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Enhancing Campus Environment: Real-Time Air Quality Monitoring Through IoT and Web Technologies

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Abstract: Nowadays, enhancing *campus environments* through mitigations of air pollutions is an essential endeavor to support academic achievements, health, and safety of students and staffs in higher educational institutes. In laboratories, pollutants from welding, auto repairs, or chemical experiments can drastically degrade the air quality in the campus, endangering the respiratory and cognitive health of students and staffs. Besides, in universities in Indonesia, automobile emissions of harmful substances such as *carbon monoxide* (CO), *nitrogen dioxide* (NO_2), and *hydrocarbon* (HC) have been a serious problem for a long time. Almost everybody is using a motorbike or a car every day in daily life, while the number of students is continuously increasing. However, people in many campuses including managements do not be aware these problems, since air quality is not monitored. In this paper, we present a real-time air quality monitoring system utilizing *Internet of Things (IoT)* integrated sensors capable of detecting pollutants and measuring environmental conditions to visualize them. By transmitting data to the *SEMAR* IoT application server platform via an ESP32 microcontroller, this system provides instant alerts through a web application and *Telegram* notifications when pollutant levels exceed safe thresholds. For evaluations of the proposed system, we adopted three sensors to measure the levels of CO, NO_2, and HC and conducted experiments in three sites, namely, *Mechatronics Laboratory*, *Power and Emission Laboratory*, and *Parking Lot*, at the State Polytechnic of Malang, Indonesia. Then, the results reveal *Good*, *Unhealthy*, and *Dangerous* for them, respectively, among the five categories defined by the Indonesian government. The system highlighted its ability to monitor air quality fluctuations, trigger warnings of hazardous conditions, and inform the campus community. The correlation of the sensor levels can identify the relationship of each pollutant, which provides insight into the characteristics of pollutants in a particular scenario.

Keywords: Internet of Things; campus air quality; pollutant detection; SEMAR; sensor technology; web application

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1. Introduction

Enhancing campus environments by tackling air pollution is an essential initiative to promote health, safety, and academic success within educational institutions [1–3]. However, air pollutants on university campuses can often arise from activities in laboratories such as welding, practical works involving automobile engines, and chemical experiments.

Each of them may emit harmful substances such as particles and nitrogen oxides [4–6]. These emissions have the potential to lower air quality, which puts students and staff at serious risk of respiratory diseases, as well as affecting their general comfort and cognitive functions [7–9].

Air quality in campuses is actually a complex issue impacted by a number of factors inside and outside, including urbanization and local climate conditions [10–12]. Because campuses can be microcosms of larger metropolitan regions [13], they are vulnerable to pollution from nearby traffic [14], industrial activities, and even construction projects within campus boundaries. These activities can significantly alter air quality, affecting the health and well-being of students, professors, and staff. As a result, it is important to monitor air quality, collect related information, and analyze air quality states at various locations on campus. This air quality information should be sent to all students on campus to avoid negative consequences on their health.

Maintaining excellent air quality on campus is crucial for any educational institution. It emphasizes the need to adopt efficient techniques to monitor and reduce air pollution. After monitoring air pollution, mitigating these emissions can be achieved by implementing strategies such as improved ventilation systems, pollutant capture devices, and sustainable practice norms. The campuses can then provide a secure learning environment that improves health, increases academic achievements, and cultivates a sense of shared responsibility for environmental stewardship by reducing air pollution.

The main sources of common pollutants on campus are automobile emissions and industrial operations. They produce NOx, HC, and CO [15,16]. If people absorb these substances, they may experience serious health consequences, such as allergies, chronic cardiovascular disorders, and respiratory problems. With these things in mind, it is critical to keep an eye on campus air quality to locate pollution hotspots and understand the consequences they have on the ecosystem and human health.

Sensors integrated with the IoT technology are essential to monitor air quality, offering an innovative solution to maintain a safe and healthy environment. Using IoT functionality, the sensors can continuously send real-time data to a centralized monitoring system, enabling campus administrators to observe air quality fluctuations instantly. This technology not only raises awareness about air quality concerns, but also helps to implement proactive strategies to foster a healthier and more supportive learning environment on campus.

In this paper, to improve the campus environment, we present a *real-time air quality monitoring system* utilizing IoT-integrated sensors capable of detecting pollutants and measuring environmental conditions to visualize them. We adopt three sensors, namely, *MQ7* for CO [17], *MQ135* for NO_2 [18], and *MQ2* for HC [19], to detect and monitor the concentrations of these dangerous compounds. By transmitting measurement data to the *SEMAR* IoT application server platform [20] through an *ESP32* microcontroller [21], this system provides instant alerts through a web application and *Telegram* notifications [22] when pollutant levels exceed safe thresholds. The campus community can quickly and easily obtain real-time air quality information.

For evaluations of the proposed system, we conducted experiments at three sites, namely, *Mechatronics Laboratory*, *Power and Emission Laboratory*, and *Parking Lot*, at the State Polytechnic of Malang, Indonesia. The results of the measurement of three compounds show that among the five categories defined by the government, the air quality at these sites is *Good*, *Unhealthy*, and *Medium*, respectively. In addition, for the high correlations between these compounds revealed that they came from the same sources, such as motorbikes or cars. The proposed system is highlighted to have the strong capability to accurately monitor air quality, trigger warnings of hazardous conditions, and inform the campus community, which validates the effectiveness of the system.

The rest of the paper is organized as follows. Section 2 introduces studies related to this paper in the literature. Section 3 introduces air pollutants in a campus and the *Air Pollutant Standard Index (ISPU)* category to evaluate air quality. Section 4 presents the design of the air quality monitoring system. Section 5 presents the implementation of the system. Section 6 evaluates the implemented system. Finally, Section 8 presents a comprehensive conclusion with future works.

2. Related Studies

In this section, we review some studies related to this paper in literature.

In 2018, Benammar et al. proposed an end-to-end system that integrates wireless sensor nodes, advanced embedded gateways, and an IoT server [23]. It enables the real-time measurement of various air quality parameters such as CO_2, CO, SO_2, NO_2, O_3, Cl_2, temperature, and relative humidity. Recognizing the critical health implications of indoor air quality, especially for vulnerable populations, this system emphasizes the importance of seamless data transmissions from sensor nodes to the IoT server, ensuring the reliable access to real-time data for remote users. However, this system did not provide the measurement of HC gases.

In 2019, Hapsari et al. developed an end-to-end system that accurately measures key pollutants such as CO_2, CO, SO_2, NO_2, O_3 and Cl_2, along with the ambient temperature and the relative humidity [24]. Recognizing the importance of *IAQM*, particularly for vulnerable indoor populations such as elderly and young children, this study emphasizes use of wireless sensor networks linked through a local gateway for efficient data processing and real-time disseminations to users via a web server. Moreover, the system leverages an open-source IoT web platform known as *Emoncms* for both live data tracking and long-term storage. Similar to previous research, this system did not provide the measurement of HC gases.

In 2020, Ng et al. developed a real-time IoT-based environmental monitoring system for outdoor use [25]. The system is designed to track multiple atmospheric pollutants including CO, *liquefied petroleum gas (LPG)*, and smoke, in addition to temperature and humidity levels. This system provides real-time data accessible to users through a smartphone application called "AirProp", and includes an alarm feature that will be activated when carbon monoxide concentrations exceed the safe threshold (50 ppm), thereby, enhancing public safety. In addition, the system incorporates a robust database that stores historical air quality data, allowing further factor analysis.

In 2020, Zhang et al. proposed a hybrid approach that uses fixed and mobile IoT sensors to measure and predict air pollution in *urban environments* [26]. Recognizing that traditional fixed sensors often do not provide comprehensive understanding of air quality due to their distances from populated areas, this study integrates mobile sensors mounted on vehicles patrolling the region, thereby, enhancing data accuracy and coverage. They developed a predictive model that uses collected data to provide timely information on air quality fluctuations, which is crucial to ensuring public health in densely populated cities.

In 2022, Jabbar et al. developed a smart long-range sensing node (*LoRa*) integrated into an IoT air quality monitoring system called *LoRaWAN-IoT-AQMS* [27]. It is designed for timely data collection and cloud updates, and is deployed in a *outdoor environment*. The system features a variety of sensors to measure key pollutants such as NO_2, SO_2, CO_2, CO, and $PM_{2.5}$, as well as temperature and humidity, all powered by a rechargeable battery and photovoltaic solar panel to ensure sustainable operation. Using a low power *LoRaWAN* connectivity solution, the system reliably collects and transmits real-time air quality data through a gateway to *The Thing Network (TTN)* IoT platform. Users access to data via a web-based dashboard and the *Virtuino* mobile application.

In 2022, Panduman et al. introduced the SEMAR IoT Server Platform, an innovative framework designed to enhance the integration and interoperability of various IoT application systems [20]. This platform facilitates real-time data aggregation, synchronization, and classification by utilizing machine learning techniques and supporting Big Data environments. SEMAR is built to be flexible and interoperable, accommodating both direct sensor connections and network-based data transmissions. The platform's modular design allows for the easy implementation of plug-in functions, enabling seamless integration with external IoT systems via REST API services. To evaluate its performance, SEMAR was tested by integrating five IoT systems, including air-conditioning guidance, indoor localization, water quality monitoring, environment monitoring, and air quality monitoring. The study highlighted SEMAR's advantages over existing IoT platforms, particularly in terms of flexibility, interoperability, and ease of integration, demonstrating its potential to serve as a robust backbone for smart city applications.

In 2023, Panduman et al. proposed an edge device framework within the SEMAR IoT Application Server Platform to enhance the utilization and flexibility of IoT systems [28]. The framework optimizes the interaction between edge devices and the SEMAR server through three key phases: initialization, service, and update. In the initialization phase, the edge device automatically downloads configuration files via HTTP communication, simplifying setup processes. During the service phase, the device standardizes sensor data formats and transmits them periodically to the server. In the update phase, configuration files are updated remotely using MQTT communication, ensuring seamless maintenance and adaptability. The framework was evaluated through applications such as the fingerprint-based indoor localization system (FILS15.4) and a data logging system, demonstrating its effectiveness in managing and standardizing diverse IoT systems. This study highlights the practical advantages of integrating edge devices with a centralized IoT server to support scalable and reliable IoT applications.

3. Air Quality Classification

In this section, we introduce air pollutants in a campus and the *Air Pollutant Standard Index (ISPU)* category to evaluate air quality.

3.1. Air Pollutants

Air pollutants typically include *lead* (PB), *sulfur dioxide* (SO_2), *carbon monoxide* (CO), *nitrogen dioxide* (NO_2), *hydrocarbon* (HC), *dust* (TSP), *fluorine index*, *chlorine*, and *sulfate index* [29,30]. Combustion activities can be sources of air pollutants without realizations. In a campus, the combustion of motor fuel turns out to be the leading contributor to air pollutants [31–34].

3.2. Three Main Air Pollutants in Campus

Among various air pollutants, we focus on CO, NO_2, and HC as the main ones on campus.

3.2.1. CO

CO is a toxic gas that is tasteless, colorless and odorless, making it invisible to the human senses [35,36]. According to [37–39], it is created by incomplete combustion of fuels such as wood, coal, oil, natural gas in cooking appliances, stoves, charcoal grills, gas range heaters, generators, and vehicle exhausts. A high level of carbon monoxide with prolonged exposure to this gas can quickly cause severe bodily damage through a variety of mechanisms, such as interference with the oxygen delivery throughout the body, inhibiting oxygen utilization, and even causing oxidative stress [40,41]. Mild carbon monoxide poisoning often presents with vague symptoms, such as nausea, headache, and fatigue. More severe poisoning can manifest in a number of forms, including loss of consciousness, acute cardiac arrest, and death [42].

3.2.2. NO_2

NO_2 is frequently involved in a variety of chemical reactions in natural and industrial operations. The combustion of fossil fuels in automobile engines, power plants, lightning strikes, and microbiological activities can produce NO_2. Because NO_2 in the environment can worsen asthma symptoms, negatively affect respiratory health, and may be associated with heart problems, it is important to monitor and reduce the level of NO_2 [43–45]. With prolonged exposure, even at the moderate level, asphyxiation can occur. Therefore, accurate identification of the level NO_2 is essential. Before NO, NO_2 is a precursor. Thermal combustion produces NO_2 as a chemical by-product. When NO_2 forms the majority of NO), N_2 is present. During high-temperature combustion, NO_2 is chemically formed. The reaction between nitrogen (N_2) and oxygen (O_2) produces nitrogen monoxide. O_2 and NO are combined to form NO_2 in a subsequent process.

3.2.3. HC

HC is the organic molecule created by chemical reactions between two primary elements, hydrogen (H) and carbon (C) [46]. These substances are created by burning fossil fuels, performing industrial operations, using organic solvents, greenhouse gas emissions (VOC), starting forest fires, and participating in microbial activities [47]. Due to their potentials for mutagenicity, carcinogenesis, and teratogenicity, HC has been the subject of a lot of research [48]. Simply put, HC is created when combustion occurs, leaving behind insufficient oxygen and the formation of CO, H_2O, and HC.

3.3. Air Pollutant Standard Index Category

Air quality can be classified by the *Air Pollutant Standard Index (ISPU)* category with a certain range of numbers in their averages of 24 h. This value is based on the *Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number P.14/MENLHK/SETJEN/KUM.1/7/2020* [29]. The values in Table 1 are adjusted based on the average values of the temperature and air pressue that are referred from the *Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG)* website [49]. This category includes *Good* with a range of 0–50, *Medium* with a range of 50–100, *Unhealthy* with a range of 101–200, *Very Unhealthy* with a range of 201–300, and *Hazardous* for values above or equal to 301. Table 1 shows the maximum values for each ISPU range of three typical pollutants, CO, NO_2, and HC. These values are given in units of $\mu g/m^3$.

However, the measured data from a sensor is often shown in units of ppm (parts per million) on the device. Therefore, Table 1 also shows the maximum values in ppm.

When air quality deteriorates and reaches the unhealthy category, NO_2 is 1000 ppm, CO 8000 ppm, and HC 215 ppm. In the hazardous category, NO_2 is 3000 ppm, CO 12,000 ppm, and HC 648 ppm. We classify it into one category using the decision tree algorithm in this paper. The following table shows the concentration thresholds for each pollutant used to assess air quality based on the ISPU category [29,30].

Table 1. Conversion of ISPU parameter concentration values every 24 h.

ISPU Category	ISPU Number	CO (µg/m^3)	NO_2 (µg/m^3)	HC (µg/m^3)
Good	000–050	4000 (3.49 ppm)	80 (0.0425 ppm)	45 (0.249 ppm)
Medium	051–100	8000 (6.99 ppm)	200 (0.1062 ppm)	100 (0.0554 ppm)
Unhealthy	101–200	15,000 (13.09 ppm)	1130 (0.6006 ppm)	215 (0.1193 ppm)
Very Unhealthy	201–300	30,000 (26.18 ppm)	2260 (1.2012 ppm)	432 (0.2396 ppm)
Dangerous	≥301	45,000 (39.27 ppm)	3000 (1.5954 ppm)	648 (0.3589 ppm)

4. Design of Monitoring System

In this section, we present the design of the *real-time air quality monitoring system*. This section explains the design of a monitoring system that includes the requirements of the system and the architecture of the system.

4.1. System Requirements

The system must detect, evaluate and inform potential risks to air quality to the public. The sensors should then be strategically placed in indoor environments inside the target campus. First, the measured data from the sensors will be sent to the microcontroller for the initial processing in real time. The processed data will then be sent to the back-end server for storage and user services.

4.2. System Architecture

Figure 1 shows the system architecture designed to detect air quality conditions that can endanger human health and the campus environment. It contains physical devices as important components of the system, including various types of sensors that will measure the concentration of pollutants such as CO, NO_2, and HC.

The sensors are connected to the controller that processes the data received. This data is then sent over the network to a server such as the *SEMAR* IoT application server [20,28]. With real-time monitoring capabilities and various AI models, it is possible to predict air quality in the future.

The system keeps history data for analysis features to process and display information on air pollution levels. The *Classification and Regression Tree (CART)* algorithm is used to analyze the air pollutant data. This algorithm allows modeling complex relationships between various variables and detecting significant patterns or trends. The implementation of the *CART* algorithm in the system allows fast and efficient data analysis, so that this system can quickly provide risk information to users when dangerous increases in pollutant levels are detected.

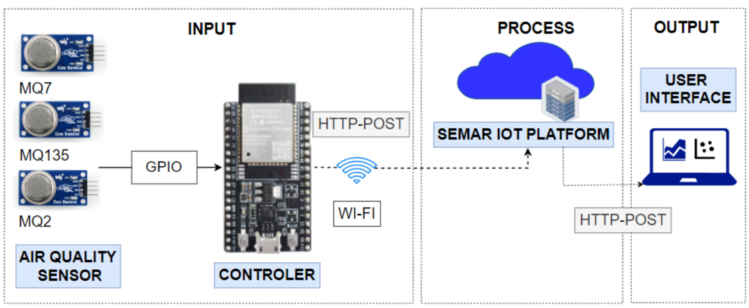

Figure 1. System architecture for air quality monitoring system.

4.3. SEMAR *IoT Application Server*

Figure 2 shows the architecture of the *SEMAR* IoT application server. *Physical Devices* continuously collect data and send them to *Data Input* of the server. Then, *Data Process* analyzes the data to provide deeper information on air pollution and the potential risks that may arise.

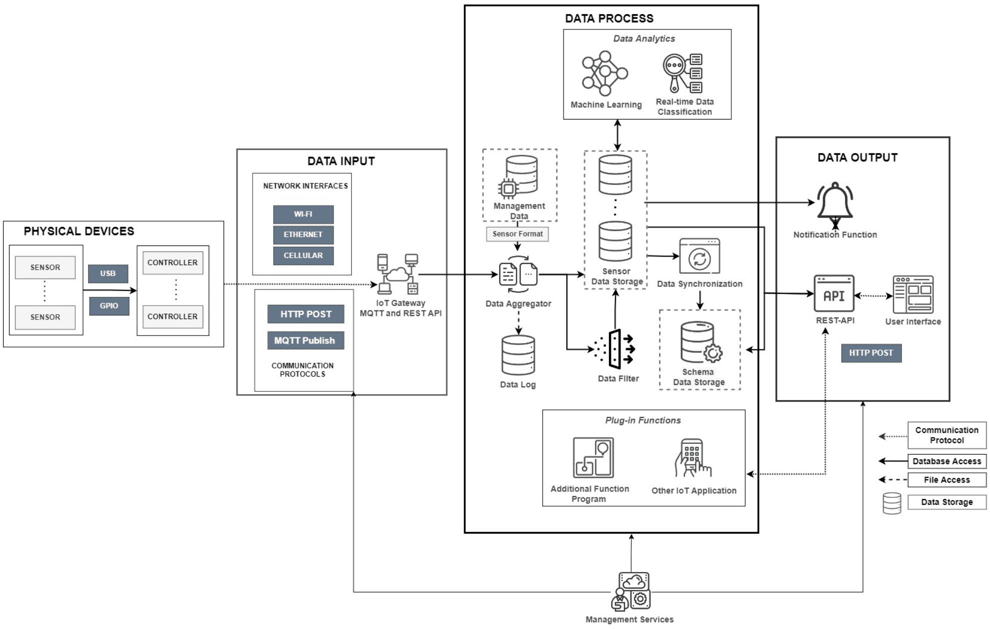

Figure 2. Design overview of SEMAR IoT server platform.

4.4. Key System Components

Here, we will explain the key components of this system. They include sensors, sensor locations, data processing functions, and data communication protocols.

4.4.1. Sensors

The system relies heavily on air quality sensors. They identify and quantify air pollutants of CO, NO_2 and HC. In addition to data collection accuracy, the sensors should run dependably for extended periods of time, integrate smoothly into the monitoring system, have low power consumptions, and allow easy maintenance.

The locations of air quality sensors are critical to enhance the effectiveness of the system. Sensors should be strategically placed in locations that can accurately reflect the necessary environments, such as work areas that are frequently used for activities. To ensure accurate readings, it is important to avoid placing the sensors near obstructions that could interfere with airflow. They should be mounted at the height appropriate for typical human exposure, typically between 1 and 3 m above the ground. Well-planned sensor allocations at multiple locations will enhance the ability of the system to monitor air quality comprehensively, providing critical data for timely warnings and interventions to protect public health, and as a resource for future research sustainability.

The following Table 2 are sensor specifications including operational range, precision, and measurement accuracy. To ensure accurate measurements, data with concentrations below 10 ppm can also be calibrated by comparing them with the reference data from standards, such as those provided by the *Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG)* [50].

Table 2. Sensor specifications for MQ7, MQ135, and MQ2 sensors.

Sensor	Operating Range	Precision
MQ7	CO: 10–10,000 ppm	±5% of reading (typical)
MQ135	CO_2: 10–1000 ppm, NH_3: 10–1000 ppm, Benzene: 10–1000 ppm, Toluene: 10–1000 ppm, Smoke: 10–1000 ppm, NO_2: 10–1000 ppm	±5% of reading (typical)
MQ2	CO: 10–1000 ppm, Smoke: 10–1000 ppm, LPG: 300–10,000 ppm, CH_4: 300–10,000 ppm, Alcohol: 300–10,000 ppm, HC: 10–1000 ppm	±5% of reading (typical)
MQ7	20 ± 2 °C, 55 ± 5% RH, requires preheating (48 h)	2 years (in normal use)
MQ135	20 ± 2 °C, 65 ± 5% RH, requires preheating (24 h)	2 years (in normal use)
MQ2	10–50 °C, 65 ± 5% RH, requires preheating (48 h)	2 years (in normal use)

4.4.2. Data Processing Unit

The data processing unit collects, processes and analyzes sensor data as the main device in the air quality monitoring system. This microcontroller unit performs the initial data filtering, regulates the flow of data from various sensors, and runs the algorithms needed for real-time analysis. Connects to a central monitoring station or a cloud service. Data aggregation, sensor calibration, and other sophisticated functions are handled in this microcontroller unit, where data analysis and threshold setting are important functions. Once the raw data are collected, the system processes them to identify patterns, detect anomalies, and determine if an air pollutant level exceeds the pre-set safety threshold that is set on the basis of the government regulatory standards.

The system can dynamically modify the threshold in response to changing environmental factors or to specific user needs. The system can lower the levels of exposure to dangerous air pollutants by assessing the data in real time and comparing it to the given parameters. This dynamic mechanism allows the system to provide automatic alarms or start automatic actions. With this feature, the air quality monitoring system is guaranteed to always provide useful information to safeguard public health, in addition to precise readings.

4.4.3. Communication Modules

As the essential part of an air quality monitoring system, the communication module transfers sensor data to a mobile device or a centralized server. In our implementation of the testbed system, the *IEEE 802.11* wireless communication protocol is used to provide lag-free data transfer and real-time monitoring. *IEEE 802.11* is well suited for many systems that require high-bandwidth communications over a wider range, making it ideal for sending large-size data to a cloud or centralized server. *Bluetooth*, on the other hand, is often used for short-range communications, especially in scenarios where the monitoring system must interact directly with mobile devices for direct data access or local controls. Integrations with mobile devices are essential to enable real-time access and control of data by system users.

An *IEEE 802.11* network can transmit data to a cloud platform or a centralized server for data processing, analysis, and storage. Users may access data through a mobile application interface or a web application interface to obtain air quality updates and reports in real time. The use of proven wireless communication protocols, such as *IEEE 802.11*, ensures compatibility and durability in a wide range of deployment scenarios, resulting in a long-term and adaptive air quality monitoring system.

4.5. User Interface Design

As the user interface, the dashboard for monitoring and managing the air quality monitoring system is designed to provide users with a comprehensive and real-time overview of environmental conditions. The dashboard has key metrics such as pollutant levels of CO, NO_2, HC, air pollution standards index (ISPU), locations and current time. Users can easily monitor their trends over time, daily summary data and historical data, and download data in csv format for further analysis on a PC. This design ensures that users can monitor air quality efficiently, receive data in a timely manner, and make informed decisions to protect their health and well-being.

4.6. Data Monitoring by Web Application

The web application serves as the central hub for data monitoring in the air quality monitoring system. The web application offers easy-to-use interfaces that display real-time data on key pollutants such as CO, NO_2, HC, and air pollution standard index (ISPU) values. The web application provides users with a customizable dashboard where they can track pollutant levels, see historical trends, and analyze data over a period of time. It also offers advanced features such as automatic data update and historical data download. Through monitoring capabilities, users are always informed about changes in air quality in a timely and effective manner.

5. System Implementation

In this section, we present the implementation of the air quality monitoring system.

5.1. System Specifications

The system specifications are explained in the hardware and the software.

5.1.1. Hardware

The hardware of the air quality monitoring system as shown in Figure 3 consists of three sensors and one microcontroller. As sensors, *MQ7* [51] is adopted to measure CO, *MQ135* [52] is for NO_2, and *MQ2* [53] is for HC. These sensors are connected to the *ESP32* microcontroller [54]. It acts as the central processing unit to collect and transmit data. In addition, a *Wi-Fi* module and a *Bluetooth* module are integrated into the *ESP32* microcontroller to enable wireless data transmission from sensors to a cloud server or mobile devices. The system is powered by a 5 V battery with a current of 0.5 A. Other devices such as resistors are necessary for integration of sensors into the microcontroller.

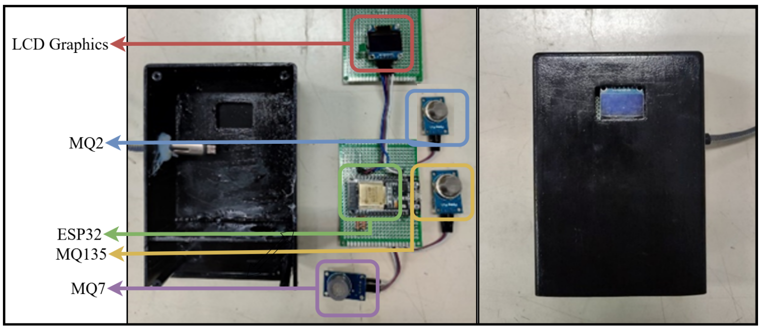

Figure 3. Hardware of air quality monitoring system.

5.1.2. Software

The software of the system is built using various programming languages and frameworks to ensure robust functionality and smooth user interaction. *C* is used for sensor data processing and integrations with the microcontroller [55], *PHP 8.0* is used for the web application [56], and *Python 3.10* is used for analyzing historical data [57]. The web application is built with responsive and user-friendly interfaces that display live data, historical trends, and customizable settings. The combination of these software ensures that the implemented system becomes robust and flexible, and is capable of meeting the demands of various use cases.

5.2. System Functions

As shown in Figure 1, the air pollution monitoring system integrates three sensors for CO, NO_2, and HC, the microcontroller, the back-end server and the web application for user interfaces.

5.2.1. Microcontroller

All data sampled from sensors are sent to the *ESP32* microcontroller for initial processing. Depending on the sensor type, analog signals, SPI, or I2C communication protocol should be selected with the appropriate input pins. It is imperative to configure the microcontroller to decipher sensor data, perform any required calibrations, and guarantee the consistent connection between the sensor and the system. The accurate setup must guarantee that the gathered data are trustworthy and ready for additional processing or examination.

The appropriate ISPU levels must be selected on the basis of the detected environmental circumstances. Actually, it is necessary to choose the upper and lower limits for pollution levels. The current level *ISPU* is automatically triggered in the system when these limits are exceeded, to perform specified actions, including sending messages or turning on actuators.

5.2.2. Back-End Server

From the microcontroller, the data are sent to the back-end server over an IEEE 802.11 network through the gateway in real time. The back-end server stores and analyzes the data. It also displays the data in web interfaces for visualizations. This system ensures efficient and timely data collection, analysis of air pollution levels, and delivery of results for air quality evaluations. For the analysis of air pollution levels, the system uses the *Classification and Regression Tree (CART)* algorithm for classification and regression tasks [58,59].

5.2.3. Web Application for User Interface

In the web interface, accessibility is the key for users to quickly comprehend the information provided and execute the required action. The web interface displays data as in Figure 4. It also allows to download the monitoring data in the csv format for further analysis and archiving purposes.

Figure 5 shows the standard interface for displaying trend graphs of sensor reading data in the *SEMAR* IoT platform [20]. The data is automatically displayed and updated in the graphic format in real-time. Figure 6 shows the interface for downloading data in various formats, to make it possible to conduct further data analysis on an individual computer.

5.2.4. Handle False Positives or False Negative

To address this issue, the system employs several strategies to minimize errors. The system is designed to detect and handle anomalies of measured data, such as *NaN* values. They may arise when a sensor fails or experiences a temporary malfunction. If a sensor produces a *NaN* value (e.g., due to hardware failure, environmental interference, or disconnection), the data is not sent to the website or the monitoring platform. This ensures to exclude erroneous or unreliable data from the analysis and presentation to users. When *NaN* values are detected, the system triggers an internal alert, which prompts a thorough inspection by the sensor. This helps identify sensor problems and ensures that only valid and accurate data is used for analysis.

To minimize the occurrence of erroneous data, we perform the periodic sensor maintenance. This process compares sensor readings with the known reference values to ensure the accuracy over time. Regular checks help detect deviations of the sensor performance that could lead to invalid readings or sensor failures, reducing the risk of *NaN* values.

Show 10 entries Search:

No	Sensor 1 (CO Detection)	Sensor 2 (NO2 Detection)	Sensor 3 (HC Detection)	Location	Nitrogen Dioxide (ppm)	Carbon Monoxide (ppm)	Hydrocarbon (ppm)	ISPU	Time
1	MQ7	MQ135	MQ2	Indoor	0.61	1.44	0.88	Good	2024-08-22 18:29:59
2	MQ7	MQ135	MQ2	Indoor	0.62	1.44	0.86	Good	2024-08-22 18:29:59
3	MQ7	MQ135	MQ2	Indoor	0.63	1.42	0.88	Good	2024-08-22 18:29:59
4	MQ7	MQ135	MQ2	Indoor	0.63	1.42	0.83	Good	2024-08-22 18:29:59
5	MQ7	MQ135	MQ2	Indoor	0.65	1.45	0.88	Good	2024-08-22 18:29:59

Figure 4. Web interface example.

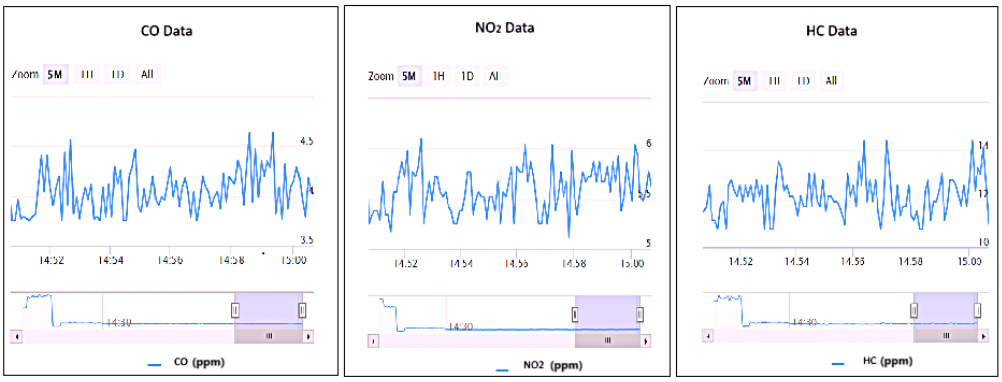

Figure 5. Data graph interface on *SEMAR* IoT server platform.

DATE	CO (ppm)	NO_2 (ppm)	HC (ppm)
2024-09-09 17:00:40	4.02	5.62	10.94
2024-09-09 17:00:35	4.04	5.77	12.57
2024-09-09 17:00:29	4.18	5.57	14.14
2024-09-09 17:00:23	3.79	5.48	13.05
2024-09-09 17:00:17	3.96	5.52	13.31

Figure 6. Data export interface on *SEMAR* IoT server platform.

5.3. Sensor Data Validation

We implemented a comprehensive 6-step validation process to ensure the accuracy and reliability of the system's data.

5.3.1. Cross-Checking with Identical Sensors

Measurements are validated by comparing readings from multiple identical sensors to ensure consistency and adherence to the manufacturer's specifications that are described in the datasheets. This step includes thorough physical checks to confirm that the sensors were in optimal condition, including visual inspection for any physical damage or wear, verifying the proper installation and alignment with the operational guidelines, and checking the power supply to ensure the stable and sufficient voltage/current during operation. If the sensor is physically usable, a sensor usage check will be carried out for several days. If the sensor can be used properly and produce data within the range according to *BMKG*, it can be concluded that the sensor is working properly. *BMKG*, which is an abbreviation of the Meteorology, Climatology, and Geophysics Agency, is an Indonesian government agency responsible for managing information related to weather, climate, geophysics, and air quality.

5.3.2. Validation Using Public Data from BMKG

After a thorough system check is performed, the data readings are compared to external data. We compare pollutant readings (e.g., NO_2 levels) with publicly available air quality data provided by *BMKG* (Figure 7) where the data is varied for certain pollutants. These data serve as a reliable reference to validate the general trend and precision of the system.

In the field of climatology, *BMKG* analyzes long-term climate patterns and provides information on potential droughts or rainy seasons. In addition, in the field of geophysics, *BMKG* monitors earthquake activities, provides early warnings of tsunamis, and helps mitigate disaster risks. *BMKG* also monitors air quality by measuring the concentration of pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), and other particles.

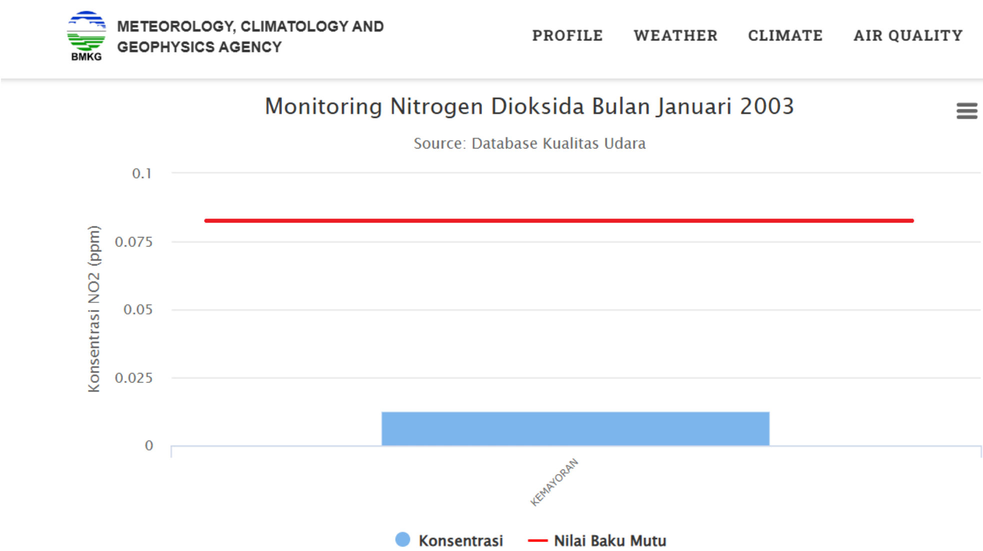

Figure 7. Indonesian comparative data by *BMKG* [50].

5.3.3. Comparison with Initial Research Data (2023)

The system performance is further evaluated by comparing data with the results obtained during the initial research that we conducted in 2023 (Figure 8). This initial data set served as a reference point, helping us verify the consistency and functionality of the system in similar test environments. Data is collected several times to see the consistency of the sensor readings at a location. All aspects are taken into account until the periodic check of the sensor performance.

No	Sensor 1 (Deteksi CO)	Sensor 2 (Deteksi NO2)	Lokasi	Karbon Monoksida (ppm)	Nitrogen Dioksida (ppm)	Waktu
1	MQ7	MQ135	Lab. Mekatronika	0.57	0.11	2023-10-24 10:40:24
2	MQ7	MQ135	Lab. Mekatronika	1.13	0.09	2023-10-24 10:39:03
3	MQ7	MQ135	Lab. Mekatronika	0.51	0.11	2023-10-24 10:38:25
4	MQ7	MQ135	Lab. Mekatronika	0.69	0.10	2023-10-24 10:37:45
5	MQ7	MQ135	Lab. Mekatronika	0.81	0.10	2023-10-24 10:37:06
6	MQ7	MQ135	Lab. Mekatronika	0.71	0.10	2023-10-24 10:36:26

Figure 8. Initial system test data as of 2023.

5.3.4. Environmental Validation (Pollutant Sources and Locations)

Sensor readings are compared across multiple locations, including campus areas near pollution sources. We chose parking lots, the mechatronics laboratory, and the power and emissions laboratory. This provides insight into the system's ability to detect varying levels of pollutants by the environmental contexts. This cross-site comparison helps us evaluate the sensor's performance in detecting pollution gradients in real-world environments.

5.3.5. Correlation Analysis Using Linear Regression

Correlation analysis is performed using the linear regression to understand the relationship between sensor readings and pollutant concentrations. This analysis helps us identify patterns and trends in the data, based on different pollution sources. The results of the regression analysis provides valuable insights into the trend of sensor readings and their responses to variations in pollutant levels.

In addition, since the three pollutants of our measurements were CO, NO_2, and HC. All of the three pollutants have certain characteristics. From the results of the correlation analysis, we can conclude that locations with the same pollutant source will give a strong positive correlation at all three levels. This indicates that sensor readings at two locations with the same pollution source tend to show a consistent and strong relationship, which strengthens the reliability of measurements in similar environments.

5.3.6. Sensor Utilization Assessment

The operational performance of each sensor is evaluated based on the duration of use, environmental conditions, and the maintenance history. These factors are monitored to identify potential deviations caused by the sensor aging or external influences. We limit the maximum use of sensors upto two months due to an anticipated damage and the decreased performance of the sensor.

By combining sensor cross-checks, comparisons with historical data and external validations, we have ensured that our results are accurate and reliable. Although full laboratory-grade calibrations were not conducted due to cost constraints, our practical approach aligns with the project's objectives and provides the confidence in the system's output.

6. Evaluation

In this section, we discuss the evaluations of the proposed air pollution monitoring system.

6.1. Three Sites for Evaluations

First, we selected three sites inside the campus of the State Polytechnic of Malang, Indonesia, for evaluations of the performance of the air quality monitoring system. They are *Mechatronics Laboratory*, *Power and Emission Laboratory*, and *Parking Lot*, since laboratories and parking lots are often places that can generate a lot of air pollutants of CO, NO_2, and HC, and can cause low air quality, which will expose students and staff to risky environments.

6.2. Results at *Mechatronics Laboratory*

First, we discuss the experiment results at *Mechatronics Laboratory*.

6.2.1. Overview of Laboratory

Figure 9 depicts the laboratory room view. There are many mechanical and electronic equipment that are used to support research and testing activities of making various electronics prototype. They produce pollutants from chemical emissions, heat, and particles when they are working. Large windows and ventilation devices attached on the ceil make good air circulations in this room, which effectively reduces indoor pollutant accumulations. The large fan on the floor helps distribute air evenly from activities in the laboratory. The results of the data collection below indicates that this location has good indoor air quality.

Figure 9. Overview and sensor location at *Mechatronics Laboratory*.

6.2.2. Sensor Location and Measurement Timing

In this first measurement, a set of sensors were placed in the *Mechatronics Laboratory*. These sensors were placed in the middle of the room from the laboratory floor about one meter away. The sensor placement is placed at the sensor mark in the figure. During data collection in the room, several activities or practicums were conducted in the room as shown in Figure 9. Measurement was carried out by turning on several sources of pollutants such as soldering, welding, practicums converting salt to electricity, 3D printing, and many more. In the room there is a blower or suction fan and ventilation outside. Data collection was carried out on 12 June 2024 at 15:02:36 to 12 July 2024 at 12:41:18. During measurements, 15 data were collected for each minute with a 4-second delay between each transmission of data.

6.2.3. Pollutant Measurement Results

Figure 10 shows the measurement results of CO, NO_2, and HC. HC increased rapidly around 12:00 due to welding, soldering, and the operation of several mechatronics activities. The exhaust gas from these activities, especially from the incomplete combustion process, can release HC. Then, around 12:35, the three pollutants suddenly dropped, because the blower or exhaust fan was activated there. All reading data for (CO), (NO_2), and (HC) were in the concentration range of 0.260 ppm to 2.265 ppm. Throughout the measurement, all pollutants were maintained at low levels, where the *ISPU* level was *Good* in the *Mechatronics Laboratory*.

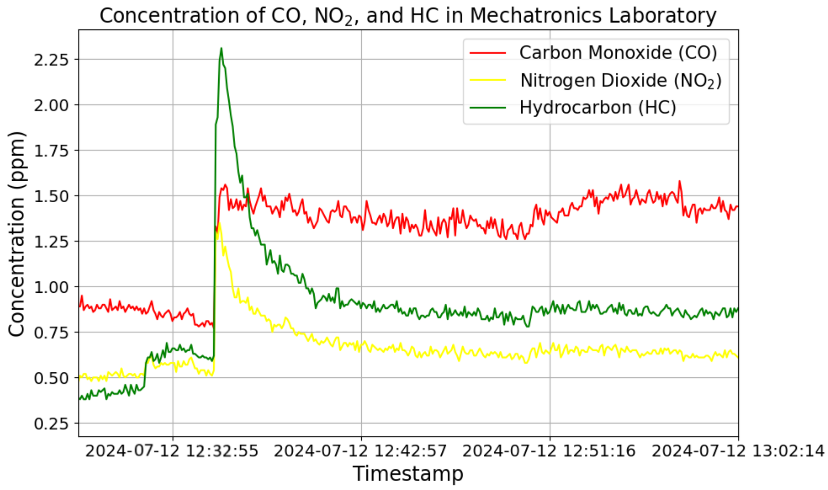

Figure 10. Reading data of CO, NO_2, and HC at *Mechatronics Laboratory*.

6.2.4. Analysis of Relationship Between Pollutants

The relationship between CO and NO_2 levels, the one between NO_2 and HC levels, and the one between CO and HC levels are analyzed. Figure 11 displays a scatter plot showing each relationship with the linear regression line. The first subplot shows a scatter plot between CO and NO_2 levels, which indicates the moderate positive correlation between them. The second subplot shows a scatter plot between NO_2 and HC levels, which indicates the very strong positive correlation between them. The third subplot shows a scatter plot between CO and HC levels, which indicates the moderate positive correlation between them. Any plot suggests the trend of the linear relationship between two pollutant levels, which suggests that all the pollutants came from the same sources at the same time.

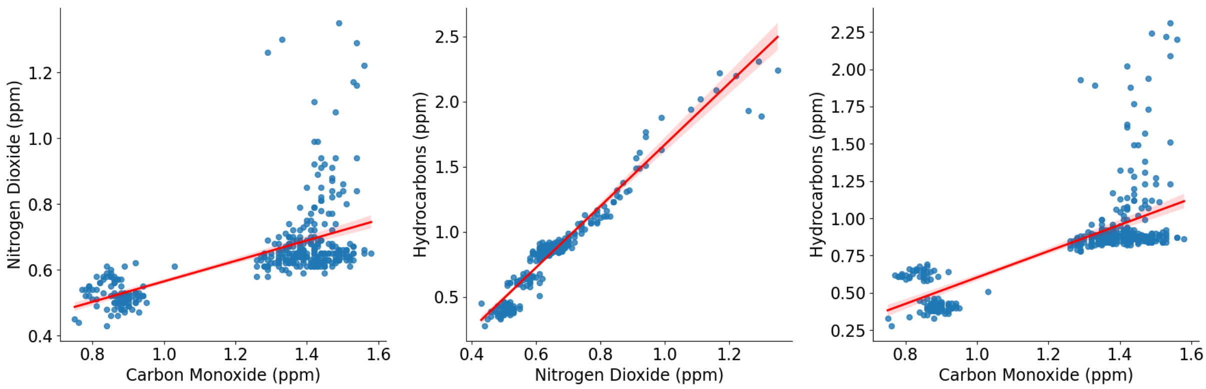

Figure 11. Relationships between CO, NO_2, and HC at *Mechatronics Laboratory*.

6.3. Results at *Power and Emission Laboratory*

Second, we discuss the experiment results at *Power and Emission Laboratory*.

6.3.1. Overview of Laboratory

Figure 12 illustrates the room overview. Gas emission testing was carried out on a motorcycle in the idle condition with repeated accelerations during this second measurement. It is noted that the motorcycle was replaced by the car when this photo was taken. This testing will accelerate the release of gas emissions including CO, NO_2, and HC. Because the vehicle is idle and the acceleration is performed repeatedly, the volume of pollutants produced is higher than when the vehicle is operating normally.

Figure 12. Overview and sensor location at *Power and Emissions Laboratory*.

6.3.2. Sensor Location and Measurement Timing

In the second measurement, a set of sensors were placed in the *Power and Emissions Laboratory*. The sensors were placed in the middle of the room from the floor at a distance of about one meter. The sensor placement is placed at the sensor mark in the figure. When collecting data indoors, testing in this laboratory was carried out by conducting several activities or practicums indoors as shown in Figure 12. They include turning on the motorcycle in the idle condition that becomes the pollutant source. There is no blower or no suction fan in the room. Ventilation exists in the room, but it is not strong and the outside of the room is closed by other buildings. Data collection was carried out on 5 September 2024. During the experiment, 15 data were collected for each minute with a 4-s interval between each data transmission.

6.3.3. Pollutant Measurement Results

The Figure 13 shows the results of measuring CO, NO_2, and HC. The pollutant source was turned on at 14:40 then the three pollutant data increased at 14:42 gradually. After 10 min the pollutant source was turned off. Then, the three pollutant data decreased at 14:49. At 14:55 the reading data gradually decreased to the average of the initial data, after the pollutant source was turned off. Due to the lack of ventilation devices for air circulation in this closed room, the risk of exposure to pollutants increases for people in this laboratory. because the initial reading data even before the pollutant source was turned on, the pollutant data in the *ISPU* range was already in the *Medium* or *Dangerous* category. All reading data for (HC), (NO_2), and (CO) are in the concentration range of 31.1 ppm to 282 ppm. During the measurement, all pollutants were maintained at *ISPU* levels ranging from *Medium* to *Unhealthy* in the *Power and Emissions Laboratory*. Therefore, it is urgently required to install blowers and strong ventilation systems in this laboratory. Besides, it is recommended that users wear masks to minimize their health impacts due to long time exposures to pollutant sources.

6.3.4. Analysis of Relationship Between Pollutants

The relationship between CO and NO_2 levels, the one between NO_2 and HC levels, and the one between CO and HC levels are analyzed. Figure 14 displays a scatter plot showing each relationship with the linear regression line. Any scatter plot indicates the strong positive correlation between the two pollutants. Again, it suggests that all the pollutants came from the same sources at the same time. CO comes from incomplete fuel combustion. CO tends to be more stable than the other two levels, which indicates that some vehicles have poor combustion. Inactive vehicle emissions can produce a lot of NO_2 and HC, especially in locations with the minimal ventilation.

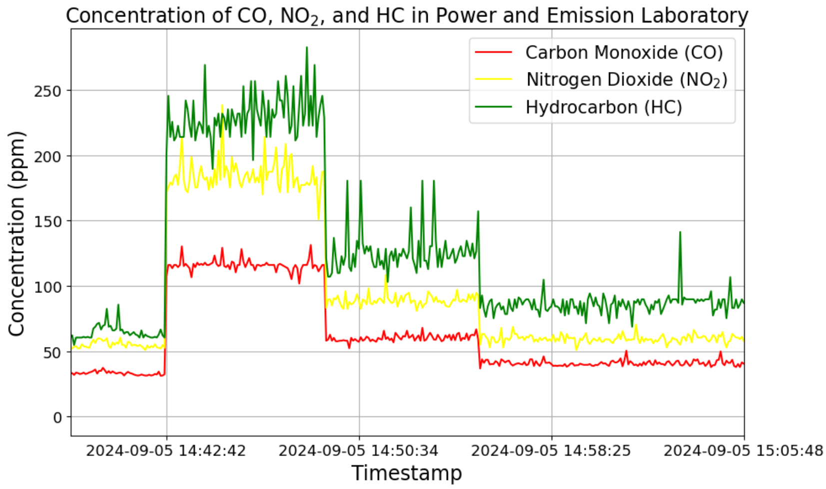

Figure 13. Reading data of CO, NO_2, and HC at *Power and Emissions Laboratory*.

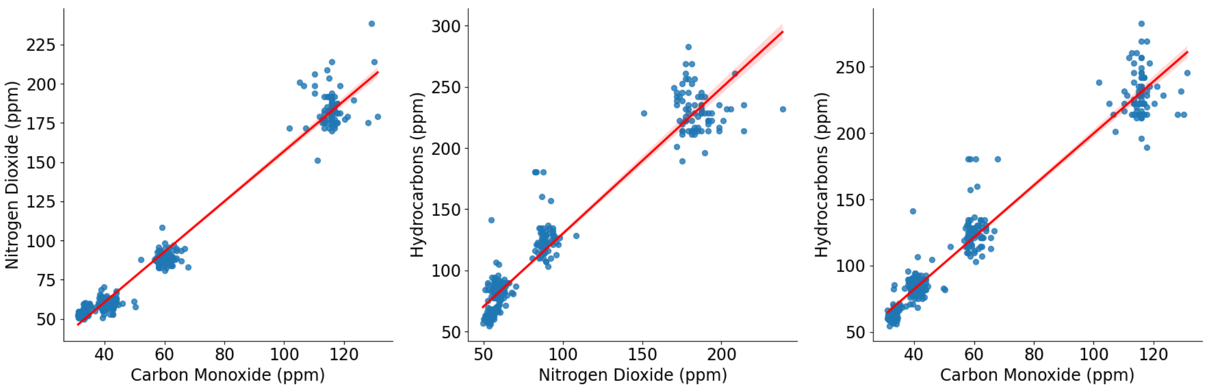

Figure 14. Relationships between CO, NO_2, and HC at *Power and Emissions Laboratory*.

6.4. Results at *Parking Lot*

Third, we discuss the experiment results at *Parking Lot*.

6.4.1. Overview of *Parking Lot*

Figure 15 illustrates the overview of the *Parking Lot*. This basement parking area is a closed environment with limited air circulations and minimal natural ventilations. A lot of motorbikes and a few cars are usually parked here, which become sources of hazardous gas emissions including CO, NO_2, and HC. When a lot of students arrive at the *Parking Lot* in the morning and leave there in the evening, the volume of pollutants produced becomes higher than other time. Based on the results of air quality measurements at this location, the data show that air quality ranges *ISPU* from *Medium* to *Dangerous* depending on the time of data collection. This can be caused by the accumulation of pollutants in vehicles that are less efficiently distributed due to lack of ventilation. In the *Parking Lot*, users (students, lecturers, staffs) are at risk of being exposed to pollutants at levels that can harm health, especially over long periods of exposure. Therefore, it is strongly recommended to improve the ventilation system, either by adding exhaust fans or increasing air circulations, to keep air quality within safe limits.

6.4.2. Sensor Location and Measurement Timing

In the third measurement, one set of sensors were placed in the *Parking Lot*. The sensors were placed in the middle of the *Parking Lot* with a distance of about one meter from the floor. The sensor placement is placed at the sensor mark in the figure. Measurements were carried out at both active hours and non-active hours of students who come to the *Parking Lot* to attend classes. There were no blowers or fans in the basement as shown in Figure 15. Ventilation into the room led outside but not to the tree area. Data collection was carried out starting on 3 September 2024. During the experiment, 15 data were taken for each minute with a 4-s interval between each data transmission.

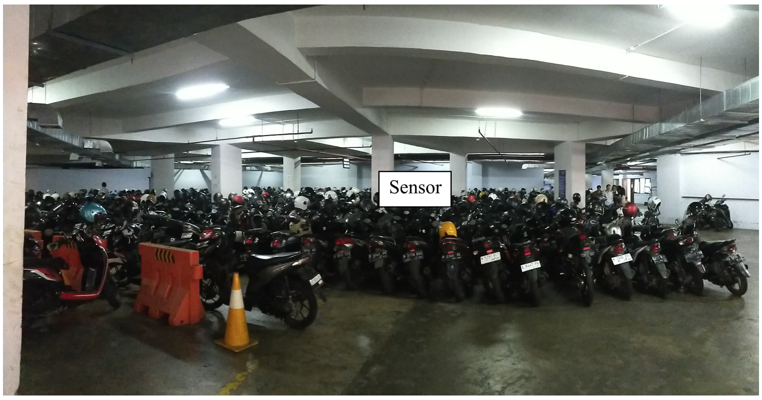

Figure 15. Overview and sensor location at *Parking Lot*.

6.4.3. Pollutant Measurement Results

Figure 16 shows the measurement results of HC, NO_2, and CO. At 7:35 AM, all the pollutants gradually increased because more students arrived at the parking. At 10:00 AM, all the pollutants were nearly constant because few motorbikes arrived or left. All readings for (HC), (NO_2), and (CO) were in the concentration range of 29.7 ppm to 85.5 ppm.

These reading data results show that the *ISPU* level for the air quality in the room was *Unhealthy* to *Dangerous*. Ventilations in this basement *Parking Lot* is very minimal and there are quite a lot of sources of pollutants. It is advised that students and others should wear masks when entering this location, and that blowers should be provided to improve air circulations.

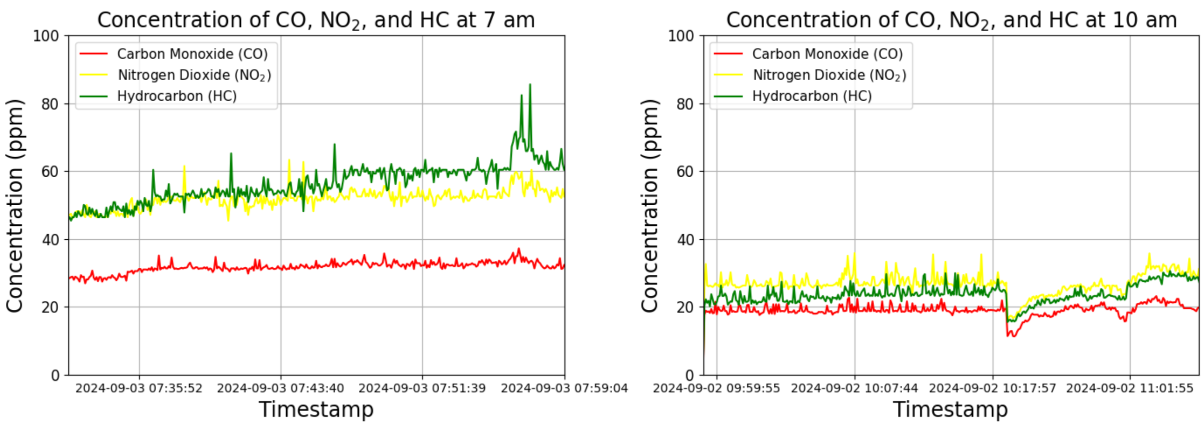

Figure 16. Reading data of CO, NO_2, and HC at *Parking Lot*.

6.4.4. Analysis of Relationship Between Pollutants

The relationship between CO and NO_2 levels, the one between NO_2 and HC levels, and the one between CO and HC levels are analyzed. Figure 17 displays a scatter plot showing each relationship with the linear regression line. The first subplot shows a scatter plot between CO and NO_2 levels, which indicates the strong positive correlation between them. The second subplot shows a scatter plot between NO_2 and HC levels, which indicates the positive correlation between them. The third subplot shows a scatter plot between CO and HC levels, which indicates the very strong positive correlation between them. Any plot suggests the trend of the linear relationship between two pollutant levels, which suggests that all the pollutants also came from the same sources at the same time.

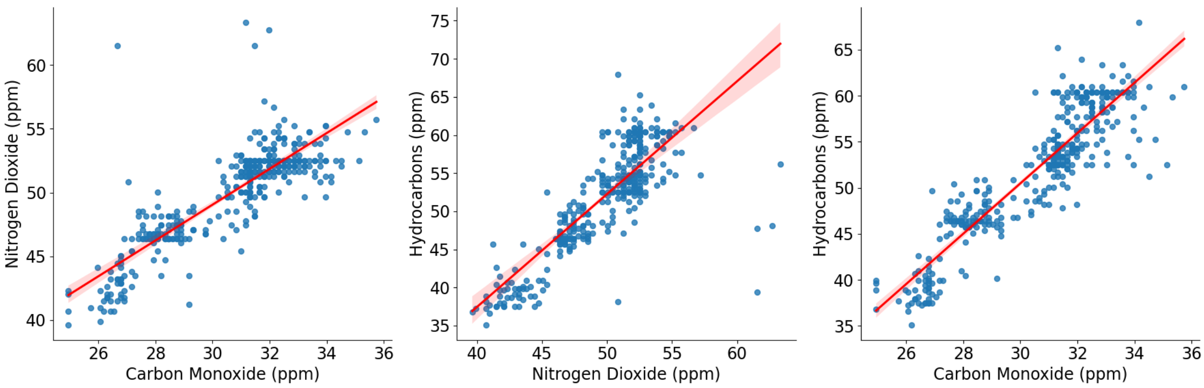

Figure 17. Relationships between CO, NO_2, and HC at *Parking Lot*.

7. Discussion

7.1. Summary of Corelation

Pollutant correlation analysis was carried out in different locations to assess the air quality performance of our monitoring system and to investigate the environmental conditions in different areas of campus. Specifically, we selected three sites on the campus of the State Polytechnic of Malang, Indonesia, *Mechatronics Laboratory*, *Power and Emission Laboratory*, and *Parking Lot*. These locations were chosen because they are often exposed to pollutants such as CO, NO_2, and HC, which can degrade air quality and pose health risks to students and staff.

7.1.1. Purpose of Analysis

This analysis aims to understand how pollutant concentrations CO, NO_2, and HC correlate with each other in campus locations, with a focus on identifying environmental patterns or trends. It also investigates whether the air quality monitoring system can reliably detect these pollutants and whether the correlations between the various pollutants are consistent between locations. Then it evaluates the impact of various sources of pollution on air quality at each location and how the system adapts to varying environmental conditions.

7.1.2. Correlation Analysis by Location

The pollutant data from the three locations were analyzed using scatter plots to observe the relationships between CO, NO_2, and HC. The scatter plots include the linear regression lines to highlight trends and relationships between pollutant levels. The analysis revealed distinct patterns between the locations, mainly based on the sources of pollution:

1. Power and Emission Laboratory and Parking Lot
   These locations share common sources of pollutions, namely motor vehicles. The scatter plots for these locations showed strong positive correlations between the three pollutants. Specifically, as the concentration of CO increased, the levels of NO_2 and HC also increased in a consistent way. This suggests that the same source (motor vehicles) is likely contributing to the elevated levels of these pollutants, leading to similar correlations at both sites. The regression lines in the scatter plots for both locations demonstrate strong linear relationships between CO, NO_2, and HC, which confirms the influences of vehicle emissions on air quality in these areas.
2. Mechatronics Laboratory
   Unlike the *Power and Emission Laboratory* and the *Parking Lot*, the *Mechatronics Laboratory* has several sources of pollutants, which can include machinery and electronic

equipments. As a result, the scatter plots for this location showed weaker correlations between CO, NO_2, and HC. Although the pollutants still exhibited positive correlations, they were not as strong as those observed at the other two locations. The data points were more scattered, reflecting the more diverse sources of pollution in the *Mechatronics Laboratory*.

7.1.3. Conclusion on Pollutant Sources and System Reliability

The results of this analysis demonstrate that the air quality monitoring system is capable of distinguishing between different pollutant sources based on their characteristic correlations. The strong correlations observed in the *Parking Lot* and in the *Power and Emission Laboratory* indicate that both locations are heavily influenced by motor vehicle emissions, resulting in similar patterns of pollutant behaviors. In contrast, the *Mechanical Laboratory*, with its different sources of pollutions, exhibited distinct correlation characteristics, highlighting the ability of the system to adapt to varying environmental factors.

These findings also support the reliability of our monitoring system, as it accurately captures and differentiates between the effects of different pollution sources in real world environments. The correlation coefficients and scatter plot trends further validate the system's performance and its capability to detect and analyze air quality based on varying sources of pollutants.

7.2. Advantages of the System

In this part, we discuss advantages of the system.

7.2.1. Cost-Effectiveness

Our system offers a highly affordable solution compared to a lot of traditional air quality monitoring systems. This makes it accessible to educational institutions and small organizations with limited budgets.

7.2.2. Ease of Deployment

The system has been designed to be easily deployed and operated. It does not require specialized infrastructure or complex installation processes, unlike many commercially available systems that often involve high setup costs and maintenance requirements.

7.2.3. Real-Time Data Processing

One of the unique features of our system is its ability to provide real-time monitoring of air quality. This is an advantage over some traditional systems that may offer periodic updates or require manual data collections and analysis.

7.2.4. Tailored Design for Campus Environments

Our system is specifically designed for monitoring air quality within campus environments, including laboratories and parking lots. This targeted approach allows more relevant and efficient data collections in these areas, whereas many existing systems are designed for general urban or industrial environments.

7.2.5. Integration with Communication Platforms

Our system integrates seamlessly with communication platforms, such as *Telegram*, to alert users when pollutant levels exceed safe limits. This real-time notification feature is often not available in conventional systems, which may only provide periodic reports without immediate actionable alerts.

These aspects demonstrate the advantages of our proposed system, which combines affordability, ease of use, real-time capabilities, and specific design features tailored to the needs of campus environments. We believe that these advantages make our system a valuable tool for air quality monitoring in academic settings.

7.3. Limitation

Below, we discuss some of the limitations of the system.

7.3.1. Sensor Accuracy

One of the major limitations of the proposed system is the possbility of declining the sensor accuracy over time. Sensors, particularly gas sensors, are subject to drift, which results in the reduced measurement accuracy. Although the routine calibration can be performed to mitigate this issue, the sensor drift is an inherent challenge in a long-term monitoring system. As a result, occasional inaccuracies in pollutant detection readings may occur, especially if sensor calibrations are not frequent enough. Therefore, routine calibrations and replacements of sensors are performed on a monthly basis in our experiments. It is noted that the calibration to the laboratory standards is not performed due to cost constraints.

7.3.2. Calibration Issues

Although we perform the periodic sensor calibration, this process is not perfect. The accuracy of the calibration depends on the availability of the reference data, where in some cases, the reference data may be limited. In addition, the calibration procedure is sensitive to environmental factors that can affect sensor performances, such as the temperature, humidity, and air pressure. Thus, achieving the perfect calibration across all the sensors is challenging, although small calibration errors can affect the quality of the detected readings.

7.3.3. Environmental Interference

Another limitation is the possibility for environmental interferences, which can affect sensor readings. Factors such as nearby sources of heat, humidity, or pollution can cause sensors to read inaccurately, leading to false positives or false negatives. Although efforts are made to place sensors at optimal locations with minimal interferences, it is impossible to completely eliminate impacts of environmental variables.

7.3.4. Sensor Maintenance and Replacement

Routine maintenance is essential to ensure that the sensor functions properly over time. However, this process can be resource-intensive and costly, especially when a large number of sensors are deployed in the field. Furthermore, a sensor may need to be replaced by a new one periodically due to the wear and tear, which will increase the operational cost of the system.

In summary, the proposed system offers significant advantages in terms of real-time air quality monitoring, while there are some limitations, such as sensor accuracy drift, calibration challenges, and environmental interference. These factors must be taken into account when assessing the overall performance and practicality of the system. We will continue to address these challenges in future works by exploring advanced calibration techniques, improving data transmission protocols, and refining sensor technologies to improve the accuracy and reliability.

7.4. Scalability

The scalability challenges of deploying our proposed air quality monitoring system on a larger campus or across multiple campuses. Expanding the system to cover a larger area or multiple locations presents several challenges. We anticipate the need for additional infrastructure and resources as the system expands. In the following, we discuss the key scalability challenges.

7.4.1. Network Infrastructure

As the system expands to cover a large campus or multiple campuses, the network infrastructure must be robust enough to handle the increasing volume of data. With more sensors deployed, the amount of data transmitted to the central server platform will increase significantly. This requires ensuring that the network has the sufficient bandwidth, reliability and range to prevent data losses or transmission delays, especially in areas with weak signals or limited connectivities. To address these challenges, the proposed system may require the installation of additional network equipments, such as gateways, routers, repeaters, or even switching from *WiFi* to *LoRa* to ensure continuous and reliable data transmissions for IoT.

7.4.2. Sensor Placement and Maintenance

With larger areas to cover, the number of sensors required to monitor air quality will increase substantially. This requires careful planning of sensor placements to ensure representative coverage across the campus. The system will need to address logistical challenges of installing, calibrating, and maintaining the sensors.

Additionally, as the number of sensors increases, the complexity of their maintenances increases. Calibrating, repairing, and periodically replacing faulty sensors will require additional resources, both in terms of time and costs. As the system scales, they can become significant challenges.

7.4.3. Data Storage and Processing

System expansion will result in a large System expansion will result in a large increase in the volume of data collected from many sensors in multiple locations. Managing data, including storage, processing, and analysis, will require additional computing resources. Cloud-based storage solutions or dedicated servers will be necessary to efficiently store and process data.

Furthermore, the system will need to enhance its data analysis capabilities to handle a larger volume of data, ensuring real-time monitoring without sacrificing performance. Advanced data processing and analytical tools will need to be integrated to support decision making on a larger scale.

7.4.4. System Coordination and Integration

As the system expands to include multiple campuses, the coordination and integration of data from multiple campuses become more complex. A centralized server platform will need to combine data from multiple locations and ensure that data remains accurate and consistent across all campuses.

The system may require additional software components to manage the integrations of data from multiple sources and to ensure seamless communications between the sensors, the central platform, and the user interfaces. This may involve implementing more sophisticated data fusion and synchronization techniques to combine data from multiple sensors and campuses.

7.4.5. Power and Energy Requirements

Larger sensor deployments will increase the energy requirement of the system. Ensuring a consistent and reliable power supply to a large number of sensors, especially in remote areas, can be challenging. Solutions such as solar-powered sensors or energy-efficient technologies will be needed to support the scalability of the system. In addition, power management solutions will be needed to ensure that sensors operate continuously without significant downtime, especially in locations without a power grid.

In conclusion, while the proposed air quality monitoring system is capable of being scaled to a larger campus or multiple campuses, this expansion will require careful planning and additional infrastructure. The key areas that need to be addressed include the network infrastructure, sensor deployment and maintenance, data storage and processing, system coordination, and power requirements. Addressing these scalability challenges will ensure that the system remains effective and reliable as it grows.

8. Conclusions

This paper presented the *real-time air quality monitoring system* utilizing IoT-integrated sensors for detecting air pollutants and evaluating environmental conditions to visualize them. By transmitting data to the *SEMAR* IoT application server platform via an *ESP32* microcontroller, this system provides instant alerts through a web application and *Telegram* notifications when pollutant levels exceed safe thresholds. For implementations and evaluations, three sensors were adopted to measure the levels of CO, NO_2, and HC, and experiments were conducted in three sites, namely, *Mechatronics Laboratory*, *Power and Emission Laboratory*, and *Parking Lot*, at the State Polytechnic of Malang, Indonesia. The results found that the air quality level was *Good*, *Unhealthy*, and *Dangerous* for the three sites among the five defined by the government, respectively.

Future works include expanding the range of pollutants monitored by integrating additional sensors including the ones for temperature and humidity, along with implementing machine learning algorithms for improved predictive capabilities. Furthermore, developing a mobile application for real-time access to air quality data and collaborating with campus authorities for user feedback could improve the involvement of the system.

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