



RESEARCH ARTICLE

An IoT-based Wireless Monitoring System for the Measurement of SO₂ and NO₂ Concentrations Emitted from a Point Source

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Abstract: This study presents an innovative and cost-effective IoT-based wireless monitoring system for real-time detection of SO₂ and NO₂ emissions, addressing limitations of conventional bulky and expensive monitoring tools. The system was designed using SO₂, NO₂, and meteorological sensors integrated with a microprocessor that processes data and transmits it to a cloud repository. Experimental work involved system design and field implementation. The system demonstrated good stability, although communication performance remained limited and may require baud-rate improvement. Field deployment successfully measured SO₂ and NO₂ emissions from sawdust and coal combustion in an incinerator, as well as NO₂ from a 96 kWh diesel generator. Results showed significant SO₂ variations with only 25% exceedance of national air-quality standards, while the generator exhaust produced an average NO₂ concentration of 6.68 ppm—far below the QSA value of 79.9 ppm. These findings confirm the system’s capability for reliable pollutant monitoring in real time. Its portability, affordability, and web-based accessibility make the system suitable for environmental management applications, especially in developing regions. The system’s novelty lies in its cost-effectiveness and real-time sensing capability, offering strong potential for broader use in industrial, vehicular, and waste-combustion emission monitoring.

Keywords: air pollution, Internet of Things (IoT), Monitoring system, NO₂ and SO₂ emissions

1 Introduction

NO_2 and SO_2 pollution have serious impacts on human health, ecological balance, and environmental degradations such as acid rain and the greenhouse effect [1–3]. Nitrogen Oxide (NOx) is mainly formed from the emission of NO_2 and NO by anthropogenic activities. NOx emissions are influenced by anthropogenic activities as their main sources are vehicular, energy production, and waste disposal emissions. The formation of NO_2 and NO could be due to reactions between N in the presence of air as well as through the decomposition process of compounds of Nitrogen. SO_2 is a poisonous reddish-brown gas with a characteristic pungent odor while NO is colorless and odorless [4]. On the other hand, sources of sulfur compounds in the atmosphere include; combustion of fossil fuels, industrial activities, vehicular traffics, biomass burning, sea spray, smelting, and biogenic activities [5–7]. Sulfur is released into the atmosphere in the form of SO_2 which during oxidation could be transformed to SO_3 , a compound that readily combines moisture to form acid rain. SO_2 is a colorless, non-flammable, soluble gas with a pungent odor [8].

Air pollutants such as SO_2 , NOx, and particulates are highly associated with various human health impacts, especially respiratory tracts disorders such as emphysema, respiratory tracts irritation, asthma bronchitis, and lung inflammation [9,10]. In many countries, NO_2 and SO_2 contribute a fairly high percentage to the overall air pollution loads. For instance, NO_2 , SO_2 and atmospheric suspended particulates were the major pollutants in China, India, Central Asia, North America, and Europe. Based on data released by REAS (Regional Emission inventory in Asia), in 2015, NO_2 and SO_2 contributed 5.21 % and 5.0 % respectively to the air pollution load in Indonesia [11]. Furthermore, these two pollutants were ranked second and third of the most dominant among the five criteria air pollutants (hydrocarbon, CO, NO_2 , SO_2 , and particulates) in many metropolitan cities of Indonesia [12].

In addition to the health impacts, air pollutants could travel several thousand kilometers from its emission source point to impact a large number of receptors at local, national, and international regions, This could be probably due to its aerodynamic nature as well as the influence of local meteorological conditions. Therefore, this scenario buttresses the need for air pollution for scientists and researchers to conduct air pollution studies especially in urban areas with multifaceted air pollution sources. Despite the advancement in technology and information management, most studies on NO_2 and SO_2 monitoring was carried out using the conventional techniques of physical sample collection and laboratory-based analysis. However, such physical monitoring has several limitations; bulky equipment, consume a lot of man-hours, expensive, and in-ability to capture simultaneous in-situ meteorology data during sampling [13].

Nowadays, a technology for monitoring air pollutants in real-time has been developed. This is based on a wireless sensor system that uses the internet as a communication medium. This technology is known as the Internet of Things (IoT). IoT is a concept that aims to expand the benefits of internet connectivity. It can identify, monitor, track, collect data, control an object or environment automatically and in real-time, and measure local meteorology simultaneously [14]. The technology is cheap and uses less time to process results, unlike the conventional approach.

IoT system has two main components; hardware and software. The hardware consists of sensors, a microcontroller, memory, an operating system, wi-fi communication, and a power source [15]. The software is a web application where information in the form of text,

images, sound, and others are stored and displayed in hypertext form for the users. The web portal serves as a gateway for accessing information and services with a unique single-user interface. The advantages of a single-user interface are sufficient browsing speed and reliability of accessed information [16].

Its current limitations of this research is Network Dependence: GSM network quality can vary, affecting data transmission (noted as "unsatisfactory" in network QoS), Sensor Calibration and Accuracy: Due to low-cost sensors, accuracy may vary, demanding regular calibration, Limited Pollutant Types: Focused on SO_2 and NO_2 ; expanding to other gases could enhance comprehensiveness, and Power Supply and Energy Efficiency: Potential issues in remote areas lacking stable power sources.

2 Research Method

The research flow diagram can be seen in Figure 1

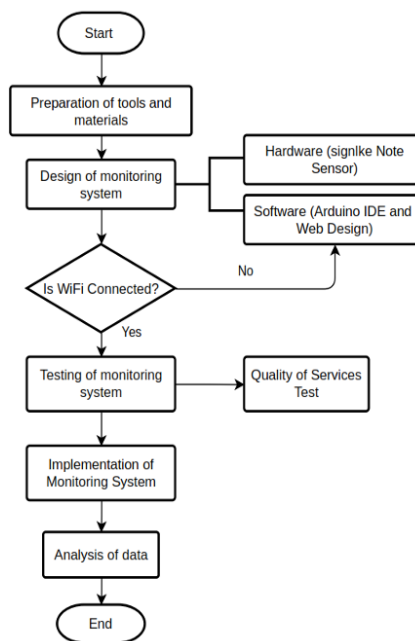


Figure 1: Flow diagram of this research

This study used hardware in the form of a single node sensor consisting of a Mega2560 microcontroller, GSM SIM900A module, 4 sensors (2 ZE03, 1 SHT15, and 1 Adafruit Anemometer), and a 2x16 character LCD. The features of the software were made use of PHP programming language and website development tools (which consists of text editor, web server, domain, and hosting features). The connection of equipment with the wireless sensor system is shown in Figure 2 is a schematic diagram of the IoT system for SO_2 and NO_2 detection in a point source of emission.

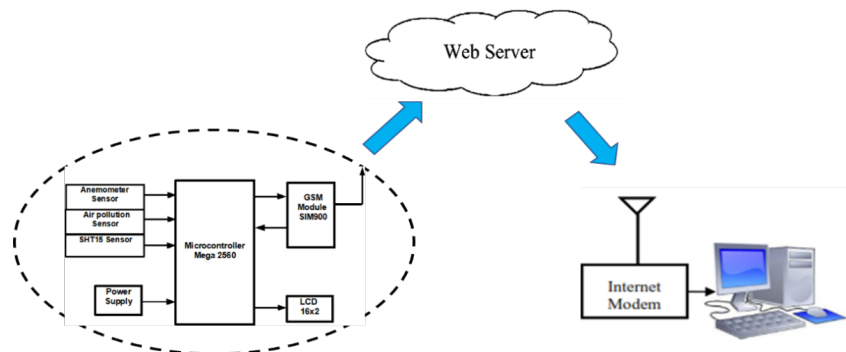


Figure 2: An overview of the detection of SO_2 , NO_2 gas pollutants, temperature, and humidity based on IoT

The IoT remote system works by converting the physical quantities (concentrations of SO_2 and NO_2 , temperature as well as humidity) which were captured by the sensor modules into analog voltages. This will be processed into digital data via Mega2560 microcontroller and transmitted through the GSM SIM900A module to a web server using the internet network. Figure 3 showed the schematic diagram of the IoT system circuit setup.

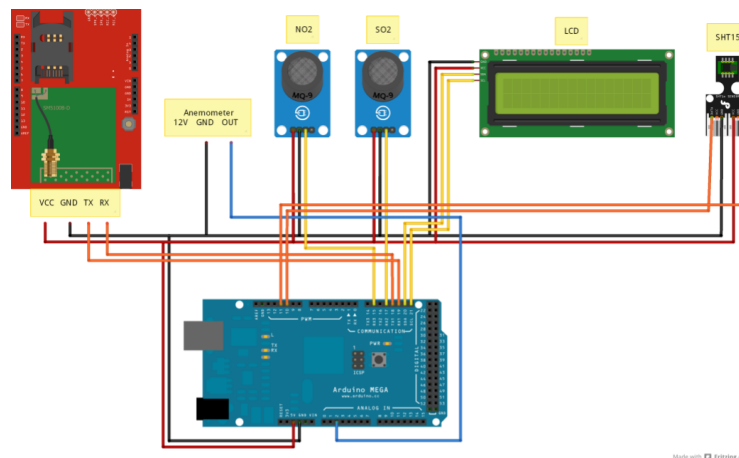


Figure 3: Schematic diagram of IoT system circuit setup

The next stage is testing the quality of network services using the Quality of Service (QoS) method, testing the stability of the system using the Chi-Square test and sensor calibration. Calibration is done by comparing the measurement results of the system created with standard tools, namely SO_2 and NO_2 gas detectors with the type BH Bosean 90A. Network service quality can be assessed based on the TIPHON and ITU-TG.1010 standards against four measured parameters, such as delay, jitter, packet loss ratio, and throughput [17]. The results would be used as quality control and assurance during the proper measurement (implementation stage). In this stage, a point source emission measurement

from sawdust, coal powder, and a mixture of the two was used to measure SO_2 concentrations. While NO_2 emission from the exhaust pipe of a diesel-driven 96 KW electric generator was measured. ?? and Figure 5 showed the schematic diagram of the IoT set-up during SO_2 and NO_2 emission measurements.

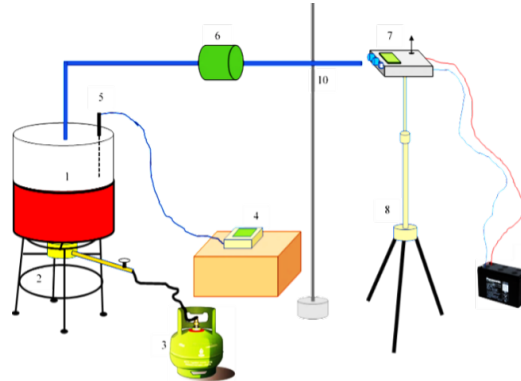


Figure 4: Schematic diagram of SO_2 measurement.

List of the features in Figure 4

1. Sample container
2. Gas stove system
3. LPG tube
4. Digital thermometer
5. Probe thermocouple sensor
6. Liquid smoke
7. Monitoring
8. Tripod
9. Accumulator
10. Support pipe

3 Results

This equipment has been successfully used to monitor and detect real-time concentrations of SO_2 and NO_2 and the results could be assessed via a web address; <https://simaruda.com>. The website has 3 main menus; Home, Database Logger, and Logout. The "Home" displays graphical data while Database Logger displays SO_2 and NO_2 data alongside corresponding sampling time in a tabular format which can be downloaded in various formats.

3.1 Network Quality Test

The network quality of the system is measured based on measurement duration and distance of the system from the emission source. Figure 6 contains four histograms which showed the measurement results of throughput, packet loss, jitter, and delay to distance.

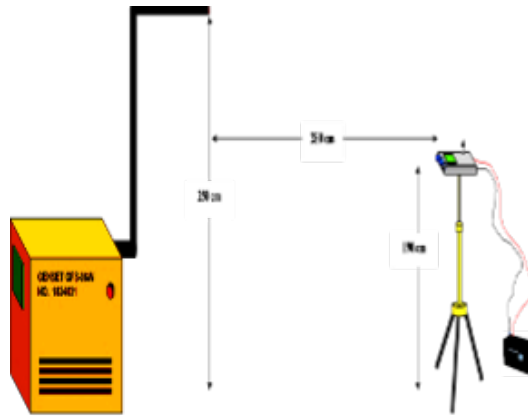


Figure 5: Schematic diagram of the NO_2 measurement.

3.2 Measurement Accuracy

The results of the SO_2 sensor calibration can be seen in Table 1

Table 1: Accuracy of measurement

No.	Duration (s)	Average Level of SO_2 (ppm)		Relative error (%)
		System 01 (X)	BH-90A Bosean	
1	0–60	0.1	0.0	0.0
2	70–120	0.7	1.0	28.3
3	130–180	1.7	2.0	17.5
4	190–270	2.6	2.8	6.8
5	280–350	3.8	4.0	5.6
6	360–420	4.6	5.0	7.7
7	430–470	3.9	4.0	3.5
8	480–510	3.3	3.4	1.7
9	520–560	2.2	2.0	8.0
10	570–600	1.6	1.8	11.4
Average				9.1

From the results of the MAPE (Mean Absolute Percentage Error) calculation, a value of 9.06% was obtained or still below <10%, this means that the measurements carried out fall into the very accurate category

3.3 SO_2 gas concentration resulting from burning sawdust, coal powder, and a mixture of the two emission sources

SO_2 concentrations emitted from the combustion of sawdust had significant variations ranging from 0 to 2.25 ppm. According to Government Regulation No. 14 of 1999 of Singapore, SO_2 concentrations measured within 1 hour had a quality standard of 900 g/Nm³ 0.34 ppm. For 500 g of sawdust, about 18 % of the data obtained exceed the national quality

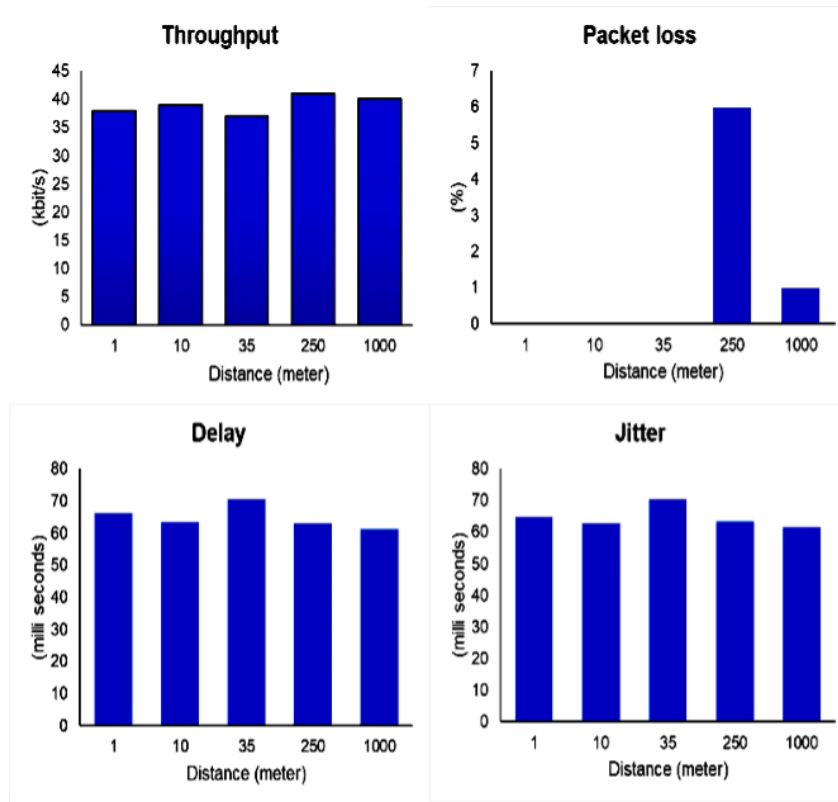


Figure 6: QoS measurements for distance variations.

standard. For 200 g of sawdust, only 25 % of the data violated the national quality standard. Figure 7 shows a graph of SO_2 concentrations emitted from the combustion of sawdust, coal powder, and a mixture of the two in an incinerator. Figure 8 shows a comparison of the combustion chamber temperatures for 200 g and 500 g of coal powder samples.

3.4 NO_2 gas concentration from the exhaust gas of a 96 KW diesel generator engine

The results of measuring the NO_2 concentration from the exhaust gas of a 96 kWh-1 diesel generator engine are shown in Figure 9

4 Discussion

4.1 Network Quality Test

Based on the ITU-TG.1010 standard, the signal is categorized as “bad” (38.75 kbps), while the other parameters are categorized as “good” and “very good”. QoS assessment based

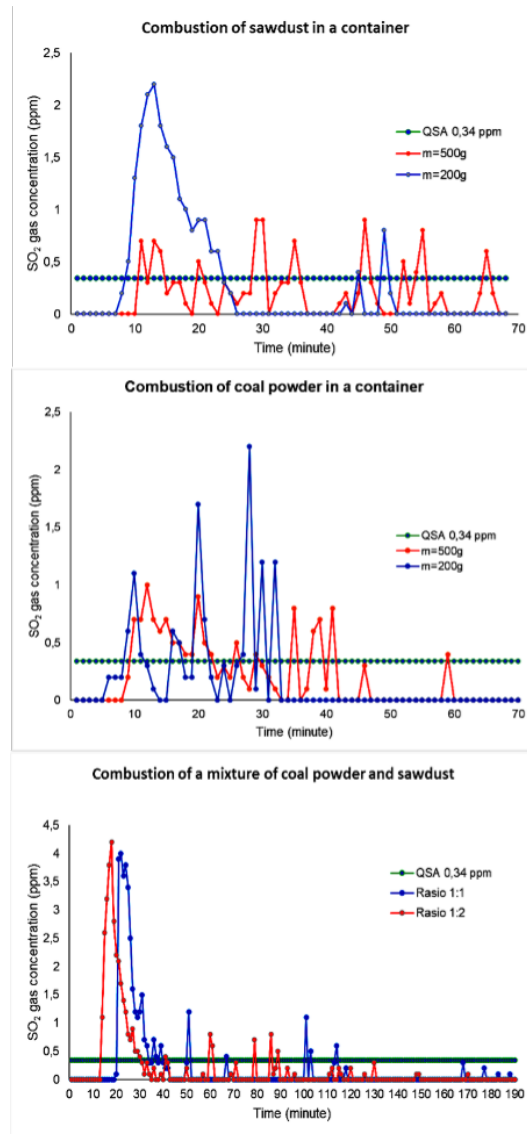


Figure 7: SO_2 gas concentration resulting from the combustion of sawdust, coal powder, and a mixture of the two emission sources.

on the Tiphon standard was also performed and the network quality was recorded as “unsatisfactory” because its average standard index value was 2.7. Unsatisfactory QoS quality could be caused by the density of internet traffic in shared hosting mode, the quality of the signal emitted by the system, and the possibility of interference (noise) on the network [18]. For the “delay” response time to distance it was obvious that the system showed insignificant variations as the values hovered around 35 to 40 kb/s. Similarly, measurement of “jitter” showed little variations, though more experiments could be done to ascertain why

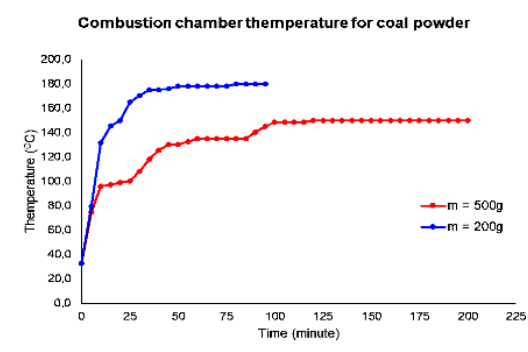


Figure 8: Combustion chamber temperature for coal powder.

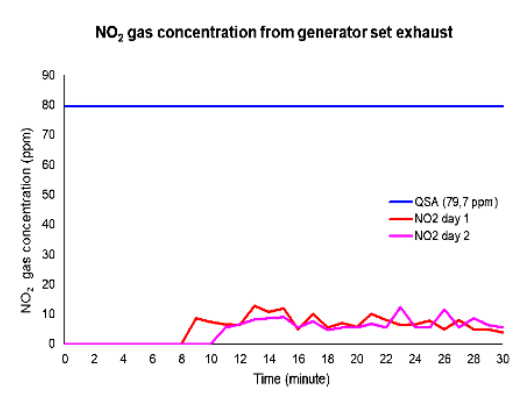


Figure 9: NO_2 gas concentrations obtained within 2 days of measurement.

the highest value was recorded at 35 m against higher distances. The packet loss could be very interesting in the future as it recorded the zero values for distances 240 m but had its peak at 250 m and decreased by 800% at 1000 m.

The tool quality control test using the chi-square method (2) with 25 degrees of freedom and a significance level of 95 % at a 0.05 confidence interval produces a χ^2 value = 0.8763, which is much smaller than the table value of 37.65. Therefore, the study concluded that the measured data of the SO_2 and NO_2 gas pollution monitoring system was significant [19]. The system stability was validated and certified ok for use.

4.2 Data analysis of SO_2 gas concentration

Statistically, the standard deviation of the error (SDE) for 500 g is 0.295 which was smaller than the value (0.577) recorded when 200 g of sawdust was burnt. Therefore it revealed that the variations in SO_2 concentration for combustion of 500 g of sawdust were better compared to that recorded for 200 g of sawdust. Conversely, the concentrations of NO_2 gas were not analyzed because their values were not up to the detection limit.

The value of SO_2 concentrations emitted from the combustion of coal powder shows that SO_2 gas was detected in the 6 minutes with 200 g of sawdust at 131.8 OC and also in the 9 minutes of combusting 500 g at 95.8 OC. For measurements at the same time, the combustion chamber temperature recorded for 200 g was higher than that of 500 g. An explanation for this difference in combustion rates of both masses. Furthermore, the combustion process is faster the smaller mass. The temperature of the combustion chamber is one of the factors that play an important role in the sample combustion process [20].

Figure 8 shows a comparison of the combustion chamber temperatures for 200 g and 500 g of coal powder samples. The combustion duration was for 100 minutes only and the combustion fuel would be extinguished at 101 min. About 28.6 % of SO_2 concentrations combusted with 500 g of sawdust violated the national quality reference standard while 84.3 % of data obtained during the combustion of 200 mg mass were below the reference standard value.

Overall, irrespective of the mass of fuel used, data on the SO_2 concentrations collected from the combustion of coal powder were over 70 % below the reference standard.

Table 2: Statistical parameters of SO_2 gas for coal powder

No.	Statistical parameters	Value	
		500g	200g
1.	Average	0.2 ppm	0.2 ppm
2.	Maximum	1.0 ppm	2.2 ppm
3.	Minimum	0.0 ppm	0.0 ppm
4.	<i>MAD</i>	0.296	0.362
5.	<i>MSE</i>	0.102	0.201
6.	<i>SDE</i>	0.319	0.448

From Table 2, it is obvious that combustion of a larger mass of coal powder yielded better values compared to values obtained when 200 g is burnt.

The comparison of the average, maximum, minimum, and difference (ΔT) of the combustion chamber temperature for each sample is presented in Table 3.

Table 3: Comparison of combustion chamber temperature for each sample

No.	Statistical parameters	Sawdust (°C)		Coal Powder (°C)		A mixture of sawdust and coal powder (°C)	
		200 g	500 g	200 g	500 g	r = 1 : 1	r = 1 : 2
1	Average	125,9	115,9	153,4	133,8	138,7	151,7
2	Maximum	140,2	150,0	180,0	150,0	145,0	170,0
3	Minimum	32,5	32,7	32,7	32,8	32,5	32,8
4	Max-Min	107,7	117,3	147,3	117,2	102,5	137,2

The average temperature recorded for the 500 was lower than that observed for burning 200 g in both fuels probably due to surface area differences. For a mixture of sawdust and coal powder as an emission source, one would expect to obtain higher combustion temperatures for ratios 1:1 and 1:2 but the two temperatures were lower than the value recorded for 200 g of coal powder. This implies that SO_2 emissions and combustion chamber temperature are dependent [20].

For the mixture of fuels with the ratio of 1:1 and 1:2, nearly 13 % of the SO_2 concentration exceeded the national quality standard respectively. This could be due to similarities in their emission source strengths. At measurements durations of 18 and 20 minutes, SO_2 concentration peaks recorded nearly the same value of 4.2 ppm and 4.0 ppm respectively for each sample ratio. The peak concentration which is 4.0 ppm for the mixed sample of sawdust–coal powder with a ratio of 1:1 was the accumulation of sawdust and coal powder peaks. Within 0 to 20 min of sampling time for combustion of 200 g of sawdust showed a peak of 2.2 ppm, while 1.7 ppm was recorded for the same mass of coal powder. Statistically, a ratio of 1:2 of sawdust to coal powder resulted in better performance than using a 1:1 ratio simply because it gave the lowest values of MAD, MSE, and SDE [21].

4.3 Data analysis of NO_2 concentration

The IoT-based system used in this study successfully detected and quantified NO_2 from the exhaust gas emitted from the diesel-electric generator engine. Measurements were carried out in 2 days at 30 minutes intervals. The concentration of NO_2 emitted by the engine was below the national reference standard. The Indonesian Minister of Environment and Forestry Regulation Number 11 of 2021 has set aside 1807.2 ppm as the threshold limit for NO_2 emitted from 100 kWh-1 capacity generators. However, in this work, a diesel-electric generator engine with a capacity of 96 kWh-1 was utilized. Unfortunately, this capacity was not listed in the Ministerial regulation document. Therefore, the study adopted the gubernatorial decree of Central Java number 5 of 2004 which stipulated the NO_2 threshold for motor vehicle emissions in Central Java. For a diesel-driven four-wheeled vehicle, the quality standard for NO_2 gas is 150 mg/Nm³ or 79.9 ppm. This value was very close to the average results (Table 4) obtained in this study.

Table 4: NO_2 statistical test results

Statistical parameters	Statistical test results	
	Day 1	Day 2
Average	7,36 ppm	6,40 ppm
Maximum	12,70 ppm	12,40 ppm
Standard deviation	0,52	0,62
Percentage of error	7,08%	9,62%
Accuracy	92,92%	90,38%

4.4 Limitations and Future Solutions

Although this system has many advantages, it explicitly has limitations related to Network Dependence, Sensor Calibration and Accuracy, Limited Pollutant Types, and Power Supply and Energy Efficiency. Solutions that can be offered include:

1. **Enhancing Network Dependence:** Integrate LTE or 5G modules for higher bandwidth and better coverage, and use dual communication modules (e.g., GSM + Wi-Fi) to ensure data transmission even if one network fails.
2. **Improving Sensor Accuracy and Expanding Pollutant Detection Capabilities:** Use multiple sensors for the same pollutant and apply statistical methods (e.g., Kalman

filtering) to improve accuracy, and incorporate dedicated sensors for CO, O₃, PM (Particulate Matter), and VOCs.

3. **Improving Power Supply and Energy Efficiency:** Use low-power microcontrollers and integrate solar panels and batteries for autonomous operation.

5 Conclusion

The SO₂ and NO₂ gas monitoring system using IoT-based wireless sensors has been successfully developed, validated, and confirmed ready for practical deployment. However, based on Tiphon standardization, the network quality used by this system is categorized as unsatisfactory, as the measured bandwidth ranged only from 0 to 337. Despite this limitation, the SO₂ and NO₂ monitoring system demonstrated a relatively good level of measurement precision and accuracy. This was confirmed through a stability test using the Chi-Square method, where the calculated value $\chi^2 = 0.876$ was smaller than the table value $\chi^2 = 37.65$, indicating stable and reliable performance.

The results of monitoring the smoke from combustion of sawdust, coal powder, and a mixture of the two fuel sources, showed high variations of SO₂ concentrations though with over 70 % conformity to the national reference-quality standard. Interestingly, 500 g of sawdust and coal powder at ratios 1:1 or 1:2 displayed a relatively low SDE. However, the concentration of gas NO₂ did not give a significant value or the probability of finding it in the sample was relatively small. Furthermore, the concentrations of NO₂ from the exhaust gas of a 96-kW h-1 diesel generator engine were found to be below national quality standards.

6 Suggestion

For Future Improvements, there are several steps that must be considered, including: Improve Network Reliability: transition to LTE or alternative communication protocols for more stable and wider area coverage, improve Sensor Accuracy: Incorporate calibration routines or sensor fusion techniques to improve data quality, expand Pollutant Coverage: Integrate sensors for additional gasses such as CO, PM2.5, and VOCs, and integrate data analytics: use AI-based techniques for predictive modeling and anomaly detection, which go beyond existing static systems.

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