IoT-based real-time indoor air quality monitoring and web server management system using Raspberry Pi

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Abstract

This study presents an IoT-based real-time indoor air quality monitoring system designed for laboratory classrooms to provide students with optimal working and learning conditions. The system uses a Raspberry Pi as a central hub for data collection, processing, and visualization, paired with sensors such as the MQ135 and DHT22 to monitor key environmental parameters, including ammonia (NH3), CO2, benzene, smoke, temperature, and humidity, in parts per million (ppm). Sensor data is collected and stored in a PostgreSQL database, and real-time visualization is performed using a Django web application. The results show elevated levels of contaminants during long soldering sessions, highlighting the need for effective ventilation strategies. The integration of the Raspberry Pi system improves the accuracy and responsiveness of air quality monitoring, providing a scalable and cost-effective solution for maintaining a safe indoor environment. Future work aims to optimize data processing algorithms and integrate advanced analytics to predict and proactively address air quality issues.

Keywords

Indoor air quality, monitoring system, low-cost prototype, pollution level, Internet of Things

1. Introduction

Most individuals spend their substantial amount of time in indoor activities, therefore maintaining indoor air quality is critical. Whether working in enclosed offices or open places with a large number of employees, air quality must be monitored and controlled to improve working conditions and employee well-being. Maintaining air quality is critical in modern educational laboratories, particularly those with soldering stations, to ensure a safe and optimal working and learning environment. In academic institutions, for the practical purpose of teaching electronics, electrical circuits are assembled, where soldering stations are often used. However, long-term use of soldering equipment can lead to the accumulation of hazardous materials in the air, which can be harmful to the health of teachers and students. In addition, such environmental elements as humidity and temperature [1] have a great impact on maintaining comfort and safety during the educational process. Maintaining optimal temperature and humidity values helps prevent deterioration of people's well-being and reduces the risk of harmful substances entering the air. The purpose of this work is to monitor the air quality and microclimate parameters in the laboratory classroom during classes and assess the need to implement an air quality control system. Implementing these improvements will improve working conditions and increase the safety and comfort of the educational process. If the room is not ventilated and too little outside air enters, pollutants can accumulate to levels that pose health and comfort problems. Active ventilation is not enough to open a window; it can also be achieved using ventilation devices.

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There are many sources of indoor air pollution, such as heating appliances, tobacco products, building materials, central heating and cooling systems, humidifiers, excess moisture, and outdoor sources [2]. Volatile organic compounds (VOCs) are gases emitted from various solid or liquid materials. These compounds encompass numerous chemicals, some of which have the potential to cause short-term and long-term adverse health effects. VOC levels are often significantly higher, sometimes up to ten times higher than outdoor levels. VOCs can originate from numerous products, including paints, varnishes, waxes, cleaning agents, disinfectants, cosmetics, and fuels. These products can release organic compounds during both usage and storage. The well-being and health of school and university students are directly affected by air quality. The paper [3] presents a systematic review of IoT-based indoor air quality monitoring systems, including an analysis of sensor types, microcontrollers, architectures, connectivity, and implementation challenges based on studies published between 2015 and 2020. Research shows that students are regularly exposed to pollutants such as CO_2, particulate matter, and volatile organic compounds (VOCs) in buildings throughout the day [4]. Although some buildings may meet current standards, these recommendations may not fully address potential indoor air quality (IAQ) issues [5]. In paper [6], monitoring methods using low-cost sensors that can collect data and raise awareness were investigated. In the work [7], ventilation methods were evaluated for their ability to improve indoor air quality where CO_2 levels were a critical indicator. Many factors influence the increase in CO_2 levels, such as the number of students, their activities, and lack of ventilation, etc. The studies showed that there is a need for improved ventilation systems, as well as more careful monitoring and re-evaluation of current air quality standards in educational institutions. Poor indoor air quality, often caused by insufficient ventilation, can lead to increased levels of pollutants such as CO_2, NO_2, and particulate matter [8], [9]. Research has shown that poor indoor air quality exposure can lead to adverse health effects and reduced cognitive performance, with students in unhealthy classroom environments performing worse on standardized tests [10]. Continuous IAQ monitoring using smart technologies and IoT sensors has been proposed to address these issues. Implementing automated controls, improving building air tightness, and using appropriate filtration methods can help reduce IAQ inefficiencies. Furthermore, smart and learning campuses can serve as living laboratories to promote education for sustainable development and raise awareness of air quality issues [11]. The authors [12] present a comprehensive indoor air quality monitoring system using a low-cost Raspberry Pi-based air quality sensor module that measures ten indoor environmental parameters, including pollutants.

The authors [13] indicate that real-time monitoring of classroom CO_2 levels can be used as a proxy for the risk of SARS-CoV-2 transmission. They implemented a customized ventilation protocol with real-time CO_2 monitoring, improving CO_2 levels in all classrooms where teachers followed it. The study [14] examined indoor environmental quality, including indoor air quality, ventilation requirements, and health impacts assessed using the Cancer Hazard Index and Risk of Cancer in a naturally ventilated school. The study examined the relationship between ventilation, CO_2, and particulate matter (PM) levels. It assessed the potential health hazards of pollutants to students using the US Environmental Protection Agency's Cancer Hazard Index and Risk of Cancer. The paper [15] presents an IoT-based system for continuous monitoring and assessment of indoor air quality (IAQ) in an educational building, which includes collecting real-time measurements of CO_2, CO, and $PM_{2.5}$ parameters, transmitting the data to a cloud platform and developing a deep learning model to predict indoor environmental conditions.

Recent research on the development of IoT-based indoor air quality monitoring and control systems uses low-cost sensors to measure pollutants such as CO, CO_2, and particulate matter, as well as readily available microcontrollers and communication modules to process and transmit data. Such projects include alarm systems and ventilation activation based on pollutant levels [16]. The authors [17] propose a system that collects, processes and transmits air quality indices to servers for storage and visualization. IoT platforms with low-cost sensors have shown good potential in improving indoor air quality management, and regular replacement of sensors is recommended for reliability. These systems can integrate data-driven algorithms for IAQ prediction and ventilation control, balancing energy efficiency with air quality improvement [18].

The rest of the article is organized as: Section 2 presents methods and materials. Section 3 gives an overview of experimental results, and Section 4 concludes the entire article and provides future work.

1.1. Main contributions

The main contributions of the article are summarized as follows:

- The study describes a system that is specifically intended for laboratory classrooms and uses a Raspberry Pi as a central hub for data collecting, processing, and display. This system uses sensors such as the MQ135 and DHT22 to monitor vital environmental parameters like ammonia (NH3), CO2, benzene, smoke, temperature, and humidity instantaneously. The data is saved in a PostgreSQL database and shown via a Django web application, providing an adaptable and cost-effective approach for ensuring a safe indoor environment.
- The findings of the study reveal that the monitoring system successfully detected high levels of pollutants, particularly during long soldering sessions, emphasizing the importance of proper ventilation in laboratory conditions. This contribution focuses on the system's practical applicability in improving air quality while also providing optimal working and learning environments for students.

2. Methods and materials

This study was conducted in the university's Electronics laboratory room, which has a total area of around 36 m^2. The laboratory room has radiators for winter heating and one large opening window (see Figure 1).

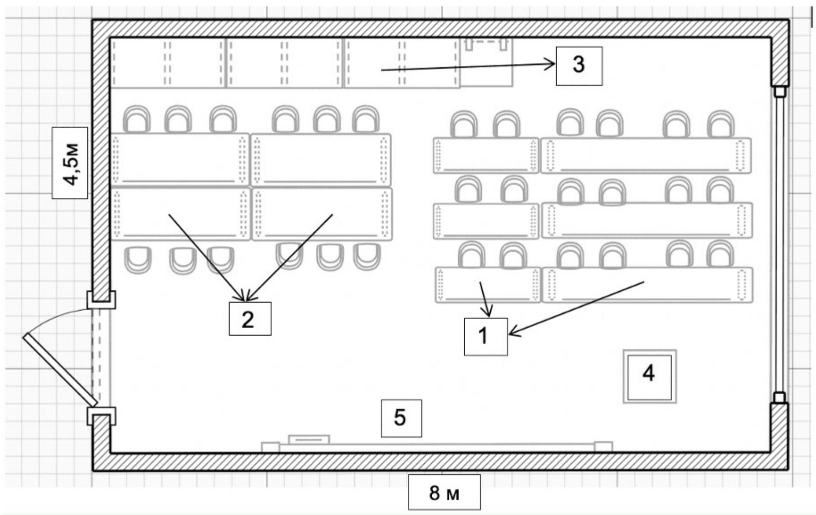

Figure 1: Electronics classroom (conditional signs: 1 - study desks; 2 - laboratory tables; 3 – cabinets; 4 - teacher's desk; 5 – board; the number of sockets is 5).

2.1. Research approach

The research included the following tasks::

- Developing a low-cost IoT-based system for real-time air quality monitoring.
- Collecting experimental data using sensors such as CO_2, temperature, and humidity.
- Data processing involves organizing and cleaning the data and preparing it for further analysis.
- Installing the monitoring system in a university laboratory to ensure a safe and optimal learning environment for students and teachers.

2.2. Research approach

The developed system for monitoring air quality in a laboratory room includes two main components. The first part of the system consists of sensors installed in the laboratory that measure air parameters such as gas concentrations. Data from the sensors is collected using an Arduino Uno microcontroller, which reads the values and transmits them to the next part of the system. The second part is a web server running on a Raspberry Pi that collects, processes, stores, and displays data. Raspberry Pi connects to the microcontroller via a serial interface or over a network and receives sensor data. The web server allows the storage of data in a local database, displays data in real-time via a web interface, sets up alerts for exceeding permissible values of pollutants or other parameters, and provides access to historical data for analyzing changes in air quality over time. The system allows teachers and students to monitor air quality in real-time, ensuring safe working and learning conditions in the laboratory room. With the help of a web server on the Raspberry Pi, it is possible to collect and display data from sensors and control connected IoT devices in real-time. The system architecture is shown in Figure 2.

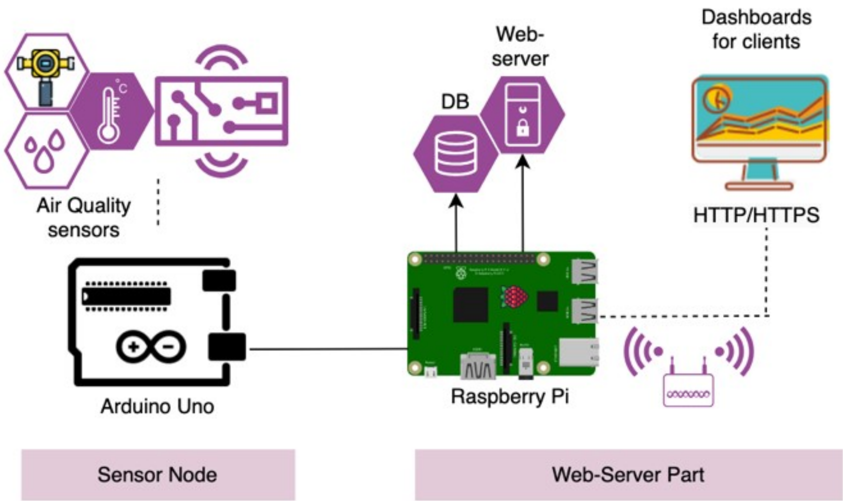

Figure 2: The architecture of the monitoring system.

Sensor data collection and transmission are critical in Raspberry Pi-based systems since they allow for real-time environmental monitoring and analysis. The central node here is the Raspberry Pi, effectively processing and storing data acquired from numerous sensors, allowing for timely responses to environmental changes. This prototype configuration enables fast and efficient identification of hazardous pollutants or deviations from optimal conditions. It also includes automatic notifications to ensure safety. In addition, remote access and real-time data display are possible with a connection to a web server implemented on Raspberry Pi. The prototype is scalable, such a solution is suitable for various conditions, not only laboratory, but also industrial. The data from the S_d sensors is collected as follows:

$$S_d = (\sum_{i=1}^{n} Gas\,Concentration_i + Temperature_i + Humidity_i, \qquad (1)$$

Data transmission process can be determined as follows:

$$Transmission = ArduinoUno(\sum_{i=1}^{n} S_{d_i}) \longrightarrow Serial\,Interface/N \longrightarrow Raspberry\,Pi, \qquad (2)$$

where, N denotes the network, n is the number of sensors, $Gas\,Concentration_i$ that includes measurements of ammonia (NH_3), CO_2, benzene, and smoke, $Temperature_i$ and $Humidity_i$ are the environmental parameters that are measured.

The Arduino Uno reads and sends the data gathered to the Raspberry Pi via a serial interface or a network connection. The data processing on a Raspberry Pi is an essential component of IoT and embedded systems, which offers a capable and inexpensive platform for performing a variety of computing tasks. The adaptable architecture of the Raspberry Pi allows it to collect and process data from several sensors at the same time, which helps for real-time applications. Once sensor data is sent to the Raspberry Pi, it can execute a variety of processing tasks, ranging from simple filtering and aggregation to more advanced analytics, depending on the application needs. The data after processing is stored locally on the Raspberry Pi, and can be transferred to cloud services or viewed in real time using a connected display or web interface. Thus, data process P_d can be calculated as follows:

$$P_d = W_s + (Raspberry\ Pi(S_d)), \tag{3}$$

where, W_s is the web server.

Real-time visualization on the Raspberry Pi with IoT support improves the device's operation and user experience. Getting quick feedback on data and visualization is the advantage of this work. Users can monitor environmental conditions, system performance, and other important parameters as they occur. This fast access to data guarantees that anomalies, such as unsafe amounts of pollution in an air monitoring system can be discovered and handled immediately that prevents possible hazards. Furthermore, real-time visualization on a Raspberry Pi allows for better decision-making because users can observe the direct impact of environmental or system changes on the data being watched. Thus, real-time visualization V_{rt} can be determined as follows:

$$V_{rt} = W_I(P_d) + Db_s + H, \tag{4}$$

where W_I denotes web interface, H is the Hist, and Db_s is the database storage

The sensors used in the architecture are the MQ135 gas sensor and the DHT22 temperature and humidity sensor (see Figure 3). The MQ135 is a low-cost indoor electrochemical gas sensor, which measures ammonia, nitrogen, oxygen, alcohols, aromatics, sulfide, and smoke together as an IAQ. The sensor must warm up for at least 24-48 hours to obtain stable gas readings. The control is carried out by an Arduino Uno board equipped with an ATmega328P microcontroller. This microcontroller operates at a clock rate of up to 16 MHz and has 32 KB of flash memory for programs, 2 KB of RAM (SRAM), and 1 KB of non-volatile memory (EEPROM). For the MQ135 sensor, we apply data cleaning since the values can fluctuate due to noise or electromagnetic interference, so a moving average filter was used.

The environmental data collection interval was one hour. Table 1 shows the main characteristics of the sensors.

Figure 3: Soldered sensors on the board.

Table 1
Hardware components and parameters of the sensor in IoT-based monitoring system

Parameter	Sensor	Accuracy	Range
Temperature (°C)	DHT22	±0.5°C	-40…80°C
Humidity (%)	DHT22	± 2%	0…100%
Gases (ppm)	MQ-135	± 3%	10…1000ppm

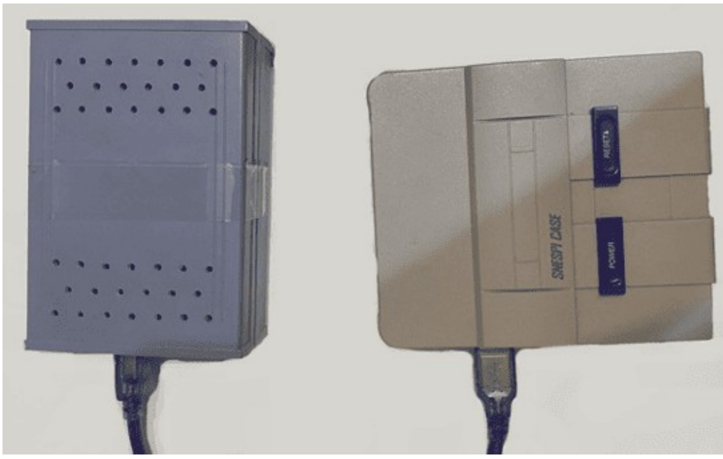

Figure 4: Indoor Air Quality Sensor in cases.

The article uses a hardware infrastructure with a Raspberry Pi 3 single-board computer hosting the web server. This third-generation model, released in February 2016, features a 1.2 GHz 64-bit quad-core ARM Cortex-A53 processor, 1 GB of RAM, and integrated 802.11n Wi-Fi and Bluetooth 4.1 modules, making it a powerful and versatile choice for various applications. The Raspberry Pi 3 web server receives data from an Arduino Uno microcontroller via a serial interface. This data collected from the sensors is stored in a PostgreSQL database. PostgreSQL, also known as Postgres, is a powerful, reliable, and flexible open-source relational database management system. Users have access to real-time sensor readings, graphical data representations, and analysis tools through a Django web interface. The web server running on the Raspberry Pi 3 is secured by scanning and monitoring important system parameters, and measures are taken to protect against DDoS attacks and SQL injection threats, including Nmap and the OpenAI API. Figure 4 shows a prototype of a low-cost monitoring system, and Figure 5 provides a system flow chart.

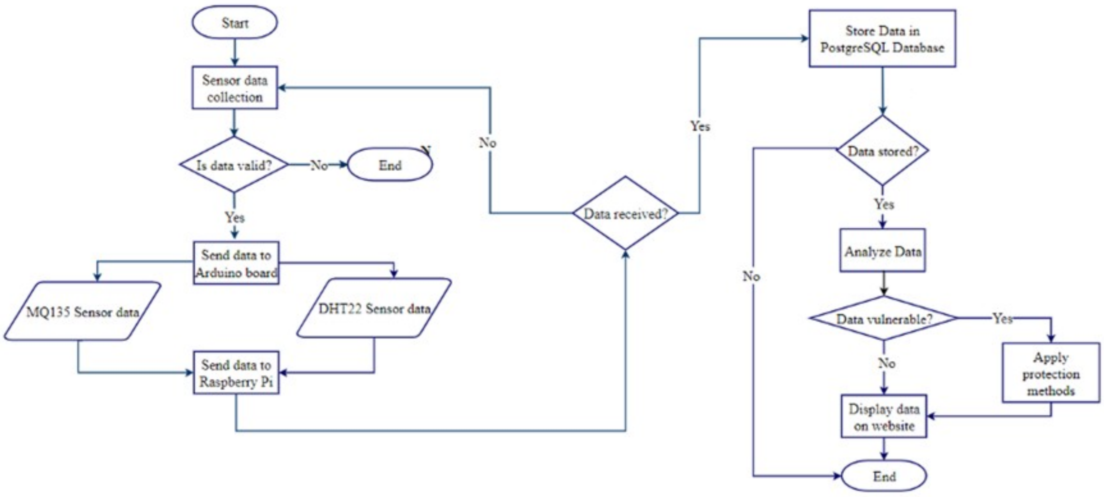

Figure 5: System monitoring for sensor data collection, validation, and analysis process.

The process starts with collecting data from the sensors connected to the Arduino board. After collecting the data, a verification process is carried out. After verification, the Arduino board captures data from the MQ135 and the DHT22 sensor. The captured data is then transmitted to the Raspberry Pi, where it is confirmed to have been received. The data is then saved to a PostgreSQL database on the Raspberry Pi web server, after which a successful save check is performed. If the data is saved correctly, it is then moved on to analysis. During the study, the data is checked for vulnerabilities, and if any are found, protective measures are taken. If no vulnerabilities are found, the data is displayed on the website.

Air quality data can be effectively analyzed and used for timely decision-making, ensuring a reliable and safe air quality monitoring system, the whole procedure is shown in Algorithm 1.

Algorithm 1: Air Quality Data Collection and Validation System
1. Initialization: o S: system; o D: sensor data; o V: validity of data; o R: data received status; o DB: PostgreSQL database; o A: analyzed data; o Vuln: data vulnerability status. 2. Start 3. Sensor Data Collection: o D⟵Collect sensor data 4. Is Data Valid?: o If V = True then ▪ Send Data to Arduino Board: ▪ D⟵Send to Arduino ▪ Send Data to Raspberry Pi: ▪ D⟵Send to Raspberry Pi 5. Data Received?: o If R = True then ▪ Store Data in PostgreSQL Database: ▪ DB⟵Store(D) 6. Is Data Stored?: o If DB is successfully stored then

- Analyze Data:
  - A⟵Analyze(DB)

7. Is Data Vulnerable?:
   - If Vuln = True then
     - Apply Protection Methods:
       - Apply protection methods(A)
   - Else
     - Display Data on Website:
       - Display(A)
8. End

Algorithm 1 shows the process of collecting and analyzing air quality data. Step 1 explains the initialization of variables. Steps 2–4 cover collecting and validating sensor data, where valid data is sent to both the Arduino and Raspberry Pi. Steps 5–6 describe storing the data in a PostgreSQL database and further analyzing it. Step 7 focuses on validating the data for vulnerabilities and applying protection if necessary. Step 8 displays the analyzed data on the website if no vulnerabilities are found.

- Air quality: This main project directory contains settings, URLs, and other configurations.
- manage.py: This command-line utility allows interaction with the Django project.
- __init__.py: This empty file signifies that this directory should be treated as a Python package.
- settings.py: This file contains configuration settings for the Django project.
- urls.py: This file contains URL declarations for the Django project.
- wsgi.py: This file contains the configuration for the WSGI (Web Server Gateway Interface) used to serve the project in production.
- asgi.py: This file contains the configuration for the ASGI (Asynchronous Server Gateway Interface) used for async-capable web servers.

As a result, the project's structure encompasses a complete system consisting of sensors, a microcontroller, a web server, and a user interface, delivering dependable monitoring and analysis of indoor air quality. Users must have the same netmask and default gateway and know the login and password information to connect to the database. All information is secured using MD5 hash.

3. Experimental results

The web dashboard, designed using the Django framework, displays environmental data, including temperature, humidity, air quality, and CO_2 levels. It uses dynamic data visualization with Django template variables and client-side JavaScript to color-code data maps based on thresholds. The toolbar has an intuitive user interface thanks to its graphical data representation and CSS styling.

Figure 6(a) depicts the hourly air quality index (AQI) for a 24-hour period. The AQI, which ranges from 35 to 90, is represented on the Y-axis, with the X-axis representing the hours of the day from midnight to 11:00 PM. The AQI begins around 45 at midnight, gradually declines until shortly before 06:00, and then rises significantly, peaking at 90 about 09:00. Following this peak, the AQI progressively drops to around 60 by 16:00. In the evening, the AQI rises again, reaching a high of 90 around 22:00 before falling somewhat around 23:00. The day has two main peaks at 09:00 and 22:00, suggesting periods of lower air quality. Air quality tends to improve around midday and early afternoon, maybe due to lower human activity or better meteorological conditions. These data illustrate daily swings in air quality, which might help plan activities to avoid poor air conditions.

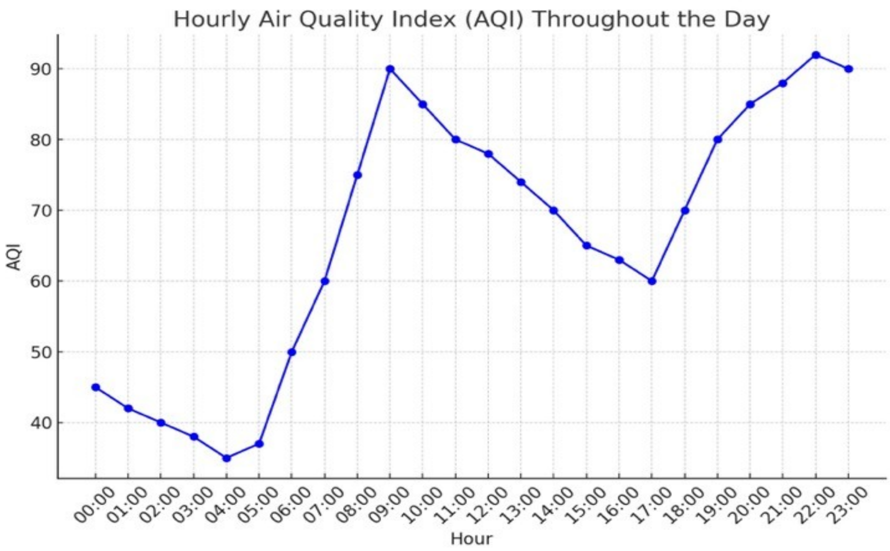

Figure 6(a): Showing AQI throughout the day.

Figure 6(b) shows the hourly Air Quality Index (AQI) during peak hours. The AQI values range from 60 to 90 and are plotted on the Y-axis, while the X-axis shows the time of day, which runs from 07:00 to 23:00. The AQI begins at 60 about 07:00 and rapidly rises to a peak of approximately 90 at 09:00. Following this peak, the AQI progressively drops during the morning and early afternoon, reaching approximately 65 by 16:00. The AQI then rises again in the evening, peaking at 90 around 22:00 before significantly falling by 23:00. This trend indicates that air quality is poorest in the early and evening hours, particularly between 09:00 and 22:00, probably due to increased human activity such as driving.

Figure 6(b): Showing AQI during peak hours.

The graphs in Figure 7 display 24-hour moving averages of air quality index (AQI), temperature, and humidity levels recorded hourly during May 2024, covering 744 hours. The AQI fluctuates between 55 and 92, with notable spikes on two specific days: one day when the AQI reached values between 90 and 92, and another with slightly lower AQI values between 83 and 85. These higher AQI readings imply times of worse air quality, but the general pattern shows oscillations between higher and lower values, demonstrating dynamic changes in air quality throughout the month. These fluctuations suggest that air quality may be affected by changing conditions in the laboratory or external environmental factors. Similarly, temperature shows regular variations, with values ranging from 23.0°C to 25.0°C, reflecting diurnal cycles likely related to laboratory activity or external influences. Humidity levels fluctuate between 26% and 30%, with peaks and troughs associated with ventilation systems, air conditioning, or outdoor weather conditions affecting the indoor environment. Overall, the 24-hour moving average smooths out short-term hourly fluctuations and reveals broader patterns in AQI, temperature, and humidity over a month.

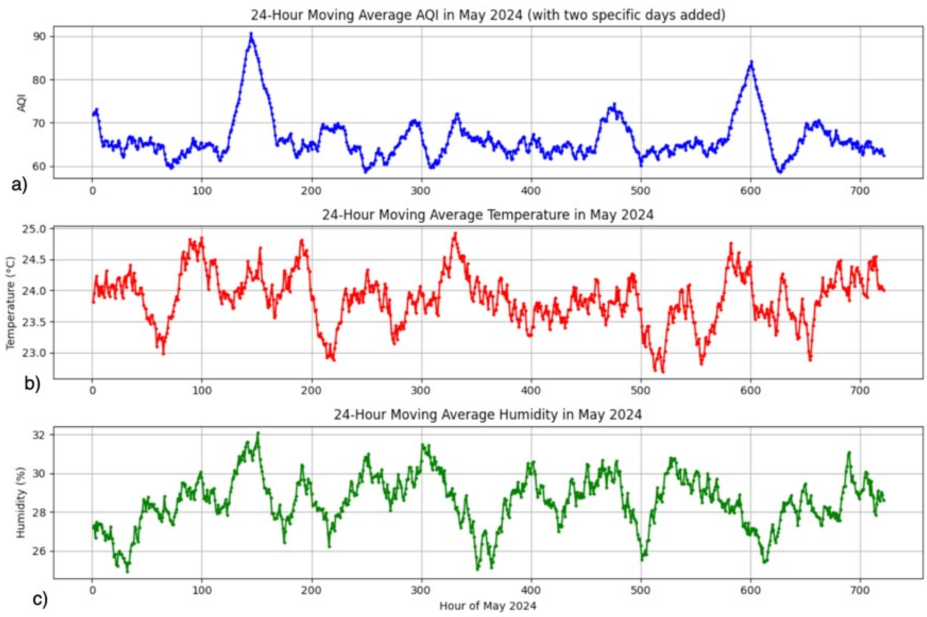

Figure 7: Time series of hourly a) AQI, b) Temperature, and c) Humidity levels with 24-hour moving averages.

On the dashboard page, users can access information about the current temperature, humidity, air quality, and CO_2 concentration (see Figure 8).

Figure 8: The dashboard of the level of pollution.

The EPA has defined the ranges and meanings of each level in the air quality index (AQI). The table in Figure 9 presents the AQI scale and a description of each level. The levels are color-coded for easy identification. Green indicates “good” air quality with an AQI below 50, yellow is “moderate” with an AQI ranging from 51 to 100, orange is considered “unhealthy for sensitive people” with a range of 101 to 150, red indicates “unhealthy” with an AQI of 151-200, purple represents “very unhealthy” with a range of 201 to 300, and anything higher than 301 is classified as "hazardous" and denoted by the color maroon.

	AQI	PM 2.5 (ug/m3)	PM 10 (ug/m3)	VOC (ppm)	CO2 (ppm)	Formaldehyde (ppm)
Good	0-50	0 - 12	0 - 54	0 - 15	400 - 650	0 - 0.2
Moderate	51 - 100	12.1 - 35.4	55 - 154	16 - 25	651 - 1500	0.21 - 0.4
Unhealthy for sensitive groups	101 - 150	35.5 - 55.4	155 - 254	26 - 50	1501 - 2000	0.41 - 0.6
Unhealthy	151 - 200	55.5 - 150.4	255 - 354	51 - 75	2001 - 2500	0.61 - 0.8
Very Unhealthy	201 - 300	150.5 - 250.4	355 - 424	76 - 100	2501 - 5000	0.81 - 1
Hazardous	301 - 500	250.5 - 500	425 - 600	101 - 150	5001 - 15000	1.01 - 1.2

Figure 9: AQI scale.

As part of the project, an Artificial Intelligence model was implemented to analyze the Apache web server and PostgreSQL database configurations automatically, which allows for the prompt identification of possible vulnerabilities and improved system security. AI generates configuration recommendations by checking access rights, data privacy, and connection security. It should be noted that the recommendations offered by AI are preventive and aimed at improving the overall security of the system and do not necessarily indicate the presence of current problems. Using this approach helps standardize security processes and minimize risks associated with the human factor. In this context, AI improves the efficiency and accuracy of security monitoring, reducing the need for manual verification and accelerating the threat detection process. This approach is especially important in the context of constantly changing cyber threats and the need to maintain the security level of the web infrastructure. In the future, it is planned to expand the model's functionality by adding support for new algorithms for analyzing complex attacks and integrating with the notification system for prompt notification of detected problems.

4. Conclusion and future work

This article presents the development of an environmental monitoring system for a laboratory room, which allows for detecting the concentration of air pollutants and monitoring the room's temperature and humidity. Several types of independent sensors were selected, and they were integrated into the Arduino microcontroller. A web server was implemented on the Raspberry Pi platform based on Python to form a single system for measuring, analyzing, and determining the air quality in the room. The module receives parameters such as temperature, relative humidity, ammonia, nitrogen, oxygen, alcohols, aromatic compounds, sulfide, and smoke as AQI and CO_2 in real-time at one-hour intervals.

In the future, we will develop an automated system to control ventilation and air conditioning systems automatically. We plan to expand the system by incorporating sensors for PM 2.5, PM 10, and CO and adding a large display for monitoring. Additionally, we will create a user-friendly interface to allow easy interaction with the HVAC system.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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