in recent global air pollution problems like ozone depletion [6–8]. Therefore, air quality monitoring and management are main subjects of concern.

According to the United States Environmental Protection Agency (EPA), indoor air is 100 times more contaminated than outside air. Most modern populations spend 80 to 90 percent of their time indoors; therefore, indoor air has a greater direct impact on human health than outside air [9–12]. Moreover, in contrast to atmospheric pollution, indoor pollutants are about 1000 times more likely to be transmitted to the lungs, causing diseases such as sick building syndrome, multiple chemical sensitivities, and dizziness. Indoor air quality management is very important, as it can prevent exposure through proactive precautionary measures [9, 13–15]. Therefore, efficient and effective monitoring of indoor air is necessary to properly manage air quality.

To reduce exposure to air contamination (especially aerosols), new measures have been pursued, including development of air quality measuring devices and air purifiers.The



(a) (b)

Figure 1: Primitive concept design of Smart-Air: (a) front and (b) back.

Ministry of the Environment in Korea assessed the efficacy of 17 widely used air quality measuring devices by analyzing their accuracy and reliability. The result showed that only two devices provided accurate readings of indoor air quality. The other devices did not present accurate measurements of aerosol and total volatile organic compounds except carbon dioxide. According to the report, the Ministry suggests that the low reliability of indoor air quality measurement values in most devices depended on many factors such as measurement methods, device structure, and data transmission. Thus, a technologically advanced air quality monitoring platform must be developed based on an understanding of the need for more accurate monitoring devices [16].

In recent years, introduction of technologies such as the Internet of Things (IoT) and cloud computing has revealed new capabilities of real-time monitoring in various fields. Thus, many scholars have studied integrating these technologies to indoor air quality monitoring system [17–21]. However, these studies were only focused on integrating an architecture of IoT platform to monitor the air quality in real time. Since the technologies feature a wireless sensor network to automatically transmit, process, analyze, and visualize data, merging these new technologies can also offer great advantages to improve indoor air quality [22–25].

Therefore, an IoT-based indoor air quality monitoring platform based on integration of cloud computing and IoT is presented in this research. Also, a device called "Smart-Air" was developed to precisely monitor indoor air quality and efficiently transmit real time data to a cloud computing-based web server using an IoT sensor network. The cloud computing based web server introduced in this platform analyzes real-time data and adds visual effects to illustrate the conditions of the indoor air quality. In addition, the web server was designed to issue alert mobile application users or facility managers of moderate or poor air quality so that responsible parties can take immediate remedial action. Real-time monitoring and a rapid alert system produce an efficient platform for improving indoor air quality. Major contributions of the proposed study are as follows:

(i) We propose the use of the Smart-Air for the precise monitoring of indoor air quality

(ii) We propose the utilization of an IoT for efficient monitoring of real-time data

(iii) We propose the adoption of cloud computing for real-time analysis of indoor air quality

(iv) We originally developed a mobile application to make the proposed IoT system with features of anytime, anywhere

(v) The device has been tested for reliability of the data and the platform has been implemented in a building to test its feasibility

2. Smart-Air

An accurate data measurement of indoor air quality is the most important factor for the platform. Thus, Smart-Air was developed to collect accurate and reliable data for indoor air quality monitoring. Because the monitoring area is not constant, the device was designed to be easily customized to an environment by using an expandable interface. Thus, various types of sensors can be installed or adjusted based on the environment. Also, a Long-Term Evolution (LTE) modem is mounted in the device to transmit detected data directly to the web server for classifying and visualizing air quality. For most IoT platforms, gateway or data loggers are installed to gather and transmit data wirelessly to the web server. However, in this study, a microcontroller was installed in the device to gather the data from the sensors and transmit it to the web server using the LTE modem, eliminating the need for a gateway and a data logger.

The most important purpose of Smart-Air is to precisely detect air quality in the perception layer of the platform that a primitive concept design of the device is shown in Figure 1. This device has an expandable interface such that multiple sensors can be installed simultaneously or easily added according to monitoring requirements. In the present study,

Table 1: Specifications of the STM 32 F407IG microcontroller.

Specification	Value
Instruction set	ARM Coretex-M4 (32-bit)
Flash memory	1024 Kbytes
SRAM (system)	192 Kbytes
SRAM (system)	4 Kbytes
12-bit ADC number of channels	24
12-bit DAC number of channels	2
Maximum CPU frequency	168 MHz
Operating voltage	1.8 V to 3.6 V
Operating temperature range	-40 to 125 Celsius

Table 2: Specifications of the laser dust sensor.

Specification	Value
Measurement particle size	0.3 to 10 μm
Measurement range	0 to 1000 $\mu g/m^3$
Time to first reading	≤8 s
Working temperature	-10 to 50 Celsius
Working humidity	0 to 95% RH (noncondensing)
Signal output	UART-TTL, PWM, IIC

Table 3: Specifications of the VOC sensor.

Specification	Value
Sensor input voltage	1 to 12 V
Operating temperature	-10 to 50 Celsius
Operating humidity	5 to 95% RH (noncondensing)
Reaction time	Less than 10 sec
Recovery time	Less than 30 sec
Power consumption	Below 460 mW
Sensitivity (β) for toluene	$0.30 \le \beta \le 0.60$ (concentration: 1.0 ppm)
Sensitivity (β) for H_2	$0.35 \le \beta \le 0.70$ (concentration: 100 ppm)
Sensitivity (β) for i-butane	$0.20 \le \beta \le 0.60$ (concentration: 100 ppm)
Accuracy	±7%

$*\beta$ = resistance after gas injection/resistance in a clean state.

the Smart-Air device consists of a laser dust sensor, a volatile organic compound (VOC) sensor, a carbon monoxide (CO) sensor, a carbon dioxide (CO_2) sensor, and a temperature-humidity sensor. Moreover, an LED strip was installed in the center of the device to visualize air quality using colors. When the quality of air changes, the device's LED changes color and wirelessly sends an alert message to the web server via LTE. Thus, the LTE modem transmits and receives data by communicating with the web server for detailed monitoring and determination of air quality as the presentation layer of the platform.

2.1. Microcontroller. The microcontroller is a compact integrated circuit used as an embedded system by receiving input from multiple sensors. In this paper, STM 32 F407IG from STMicroelectronics was selected, since it is designed for high performance and integration. The core of the microcontroller is the ARM 32-bit Coretex-M4 CPU that incorporates high-speed embedded memory. Table 1 summarizes the specifications of the STM 32 F4071G microcontroller [26].

2.2. Laser Dust Sensor. South Korean air space contains a very high level of aerosol, especially PM 2.5 and PM 10 [27–29]. A laser dust sensor, model PM2007 from Wuhan Cubic Optoelectronics Co., was installed in Smart-Air to measure and monitor concentrations of aerosol. This sensor can detect and output real-time particle mass concentrations for PM 2.5 and PM 10, which are defined as the fraction of particles with aerodynamic diameters smaller than 2.5 and 10 μm, respectively. The main features of the sensor are high sensitivity and accuracy in the range of 0 to 10000 $\mu m/m^3$ for 0.3 to 10 μm sized particles. This model also has a quick response time that can output real-time accurate particle mass concentration. The main specifications of the fine-dust sensor are provided in Table 2 [30].

2.3. Volatile Organic Compound Sensor. Volatile organic compounds (VOCs) are hydrocarbon-based products such as petroleum products and organic solvents that are easily vaporized in air due to high vapor pressure. Also, organic materials such as liquid fuels, paraffins, olefins, and aromatic compounds, which are commonly used in the living environment, are defined as VOCs. These compounds may cause damage to the nervous system through skin contact or respiratory inhalation, indicating the importance of monitoring [15, 31]. A VOC sensor module GSBT11-P110 from Ogam Technology is installed in Smart-Air. The sensor detects many types of VOCs, such as formaldehyde, toluene, benzene, xylene, and organic solvents, and the main specifications are illustrated in Table 3 [31].

2.4. Carbon Monoxide Sensor. Carbon monoxide is a toxic product of incomplete combustion of carbon compounds such as gas, petroleum, and coal. When CO gas is absorbed in the human body, it binds to hemoglobin in place of oxygen and induces hypoxia by obstructing the oxygen supply. CO gas can be generated from many sources, mainly human activities such as heating systems, cooking facilities, or burning fuel to power vehicles [8, 32]. Therefore, a CO sensor module GSET11-P110 from Ogam Technology is mounted in the device to detect and monitor CO. This sensor is a semiconductor-based gas sensor that is less expensive and easier to operate than a nondispersive infrared sensor. Additionally, it is possible to detect CO gas with high sensitivity; the specifications of the CO sensor are listed in Table 4 [33].

2.5. Carbon Dioxide Sensor. Although CO_2 is produced both naturally and through human activities, it is not classified as an air pollutant. However, it is treated as a pollutant because the amount of oxygen required for breathing becomes insufficient at high concentrations of CO_2 in an indoor space. CO_2 is a representative greenhouse gas that causes global warming

Table 4: Specifications of the CO sensor.

Specification	Value
Sensor input voltage	1 to 12 V
Operating temperature	-10 to 50 Celsius
Operating humidity	5 to 90% RH (non-condensing)
Reaction time	Less than 10 sec
Recovery time	Less than 30 sec
Power consumption	Below 380 mW
Sensitivity (β) for CO	$0.30 \le \beta \le 0.60$ (concentration: 100 ppm)
Sensitivity (β) for tobacco	$\beta \le 0.60$ (concentration: 2000 ppm)
Sensitivity (β) for ethyl alcohol vapor	$\beta \le 0.50$ (concentration: 50 ppm)
Accuracy	±7%

Table 5: Specifications of the CO_2 sensor.

Specification	Value
CO_2 measurement range	0-2000 ppm up to 0-10000 ppm
Resolution	10 ppm
Accuracy	40 ppm + 2% reading
Response time	30 sec
Maximum drift	±2% FS
Operating voltage	DC 5 V ± 5%
Operating current	Average: 70 mA, peak: 120 mA
Operating temperature	0 to 50 Celsius
Operating humidity	0 to 90% RH (noncondensing)

[22, 34]. Thus, the CO_2 gas sensor module CM1103 is installed to detect and monitor CO_2 concentrations. The sensor uses nondispersive infrared technology (NDIR) that have advantages of high precision, fast response, and factory calibration. Also, it features excellent long-term stability with low power consumption. The detailed specifications are listed in Table 5 [35].

2.6. Temperature-Humidity Sensor. According to the Ministry of the Environment Korea, comfort of the indoor environment is greatly influenced by temperature and humidity [36]. Thus, a temperature-humidity sensor, model DHT11 from OSEPP Electronics, is installed in Smart-Air to measure temperature and humidity. The sensor guarantees high reliability and excellent long-term stability using a digital signal acquisition technique. The sensor is strictly calibrated in the lab, and the calibration coefficients are stored as programs in the memory for application during the sensor's internal detection process. The specifications of the temperature-humidity sensor are listed in Table 6 [37].

2.7. Network Modem. Since networking is important in IoT technology to connect the Smart-Air with web servers for monitoring, determining, and visualizing indoor air quality,

Table 6: Specifications of the temperature-humidity sensor.

Specification	Value
Measurement range	0 to 50 Celsius 20 to 90% RH
Temperature accuracy	±2 Celsius
Humidity accuracy	±5% RH
Response time	6 to 15 sec

Table 7: Specifications of the LTE module.

Index	Specification
Communication method	LG U+ LTE B5/B7 FDD cat. 4
Band	LTE FDD 850 MHz(B5)/2.6 GHz(B7)
Interface	DB9 RS-232, RJ-45 ethernet, GPIO
Data speed	150 mbps DL/50 mbps UL
Input voltage	4.5 to 5.5 V
Operating temperature	-20 to 60 Celsius

a model RCU890L LTE modem from Woojin Networks was mounted in the device. The LTE modem is a mobile communication terminal device with widespread network coverage and can transmit, receive, and execute data anywhere in real time. Therefore, the modem provides a connection between the device and web server. The modem uses LG U+ LTE B5/B7 FDD Cat. 4 as the communication method; other characteristics are shown in Table 7 [38].

2.8. LED Strip. The proposed platform was designed to alert users and managers through the web server and mobile application when poor air quality is detected. However, the platform cannot alert everyone in the area. Therefore, a WS2812 LED strip from WorldSemi is mounted in the center of the device to immediately display colors depending on air quality defined based on the Ministry of Environment, Korea.

2.9. Reliability Tests. Since the accuracy of the sensors installed in Smart-Air is the most important factor in monitoring air quality, experimental efforts have focused on verifying the reliability of the sensors. The sensors were tested for the reliability according to the protocols from the Korea Testing Laboratory that was approved by the Ministry of Environment, Korea [16].

The VOC and CO sensors required calibration before the Smart-Air reliability test and were calibrated in a 1 m × 1 m × 1 m-sized acryl chamber. The CO_2 sensor and temperature-humidity sensor did not need extra calibration since they were precalibrated in the factory. In total, five sensors were tested based on the protocols of the Ministry: laser dust sensor, VOC sensor, CO sensor, CO_2 sensor, and temperature-humidity sensor. Two types of chambers were used to provide a constant environment for the experiments. For laser dust and VOC sensors, an acryl chamber was used because the experiment was not affected by temperature or humidity. A

Table 8: Measurements from the reliability test of the laser dust sensor.

	Inserted flow: 1 L/min			Inserted flow: 2.5 L/min		
	@ 1 minute	@ 30 minutes	@ 60 minutes	@ 1 minute	@ 30 minutes	@ 60 minutes
Smart-Air (A) (μg/m^3)	92	93	92	95	96	97
Smart-Air (B) (μg/m^3)	92	93	92	96	97	96
Smart-Air (C) (μg/m^3)	92	93	91	96	97	96
GRIMM 1109 (μg/m^3)		93			97	

temperature-humidity chamber was used with an accurate set temperature and humidity of 19°C and 55%, respectively, for the CO sensor, CO_2 sensor, and temperature-humidity sensor. Both chambers provided a constant environment suitable for the experiments. Then, the data were observed and extracted from the web server and application to assess the performance of the platform.

2.9.1. Laser Dust Sensor. The laser dust sensor was precalibrated in the factory, so only a reliability test was required to verify the data from Smart-Air. To test the accuracy of the laser dust sensor installed in the device, two types of experiments were performed based on aerosol concentration. The first method utilized a chamber experiment and was compared to a gravimetric method. The other method was a field test that compared the sensor data to that of a certified fine-dust measurement device to evaluate the reliability of real-time monitoring. In this study, a combination of the two methods was performed. The Ministry recommended and used GRIMM's light-scattering fine-dust measurement device because it used a light-scattering method for detection. This method is known to be the most reliable for detection due to the factory calibration. In the experiment, data from three Smart-Air devices were measured and compared to the data obtained from GRIMM 1109. The devices were placed in the acryl chamber, and external air was injected into the chamber at a flow rate of 1 L/min or 2.5 L/min. The data were measured at 1, 30, and 60 minutes after device installation. Then, the readings were compared to those of GRIMM 1109 to assess accuracy and reliability.

The results of the reliability test for the laser dust sensor installed in Smart-Air are shown in Table 8. A comparison of the data of GRIMM 1109 sensor, which was certified by the Ministry of Environment, Korea, with that of the sensor installed in Smart-Air was used to assess the accuracy of the sensors. The same experiment was conducted with the two different flows of 1 L/min and 2.5 L/min. For each experiment, GRIMM 1109 and three Smart-Air devices, which were presented as Smart-Air (A), (B), and (C), sensed the concentrations of fine dust. GRIMM 1109 showed its reading at 30 minutes after flow introduction as designed. Detection of fine dust by the sensors from Smart-Air devices was performed at 1, 30, and 60 minutes after flow insertion. The concentrations measured by the sensors showed constant and stable values independent of the model. The data measured by the sensor installed in Smart-Air and GRIMM 1109 were very similar 30 minutes after insertion. At a flow of 1 L/min, the concentration was 93 μg/m^3. At a flow of 2.5 L/min, the concentration was 97 μg/m^3. The data collected from the sensors were similar to that from the certified devices, indicating the high reliability of the sensors.

2.9.2. VOC Sensor. The VOC sensor used in the study was selected based on an investigation by the Ministry of Environment, Korea. The sensor is a semiconductor type that can have a small diffusion effect and requires data verification. Accordingly, calibration and a chamber test were conducted to test the reliability of the VOC sensor. To calibrate the sensor, Smart-Air was placed in an acrylic chamber with a PID-type VOC sensor, i.e., MiniRAE 3000 from RAE Systems. The PID type VOC sensor was the most accurate and reliable type to detect VOCs. After the sensors were placed, about 1 inch of incense was burned to create a VOC compound to measure. The collected data from Smart-Air were calibrated against those from the PID-type VOC sensor. After calibration, a chamber test was performed to test the reliability of the VOC sensors, a common procedure adopted by the Ministry. After placing the Smart-Air in the chamber, N_2 was injected to clean the chamber. To test the accuracy of the measurement sensor, toluene gas was injected at different concentrations. In this study, three values of concentrations were selected and injected in ascending order: 480 μg/m^3, 1000 μg/m^3, and 1600 μg/m^3. After each injection, the data observed from the device were compared to the actual injected concentration to confirm the reliability of the measurement.

Both Smart-Air devices and MiniRAE 3000 were placed in the acryl chamber to obtain the data in the same conditions with a constant environment. As the incense was burned, the gas concentration increased as the voltage output signal of the VOC sensor increased, showing a linear relationship. This excludes any possible effects of gas concentration, and the relationship is illustrated in Figure 2.

After calibration, a reliability test was performed for the VOCs to test the accuracy of the data following the standards from the Ministry, and the results are shown in Figure 3. The measured value was very similar to the actual concentration of toluene. When a concentration of 480 μg/m^3 was injected at 14:24, the reading presented an accurate value at 15:10. When a concentration of 1000 μg/m^3 was injected at 15:22, the reading was accurate at 16:19. When a concentration of 1600 μg/m^3 was injected, an accurate measurement was observed at 17:40. At the highest concentration at 1600 μg/m^3, the reading was higher than the actual initial value because the gases required adequate time to uniformly mix in the chamber. The results showed that the

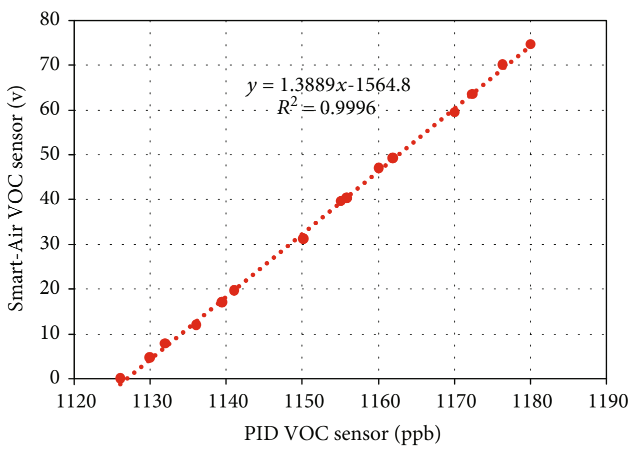


FIGURE 2: Calibration results of the VOC sensor.

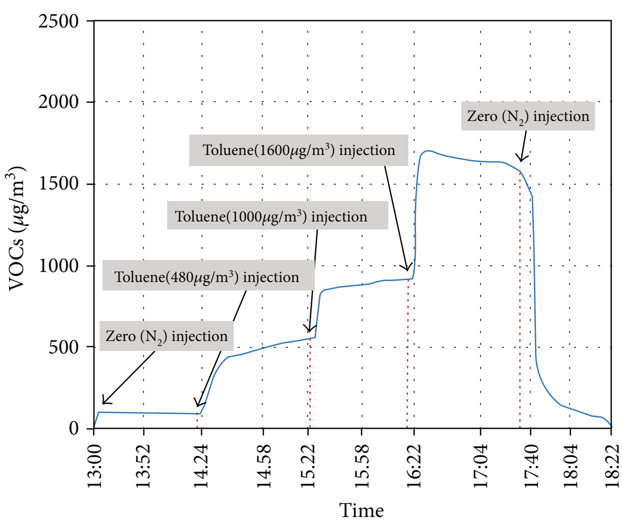


FIGURE 3: Reliability test results of the VOC sensor.

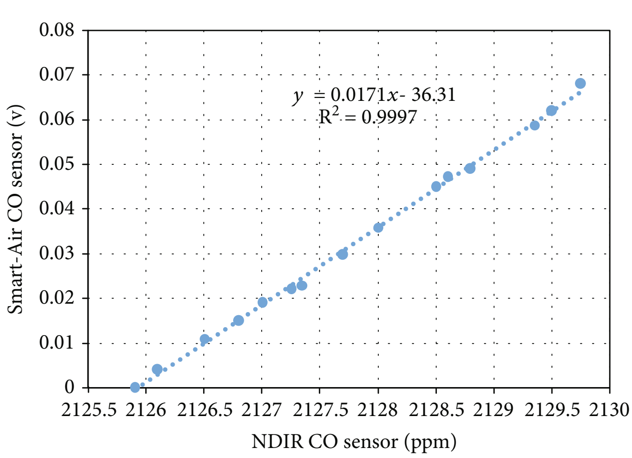


FIGURE 4: Calibration results of the CO sensor.

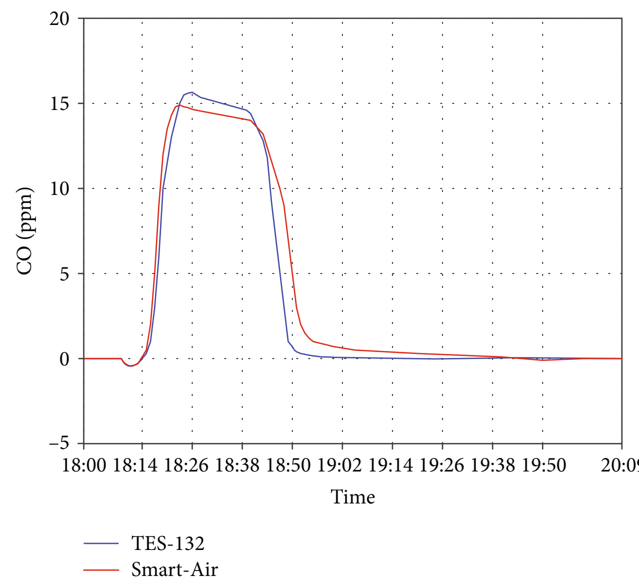


FIGURE 5: Reliability test results of the CO sensor.

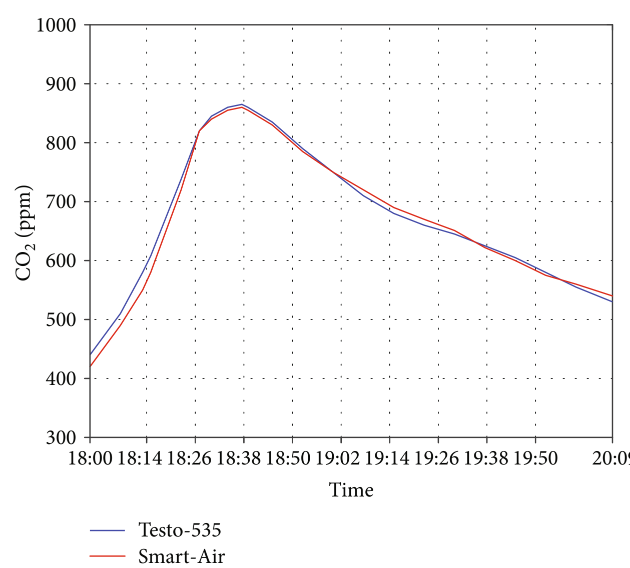


FIGURE 6: Reliability test results of the CO_2 sensor.

sensor can detect and present accurate readings in a short period of time. Thus, the device was suitable for monitoring indoor air quality.

2.9.3. CO Sensor. The CO sensor used in the study is also a semiconductor type, which is not the official standard CO sensor for indoor air quality measurements. TES-1372 from TES was used in the experiments for calibration and reliability testing because the Ministry recommended an NDIR-type measurement device. The same calibration method used for the VOC sensor was used for the CO sensor. A reliability test was performed after calibration. After the devices were placed in the sample chamber, incense (about 1-inch-long)

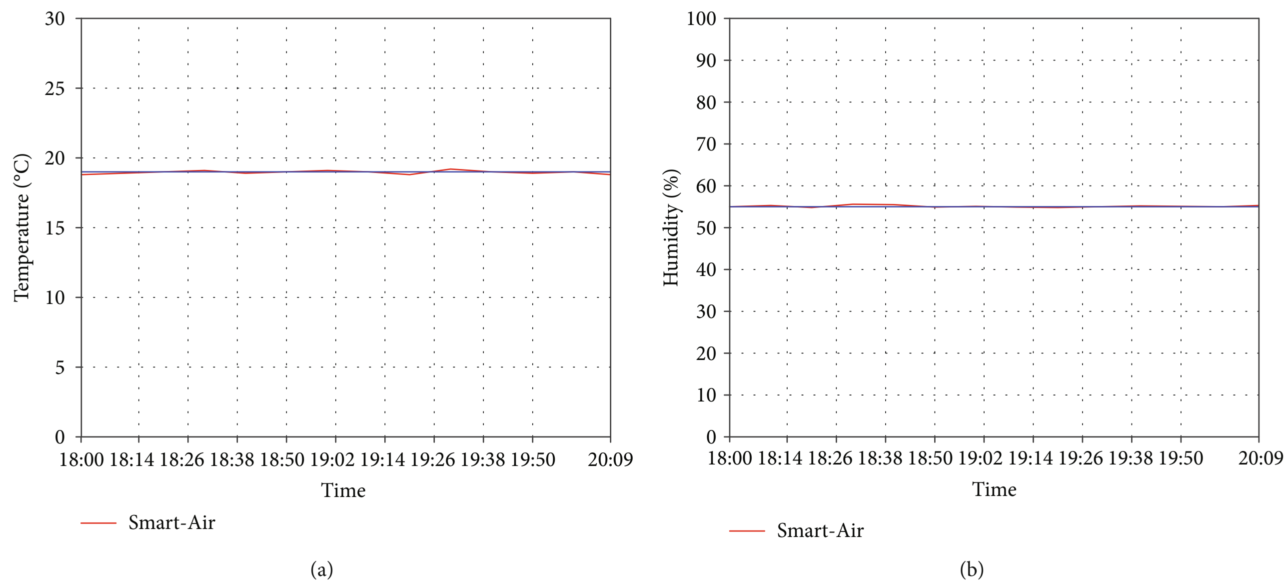


Figure 7: Reliability test results for (a) temperature and (b) humidity.

in a metal cup was placed inside and lighted. The CO sensor from Smart-Air and the NDIR-type device detected the increased concentration of CO associated with the combustion. The data collected from the two devices were compared to evaluate the accuracy of the CO sensor.

The CO sensor was calibrated with the same process used for the VOC sensor calibration. The Smart-Air and the TES-132, a certified device, were placed in the same chamber to measure the concentration of CO gas from the incense. Similar to the VOC sensor, the CO level increased as the voltage output signal increased. The linear conversion model for calibration of the CO sensor is presented in Figure 4.

After calibrating the CO sensor of Smart-Air, the device was placed in the chamber with TES-132 for reliability testing. The results of the reliability test for the CO sensor are provided in Figure 5. The data collected by the NDIR-type CO measurement device showed that the concentration of CO in the chamber dramatically increased with time after incense lighting, gradually decreased with completion of burning, and then dropped dramatically after loss of combustion. The data presented by the CO sensor were similar, indicating the efficacy of the CO sensor. If the device is to be used for a long period of time, periodic maintenance may be required to reduce the possibility of errors. As explained in the experimental method, the assessment of CO sensors followed the standard procedures performed and suggested by the Ministry of Environment, Korea. The contamination level detected from the sensor and certified device generally showed the same trends, supporting the high reliability of the sensor. However, further experiments are required to increase the accuracy of concentration measurement.

2.9.4. CO_2 Sensor. According to the Ministry of Environment, Korea, an NDIR-type sensor is used for verifying CO_2 measurement devices due to its high accuracy in detection of CO_2. A CO_2 calibration is performed during sensor manufacturing and is not required for NDIR-type sensors after purchase. Furthermore, these sensors have high stability and do not deteriorate upon exposure to gases or experience sensor burnout. Since the sensor is precalibrated, only a reliability test was performed. A Testo-535, a commercial certified NDIR-type CO_2 measurement device, and the Smart-Air were placed in the temperature-humidity chamber to measure the concentration of CO_2. The reliability of the device was assessed by comparing its result to that of

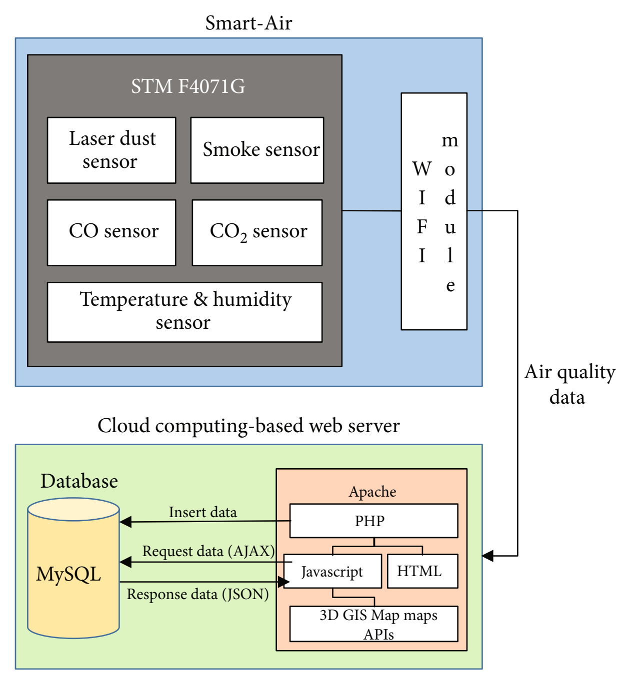


Figure 8: Configuration diagram for the IoT-based indoor air quality monitoring platform.

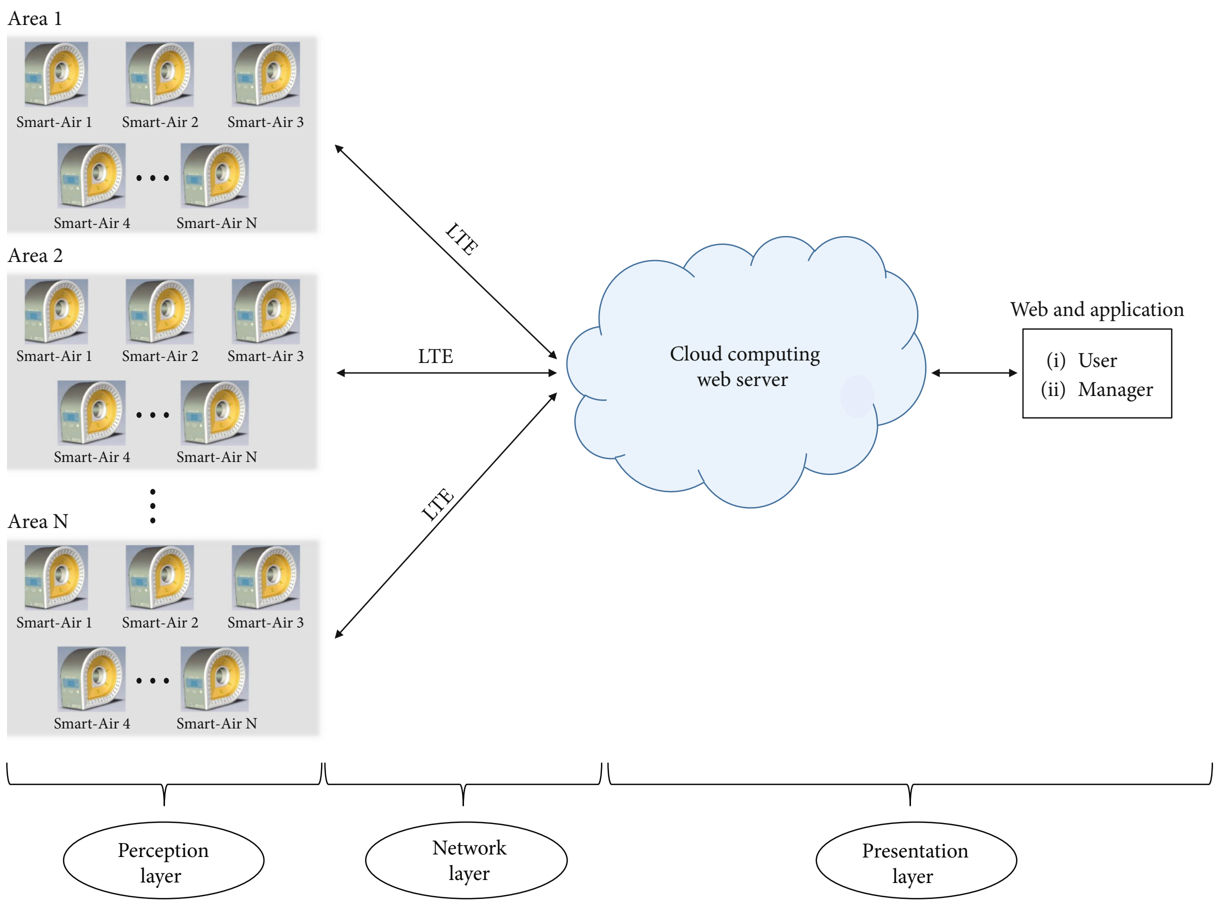


Figure 9: Block diagram of the IoT-based indoor air quality monitoring platform.

Testo-535. The experiment was conducted in the same manner as the method used for the CO sensor. About 1 inch of incense was lighted in a metal cup near the two devices placed in the chamber to sense the CO_2 concentration after incense lighting. The data presented by the two devices were compared to assess the reliability of the CO_2 sensor.

The CO_2 sensors from Smart Air and Testo-535 sensed an increase in CO_2 concentration after lighting until 18:38. As the incense burned, the CO_2 concentration gradually decreased. The two CO_2 sensors presented similar trends, indicating the high reliability of the device, as demonstrated in Figure 6. Therefore, the reliability of the sensor was verified through the experiment.

2.9.5. Temperature-Humidity Sensor. The temperature-humidity sensor was precalibrated in a factory instead of in a laboratory to produce greater accuracy and reliability. Although additional calibration of the sensor was not required, a reliability test was performed. Thus, Smart-Air was placed in the chamber for 2 hours with temperature and humidity set points of 19°C and 55%, respectively. The sensed temperature and humidity were compared to the initial set values for testing the accuracy of the sensor.

The chamber used in the experiment independently maintained specific humidity level and temperature of 19°C and 55%, respectively. The measurements of temperature and humidity from the sensor were observed using an application, and the data were extracted from the web server, as shown in Figures 7(a) and 7(b), respectively. The data collected by the sensor were compared to the initial set values of the chamber. Smart-Air presented measurements as accurate as the set values, verifying the high reliability of the sensor and showing that it did not need extra calibration.

3. An IoT-Based Indoor Air Quality Monitoring Platform

The IoT-based indoor air quality monitoring platform is primarily divided (Figure 8) into the Smart-Air and the web server. The set of sensing devices necessary to collect the data to analyze air quality comprised a laser dust sensor, a CO sensor, a CO_2 sensor, a VOC sensor, and a temperature and humidity sensor. Each device transmitted data to the web server via the LTE module to determine air quality and visualize the result. Furthermore, cloud computing technology was integrated with a web server. The main benefits of the cloud computing-based web server are faster speed, flexibility, and greater accessibility. The web server provided faster and more flexible data processing functions with a large amount of data, which is essential for a monitoring platform. The cloud computing-based web server is easily accessible

Figure 10: The Smart-Air (a) when indoor air quality is good and (b) when the light is set to purple.

through most browsers to allow ubiquitous monitoring. In this study, Amazon Web Services (AWS) was used as the web server to analyze, visualize, and present the data collected from Smart-Air. Also, the web server provides a database to store that data in the cloud. Furthermore, a mobile application was developed for the system to visualize air quality with the web server "anywhere, anytime" in real time.

The platform is designed based on an architecture of IoT platform that is mainly comprised of three components: (i) perception layer, (ii) a network layer, and (iii) presentation layer. The perception layer is the sensing component to collect data using sensors or any measuring devices. The network layer is responsible for transmitting the detected data using a wireless network module. Finally, the presentation layer allows data visualization and storage for efficient monitoring [39–41].

A block diagram of the IoT-based indoor air quality monitoring platform is shown in Figure 9. For the perception layer of the platform, multiple Smart-Air devices are used for detecting the data needed to analyze the air quality. Also, the LTE modem is mounted in the devices as the network layer. The data collected from each of these devices were sent to the web server via LTE. For the presentation layer, a cloud computing-based web server is used for the platform. The server gathered the data to evaluate air quality based on the Indoor Air Quality Control Act from the Ministry of Environment, Korea. Managers and users with specified access to the monitoring data can continuously monitor air quality anytime and anywhere via smart devices. Another feature of the server is that it automatically sends a warning message to managers and other related personnel whenever the quality of air decreases. Therefore, they can react immediately to improve the air quality.

3.1. Smart-Air. When a monitoring area has been determined, the specific types of air pollutants present must be considered. As mentioned above, Smart-Air has an expandable interface such that multiple sensors can be added to the microcontroller. Furthermore, the platform can monitor a large area or many areas simultaneously using multiple

Table 9: Specifications of the web server.

Index	Specification
Type of instance	T2 medium
Storage (GB)	EBS only
Memory (GiB)	4
vCPUs	2
Clock speed (GHz)	Maximum 3.3
CPU credits/hr	24
Networking performance	Low to medium

Smart-Air devices. Then, each device is classified by area to visualize the data. Each Smart-Air device transmits air quality data to the web server via LTE and automatically indicates the air quality for the specific area by LED color. Moreover, each device can be set to present a unique color of LED through the application or web server, as shown in Figure 10.

3.2. IoT Network. Since multiple Smart-Air devices can be used for efficient and precise monitoring, a wireless sensor network is very important for the platform. Although the network layer for most of the IoT-based air quality monitoring platform consists of the IoT gateway, the microcontroller is used as the IoT gateway to transmit and receive sensed data. Each Smart-Air device has its own microcontroller with an LTE modem. Thus, the data from each device are transferred wirelessly in the form of TCP/IP packets from the device to the web server via LTE [42, 43]. Then, the data are gathered and analyzed through the web server for visualization and storage.

3.3. Cloud Computing-Based Web Server. The IoT-based indoor air quality monitoring platform requires a server to efficiently analyze the data from Smart-Air and visualize the indoor air quality. To control and monitor multiple Smart-Air devices at the same time and save the data, AWS was used as the server. As AWS is a commercially certified cloud

Table 10: Standards for indoor air quality.

Condition	Type of air pollutant			
	Aerosols (μg/m^3)	CO (ppm)	CO_2 (ppm)	VOCs (μg/m^3)
Good	≤100	≤10	≤1000	≤400
Moderate	$100 < {}^*\alpha \leq 150$	$10 < {}^*\alpha \leq 25$	N/A	$400 < {}^*\alpha \leq 500$
Poor	>150	>25	>1000	>500

$^*\alpha$ = measured value.

computing platform, significant amounts of time and money were saved in platform development, and errors were minimized. Furthermore, no separate database is needed to analyze and save data when using the AWS server.

The cloud computing-based port structure stability evaluation platform used the Elastic Compute Cloud (EC2) as the hypertext preprocessor (PHP) among the Amazon-supported application programming interfaces (APIs). EC2 is optimized for the platform because it offers stable support for dynamic instantiation and configuration of the virtual machine instance. The platform utilizes a T2 medium as an extensible instance, as specified and indexed in Table 9 [38, 44]. Also, the server was designed with the web programming language PHP, while MySQL was used as the database for data retention.

3.4. Application. An application for the IoT-based indoor air quality monitoring platform was developed to efficiently monitor the data and alert users and related personnel. Therefore, air quality was monitored both with the web server and with associated smart devices through the application. Air quality monitoring was easy and efficient using the application as it provided access anytime using smart devices. The application was designed to be very similar to the web server developed for Android OS version 4.1.1 using hypertext markup language, cascading style sheets, JavaScript, and PHP.

3.5. Conditions for Air Quality. To classify indoor air quality from the data, the IoT-based indoor air quality monitoring platform utilized standards for indoor air quality based on the indoor Air Quality Control Act. The act was instituted in 2007 by the Ministry of Environment, Korea to protect and manage indoor air quality to prevent health and environmental harm [36]. Based on the act, air quality is defined as good, moderate, or poor. The thresholds were automatically set as shown in Table 10 when Smart-Air was registered to the platform. However, the thresholds can be manually changed for a specific area via the web server based on user preferences.

Also, temperature and humidity are key factors affecting the comfort of indoor environments. Conditions for a comfortable indoor environment with respect to temperature and humidity were determined based on the Korea Meteorological Administration (KMA) and are listed in Table 11 [36]. If the temperature is neither good nor bad, the platform defines the condition as moderate. However, the thresholds for temperature and humidity are merely recommendations that can be edited according to user preferences for the desired indoor conditions.

Table 11: Recommended temperature and humidity by the KMA.

Condition	Temperature (Celsius)	Humidity (%)
Good	$18 \leq \alpha \leq 20$	$55 \leq \alpha \leq 65$
Poor	<15 or >30	<30 or >80

3.6. Alert System. Although monitoring air quality in real time is important, the alert system is necessary to announce the need for change to prevent environmental harm. With the alert system, users or the manager of the platform can take immediate action to improve air quality. Therefore, AWS provides an application called Amazon Simple Notification Service for the alert system as an open library used in the IoT-based indoor air quality platform. Therefore, the web server was designed to issue a pop-up message in the application to alert the manager and users when the condition of the air was moderate or poor. Furthermore, semiconductor-type sensors that required inspection for calibration or deterioration due to long-term use were installed in Smart-Air. Therefore, the web server was designed to provide an automatic alert message when the device reached one year of use. The system automatically recommends inspections of the device via a pop-up message.

Furthermore, an LED strip was installed in the device such that the air quality conditions for the area can be recognized by nearby people. The device was designed to change the LED light color to match the current condition. Thus, the color will change to yellow and red when the conditions are moderate and poor, respectively.

4. Experimental Testing

Experimental efforts have focused on implementation of the IoT-based indoor air quality monitoring platform. Multiple Smart-Air devices were installed in the Jaesung Civil Engineering Building, Hanyang University, to test the feasibility of the platform. The entire installation consisted of the Smart-Air, cloud computing-based web server, and the application.

4.1. Installation. A total of seven Smart-Air instruments were installed to monitor indoor air quality in the Jaesung Civil Engineering Building, as shown in Figure 11. The building has two entrances, a main entrance and a back entrance located on the second floor, near which two Smart-Air

(a) (b)

Figure 11: (a) Smart-Air ID No. 6 installed in the main entrance and (b) Smart-Air ID No. 1 installed in laboratory room 110.

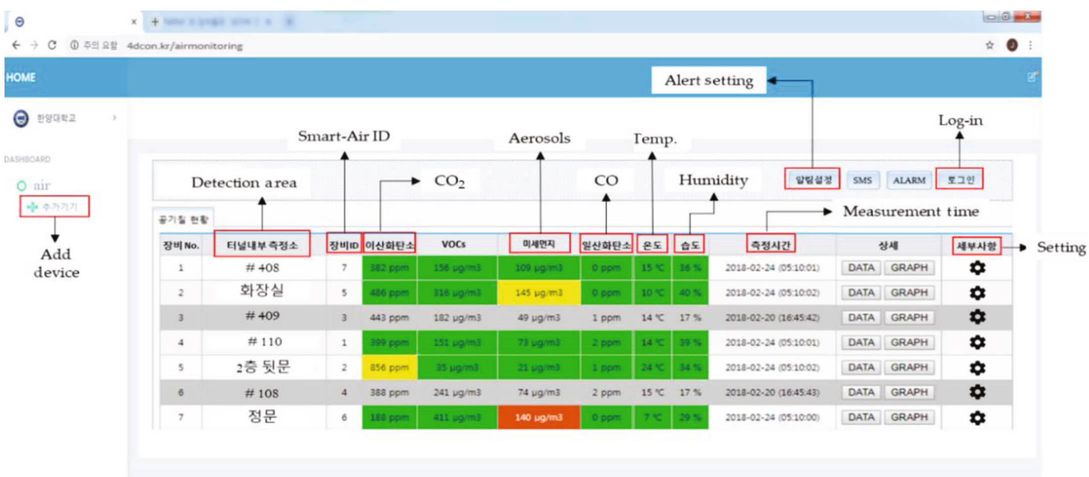


Figure 12: Cloud computing web server of the IoT-based indoor air quality monitoring platform.

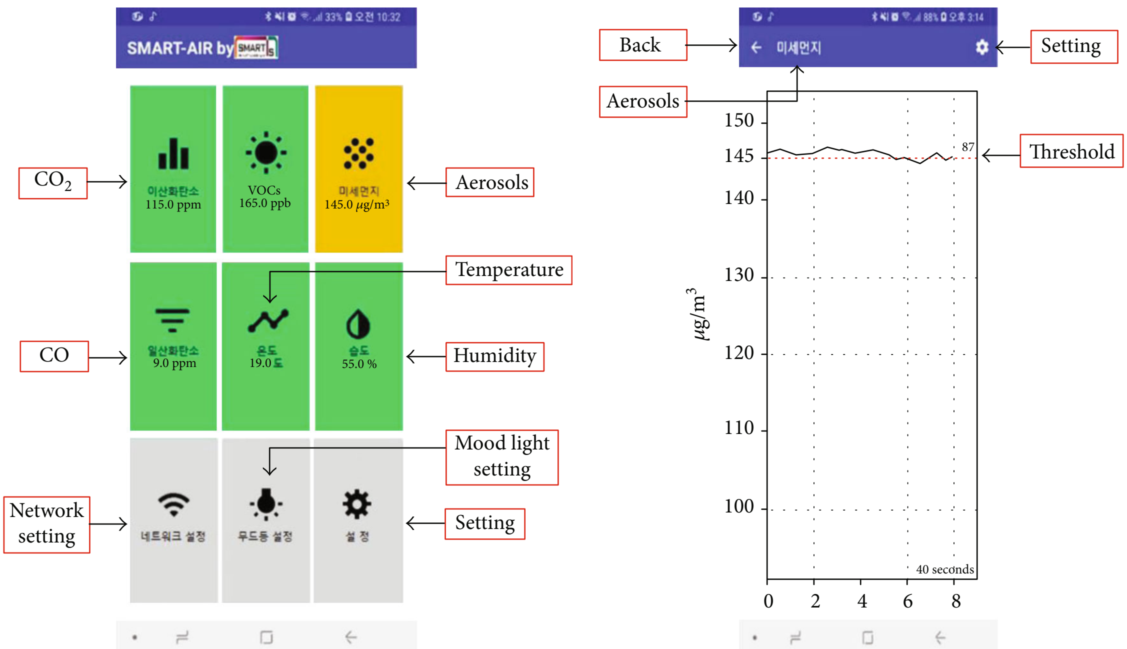
devices, ID No. 6 and ID No. 2, were installed. Also, four devices (ID No. 4, ID No. 1, ID No. 7, and ID No. 3) were placed in four laboratories (rooms 108, 110, 408, and 409, respectively). The last Smart-Air, ID No. 5, was installed in a restroom located on the 1st floor.

4.2. Cloud Computing-Based Web Server. The cloud computing-based web server was enabled after installing the Smart-Air to analyze the detected data and visualize the indoor air quality for the platform. The web server used in the research is shown in Figure 12. The data from each device were classified by area and ID of the device. Also, the measured data from each sensor of the device were displayed in the web server. The server provided a datasheet and graph for the current set of stored data with measured times that can be extracted for review. Furthermore, the data were visualized and color-coded based on the current air quality. The color of the device changed to yellow or red along with activating the alert system when the air quality was moderate or poor. Therefore, the manager or user can take necessary action to improve the air quality. Furthermore, the server stores the air quality data in the database of the cloud server to be reviewed when needed.

4.3. Application. To remotely monitor air quality, a mobile application was enabled after the web server was activated. After the desired monitoring device was selected, the condition of air quality was shown based on the types of air pollutants, as shown in Figure 13(a). Each component monitored as an air pollutant was displayed by color according to the web server. Additionally, when the specific types of air pollutants in the main page were selected, detailed monitoring of the pollutants was available based on a real-time graph as shown in Figure 13(b). Furthermore, the application alerts the user through a pop-up message when the condition of the air pollutant was moderate or poor.

5. Results

The goal of the experiment was to perform an initial implementation of the platform to monitor indoor air quality.



(a) (b)

Figure 13: The application of the IoT-based air quality monitoring platform: (a) main page and (b) a real-time graph of aerosol data.

(a) (b)

Figure 14: (a) A pop-up message from the application when the condition of aerosol was moderate. (b) Smart-Air response when the condition was poor.

Smart-Air wirelessly transmitted the detected data to the web server, which successfully classified the condition of indoor air quality and displayed it via both the web and the application. Also, the data were saved in the database of the web server as designed such that further studies can be performed on trends of air quality. The experiment showed poor conditions in entrances of the building because it is exposed to outside air more than other locations. However, the platform successfully alerted and visualized poor air quality, as shown in Figure 14. The device changed the LED light color to match the current condition and alerted the manager via a pop-up message as shown in Figure 14(a). Also, LED lights installed in the device successfully displayed the condition especially when the air quality was poor as shown in Figure 14(b). Thus, the manager of the building was able to monitor the air quality of the building ubiquitously and take steps to improve the air quality.

Considering the nature of the platform, it is important to perform qualitative analysis based on user experience. In the experiment, interviews were conducted with building managers who used the platform to manage air quality. Interviewees were very satisfied with its ability to monitor air quality. When air quality was moderate or poor, managers were alerted to the condition and able to react immediately to improve air quality. Positive comments were received from the managers regarding data precision and information collection in real time.

During the experiment, it was proven that the platform not only provided accurate data but also meaningful information in real time to save energy. The platform also monitors temperature and humidity to provide optimum environment for the area. By operating ventilation system when it is necessary along with the heating and air-conditioning system, people in the area were satisfied with the improved condition and saved energy.

6. Conclusions

In this paper, the development of an IoT-based indoor air quality monitoring platform is presented. Experiments were performed to verify the air quality measurement device used in the platform based a method suggested by the Ministry of Environment, Korea. We verified the accuracy of indoor air quality monitoring and the desirable performance of the device. Also, experiments making use of the platform were conducted and demonstrated suitable performance and convenience of the air quality monitoring platform. Several achievements of the platform were accomplished, including the following: (1) indoor air quality can be efficiently monitored anywhere and in real time by using an IoT and a cloud computing technologies; (2) the platform used Amazon Web Services as a certified web server for security of the platform and the data; (3) the Smart-Air device has an expandable interface, and the web server is also easily extendable, allowing easy application to various environments through the addition of appropriate sensors to the device or installing more Smart-Air devices to appropriate monitoring locations.

Future work will involve further testing of the device and the platform. In this paper, the experiment focused on testing the reliability of the device and implementing the platform, where more tests are necessary to ensure data accuracy for long time periods. In addition, ventilation system can be connected to the platform. Thus, the system can be automatically operated to improve the air quality whenever the air quality is not good.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

J.J. and B.J. conceptualized the study and J.J., J.K., and S.K. performed the investigations. J.J. and W.H. developed the methodology. JJ wrote the original draft of the manuscript while BJ supervised the research. J.J., J.K., and S.K. reviewed and edited the manuscript. All authors read and approved the final manuscript.

References

[1] G. Parmar, S. Lakhani, and M. Chattopadhyay, "An IoT based low cost air pollution monitoring system," in *2017 International Conference on Recent Innovations in Signal processing and Embedded Systems (RISE)*, Bhopal, India, October 2017.

[2] K. Okokpujie, E. Noma-Osaghae, O. Modupe, S. John, and O. Oluwatosin, "A smart air pollution monitoring system," *International Journal of Civil Engineering and Technology*, vol. 9, pp. 799–809, 2018.

[3] K. A. Kulkarni and M. S. Zambare, "The impact study of houseplants in purification of environment using wireless sensor network," *Wireless Sensor Network*, vol. 10, no. 03, pp. 59–69, 2018.

[4] World Health Organization, *Air Pollution and Child Health-Prescribing Clean Air*, WHO, Geneva, Switzerland, 2018, September 2018, https://www.who.int/ceh/publications/Advance-copy-Oct24_18150_Air-Pollution-and-Child-Health-merged-compressed.pdf.

[5] G. Rout, S. Karuturi, and T. N. Padmini, "Pollution monitoring system using IoT," *ARPN Journal of Engineering and Applied Sciences*, vol. 13, pp. 2116–2123, 2018.

[6] B. C. Kavitha, D. Jose, and R. Vallikannu, "IoT based pollution monitoring system using raspberry–PI," *International Journal of Pure and Applied Mathematics*, vol. 118, 2018.

[7] D. Saha, M. Shinde, and S. Thadeshwar, "IoT based air quality monitoring system using wireless sensors deployed in public bus services," in *ICC '17 Proceedings of the Second International Conference on Internet of things, Data and Cloud Computing*, Cambridge, United Kingdom, March 2017.

[8] J. Liu, Y. Chen, T. Lin et al., "Developed urban air quality monitoring system based on wireless sensor networks," in *2011 Fifth International Conference on Sensing Technology*, pp. 549–554, Palmerston North, New Zealand, December 2011.

[9] United States Environmental Protection Agency, *Managing air quality - air pollutant types*October 2018, https://www.epa.gov/air-quality-management-process/managing-air-quality-air-pollutant-types.

[10] C. Arnold, M. Harms, and J. Goschnick, "Air quality monitoring and fire detection with the Karlsruhe electronic micronose KAMINA," *IEEE Sensors Journal*, vol. 2, no. 3, pp. 179–188, 2002.

[11] S. Abraham and X. Li, "A cost-effective wireless sensor network system for indoor air quality monitoring applications," *Procedia Computer Science*, vol. 34, pp. 165–171, 2014.

[12] O. A. Postolache, D. J. M. Pereira, and S. P. M. B. Girão, "Smart sensors network for air quality monitoring applications," *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 9, pp. 3253–3262, 2009.

[13] Y. Jiangy, K. Li, L. Tian et al., "MAQS: a personalized mobile sensing system for indoor air quality monitoring," in

Proceedings of the 13th international conference on Ubiquitous computing, pp. 271–280, Beijing, China, September 2011.

[14] S. Bhattacharya, S. Sridevi, and R. Pitchiah, "Indoor air quality monitoring using wireless sensor network," in *2012 Sixth International Conference on Sensing Technology (ICST)*, pp. 422–427, Kolkata, India, December 2012.

[15] S. Zampolli, I. Elmi, F. Ahmed et al., "An electronic nose based on solid state sensor arrays for low-cost indoor air quality monitoring applications," *Sensors and Actuators B: Chemical*, vol. 101, no. 1-2, pp. 39–46, 2004.

[16] Ministry of Environment, *Investigation results of Ministry of Environment*March 2019, http://www.me.go.kr/home/web/board/read.do?boardMasterId=1&boardId=727840&menuId=286.

[17] G. Marques, C. Ferreira, and R. Pitarma, "Indoor air quality assessment using a CO2 monitoring system based on Internet of Things," *Journal of Medical Systems*, vol. 43, no. 3, p. 67, 2019.

[18] M. Tastan and H. Gokozan, "Real-time monitoring of indoor air quality with internet of things-based E-nose.," *Applied Sciences*, vol. 9, no. 16, article 3435, 2019.

[19] A. Rackes, T. Ben-David, and M. S. Waring, "Sensor networks for routine indoor air quality monitoring in buildings: impacts of placement, accuracy, and number of sensors," *Science and Technology for the Built Environment*, vol. 24, no. 2, pp. 188–197, 2018.

[20] M. Benammar, A. Abdaoui, S. Ahmad, F. Touati, and A. Kadri, "A modular IoT platform for real-time indoor air quality monitoring," *Sensors*, vol. 18, no. 2, p. 581, 2018.

[21] S. Wang, S. Chew, M. Jusoh, A. Khairunissa, K. Leong, and A. Azid, "WSN based indoor air quality monitoring in classrooms," *AIP Conference Proceedings*, vol. 1808, article 020063, 2017.

[22] S. Kamble, S. Mini, and T. Panigrahi, "Monitoring Air Pollution: An IoT Application," in *2018 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, Chennai, India, March 2018.

[23] GSMA, *Air quality monitoring using IoT and big data: a value generation guide for mobile operators*, 2018, September 2018, https://www.gsma.com/iot/wp-content/uploads/2018/02/iot_clean_air_02_18.pdf.

[24] H. Ghayvat, S. Mukhopadhyay, X. Gui, and N. Suryadevara, "WSN- and IOT-based smart homes and their extension to smart buildings," *Sensors*, vol. 15, no. 5, pp. 10350–10379, 2015.

[25] K. Gupta and N. Rakesh, "IoT based automobile air pollution monitoring system," in *2018 8th International Conference on Cloud Computing, Data Science & Engineering (Confluence)*, Noida, India, January 2018.

[26] STMicroelectronics, *STM32F407 specification*, 2016, October 2018, https://www.st.com/en/microcontrollers/stm32f407-417.html?querycriteria=productId=LN11.

[27] Y. Cho, E. Shin, K. Cho et al., "Study on the continuous monitoring of particulate matters concentrations in the subway station," *Korean Society for Railway*, pp. 3242–3247, 2009.

[28] G. Kim, "Implementation of indoor air quality monitoring system for subway stations," *Journal of the Institute of Electronics Engineers of Korea*, vol. 50, pp. 1610–1617, 2013.

[29] S. Kim, H. Kang, Y. Son et al., "Compensation of light scattering method for real-time monitoring of particulate matters in subway stations," *Journal of Korean Society for Atmospheric Environment*, vol. 26, no. 5, pp. 533–542, 2010.

[30] Wuhan Cubic Optoelectronics Co, *Laser Dust Sensor Module PM2007*October 2018, http://www.gassensor.com.cn/product_detail_en/Particle_Sensor/PM2007.

[31] Ogam Technology, *(2009) Ogam Technology product information GSBT11*October 2018, https://www.eleparts.co.kr/data/goods_old/design/product_file/ogam-tech/GSBT11/GSBT11.pdf.

[32] J. Liu, Y. Chen, T. Lin et al., "An air quality monitoring system for urban areas based on the technology of wireless sensor networks," *International Journal on Smart Sensing and Intelligent Systems*, vol. 5, no. 1, pp. 191–214, 2012.

[33] Ogam Technology, *(2013) Ogam Technology product information GSET11*October 2018, https://eleparts.co.kr/data/goods_old/data/GSET11_Kc.pdf.

[34] A. Mofarrah and T. Husain, "A holistic approach for optimal design of air quality monitoring network expansion in an urban area," *Atmospheric Environment*, vol. 44, no. 3, pp. 432–440, 2010.

[35] Wuhan Cubic Optoelectronics Co, *(2013) User manual for carbon dioxide* CO_2 *sensor module*October 2018, http://pdf.directindustry.com/pdf/wuhan-cubic-optoelectronics-co-ltd/ndir-carbon-dioxide-sensor-co2-sensor-cm1102-user-manual-dual-beam/54752-614013.html.

[36] Ministry of Environment, *Indoor air quality control act for multi-use facilities*September 2018, http://www.law.go.kr/%EB%B2%95%EB%A0%B9/%EB%8B%A4%EC%A4%91%EC%9D%B4%EC%9A%A9%EC%8B%9C%EC%84%A4%EB%93%B1%EC%9D%98%EC%8B%A4%EB%82%B4%EA%B3%B5%EA%B8%B0%EC%A7%88%EA%B4%80%EB%A6%AC%EB%B2%95/(12216,20140107).

[37] OSEPP Electronics, *DHT11 humidity & temperature sensor*October 2018, https://www.mouser.com/ds/2/758/DHT11-Technical-Data-Sheet-Translated-Version-1143054.pdf.

[38] B. Jo, J. Jo, R. M. A. Khan, J. Kim, and Y. Lee, "Development of a cloud computing-based pier type port structure stability evaluation platform using fiber Bragg grating sensors," *Sensors*, vol. 18, no. 6, 2018.

[39] Y. J. Fan, Y. H. Yin, L. D. Xu, Y. Zeng, and F. Wu, "IoT-based smart rehabilitation system," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 2, pp. 1568–1577, 2014.

[40] D. Pavithra and R. Balakrishnan, "IoT based monitoring and control system for home automation," in *2015 Global Conference on Communication Technologies (GCCT)*, Thuckalay, India, April 2015.

[41] C. Stergiou, K. Psannis, B. Kim, and B. Gupta, "Secure integration of IoT and cloud computing," *Future Generation Computer Systems*, vol. 78, pp. 964–975, 2018.

[42] W. Lu, H. He, and L. Dong, "Performance assessment of air quality monitoring networks using principal component analysis and cluster analysis," *Building and Environment*, vol. 46, no. 3, pp. 577–583, 2011.

[43] S. Devarakonda, P. Sevusu, H. Liu, R. Liu, L. Iftode, and B. Nath, "Real-time air quality monitoring through mobile sensing in metropolitan areas," in *UrbComp '13 Proceedings of the 2nd ACM SIGKDD International Workshop on Urban Computing*, Chicago, Illinois, August 2013.

[44] J. Jo, B. Jo, R. M. A. Khan, and J. Kim, "A cloud computing-based damage prevention system for marine structures during berthing," *Ocean Engineering*, vol. 180, pp. 23–28, 2019.