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IMPLEMENTATION OF INDOOR AIR QUALITY MONITORING SYSTEMS OF PARTICULATE MATTER 2.5 BASED ON THE INTERNET OF THINGS

Nafi'atul Irbah[1], Globila Nurika[1]*, Andrei Ramani[1]

[1]Department of Public Health, Faculty of Public Health, Jember University, Jember 68121, Indonesia

Corresponding Author:
*) nurikaglobila@unej.ac.id

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Abstract

Introduction: *Indoor air quality significantly influences human health because humans can do work and rest indoors. Particulate Matter ($PM_{2.5}$) is ranked 5th as the leading risk factor for death in the world and causes more than 103 million disabilities. $PM_{2.5}$ concentrations are the highest, so a monitoring system is needed that can monitor air conditions in real-time and continuously.* ***Methods:*** *Research was conducted using the Research and Development (R&D) type. The scope of the research method is making prototypes and fieldtesting tools. Determination of field test locations is based on indicators such as (i) inadequate ventilation in the respondent's house so that air circulation does not run well; (ii) The family room and bedroom are close to the kitchen and waste incinerator, which has the potential to produce $PM_{2.5}$ pollutants. Data analysis used descriptive analysis to get a picture of indoor air quality.* ***Results and Discussion:*** *The designed monitoring system was calibrated with the Air Quality Monitor 8 in 1 $PM_{2.5}$ tool. The average $PM_{2.5}$ concentration measurement for 24 hours showed that all test points exceeded the standard limit. Room 3 (family room) had the highest $PM_{2.5}$ concentration, while room 4 (bedroom) had the lowest $PM_{2.5}$ concentration.* ***Conclusion:*** *The area of air ventilation, mining activities, mining product transportation activities, the intensity of watering roadsides and home yards, and cooking activities influence $PM_{2.5}$ concentrations.*

INTRODUCTION

Indoor air quality has a significant influence on human health because humans can do work and rest indoors. Indoor air pollutant levels are 2 to 5 times higher than outdoors and can even be 100 times higher in some instances (1). Indoor pollution takes the form of dust, gas, dirt, and chemicals originating from smoking, cooking, and other activities (2). Indoor air quality in homes tends to be low because they do not have good air circulation and filtration systems (3). The indoor air pollutants are Particulate Matter 2,5 ($PM_{2.5}$), Particulate Matter 10 (PM_{10}), CO (Carbon Oxide), NO (Nitrogen Oxide), and SO (Sulfur Dioxide). Indoor air pollution can have a direct or indirect impact on public health and causes 3.2 million deaths per year (4). Diseases caused by indoor air pollution are bronchitis, lung cancer, and Chronic Obstructive Pulmonary Disease (COPD) (5).

Particulate Matter ($PM_{2.5}$) is ranked 5th as the leading risk factor for death in the world and causes more than 103 million disabilities (6). Global health losses due to $PM_{2.5}$ air pollution reach $81 trillion, equivalent to 6.1% of the total global Gross Domestic Product (GDP) (7). $PM_{2.5}$ pollutants come from combustion, cigarette smoke, use of firewood, mining activities, and agricultural activities (8). The average $PM_{2.5}$ concentration in Indonesia in 2022 was 30.4 μg/m3. Indonesia is ranked 26th globally and 1st in Southeast Asia, producing the highest $PM_{2.5}$ pollutant (9).

Monitoring $PM_{2.5}$ concentrations in indoor air must be done in real-time and continuously to maintain the quality of public health. Implementing real-time monitoring can exploit the development of Internet of Things (IoT) technology. IoT technology can monitor air quality in real-time by utilizing sensors connected to the internet so that measurements can be carried out continuously even though the monitoring is carried out

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at a long distance.

Kapuran Hamlet, located in Grenden Village, Jember Regency, has limestone mining, which causes air quality to decline. Burning biomass in lime mining can produce smoke containing various pollutants, such as $PM_{2.5}$, which can float in the air for long periods. $PM_{2.5}$ can move within a radius of 200-1000 meters depending on wind direction and speed. Lime from dust particles ($PM_{2.5}$) can cause health problems, such as bronchitis, shortness of breath, and pneumoconiosis (10). The presence of $PM_{2.5}$ impacts not only workers but also communities around mining, which breathe polluted air for approximately 24 hours/day. Based on Jember District Health Service data, acute bronchitis is included in the top 15 morbidity rates. Cases of acute bronchitis in 2022 increased up to 190 cases and in 2023 up to 214 cases (11).

The results of a preliminary study by testing air samples in the laboratory conducted in five rooms for three trials resulted in the highest average $PM_{2.5}$ concentration of 49 μg/m^3. Indoor measurements were carried out in locations that did not have sufficient air ventilation and were close to kitchens and waste incinerators. Measurements were carried out in the afternoon because, at that time, there were activities for burning rubbish and transporting lime mining products. The concentration of $PM_{2.5}$ in indoor air exceeds the quality standards (25 mg/m^3), so air quality monitoring is required. Therefore, an IoT-based $PM_{2.5}$ indoor air quality monitoring system can be implemented in the Kapuran Hamlet, Grenden Village, Jember Regency to make it easier for the community to monitor air quality in real-time.

METHODS

Research Design

The type of research used is Research and Development (R&D). The scope of the R&D research method used is making prototypes followed by testing tools in the field. This research was conducted to test the effectiveness of an Internet of Things-based $PM_{2.5}$ monitoring tool so that the final results will produce a real-time indoor air quality ($PM_{2.5}$) monitoring tool. The internet of things-based $PM_{2.5}$ monitoring tool uses a G5 PMS5003 dust sensor which is equipped with a fan to detect dust in the air.

The PMS5003 is a digital universal particle concentration sensor based on the principle of laser scattering. It can continuously collect and calculate the number of suspended particulates in different air volumes per unit volume, that is, the particle concentration distribution, and then convert it into mass concentration. The sensor can be embedded in a variety of suspended particles in the air associated with the concentration of instrumentation or environmental improvement equipment, to provide timely and accurate concentration data. The sensor uses the principle of laser scattering. It means that the laser light on the particles in the air and making the scattering, while collecting scattered light at a particular angle, resulting in scattered light intensity with time curve. Furthermore, the microprocessor uses the algorithm based on Mie (MIE) to obtain the equivalent particle size of the particles and the number of particles with different particle diameters per unit volume. The dust level that has been detected will be read in μg/m^3.

Presentation of data using pictures and graphs. Data analysis was carried out descriptively to find out the picture or situation of $PM_{2.5}$ indoor air quality in one of the community houses in Kapuran Hamlet, Grenden Village, Jember Regency. This research has received an ethical certificate from the Faculty of Public Health, Jember University, with Number 442/KEPK/FKM-UNEJ/I/2024.

Research Location

The research location consisted of the tool design and testing locations. The tool design was conducted at the Integrated Laboratory of the Faculty of Public Health, Jember University. Equipment was tested in one of the community houses located in Kapuran Hamlet, Grenden Village, Puger District, Jember Regency (Figure 1 and 2). The equipment testing was located within a radius of 200-400 meters from the limestone mining area. It is included in the transportation crossing area for the transportation of mining products. This condition has a high potential for $PM_{2.5}$ contamination to be found indoors. Determining the field test location was based on two indicators, namely (i) inadequate ventilation in the respondent's house so that air circulation did not run well; (ii) the family room and bedroom are close to the kitchen and waste incinerator, which has the potential to produce $PM_{2.5}$ pollutants. The research process requires tools and materials to be run according to the objectives. The tools and materials needed are listed in Table 1.

Table 1. Research Tools and Materials

Tool(s)	Material(s)
Laptop/PC (Acer Nitro 5 AN515)	ESP32 Devkit 1
Multimeter digital	Dust sensor G5 PMS5003
Power supply	Jumper Cable
Screwdriver	Project Board
Plier	Tin
Solder	LCD Oled full color screen LCD 1.3 inch
Scissor	Clear acrylic case 2 mm
Cutter	Lithium battery 2200mAh
blynk and arduino IDE	Power Bank Module 18650 USBType C Output 5V 2A
Corel Draw X7	WiFi (internet connection)
Air Quality Monitor 8 in 1 $PM_{2.5}$	

$PM_{2.5}$ parameters detection in the air used a Dust sensor. The workflow of this air quality monitoring system is depicted in Figure 3. $PM_{2.5}$ concentration readings are carried out by the ESP32 microcontroller, which obtains information from the dust sensor. The dust sensor used can detect $PM_{2.5}$, PM_{10}, and PM_1 so that the microcontroller can specifically read $PM_{2.5}$, PM_{10}, and PM_1 levels according to the sensor detection results. The reading results will be sent to the LCD (Liquid Crystal Display) and streamed via WiFi. The LCD functions to display data on the tool display. WiFi networking helps send data to the Blynk platform, which can display graphs and monitor $PM_{2.5}$ concentration from a distance. The prototype design of the tool is shown in Figure 4.

Figure 1. Point Sample Location

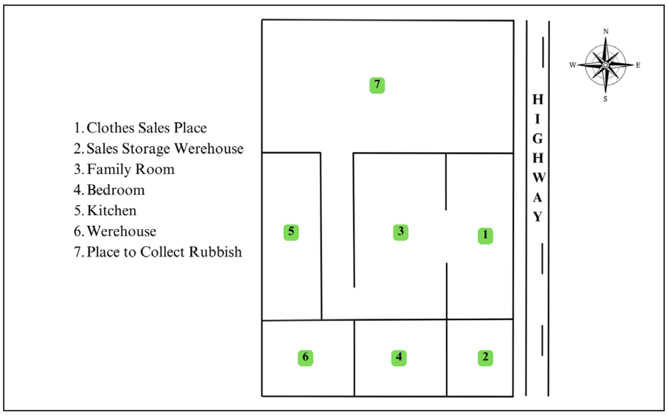

Figure 2. Field Testing Indoor Point

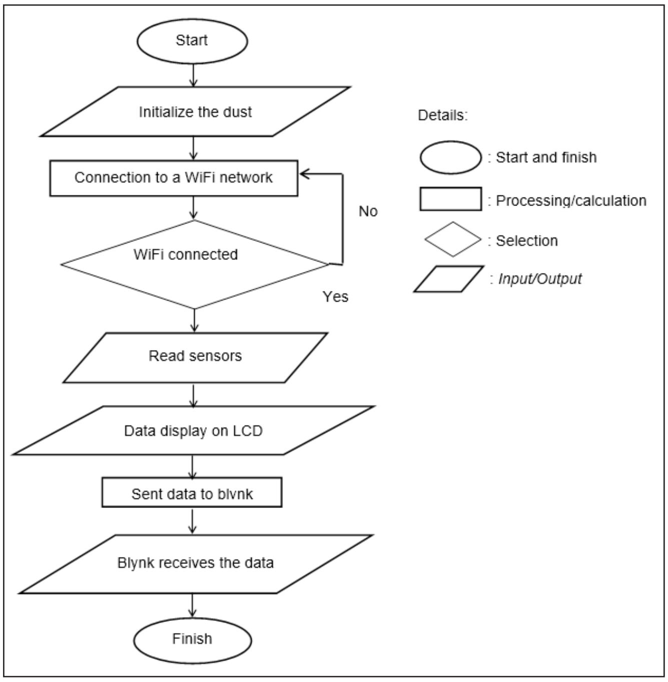

Figure 3. IoT Based Monitoring System Work Flowchart

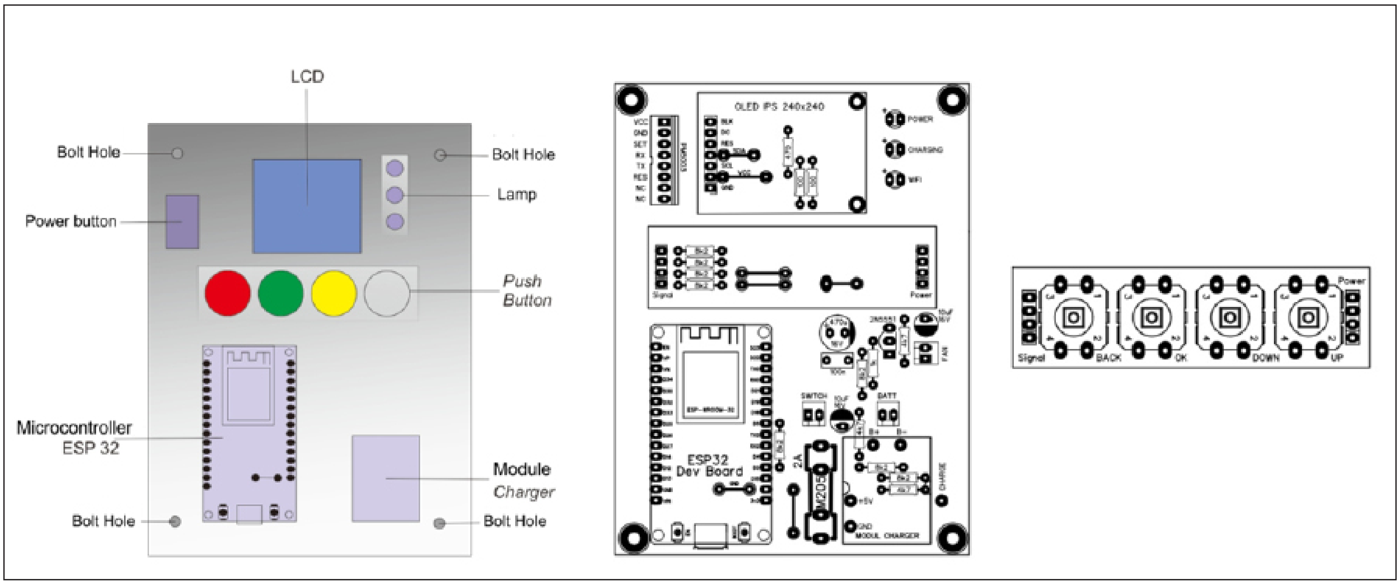

Figure 4. Prototype Design

Tool Testing

The testing process is divided into sensor testing and application system testing. Sensor testing aims to see the function of the tool by comparing the accuracy of the tool made and the Air Quality Monitor 8 in 1 $PM_{2.5}$ tool under the same air conditions. Application testing is carried out by comparing the values that appear between the LCD screen and the Blynk application. Testing is also carried out to determine how big the data transmission failure is using ESP32 Devkit 1. Error testing can use the error percent formula as follows (12).

$$\text{Error}\,\% = \frac{|approx - exact|}{exact}\, x\ 100$$

$$\text{Absolute Error} = |\text{Approx} - Exact|$$

Details:

Approx = Tool testing value

Exact = Value comparison tools

Field Testing

The field test sample is an air sample with the parameter variable $PM_{2.5}$. Tests were carried out in five rooms out of seven in the house respondents. This research did not use two rooms because respondents did not permit them. Each room was measured at one point for 1x24 hours.

RESULTS

Hardware Design of a $PM_{2.5}$ Based Remote Monitoring System for Indoor Air Quality Internet of Things

Hardware design applied ESP32 microcontroller and dust sensor. Programming on the board used the Arduino IDE application. The hardware output is listed on the hardware LCD (Figure 5). The LCD on the hardware has four displays. The first display contains information on the $PM_{2.5}$, $PM_{1.0}$, and PM_{10} concentrations in the air in real-time in µg/m^3 units. The second display contains information on battery-related percentage (SOC %) and voltage (volts). The third display presents the CPU temperature or temperature (°C) of the ESP32 microcontroller. The fourth display contains information related to the internet connection (WiFi). The maximum internet connection speed is 0 dBm. The smaller the number, the lower the internet connection speed.

(a) Concentration layer display of PM 2.5; PM 1.0; and PM 10 **(µg/m3)**

(b) Power Tool layer view; SOC %; and VOLT

(c) Tool screen display (CPU temperature)

(d) Wifi usage status (device name, IP address, and signal)

Figure 5. LCD Display

The hardware is designed as a portable device that is easy to carry. The hardware uses two 2200 mAh lithium batteries. Based on tests that have been carried out, this hardware can be used for 4 hours. The test was carried out at 09.00 PM with the 99%-charged battery, then at 01.00 AM, the battery was 0%, and the hardware was off. The hardware measures 12 x 9 x 5.1 cm. The hardware casing uses explicit acrylic material with a thickness of 2 mm, so it is light and easy to see the components inside.

Software Design of a $PM_{2.5}$ Based Remote Monitoring System for Indoor Air Quality Internet of Things

Software design used Blynk dashboard and Blynk apps. The software output is listed on the Blynk dashboard using a laptop/PC device, while the Blynk apps use a smartphone device (Figure 6). Blynk is a medium for receiving and displaying data that the microcontroller has received via an internet connection. In addition, Blynk has functions for controlling microcontrollers, controlling hardware remotely, and providing information about conditions detected by the hardware. Blynk apps can be used for Android and IOS Operating Systems (OS).

The dashboard on Blynk functions to display data that Blynk has received. The dashboard that has been designed displays $PM_{2.5}$, $PM_{1.0}$, and PM_{10} concentrations, battery capacity, internet connection information, microcontroller temperature, sensor power button, restart button, and restart time. The timeline feature functions to provide an overview of time or activities related to IoT devices, analyze data that has been received, display notifications, and provide information if there are security changes.

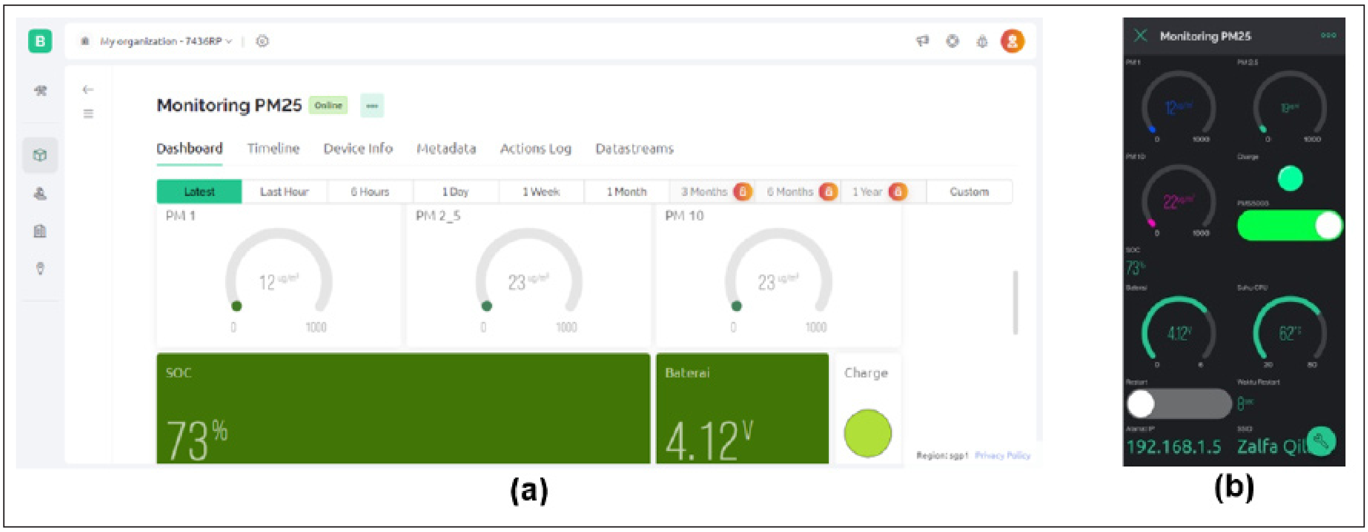

Figure 6. (a) Blynk Dashboard Display; (b) Blynk Apps

The device info feature displays information related to devices connected to the platform. The information includes device information, connection status, network details, power monitoring, software version, activity history, security management, and Arduino code. The metadata feature functions to provide additional information that describes the primary data. The actions log feature functions to record or display action logs directly. The data streams feature functions to manage the sending and receiving of data between physical devices and the Blynk application. The data sent comes from sensors or devices connected to the microcontroller. The data streams that have been designed contain $PM_{2.5}$, $PM_{1.0}$, and PM_{10}, battery, SOC, CPU temperature, SSID, IP address, restart, restart time, PMS5003, and charge. The display on the Blynk dashboard is the same as on the Blynk app.

Sensor Testing of a $PM_{2.5}$ Based Remote Monitoring System for Indoor Air Quality Internet of Things

Sensor testing was carried out by comparing the reading results between the Dust sensor and the Air Quality Monitor 8 in 1 $PM_{2.5}$ tool to determine the magnitude of the sensor reading error. Tests were carried out ten times in different rooms. One experiment was carried out in each room. Each room has different ventilation characteristics, so it has a combination of $PM_{2.5}$ contamination levels.

Table 2. Sensor Test Data

Room	Dust Sensor Reading (µg/m³)	Air Quality Monitor 8 in 1 $PM_{2.5}$ Readings (µg/m³)	Error Percentage (%)	*Absolute Error*
1	35	35	0.00	0.0
2	36	36	0.00	0.0
3	36	36	0.00	0.0
4	34	34	0.00	0.0
5	33	33	0.00	0.0
6	34	34	0.00	0.0
7	35	35	0.00	0.0
8	35	35	0.00	0.0
9	35	36	2.78	1.0
10	38	38	0.00	0.0
		Average	0.28	
			MAE	0.1

The sensor test results in Table 2 show that in the 9th room, the dust sensor readings are different from the Air Quality Monitor 8 in 1 $PM_{2.5}$ readings because of the sensitivity difference between the two sensors. The average error value in sensor testing is 0.28%, with a Mean Absolute Error (MAE) value of 0.1. The test results show that there is a difference in readings on 1 test among ten tests.

Blynk Application Testing of a $PM_{2.5}$ Based Remote Monitoring System for Indoor Air Quality Internet of Things

Testing the Blynk application is carried out by comparing the values between the LCD or dust sensor readings and Blynk. The test was carried out ten times in a row. Based on Table 3, testing the blink application, it was found that the average percentage error and absolute error were 0%. The test results show that the Blynk readings are the same as the Dust sensor readings, and there is no delay in data transmission.

Table 3. Application Testing

Testing	Blynk Reading (µg/m³)	Dust Sensor Reading (µg/m³)	Error Percentage (%)	*Absolute Error*
1	53	53	0	0
2	52	52	0	0
3	56	56	0	0
4	48	48	0	0
5	50	50	0	0

Testing	Blynk Reading (µg/m³)	Dust Sensor Reading (µg/m³)	Error Percentage (%)	*Absolute Error*
6	47	47	0	0
7	46	46	0	0
8	46	46	0	0
9	53	53	0	0
10	53	53	0	0
	Average		0	0
		MAE	0	0

Advantages and Disadvantages of a $PM_{2.5}$ Based Remote Monitoring System for Indoor Air Quality Internet of Things

The advantage of the Internet of Things-based $PM_{2.5}$ indoor air quality monitoring system compared to the 8-in-1 $PM_{2.5}$ Air Quality Monitor tool is that this tool can monitor remotely, while the disadvantage is that there is more potential for null data due to an unstable internet connection.

Implementation of a $PM_{2.5}$ Indoor Air Quality Monitoring System Based on the Internet of Things

Field testing was conducted in five rooms: places for selling clothes. warehouse for storing clothes, family room, bed, and kitchen. The monitoring tool was placed at a height of 1.5-2 meters. This height determination was based on the height of the High Volume Air Sampler (HVAS) tool, which is used to take samples of particulates in the air. Measurements for each room were carried out continuously for 24 hours. The data used have the highest, lowest, and average values for each hour. Based on Minister of Health Regulation Number 2 of 2023 concerning Implementing Regulations of Government Regulation Number 66 of 2014 concerning Environmental Health, the maximum concentration of $PM_{2.5}$ indoors is 25 µg/m³ with measurements for 24 hours.

Room Testing 1 of a $PM_{2.5}$ Indoor Air Quality Monitoring System Based on the Internet of Things

Room 1 is located at the front of the house, about 2.5 meters from the main road. This room does not have ventilation but has a door that has the potential for pollutants to enter. The results of tool testing can be seen in Figure 7. Measurements were carried out on Thursday-Friday, 11-12 January 2024. Figure 7 shows that the highest hourly average concentration occurre at 09.00 PM and the lowest concentration at 02.00 PM. The highest concentration of $PM_{2.5}$ occurred because at 09.00 PM, the mining product transportation activity was still operating, and the house owner did not water the roadside area and yard, causing dust to enter the house.

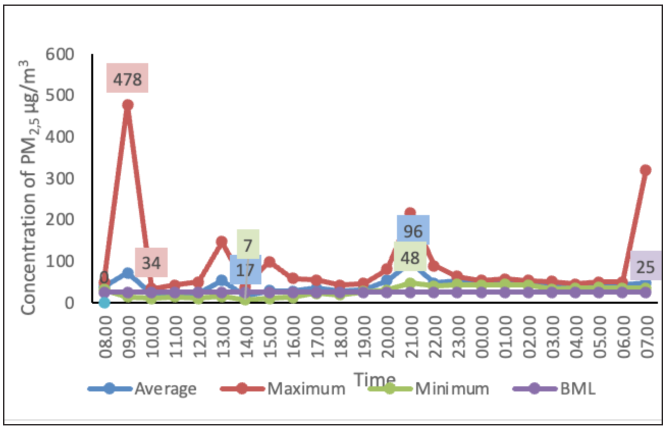

Figure 7. $PM_{2.5}$ Concentration in Room 1

The lowest concentration occurred at 02.00 PM because the house owner watered it, so the ground was wet, and dust did not spread. The $PM_{2.5}$ concentration reached its highest point at 09.00 AM with a particle number of 478 µg/m³. This condition occurred because, at that time, mining product transportation activities were already underway, and the road conditions were dusty. The average measurement of $PM_{2.5}$ concentration in indoor air for 24 hours is 40 µg/m³, so the $PM_{2.5}$ concentration in room 1 exceeds environmental quality standards.

Room Testing 2 of a $PM_{2.5}$ Indoor Air Quality Monitoring System Based on the Internet of Things

Room 2 is located to the south of room 1. This room does not have air ventilation, so air circulation does not run well. Measurements were carried out on Friday-Saturday 12-13 January 2024. The results of $PM_{2.5}$ concentration measurements are listed in Figure 8. Based on Figure 8, $PM_{2.5}$ concentrations tend to fluctuate. The highest hourly average $PM_{2.5}$ concentration was 101 µg/m³ at 01.00 AM, and the lowest was 13 µg/m³ at 12.00 AM. The highest $PM_{2.5}$ concentration reached 418 µg/m³ at 09.00 PM.

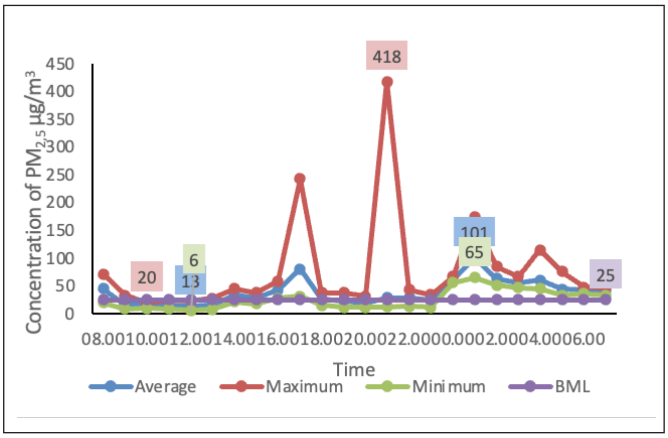

Figure 8. $PM_{2.5}$ Concentration in Room 2

This condition occurred because the house owner did not water at night while the mining product transportation activity was still operating. It was also raining during the day, so the road conditions were dry and dustier at night. The rain occurred around 10.00 AM -12.00 PM, causing the $PM_{2.5}$ concentration to be low at 12.00 PM, while at 09.00 PM and 01.00 AM, the concentration was high.

Air conditions at 10.00 AM -01.00 PM had $PM_{2.5}$ concentrations that tended to be stable and low. This condition was because, specifically on Fridays from 11.00 AM – 01.00 PM, transportation of mining products could not be carried out. The restrictions were made because there were Friday prayer activities for the Muslim community. The average $PM_{2.5}$ concentration measurement for 24 hours in room 2 was 38 μg/m³, so the concentration exceeded environmental quality standards.

Room Testing 3 of a $PM_{2.5}$ Indoor Air Quality Monitoring System Based on the Internet of Things

Room 3 had the same characteristics and was located parallel to room 1. Room 3 did not have air ventilation, so the air circulation in room 3 came from the entrance to the house, which was in room 1. Measurements in room 3 were carried out on Saturday-Sunday, January 13-14, 2024. The test results in Figure 9 show that the highest $PM_{2.5}$ concentration reached 391 μg/m³ at 07.00 AM. The highest concentration occurs because there is no watering of the roadside and yard, so dust enters the house.

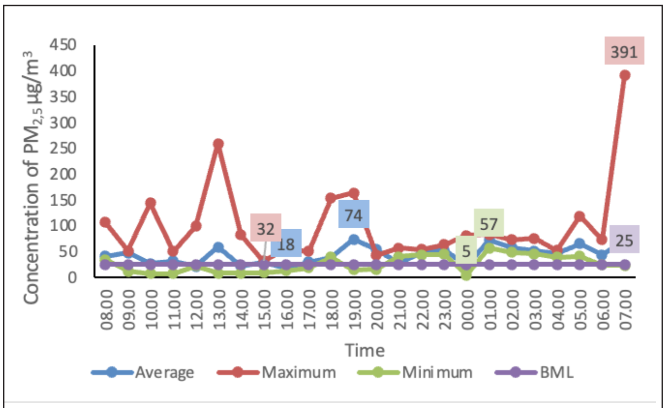

Figure 9. $PM_{2.5}$ Concentration in Room 3

The highest hourly average $PM_{2.5}$ concentration occurred at 07.00 PM, while the lowest concentration occurred at 04.00 PM. It was due to watering activities carried out by the homeowners who usually watered the roadside and yard three times daily, namely in the morning, afternoon, and evening. However, at 07.00 AM, the house owner did not water because he was not home, and the mining product transportation activity was already operating.

Transportation of mining products on Sundays was different from regular days. It was carried out for 24 hours, whereas on regular days from 06.00-08.00 AM, transportation activities were prohibited from operating. The average $PM_{2.5}$ concentration measurement for 24 hours in room 3 was 44 μg/m³, so the concentration exceeded environmental quality standards.

Room Testing 4 of a $PM_{2.5}$ Indoor Air Quality Monitoring System Based on the Internet of Things

Room 4 was a bedroom with air ventilation. The ceiling condition in room 4 did not meet the requirements because it was made of bamboo and experienced weathering. Air measurements in room 4 were carried out on Sunday-Monday 14-15 January 2024. The results of measuring the $PM_{2.5}$ concentration in room 4 (Figure 10) show that the $PM_{2.5}$ concentration tends to be stable. The highest concentration of $PM_{2.5}$ and the highest hourly average occurred at 08.00 AM at 275 μg/m³ and 70 μg/m³ because the mining transportation activity was already operating, and the house owner did not water the roadside and yard of his house. The lowest hourly average $PM_{2.5}$ concentration occurred at 02.00 AM, namely 10 μg/m³ because it drizzled at 01.00 AM. The average $PM_{2.5}$ concentration measurement for 24 hours in room 4 was 30 μg/m³, so the concentration exceeded environmental quality standards.

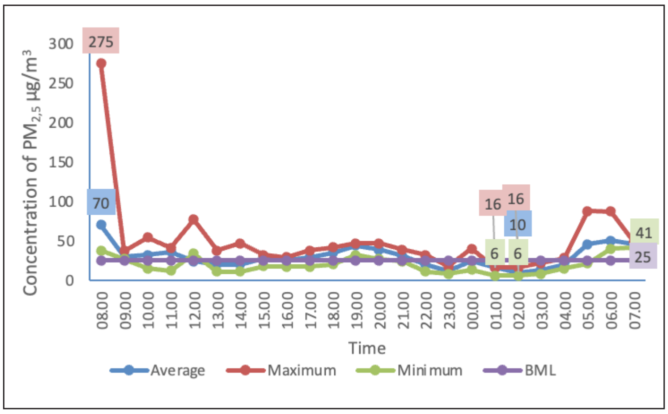

Figure 10. PM2.5 Concentration in Room 4

Room Testing 5 of a $PM_{2.5}$ Indoor Air Quality Monitoring System Based on the Internet of Things

Room 5 was a kitchen, and there was no air ventilation. Air condition measurements in room 5 were carried out on Monday-Tuesday, 15-16 January 2024. The results of measuring the $PM_{2.5}$ concentration in room 5 (Figure 11) show that the $PM_{2.5}$ concentration tends to be high in the morning because of cooking activity, especially at 06.00-07.00 AM. The highest $PM_{2.5}$ concentration in room 5 was 161 μg/m³ and occurred at 09.00 PM. This was because the house owner did not water at night while the mining product transportation activity was still operating. The lowest hourly average $PM_{2.5}$ concentration occurred at 12.00 PM, 10 μg/m³. The average $PM_{2.5}$ concentration measurement for 24 hours in room 5 was 32 μg/m³, so the concentration exceeded environmental quality standards.

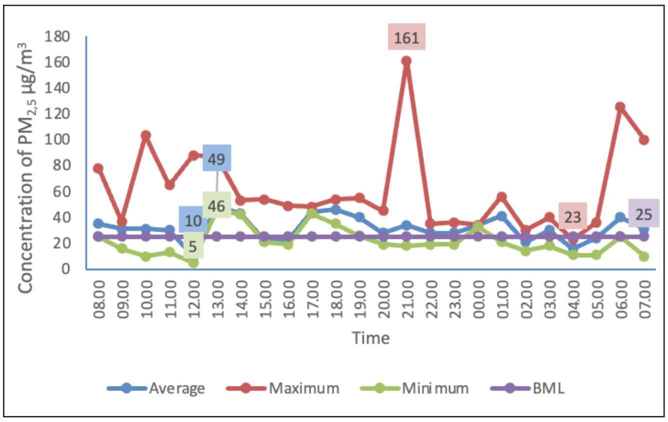

Figure 11. $PM_{2.5}$ Concentration in Room 5

DISCUSSION

Design of a $PM_{2.5}$ Based Remote Monitoring System for Indoor Air Quality Internet of Things

The monitoring system design is carried out in two stages: prototype design and tool testing. Tool testing can be done by testing the validity of the system. The system validity test is carried out to determine the level of accuracy of the monitoring system created using existing tools. Testing is carried out by comparing the values between the original measuring device and the monitoring system created in the same air conditions and then calculating the error value. The tolerable error value does not exceed 1% (13-15).

Testing the validity of the monitoring system is carried out in two stages, namely sensor testing and application testing. The results in Table 2 show that the error percentage on the sensor is 0.28%, so the dust sensor has been calibrated. Table 2 shows that 1 out of 10 trials needed to be more accurate between the numbers on the LCD monitoring system and those on the Air Quality Monitor 8 in 1 $PM_{2.5}$. This discrepancy can be influenced by the sensitivity level of the sensor in reading particulates in the air (16). However, this discrepancy can still be tolerated.

Blynk application testing was carried out ten times in sequence. Based on the test results listed in Table 3, the resulting error rate is 0% so that the Blynk application does not exceed the tolerance limit and has been validated. The Blynk application's validity level is influenced by the internet connection (17). A weak internet connection causes delays in sending data from the microcontroller to the Blynk so that the numbers that appear on the LCD are different from those on the Blynk (18). A disconnected internet condition causes data not to be sent to Blynk, and the status listed on Blynk is offline (19). An internet connection using WIFI is more stable than cellular data, so it is more recommended to use WIFI (20).

Implementation of a $PM_{2.5}$ Indoor Air Quality Monitoring System Based on the Internet of Things

Field test results show that all points have an average $PM_{2.5}$ concentration that exceeds the standard limit based on Minister of Health Regulation Number 2 of 2023 concerning Implementing Regulations of Government Regulation Number 66 of 2014 concerning Environmental Health. Each room has different air condition characteristics and average $PM_{2.5}$ concentrations. The order of rooms that have the highest to lowest average $PM_{2.5}$ concentration is room 3 (44 μg/m³), room 1 (40 μg/m³), room 2 (38 μg/m³), room 5 (32 μg/m³), and room 4 (30 μg/m³). The most minor average $PM_{2.5}$ concentration, namely room 4, has a difference of 5 μg/m³ from the maximum limit, while the highest average $PM_{2.5}$ concentration has a difference of 19 μg/m³.

Room 3 has the highest concentration of $PM_{2.5}$ because this room is located parallel to the door in room 1. Room 3 and room 1 do not have a barrier in the form of a wall so that dust entering through the door can enter room 3 directly. This dust comes from lime mining activities, transporting mining products, and other transportation activities. The highest $PM_{2.5}$ concentration occurred at 07.00 AM. $PM_{2.5}$ concentrations tend to be high in the morning to evening due to high levels of human activity, including mining and transporting mining products. Mining activities and transporting mining sand affect $PM_{2.5}$ levels in the air (21).

$PM_{2.5}$ concentrations remained above standard from night to early morning. These results contradict Farihah and Sumeru's research in 2021, where particulate concentrations tend to be low at night until early morning due to minimal human and vehicular activity (22). Mining product transportation activities in the Kapuran Hamlet area, Grenden Village, Jember Regency are ongoing from 01.00 PM to 06.00 AM, causing $PM_{2.5}$ concentrations to remain high at night and early in the morning.

Room 4 has the lowest $PM_{2.5}$ concentration based on initial measurements using the Air Quality Monitor 8 in 1 $PM_{2.5}$ tool and during field testing. Room 4 is the only room that has air ventilation. Air ventilation affects the concentration of particulates indoors (23). However, the air ventilation in room 4 is less than 10% of the floor area, so it does not meet the requirements (14). This ventilation condition aligns with the measurement results, which state that the $PM_{2.5}$ concentration in room 4 exceeds the maximum standard limit.

Field tests that have been carried out show inconsistent results, such as sudden spikes in $PM_{2.5}$ concentrations at uncertain times. The intensity of mining and transportation of mining products, weather conditions, cooking activities, and watering roadsides and yards influence the instability of $PM_{2.5}$ concentrations. Mining activities and transporting mining products using heavy equipment can increase $PM_{2.5}$ concentrations in the air (24).

Mining activities influence $PM_{2.5}$ concentrations, even though the highest concentrations do not occur during mining operation hours. Mining operating hours start at 08.00 AM and continue to 01.00 PM. Based on the test results, in rooms 1,3, 4, and 5, the $PM_{2.5}$ concentration tends to fluctuate and is higher from morning to noon compared to night. These results are in line with research conducted by Monica and friends in 2021; rock mining can cause air quality to decrease and increase $PM_{2.5}$ concentrations (25).

Mining product transportation activities occur from 08.00 AM to 06.00 AM except on Fridays. Mining product transportation activities may not operate from 11.00 AM -01.00 PM. This restriction was carried out because Muslim people did Friday prayers. If transportation is carried out non-stop on holidays, provided that at 06.00 AM - 08.00 AM, the vehicle carrying mining products is driven at low speed. Therefore, the highest intensity time for vehicles to transport mining products is unknown. Based on research results, the density of vehicles transporting mining products occurs at different times every day. The operational hours for transporting mining products affect the level of $PM_{2.5}$ in the air (26).

Weather conditions affect the concentration of $PM_{2.5}$; if it rains, there will be a decrease in the concentration of $PM_{2.5}$ in the air. Rainfall can reduce $PM_{2.5}$ concentrations by up to 40% with the air cleaning of small particles (27). However, the air conditions after a while of rain are dustier than before. Dust comes from the soil on the road, which is already dry, and is exacerbated by the tires of mining vehicles carrying sand, thus producing more dust in the air. Apart from that, cooking activities also affect $PM_{2.5}$ concentrations. Based on test results in room 5 (kitchen), $PM_{2.5}$ concentrations increase during cooking activity. These measurement results align with another research results $PM_{2.5}$ concentrations in the kitchen tend to be higher than in other rooms because of cooking activity (28).

Inconsistent measurement results are also influenced by the intensity of watering the roadside and yard. Watering roads is one of the air management efforts to reduce $PM_{2.5}$ concentrations (29). A 1-meter-long road that has been watered will remain wet for 10 minutes so that the watering intensity is carried out every two hours (26). Homeowners usually water three times a day, namely morning, afternoon, and evening, so the $PM_{2.5}$ concentration still exceeds the standard limit even though watering has been carried out. When the research was conducted, the homeowner did not water regularly, so the $PM_{2.5}$ concentration measurement results needed to be more consistent.

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CONCLUSION

This research can conclude that the monitoring system has met the accuracy level with the Air Quality Monitor 8 in 1 $PM_{2.5}$ tool and can be applied in the community environment up to the household level. In addition, the field testing results at all field test points have an average $PM_{2.5}$ concentration that exceeds the quality standard limit based on Minister of Health Regulation Number 2 of 2023 concerning Implementing Regulations of Government Regulation Number 66 of 2014 concerning Environmental Health. Room 3 (living room) has the highest $PM_{2.5}$ concentration, while room 4 (bedroom) has the lowest $PM_{2.5}$ concentration. $PM_{2.5}$ concentrations are influenced by the area of air ventilation, mining activities, mining product transportation activities, cooking activities, and the intensity of watering roadsides and home yards.

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