Indonesian Journal of Electrical Engineering and Computer Science
Vol. 26, No. 1, April 2022, pp. 105~115
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v26.i1.pp105-115

Low-cost nitrogen dioxide monitoring station based on metal oxide sensor and cellular network

Rady Purbakawaca[1], Arief Sabdo Yuwono[2], Husin Alatas[3], I Dewa Made Subrata[1]
[1]Department of Mechanical and Biosystems Engineering, Faculty of Agricultural Engineering and Technology, IPB University, Bogor, Indonesia
[2]Department of Civil and Environmental Engineering, Faculty of Agricultural Engineering and Technology, IPB University, Bogor, Indonesia
[3]Department of Physics, Faculty of Mathematics and Natural Sciences, IPB University, Bogor, Indonesia

Article Info

Article history:

Received Nov 10, 2021
Revised Feb 7, 2022
Accepted Feb 12, 2022

Keywords:

Air monitoring
GSM network
Low-cost sensor
MiCS-6814
MOX
Nitrogen dioxide

ABSTRACT

Air pollution has a negative impact on the environment and human health. Meanwhile, the number of conventional air quality monitoring stations is minimal due to high procurement and operational costs. This study proposes a nitrogen dioxide (NO_2) pollutant measurement system using the metal oxide sensor (MOX) sensor and cellular network for data transmission in the measurement area. A calibration curve is used to measure NO_2 levels based on the sensor's internal resistance changes. Measurement data of NO_2 concentration, air temperature, relative humidity, and geospatial information are compiled and sent via global positioning system (GSM), general packet radio service (GPRS) radio communication with transmission intervals of every minute. The database server processes the data and displays it on the web application. System testing results at the Tugu Kujang Bogor at 15:38:00-16:38:00 September 23, 2021, showed that the concentration of NO_2 ranged from 0.16-0.52ppm with an average of 270 ppb with an AQI of 133 in the unhealthy category for the sensitive group. The measured NO_2 levels are outside the range of the NO_2 concentration database in the industrial areas of Bogor and Jakarta for the 2016-2020 period. Therefore, this system provides an excellent opportunity to obtain real-time measurement data in the field.

Corresponding Author:

Arief Sabdo Yuwono
Department of Civil and Environmental Engineering
Faculty of Agricultural Engineering and Technology IPB University
Bogor, Indonesia
Email: arief.sabdo.yuwono66@gmail.com

1. INTRODUCTION

A serious environmental problem faced in the world in recent times is air pollution. The use of fossil fuel-based energy in the industrial and transportation sectors is a significant cause of releasing pollutants (hydrocarbons, nitrogen oxides, carbon monoxide, and particulates) into the ambient air system, causing severe public health problems [1], [2]. NOx is a pollutant that contributes to air pollution and increases ambient air concentration. NOx includes nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), dinitrogen trioxide (N_2O_3), and dinitrogen tetroxide (N_2O_4) [3].

One of the principal pollutants of concern is nitrogen dioxide gas (NO_2) produced from the conversion of NO with volatile organic compounds. In the short term, NO_2 concentrations exceeding 200 $\mu g/m^3$ can cause significant respiratory tract inflammation [4]. Meanwhile, nitric and nitric acids are formed by photo-oxidation of NO, hydrocarbons (HC), and ozon (O_3), a source of nitric acid rain [5]. NO_2 can irritate the respiratory system, chronic obstructive pulmonary, asthma, emphysema, bronchitis, nitration of heme to form nitroso hemoglobin, and increased risk of heart and cardiovascular disease have been reported in the literature [6]–[8].

Air pollution and air quality monitoring efforts have received public attention in Indonesia. The government has implemented stricter laws to control air pollution and built automatic air quality monitoring stations that operate actively and continuously in addition to existing conventional methods. The authority installs stationary air quality monitoring stations in specific locations based on the measurement strategy and criteria for establishing monitoring stations. There are 46 monitoring stations under the Ministry of Environment and Forestry spread across the five largest islands in Indonesia. The island of Java is where the most monitoring stations are placed due to the dense population and activities in urban areas. A total of nine stations are spread across major cities on the island of Java, and this number is still far from ideal. Under these conditions, an accurate and low-cost air pollution monitoring system installed in many areas can help increase the coverage area of the existing air quality monitoring system.

The main requirements of a low-cost air quality monitoring system are accuracy, affordability, and real-time data transmission. Data transmission can be designed using a low-cost wireless sensor network (WSN) to improve the temporal distribution of the spatial resolution of the measured pollutant concentration [9]. In the paper, Rasyid *et al.* [10] has successfully implemented an environmental monitoring system based on the KAA-IoT platform with the scalability of data delivery, transaction speed, throughput, concurrency, and response time. In addition, it ensures that data generated by monitoring tools can be collected in an information center and used for broader purposes [11], [12]. The data collected can be processed to estimate pollution levels, alarms, and warning systems based on ambient temperature and relative humidity [13]. The air pollution monitoring system developed by [14] increased spatial resolution and described the variability of pollutant gas concentrations in various locations by embedding GPS on the monitoring device.

Therefore, this research's main objective is to design an air quality monitoring system focusing on measuring pollutant NO_2. This research builds a NO_2 gas measurement system using an inexpensive MiCS-6814 sensor and a weather sensor integrated with the AT2560 controller and equipped with a SIM7000E wireless data transmission module. Web applications and databases have been developed to collect and process sensor measurement data such as NO_2 concentration, temperature, relative humidity, time stamp, and monitoring locations. The nitrogen dioxide concentration data measured by the system was validated with a third-party NO_2 concentration database to verify the system's measurement results.

2. METHOD

This research was carried out comprehensively, covering the stages of studying literature on the characteristics of NO_2 pollutants, designing and implementing a NO_2 monitoring system, collecting and processing NO_2 concentration monitoring data, and comparing the NO_2 concentration monitored as primary data with the NO_2 database provided by a third party as secondary data, as in Figure 1.

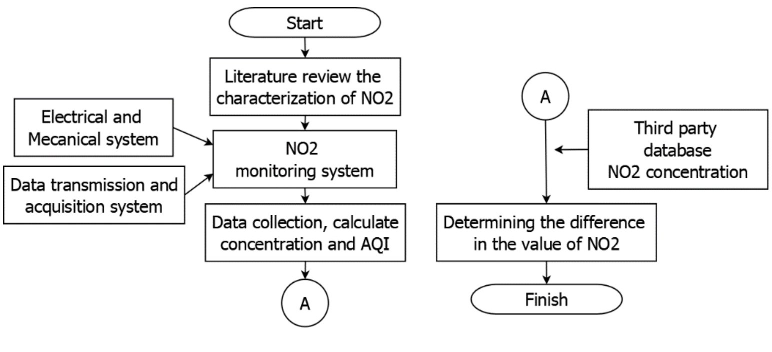


Figure 1. Research overview

2.1. Concept and design

The sensor nodes developed are solar-powered, weather-resistant, and stationery designs. In addition, the sensor nodes can measure NO_2 pollutants, air temperature, relative humidity, and geospatial indicators such as latitude and longitude indicate the sensor unit's location. Over the last few decades, many gas sensors have been developed based on materials and sensing methods. Based on this, gas sensors can be classified into catalytic combustion, electrochemical, thermally conductive, infrared absorption, paramagnetic, solid electrolyte, and metal oxide semiconductor sensors [15]. Metal oxide (MOX) and electrochemical (EC) sensors are two low-cost gas sensors that are widely reported to measure ambient air pollution [16], [17]. The MOX sensor has wide commercial availability at a low-cost [18] compared to the EC sensor. However, the EC sensor has a linear response to the target gas concentration [19]. Based on Table 1, MOX sensors have advantages over other sensors, especially in sensitivity, response time, stability, price, integration with instrumentation systems, and maintenance.

Table 1. Comparison of gas sensor types [15]

Parameter	Gas sensor variant				
	Semiconductor	*Catalytic combustion*	*Electrochemical*	*Thermal conductive*	*Infrared absorption*
Sensitivity	E	G	G	B	E
Accuracy	G	G	G	G	E
Selectivity	P	B	G	B	E
Response time	E	G	P	G	P
Stability	G	G	B	G	G
Durability	G	G	P	G	E
Maintenance	E	E	G	G	P
Cost	E	E	G	G	P
The flexibility of integration	E	G	P	G	B

In general, the sensor node consists of two primary systems, namely, sensors and wireless communication (see Figure 2). The sensor module consists of a MiCS-6814 OX sensor that can detect NO_2, NO, and H_2 gases with a measurement range of 0.05–10.0ppm, 0.1–1.0ppm, and 1–1000ppm, respectively [20]. This sensor was selected based on its ability to monitor a wide range of gases and its very affordable cost—however, usually, the lower the price, the lower the accuracy [21].

The SIM7000E communication module is a chipset capable of receiving, storing, and transmitting data wirelessly over global positioning system (GSM), general packet radio service (GPRS) cellular networks [22]. The communication module is also equipped with a GPS so that it is possible to know the position of nodes using geospatial information. The power supply module uses solar panels and circuitry to recharge the 12V/ 7.2 AH valve regulated lead acid (VRLA) battery that powers all the node's electronic components, as shown in Figure 2.

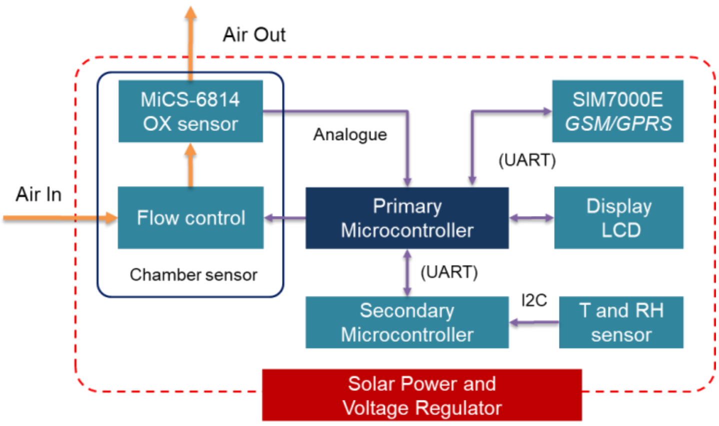


Figure 2. The electrical schematic of the ambient NO_2 monitoring system

The costs for all electronic and mechanical components to build sensor nodes are detailed in Table 2. The costs include PCB manufacturing and assembly, internet, and cloud server subscription costs for 800 USD, as presented in Table 2. This cost is lower when compared to commercially available air pollution sensors, which cost more than 5000-10000 USD. Automated air quality monitoring systems that can measure air pollutants are often more expensive but have very high selectivity and accuracy than low-cost sensors [23].

2.2. Microcontroller and driver circuitry

The sensor node uses the AT2560 chipset, available in an Arduino 2560 board. The microcontroller chipset can be embedded with firmware to measure signals from sensors, access modules such as GSM/GPRS modules, display data, and others. Three universal asynchronous receiver and transmitter (UART) channels are required for the main microcontroller to access the wireless communication module, the secondary microcontroller, and the Nextion display module. These three modules have chipsets that reduce the computational load and time of the main microcontroller.

The MiCS-6814 sensor is a micro-electro-mechanical system (MEMS) chip produced by SGX sensortech to detect pollution from environments and industries. MiCS-6814 is a compact MOX sensor with three utterly independent sensing elements in one package: RED sensor, OX sensor, and NH_3 sensor. Concerning the design of the NO_2 pollutant measurement system, MiCS-6814 was chosen because there is a sensing element in the form of an OX sensor that can detect NO_2 with characteristics are shown in Table 3.

Table 2. Cost to build NO_2 monitoring system

Component	Approximate cost (USD)
MCU AT2560 (Primary controller)	51.50
MCU Atmega 328 (Secondary controller)	35.41
SIM7000E	63.00
Sensor MiCS-6814 and Weather sensor	288.71
Box enclosure, solar panel, and battery VRLA	111.72
Nextion LCD	80.05
Miscellaneous	200.00
Total cost	**800.39**

Table 3. The electrical characteristic of the OX sensor [20]

Characteristic OX sensor	Symbol	Typical	Min	Max	Unit
Sensing resistance in the air	R_0	-	0.8	20	kΩ
Typical NO_2 detection range	FS	-	0.05	10	ppm
Heating voltage	V_H	1.7	-	-	V
Heating resistance at nominal power	R_H	66	59	73	Ω
Voltage supply heating current	V_{supply}	-	4.9	5.1	V
Relative humidity range	RH	-	5	95	% RH
Ambient operating temperature	T_{amb}	-	-30	85	°C

The MiCS-6814 document number 1143 revision 8, the sensor power supply circuit recommended by the manufacturer, and the sensor signal measurement circuit are presented in Figure 3(a). Figure 3(b) shows the resistance value of R_1 of 130 Ω in series with the heating resistance of the OX sensor to obtain the correct heating element temperature. When the circuit is given a single 5V power supply, the voltage generated on the heating element (V_H) is 1.7 V. A single resistance value R_6 of 56 kΩ (resistance load), which is connected with the internal resistance of the R_S sensor (resistance when there is a gas target) [24]. Therefore, the OX sensor signal output path marked "NO_2_VALUE" is connected to the 10-bit ADC microcontroller based on the voltage divider principle [25]. The ratio of resistance R_s and R_o (resistance sensor in clean air) is mathematically expressed as follows [26].

$$R_s = R_L \times \left(V_{supply} - V_{output}\right)/V_{output} \quad (1)$$

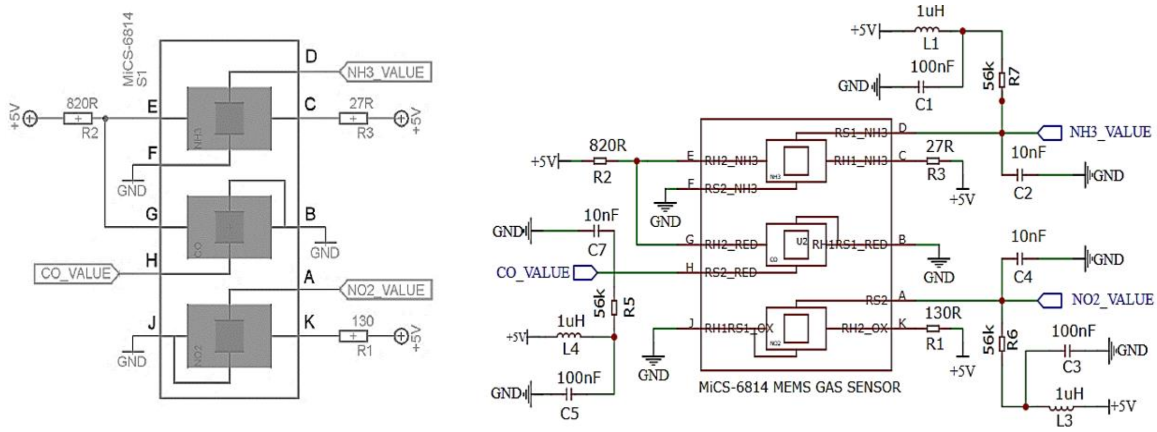
This paper selects an Average Moving Filter (MAF) as a general denoising method equivalent to low pass filtering [27]. MAF works by averaging several points within a specified data point range from the input signal to produce each output signal point, as in (2). For this research, in an interval of 1 s, the sensor value reading is 33 times and is processed into one MAF value in the form of y[k].

$$y[k] = \frac{1}{N}\sum_{n=0}^{N-1} x[k+n] \quad (2)$$

where N is the number of data before the output signal, and y is the output signal.

2.3. Network configuration

GPRS is part of the GSM which can be used as a data transmission protocol for air quality measurement tools [28], [29]. SIM7000E is a Tri-Band LTE-FDD and Dual-Band GPRS/EDGE wireless module that supports LTE CAT-M1and NB-IoT [22]. The data collected from the sensor nodes are sent to the server to be displayed on a web page. Thus, the transmitted data can reach the end-user through two stages: from the device to the network server and from the network server to the application server see Figure 4.



(a) (b)

Figure 3. MiCS-6814 (a) supply circuit [20] and (b) measurement circuit [24]

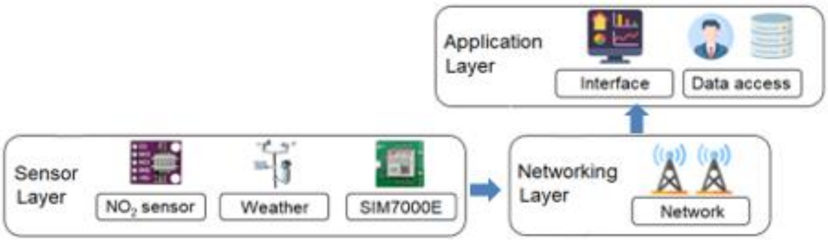


Figure 4. Data transmission architecture

2.4. Mechanical design

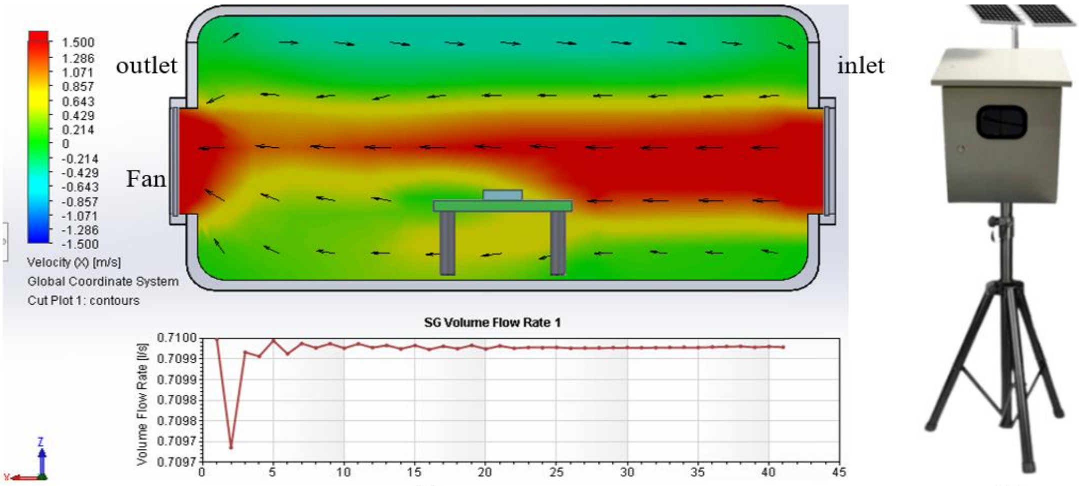
The node consists of two primary enclosures (Figure 5). The first cover is a chamber that houses sensors and drivers, while the second covers the primary control circuit and solar panels. Figure 5(a) and Figure 5(b) show the design of the sensor chamber, which is in the form of a box with dimensions of 110x60x50 mm, the thickness of 1 mm, and has inlet and outlet ventilation for circulating pollutant gases and air. The airflow rate through the sensor was set at 0.70 L/m. In addition, this study installed a DC fan at the outlet chamber, simulated to have the same flow rate. The fan is regulated using pulse width modulation control using TIP 122.

2.5. Index and concentration level of NO_2

The method of determining air quality status is based on calculating the air quality index (AQI) according to the US EPA standard for daily air quality reporting. The main parameters for indexing include particulate matter (diameter less than 10 µm and 2.5 µm diameter), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and sulfur dioxide (SO_2). Air pollutant levels are converted into air quality indexes and categories for each pollutant [30]. In this study, the server calculates the index value of the NO_2 concentration value sent from the node using the (3) by referring to Table 4 to determine the two breakpoint values that cover the observed concentration (C_p) [14].

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} (C_p - BP_{Lo}) + I_{Lo} \tag{3}$$

Where BP_{Hi} and BP_{Lo} are concentration breakpoint that is the higher and lower than or equal concentrations of the air pollutant, I_{Hi} and I_{Lo} are the AQI values that corresponded to those concentration breakpoints, and I_p is the AQI values corresponding to pollutant concentration *p*, in this case, NO_2.



(a) (b)

Figure 5. Design chamber (a) airflow simulation and (b) stationary system

Table 4. The concentration breakpoint for AQI of NO_2 [30]

AQI	Breakpoint concentration of NO_2 (ppb) 1-hour	Category	Color
0-50	0-53	Good	Green
51-100	54-100	Moderate	Yellow
101-150	101-360	Unhealthy for Sensitive Groups	Orange
151-200	361-649	Unhealthy	Red
201-300	650-1249	Very unhealthy	Purple
301-400	1250-1649	Hazardous	Maroon
401-500	1650-2049	Hazardous	Maroon

3. RESULTS AND DISCUSSION

The comprehensive implementation that has been carried out is presented in Table 5. The system starts at the sensor node by turning on the device and then initializing the connection to the cellular network, collecting data, constructing the data packet format, sending and displaying data on the monitoring dashboard. Finally, the sensor node sends the measurement data to the server using the TCP/IP protocol in JavaScript object notation (JSON), as provided in Table 6.

Table 5. The NO_2 monitoring system algorithm

Input: Measure pollution, temperature, relative humidity, and air quality index of NO_2 pollutant **Output:** Web app with all features pollution control
Algorithm **Step 1:** Initialize device to connect GSM, GPRS network, and set an interval for 1 minute **Step 2:** Read sensor MiCS-6814 (for 1 s reading 33 times) **Step 3:** Read sensor temperature and relative humidity (for 1 s reading one time) **Step 4:** Get timestamp and geospatial information from the GSM module **Step 5:** Compile Data In JSON Format, connect to TCP/IP port to send data and display data to the LCD **Step 6:** Data is stored in an appropriate format, and the server sends the response success or fail **Step 7:** The server's response is displayed in LCD to verify that the data success or fail **Step 8:** Data displayed in the dashboard (Fetching data for google maps and graphs)

It is essential to check and test the commands on the Arduino sketch based on the algorithm that has been designed to ensure that the NO_2 sensor works as expected. The algorithm for reading the NO_2 signal and converting the digital value to the NO_2 pollutant concentration unit is shown in Table 7. Unfortunately, the calibration curve in Figure 6 is only available as a graph without any calibration equations in mathematical notation. Therefore, this study has presented the calibration equation by overlaying the calibration curve of the datasheet with a graph made in excel. This simple method visually relies on a difference between the datasheet calibration curve and the mathematical equation.

Table 6. JSON structure for NO_2 monitoring system

JSON	Description
{"sTime": "0000-00-00 00:00:00",	The timestamp of reading the sensor value
"NO_2": 0, "T": 0,"RH": 0	NO_2 concentration, temperature and relative humidity
"lat": 0.000000,"lon": 000.00000,	Geospatial information: altitude and longitude
"devID": "device_name",	Unique sensor node identity (Primary key)
"username": "username", "password": "password"}	Basic authentication (Restricted)

Table 7. The NO_2 monitoring system algorithm

Input: pin number, sample time, heating time
Output: NO_2 concentration in the environment
Algorithm
Step 1: Make sure the NO_2 sensor is connected to the appropriate analog pin
Step 2: The process of heating the sensor and reading the output signal of the MiCS-6814 sensor, especially the OX sensor, and sensing resistance in clean air (R_o)
Step 3: Sensing the OX sensor resistance (R_s) and converting the resistance ratio value (R_s/R_o) to the NO_2 pollutant concentration using the calibration curve, as shown in Figure 6

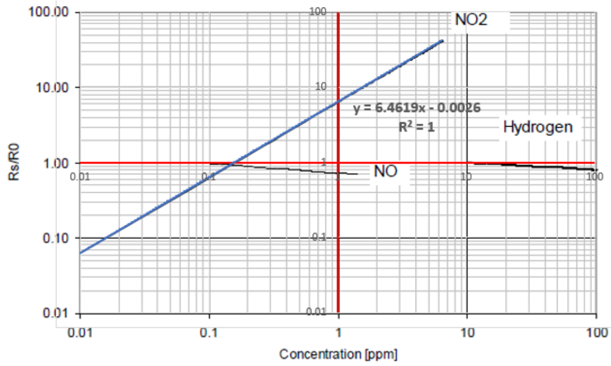


Figure 6. The OX sensor calibration curve on the MiCS-6814 sensor [20]

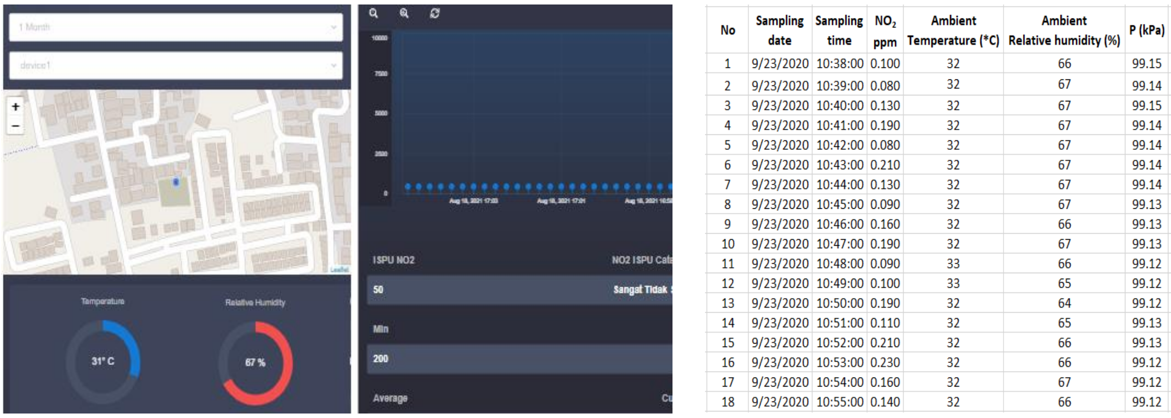
Based on Figure 6, the mathematical equation expresses y in the ratio of $^{R_s}/_{R_o}$ and x in NO_2 concentration. Therefore, it is necessary to reverse it to obtain a formula for calculating NO_2 concentration.

$$x = \left(^{1}/_{6.4619}\right) \times (y + 0.0026) \quad (4)$$

Where x is the ratio of $^{R_s}/_{R_o}$ without units, and y is the concentration of NO_2 in ppm.

The web application is built using the Go-Lang programming language and JavaScript with the VueJS framework. The web application is designed to respond to the user's mobile display appropriately, as represented in Figure 7(a). The primary function of the dashboard is to display and store sensor readings. The sensor node must be registered in the web application to get the device id embedded in the JSON data as the value of the "devID" key and the primary authentication username and password. Only data sent by registered sensor nodes can be stored and displayed.

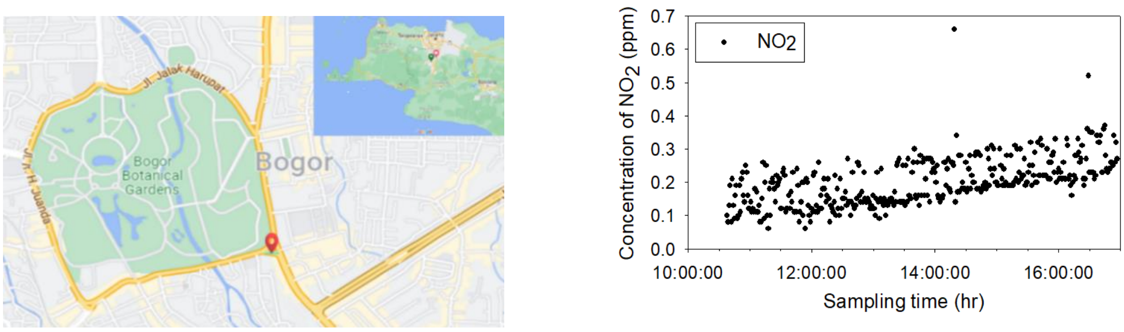
Figure 7(b) shows the display of data downloaded from a web application containing data that the sensor node has sent in a comma-separated values (CSV) file. CSV files are built to make it easier for users to analyze further, create graphs, and make descriptive statistical analyses to find out the maximum, minimum, average, range, and so on. The NO_2 pollutant monitoring system was tested at the Tugu Kujang Landmark, Pajajaran Bogor Botanical Gardens Road, as shown in Figure 8(a). The determination of this location is due to the large number of motorized vehicles passing through the location. The test was carried out on September 23, 2021, for 6 hours with an interval of 1 minute, and the NO_2 concentration data is presented in Figure 8(b). Statistical analysis showed that NO_2 concentration ranged from 0.06-0.66ppm with an average of 0.20ppm. In the time range 15:38:00-16:38:00, the NO_2 concentrations ranged from 0.16-0.52ppm with an average of 0.27ppm. The average NO_2 concentration converted into ppb units according to Table 4. The AQI (NO_2 1-hour) was calculated and obtained 133 with an unhealthy for sensitive groups category in Table 8.



No	Sampling date	Sampling time	NO_2 ppm	Ambient Temperature (°C)	Ambient Relative humidity (%)	P (kPa)
1	9/23/2020	10:38:00	0.100	32	66	99.15
2	9/23/2020	10:39:00	0.080	32	67	99.14
3	9/23/2020	10:40:00	0.130	32	67	99.15
4	9/23/2020	10:41:00	0.190	32	67	99.14
5	9/23/2020	10:42:00	0.080	32	67	99.14
6	9/23/2020	10:43:00	0.210	32	67	99.14
7	9/23/2020	10:44:00	0.130	32	67	99.14
8	9/23/2020	10:45:00	0.090	32	67	99.13
9	9/23/2020	10:46:00	0.160	32	66	99.13
10	9/23/2020	10:47:00	0.190	32	67	99.13
11	9/23/2020	10:48:00	0.090	33	66	99.12
12	9/23/2020	10:49:00	0.100	33	65	99.12
13	9/23/2020	10:50:00	0.190	32	64	99.12
14	9/23/2020	10:51:00	0.110	32	65	99.13
15	9/23/2020	10:52:00	0.210	32	66	99.13
16	9/23/2020	10:53:00	0.230	32	66	99.12
17	9/23/2020	10:54:00	0.160	32	67	99.12
18	9/23/2020	10:55:00	0.140	32	66	99.12

(a) (b)

Figure 7. Development of (a) web application display view and (b) NO_2 data monitoring in CSV format



(a) (b)

Figure 8. The NO_2 (a) sampling locations and (b) measurement results

Table 8. AQI of NO_2 pollutants at the Tugu Kujang Landmark, Pajajaran Bogor Botanical Gardens Road

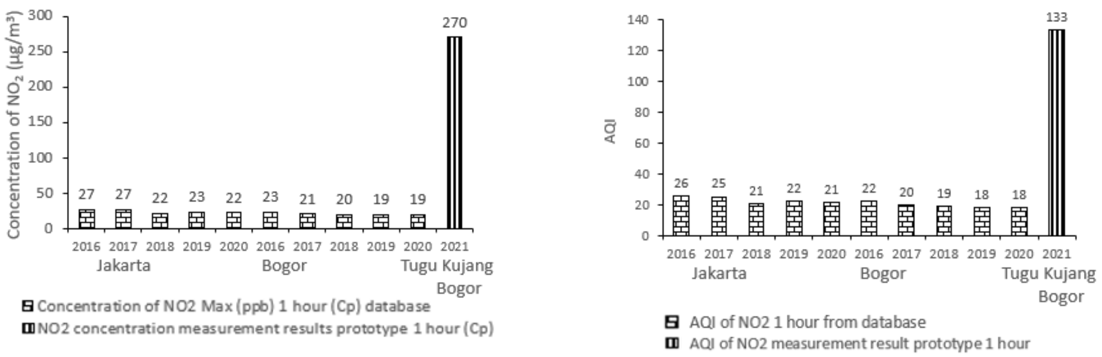
Sampling point	Year	Concentration of NO_2 (ppb) 1 hour	Concentration breakpoint of NO_2 (AQI 0-50)		AQI breakpoint		AQI	AQI Category and color
		(Cp)	BP_{LO}	BP_{Hi}	I_{LO}	I_{Hi}		
Tugu Kujang, Jalan Raya Pajajaran Bogor Botanical Gardens, Bogor City	2021	270	101	360	101	150	133	Unhealthy for Sensitive Groups

In this study, secondary data used to help validate the measurement results is a database of NO_2 concentrations in the Bogor and Jakarta areas provided by PT Unilab Perdana with conventional methods according to government regulations, as summarized in Table 9. In the 2016-2020 period, NO_2 concentration monitoring data in the city of Jakarta was obtained from 4017 samplings, most of which were spread in industrial areas with NO_2 concentrations in the range of 6-51 µg/m^3. In the same period, monitoring data on NO_2 concentrations in the Bogor district were obtained from 396 samplings, almost entirely in industrial areas with a NO_2 concentration of 14-44 µg/m^3. The AQI of NO_2 is defined by first converting the maximum concentration value at each location and year into ppb units considering the molecular weight of NO_2. According to US-EPA standards, the calculation results show that AQI is in a good category.

A comparison of the NO_2 measurement data by the prototype with the NO_2 database is presented in Figure 9. The comparison determines whether the NO_2 concentration reading by the design system approximates the value of the NO_2 concentration measurement database, as shown in Figure 9(a). It becomes essential to know the operational performance of a system designed with limitations in providing standard equipment or even accessing data from a government continuous air quality monitoring system. Measurement of NO_2 gas using a system that is much higher than the NO_2 concentration database causes the results of the AQI NO_2 prototype calculation to be higher than the database, as shown in Figure 9(b). It could be due to the ability of the MiCS-6814 sensor to detect that the target gas is not selective (see Figure 6). In addition, motor vehicle exhaust CO, NOx, and HC, especially NOx, can cause errors in the sensor output signal, thereby increasing the measurement results of NO_2 concentrations.

Table 9. The NO_2 concentration database in the Bogor and Jakarta areas in the 2016-2020 period

Sampling point	Number of data	Year	Concentration of NO_2 (µg/m^3) 1 hour			Concentration max. of NO_2 (ppb) 1 hour (Cp)	Concentration breakpoint of NO_2 (AQI 0-50)		AQI breakpoint		AQI	AQI Category and color
			Max.	Min.	Ave.		BP_{LO}	BP_{Hi}	I_{LO}	I_{Hi}		
Jakarta City	4017	2016	51	6	31	27	0	53	0	50	48	Good
		2017	50	11	31	27	0	53	0	50	47	Good
		2018	41	18	30	22	0	53	0	50	39	Good
		2019	44	16	30	23	0	53	0	50	42	Good
		2020	42	14	32	22	0	53	0	50	40	Good
Bogor city	396	2016	44	14	30	23	0	53	0	50	42	Good
		2017	39	14	29	21	0	53	0	50	37	Good
		2018	37	23	29	20	0	53	0	50	35	Good
		2019	36	20	28	19	0	53	0	50	34	Good
		2020	36	15	29	19	0	53	0	50	34	Good



(a) (b)

Figure 9. The comparison of the results of (a) measurements of NO_2 concentrations at Tugu Kujang Bogor against databases of NO_2 concentrations in Jakarta and Bogor, and (b) final difference of AQI value between database and prototype

The results of measuring NO_2 concentration using a system with a NO_2 concentration database can also be caused by using a calibration formula based on the datasheet provided by the manufacturer. The relationship between R_s/R_o and NO_2 concentration in the datasheet occurs under controlled conditions at 25 °C and 50% relative humidity. However, when measuring NO_2 in the field, the environmental temperature and humidity conditions changed in the range of 29.3–33.2 °C and 60–85.3 %. It means that the output signal drifts due to changes in temperature and humidity in the environment so that the gas sensor's accuracy and measurement stability are affected. Therefore, a temperature and humidity compensation strategy is needed for sensors with hardware and software approaches such as the one developed. In addition, the use of calibration equations provided by the manufacturer results in less accurate measurements. Therefore, the sensor needs to be calibrated with standard equipment [31] and a temperature and humidity compensation strategy with a hardware and software approach developed by [32] to improve the measurement accuracy.

4. CONCLUSION

This study proves that the NO_2 pollutant measurement system using a low-cost gas sensor based on cellular communication can provide a high opportunity to obtain data from the sensor node at the sampling location. Furthermore, air quality measurements can be carried out using a cheap sensor, MiCS-6814. However, measuring NO_2 concentrations at Tugu Kujang Bogor are outside the range of the NO_2 concentration database in Bogor City and Jakarta in the 2016-2020 period. Nevertheless, the low-cost MiCS-

6814 sensor has considerable for further development by applying temperature and relative humidity compensation algorithms.

ACKNOWLEDGEMENTS

We are grateful to the PT. Unilab Perdana and IPB University's unwavering support for study scholarships made this research possible.

REFERENCES

[1] N. R. S. Olmo, P. H. do N. Saldiva, A. L. F. Braga, C. A. Lin, U. de P. Santos, and L. A. A. Pereirai, "A review of low-level air pollution and adverse effects on human health: Implications for epidemiological studies and public policy," *Clinics*, vol. 66, no. 4, pp. 681–690, 2011, doi: 10.1590/S1807-59322011000400025.

[2] E. Lavaine, "An econometric analysis of atmospheric pollution, environmental disparities and mortality rates," *Environmental and Resource Economics*, vol. 60, no. 2, pp. 215–242, 2015, doi: 10.1007/s10640-014-9765-0.

[3] C. K. Varshney and A. P. Singh, "Passive samplers for NOx monitoring: A critical review," *Environmentalist*, vol. 23, no. 2, pp. 127–136, 2003, doi: 10.1023/A:1024883620408.

[4] M. Iriti, P. Piscitelli, E. Missoni, and A. Miani, "Air pollution and health: the need for a medical reading of environmental monitoring data," *International Journal of Environmental Research and Public Health*, vol. 17, no. 7, 2020, doi: 10.3390/ijerph17072174.

[5] Q. Zhang, G. N. Geng, S. W. Wang, A. Richter, and K. Bin He, "Satellite remote sensing of changes in NO x emissions over China during 1996-2010," *Chinese Science Bulletin*, vol. 57, no. 22, pp. 2857–2864, 2012, doi: 10.1007/s11434-012-5015-4.

[6] W. Q. Gan, H. W. Davies, M. Koehoorn, and M. Brauer, "Association of long-term exposure to community noise and traffic-related air pollution with coronary heart disease mortality," *American Journal of Epidemiology*, vol. 175, no. 9, pp. 898–906, 2012, doi: 10.1093/aje/kwr424.

[7] G. B. Hamra, F. Laden, A. J. Cohen, O. Raaschou-Nielsen, M. Brauer, and D. Loomis, "Lung cancer and exposure to nitrogen dioxide and traffic: A systematic review and meta-analysis," *Environmental Health Perspectives*, vol. 123, no. 11, pp. 1107–1112, 2015, doi: 10.1289/ehp.1408882.

[8] H. Olstrup, C. Johansson, B. Forsberg, and C. Åström, "Association between mortality and short-term exposure to particles, ozone and nitrogen dioxide in Stockholm, Sweden," *International Journal of Environmental Research and Public Health*, vol. 16, no. 6, 2019, doi: 10.3390/ijerph16061028.

[9] T. S. Gunawan, Y. M. S. Munir, M. Kartiwi, and H. Mansor, "Design and implementation of portable outdoor air quality measurement system using arduino," *International Journal of Electrical and Computer Engineering*, vol. 8, no. 1, pp. 280–290, 2018, doi: 10.11591/ijece.v8i1.pp280-290.

[10] M. U. H. Al Rasyid, M. H. Mubarrok, and J. A. N. Hasim, "Implementation of environmental monitoring based on kaa iot platform," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 6, pp. 2578–2587, 2020, doi: 10.11591/eei.v9i6.2578.

[11] A. L. Clements *et al.*, "Low-cost air quality monitoring tools: From research to practice (A workshop summary)," *Sensors (Switzerland)*, vol. 17, no. 11, pp. 1–20, 2017, doi: 10.3390/s17112478.

[12] A. Samad, F. E. M. Mimiaga, B. Laquai, and U. Vogt, "Investigating a low-cost dryer designed for low-cost PM sensors measuring ambient air quality," *Sensors (Switzerland)*, vol. 21, no. 3, pp. 1–18, 2021, doi: 10.3390/s21030804.

[13] W. J. Ng and Z. Dahari, "Enhancement of real-time IoT-based air quality monitoring system," *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 1, pp. 390–397, 2020, doi: 10.11591/ijpeds.v11.i1.pp390-397.

[14] A. M. Talib and M. N. Jasim, "Geolocation based air pollution mobile monitoring system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 23, no. 1, p. 162, 2021, doi: 10.11591/ijeecs.v23.i1.pp162-170.

[15] G. Korotcenkov, "Metal oxides for solid-state gas sensors: What determines our choice?," *Materials Science and Engineering B: Solid-State Materials for Advanced Technology*, vol. 139, no. 1, pp. 1–23, 2007, doi: 10.1016/j.mseb.2007.01.044.

[16] E. G. Snyder *et al.*, "The changing paradigm of air pollution monitoring," *Environmental Science and Technology*, vol. 47, no. 20, pp. 11369–11377, 2013, doi: 10.1021/es4022602.

[17] A. C. Rai *et al.*, "End-user perspective of low-cost sensors for outdoor air pollution monitoring," *Science of the Total Environment*, vol. 607–608, pp. 691–705, 2017, doi: 10.1016/j.scitotenv.2017.06.266.

[18] R. Piedrahita *et al.*, "The next generation of low-cost personal air quality sensors for quantitative exposure monitoring," *Atmospheric Measurement Techniques*, vol. 7, no. 10, pp. 3325–3336, 2014, doi: 10.5194/amt-7-3325-2014.

[19] M. I. Mead *et al.*, "The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks," *Atmospheric Environment*, vol. 70, pp. 186–203, 2013, doi: 10.1016/j.atmosenv.2012.11.060.

[20] SGX sensortech, "The MiCS-6814 is a compact MOS sensor with two fully independent sensing elements on one package.," pp. 1–5, 2017.

[21] G. Marques and R. Pitarma, "A cost-effective air quality supervision solution for enhanced living environments through the internet of things," *Electronics (Switzerland)*, vol. 8, no. 2, pp. 1–16, 2019, doi: 10.3390/electronics8020170.

[22] Shanghai SIMCom Wireless, "Application note SIM7000 Series." 2018, [Online]. Available: https://simcom.ee/documents/?dir=SIM7000x.

[23] S. Ali, T. Glass, B. Parr, J. Potgieter, and F. Alam, "Low cost sensor with IoT LoRaWAN connectivity and machine learning-based calibration for air pollution monitoring," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, no. c, 2021, doi: 10.1109/TIM.2020.3034109.

[24] A. N. Abdullah, K. Kamarudin, S. M. Mamduh, and A. H. Adom, "Development of MOX gas sensors module for indoor air contaminant measurement," in *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 705, no. 1, doi: 10.1088/1757-899X/705/1/012029.

[25] P. Megantoro, S. A. Aldhama, G. S. Prihandana, and P. Vigneshwaran, "IoT-based weather station with air quality measurement using ESP32 for environmental aerial condition study," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 19, no. 4, pp. 1316–1325, 2021, doi: 10.12928/TELKOMNIKA.v19i4.18990.

[26] L. R. Definition, O. Principle, L. R. Adjustment, and M. Circuit, "MiCS application note how to set-up load resistance for MiCS sensors measurements," *How to set-up load resistance for MiCS sensors measurenment*, no. September. pp. 1–2, 2014.

[27] E. Bassey, J. Whalley, and P. Sallis, "An evaluation of smoothing filters for gas sensor signal cleaning," *The Fourth International Conference on Advanced Communications and Computation*, no. c, 2014, pp. 19–23.
[28] S. Dhingra, R. B. Madda, A. H. Gandomi, R. Patan, and M. Daneshmand, "Internet of things mobile-air pollution monitoring system (IoT-Mobair)," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 5577–5584, 2019, doi: 10.1109/JIOT.2019.2903821.
[29] H. F. Hawari, A. A. Zainal, and M. R. Ahmad, "Development of real time internet of things (IoT) based air quality monitoring system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 13, no. 3, pp. 1039–1047, 2019, doi: 10.11591/ijeecs.v13.i3.pp1039-1047.
[30] US EPA, "Technical assistance document for the reporting of daily air quality – the air quality index (AQI)," *Environmental Protection*, p. 22, 2018, [Online]. Available: https://airnowtest.epa.gov/sites/default/files/2018-05/aqi-technical-assistance-document-may2016.pdf.
[31] P. Han *et al.*, "Calibrations of low-cost air pollution monitoring sensors for CO, NO2, O3, and SO2," *Sensors (Switzerland)*, vol. 21, no. 1, pp. 1–18, 2021, doi: 10.3390/s21010256.
[32] P. Xu, K. Song, X. Xia, Y. Chen, Q. Wang, and G. Wei, "Temperature and humidity compensation for MOS gas sensor based on random forests," *Communications in Computer and Information Science*, vol. 762, pp. 135–145, 2017, doi: 10.1007/978-981-10-6373-2_14.

BIOGRAPHIES OF AUTHORS

Rady Purbakawaca received his B.Sc. (Hons.) in the Department of Physics from IPB University, Indonesia in 2013 and M. Sc in Department of Civil and Environmental Engineering from IPB University, Indonesia in 2015. He is currently pursuing Dr. at the Department of Mechanical and Biosystem Engineering, IPB University. His research interest includes IoT, M2M network, Environmental Monitoring, Embedded System. He can be contacted at email: purbakawaca09rady@apps.ipb.ac.id.

Arief Sabdo Yuwono is a Professor in the Civil and Environmental Engineering, Faculty of Agricultural Engineering and Technology, IPB University. He completed his bachelor a BS degree in Agricultural Engineering from Bogor Agricultural University, Indonesia, in 1989, MSc in Environmental Sanitation from Universiteit Gent, Belgium, in 1996, and a Ph.D. degree in Bio-Environmental Engineering from Universitaet Bonn, Germany, in 2003. His research interests include environmental monitoring water and air pollution quality control. In addition, he was an air quality and noise expert, air emission expert, and environmental and agricultural specialist. He can be contacted at email: arief.sabdo.yuwono66@gmail.com.

Husin Alatas is a Professor in the Physics Department, Faculty of Mathematics and Natural Sciences, IPB University, Bogor, Indonesia. He received a BS, MSc, and a Ph.D. degree from Bandung Institute of Technology, Indonesia, in 1995, 1998, and 2005, respectively. Currently, he is Head of the Theoretical Physics Division at IPB University. He is also a member of the Indonesia Center for Theoretical and Mathematical Physics (ICTMP), Indonesian Optical Society (InOS), and Optical Society of America (OSA). His research interest includes the theory and modeling of the photonic crystal-based sensor. He can be contacted at email: s.h.alatas@gmail.com.

I Dewa Made Subrata is an Associate Professor in the Department of Mechanical and Biosystem Engineering, Faculty of Agricultural Engineering and Technology, IPB University, Bogor, Indonesia. A BS at Bogor Agricultural University in 1986, his Master degree at Shimane university Japan in 1995, and his Ph.D. degree at The United Graduate School of Agricultural Sciences, Tottori University, Japan, in 1998. His main research topic is Robotic and Automation in Agriculture. He can be contacted at email: dewamadesubrata.ipb@gmail.com.