Multisensor monitoring system for detecting changes in weather conditions and air quality in agricultural environments

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Abstract

The increasing impact of climate change and the need for precision agriculture demand reliable environmental monitoring solutions. This study aims to develop a real-time, multisensory-based environmental monitoring system that displays data via an I2C LCD and a user-friendly web interface. The system utilizes an ESP32 microcontroller connected to a range of sensors, including the DHT22 (for temperature and humidity), MQ-7 and MQ-135 (for CO and CO_2), LDR (for light intensity), a rain sensor, and an anemometer (for wind speed). Testing was conducted over eight hours under various environmental conditions, both indoors and outdoors. Validation was performed by comparing the sensor readings with those from standard measuring instruments. The results showed that the DHT22 sensor had a low error rate of 0.62% for temperature and 0.38% for humidity. Other sensors demonstrated low standard deviation values, indicating stable and consistent measurements. The system also exhibited responsive and accurate performance in detecting changes in environmental parameters. Therefore, this system is effective as an environmental monitoring tool for agricultural applications and can support early decision-making based on environmental condition changes.

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1. Introduction

Indonesia, as a country with a maritime tropical climate, ranks among the top three most vulnerable nations to the impacts of climate change due to its low resilience and limited adaptive capacity (Kurniadi et al, 2024). This vulnerability has a direct impact on the agricultural sector, which serves as a cornerstone of food security and national economic stability. Amidst rapid population growth and extensive land conversion, the country's dependence on food imports, combined with the limited adoption of advanced agricultural technologies, has further exacerbated the fragility of the national food system (Rozaki, 2021). Rapid changes in environmental conditions such as rising temperatures and decreasing humidity can disrupt plant growth cycles, reduce agricultural productivity, and heighten the risk of pest infestations and plant disease outbreaks (FAO, 2021).

Air quality is a critical factor that significantly influences the stability of agricultural ecosystems. Elevated concentrations of carbon dioxide (CO_2) can inhibit the photosynthesis process. In contrast, the presence of carbon monoxide (CO) serves as an indicator of air pollution levels that pose risks to both plant and human health (WHO, 2022). According to data from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG, 2023) the average temperature in Indonesia has risen by approximately 0.03°C per year since 1981, indicating a persistent trend of climate change with the potential to impact agricultural productivity negatively. Furthermore, the rapid pace of urbanization and the large-scale conversion of agricultural land into industrial and residential zones are increasingly limiting the availability of land for food production.

One promising solution to address the challenges faced by agriculture in the context of climate change is the implementation of the Internet of Things (IoT), which enables the automated collection, transmission, and visualization of data through interconnected networks. IoT-based monitoring systems enhance operational efficiency and support data-driven decision-making processes. (Nor Diana et al, 2022) found that farmers in

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Southeast Asia have become increasingly aware of the impacts of climate change and have begun adopting local adaptation strategies such as business diversification and resource management, highlighting the urgent need for precision monitoring technologies like IoT systems. (Xu et al, 2022) explained that the application of IoT in agriculture involves a network of interconnected devices that facilitates the seamless exchange of information between crops, environmental conditions, and farming equipment. This technology is capable of integrating various environmental parameters, including temperature, humidity, light intensity, gas concentrations, and weather patterns, into a comprehensive, real-time monitoring system.

Previous studies have developed IoT-based environmental monitoring systems using various approaches and sensor configurations (Sharma & Prakash, 2021) employed the ESP8266 microcontroller and the ThingSpeak platform; however, their system was limited to monitoring basic environmental parameters. Similarly, (Kishorebabu & Sravanthi, 2020) designed a system that relied on conventional electrical power sources but lacked gas monitoring capabilities. The approach proposed (Singh & Asim, 2021) also shared these limitations, as it did not incorporate essential variables such as wind speed and air quality. Conversely, (Shahadat et al, 2020) utilized the Blynk platform as the monitoring interface, although the system's features were relatively limited and the overall design remained simplistic. However, existing monitoring systems lack a comprehensive, open, and integrated approach that simultaneously addresses multiple critical parameters. Temperature, humidity, light intensity, wind speed, rainfall, CO, and CO_2 are essential indicators in agricultural monitoring.

In the context of system testing and validation, (Wardani et al., 2023) reported that the DHT22 sensor, when applied in a greenhouse environment, demonstrated good accuracy, with root mean square (RMS) error values of 1.48°C for temperature and 3.18% for humidity. Similarly, (Tawfeek et al,2022) developed an IoT-based innovative greenhouse system that not only monitored environmental parameters in real time such as temperature, humidity, light intensity, and soil moisture but also integrated an artificial neural network (ANN)-based automatic control mechanism. This system was capable of regulating devices such as fans, pumps, and lights to maintain optimal conditions for plant growth and development. (Zhong et al, 2024) adopted a comparable approach by employing an STM32 microcontroller as the control hub, integrating sensors for temperature, humidity, soil moisture, and light. Their system enabled real-time monitoring and automated control of devices, such as water pumps and LEDs, to adjust humidity and lighting levels according to plant requirements. On the other hand, (Hassan et al., 2020) also proposed an environmental monitoring system, however, the range of monitored parameters remained limited, as it did not include variables such as light intensity, wind speed, or rainfall.

In general, previously developed systems have not succeeded in integrating all critical parameters into a single, adaptive, efficient, and comprehensive platform. In reality, parameters such as temperature, humidity, light intensity, wind speed, rainfall, and concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) are essential indicators for supporting data-driven precision farming practices that are responsive to dynamic environmental changes. This study aims to design and implement a multisensor-based environmental monitoring system capable of tracking various environmental parameters in real time. The system utilizes an ESP32 microcontroller, integrated with a range of specialized sensors, and displays the collected data simultaneously through an I2C LCD and a user-friendly web-based dashboard. The primary objective of this research is to develop an accurate and responsive monitoring system to support early decision-making in response to environmental changes on agricultural land. Additionally, this study aims to make a scientific contribution to the integration of IoT and multisensor technologies for data-driven environmental monitoring applications.

2. Method

This study designs an environmental monitoring system capable of detecting seven key parameters: temperature, air humidity, light intensity, rainfall, wind speed, and the concentrations of carbon monoxide (CO) and carbon dioxide (CO_2). The system comprises two main components: a hardware unit responsible for data acquisition and transmission, and a web-based platform used for real-time data visualization. The research method flowchart can be seen in Figure 1.

Figure 1. Research method flowchart

Figure 1 illustrates the flow of the research stages, beginning with the literature review and continuing through to the data analysis phase. This study involves the design of a weather and air quality monitoring system, the integration of various hardware and software components, and the comprehensive testing and validation of the system to ensure its performance, reliability, and data integrity.

The ESP32 microcontroller functions as the central data processing unit, receiving input from all connected sensors. The DHT22 sensor measures temperature and humidity, while the MQ-7 detects carbon monoxide (CO) concentration. The MQ-135 is used for measuring carbon dioxide (CO_2) levels. The light-dependent resistor (LDR) measures light intensity, the rain sensor detects rainfall, and the anemometer measures wind speed. The data collected from each sensor is displayed locally on an I2C LCD screen and simultaneously transmitted to a server, enabling real-time remote monitoring.

Each sensor used in this system underwent a testing and calibration process to ensure adequate levels of accuracy and precision. The DHT22 sensor was validated using a hygrothermometer as a reference instrument, following standard procedures, and demonstrated good accuracy in measuring temperature and humidity, with tolerances of ±0.5°C and ±2–5%, respectively (Zafeiriou, 2024). The MQ-7 and MQ-135 gas sensors were tested under two conditions baseline (normal air) and exposure to lighter gases, simulating the presence of air pollutants. The LDR sensor was evaluated by comparing its responses under illuminated and dark conditions. In contrast, the rain sensor module was tested in both wet and dry scenarios to confirm its sensitivity to rainfall. The anemometer was assessed using a fan to simulate airflow, enabling direct observation of changes in wind speed readings.

The data collection process was conducted in both indoor and outdoor environments over several hours to capture representative variations in environmental conditions. Sensor readings were subsequently analyzed and utilized as the basis for calculating the overall accuracy and precision of the monitoring system.

Accuracy was calculated using the percentage error formula relative to the standard reference value, as shown in Equation 1 (Megantoro et al, 2021).

$$Error = \left| \frac{\text{Standart Value} - \text{test value}}{\text{Standart value}} \right| \quad (1)$$

Precision was determined by calculating the standard deviation of multiple measurements, as defined by the formula in Equation 2 (Megantoro et al., 2021).

$$\sigma x = \frac{\sqrt{\sum_{i-1}^{n}(x_i - x)}}{(n-1)} \quad (2)$$

The system is powered by an 18V 20Wp solar panel, which charges a 12V 2100mAh lithium battery via a solar charge controller with a maximum current of 10A. This configuration enables the device to operate autonomously, without dependence on conventional electricity sources (PLN), thereby enhancing the system's flexibility and sustainability in field applications. This methodological framework is designed to produce an efficient, practical, and accurate environmental monitoring system that supports data-driven decision-making in agricultural activities through comprehensive and real-time monitoring of environmental conditions.

3. Results and Discussion

This study aims to evaluate the performance of a multisensor-based monitoring system in detecting changes in weather conditions and air quality within agricultural environments. The system is designed to integrate multiple sensors that measure temperature, humidity, light intensity, wind speed, carbon monoxide (CO) and carbon dioxide (CO_2) concentrations, as well as general weather conditions (rain/bright). Each sensor undergoes testing to assess its accuracy and precision in real-time environmental detection. The analysis is conducted by comparing the sensor readings against standard reference instruments. The results indicate that the combination of sensors employed in the system is capable of accurately and responsively detecting environmental changes. Therefore, the system demonstrates strong potential as a decision-support tool in precision agriculture, particularly in mitigating the risks posed by extreme weather fluctuations and declining air quality, both of which can adversely impact crop development.

3.1. System Design

This section outlines the design and core architecture of the developed environmental monitoring system. The system utilizes an ESP32 microcontroller as its central data processing unit, interfaced with various sensors to measure environmental parameters in real-time. The system architecture aligns with modern Internet of Things (IoT) frameworks applied in the agricultural sector. (Seetaram et al, 2024) emphasized that the ESP32 plays a pivotal role in providing both data processing capabilities and Wi-Fi connectivity, while also enabling the automatic control of actuators based on sensor feedback to maintain optimal microclimate conditions in greenhouse environments. As a microcontroller equipped with Wi-Fi and Bluetooth support, the ESP32 has been widely adopted in IoT-based research, including the work by (Vidhyavani et al, 2020), which demonstrated its effectiveness in environmental monitoring systems. Further support for this configuration is found in a study by (Tomar & Saroha, 2024), who utilized the ESP32 as the core component of an innovative greenhouse system to monitor environmental parameters in real-time and automatically control fans, pumps, and lights to maintain optimal growing conditions. All data collected by the system is processed and displayed locally via an LCD screen, while simultaneously being transmitted to a web-based dashboard that serves as a remote monitoring interface.

Figure 2 illustrates the overall workflow of the designed environmental monitoring system, which is composed of three main components: input, processing, and output. At the input stage, a set of environmental sensors is employed to measure key parameters. These include the DHT22 sensor for air temperature and humidity, the MQ-7 and MQ-135 sensors for detecting carbon monoxide (CO) and carbon dioxide (CO_2) concentrations, an LDR sensor for measuring light intensity, an anemometer for wind speed, and a rain sensor to determine weather conditions (rain or bright). The data collected by each sensor is then processed by the ESP32 microcontroller and forwarded to the output stage, where it is displayed in real time on both an LCD screen and a web-based dashboard.

All sensors are connected to the ESP32 microcontroller, which serves as the central processing unit during the processing stage. The ESP32 is responsible for collecting data from each sensor, processing it locally, and transmitting the data to a remote server using the HTTP protocol via the POST method. The transmitted data is then stored in a database integrated with cloud-based services. In the output stage, environmental data is presented through two interfaces: a local LCD screen that displays real-time information directly at the device location, and a web-based monitoring dashboard that enables users to access real-time data remotely via the internet. The process of the blog diagram system can be seen in Figure 2.

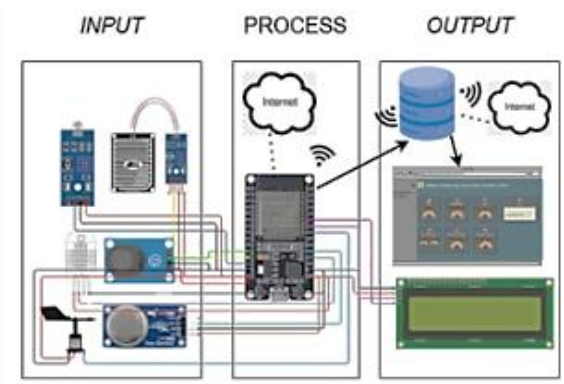


Figure 2. System Diagram Blog

3.1.1. Hardware Design

At this stage, a wiring diagram is developed to illustrate the connections among the hardware components. This diagram is essential to ensure that each sensor and module is correctly connected to the microcontroller, enabling the system to operate according to its intended specifications.

Figure 3 illustrates the ESP32 microcontroller as the central control unit responsible for data acquisition and processing from multiple sensors. The connected components include:

a. DHT22 sensor for measuring temperature and humidity

b. MQ-7 sensor for detecting carbon monoxide (CO) gas

c. MQ-135 sensor for detecting carbon dioxide (CO_2) gas

d. LDR sensor for measuring ambient light intensity

e. Anemometer for detecting wind speed

f. Rain sensor for identifying rainfall

g. 16x2 I2C LCD for displaying real-time data

h. lithium battery (3.7V, 2200 mAh) and solar panel connected via a solar charge controller as the power source

Each component in the system is connected to the GPIO and ADC pins of the ESP32 microcontroller by standard design practices for IoT-based devices. The optimal arrangement of wiring ensures accurate signal transmission while minimizing electromagnetic interference and power loss. Consistent with the findings of (Sharma et al., 2025), the design and utilization of ADC and GPIO configurations on the ESP32 must account for low latency, high signal integrity, and energy efficiency to sustain both the performance and operational longevity of IoT devices. This is further supported by the work of (Zhang et al., 2025), who successfully developed a 10-bit/20 MS/s pipelined ADC architecture with a power consumption of ≤5 mW and high SNR/SNDR performance. These studies highlight the crucial importance of designing ADCs properly and optimizing system layout to enhance the overall efficiency and measurement accuracy of ESP32-based IoT systems.

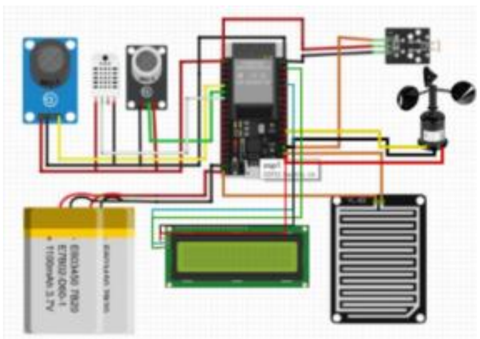


Figure 3. Hardware wiring diagram

This hardware configuration aligns with the design principles outlined by (Szczurek et al., 2024), who emphasized that integrating sensors on a compact PCB layout can enhance signal stability, simplify maintenance, and support scalability in field applications.

3.1.2. Software Design

The software design phase focuses on developing the user interface (front end) and the data management system (back end). The front end is built using HTML and CSS, visually presenting environmental data in real-time. The backend is developed using PHP and a MySQL database and is responsible for storing, retrieving, and managing data communication from the ESP32 microcontroller.

Balsamiq is employed as a wireframing tool to visualize the interface layout. Balsamiq accelerates design iterations and facilitates the structuring of components and navigation flows within the application. Figure 4 presents a dashboard interface designed to display key environmental parameters, including:

a. Temperature and humidity

b. Light intensity

c. Weather conditions (rain/sunny detection)

d. Air quality (CO and CO_2 concentrations)

e. Wind speed

f. An interactive map indicating the hardware location

Each element is represented using intuitive icons and graphical meters to enhance readability and improve user interaction. The interface is optimized for real-time monitoring to support fast and informed decision-making in agricultural or environmental applications.

Figure 4. Monitoring website appearance design

3.2. System Operating Principles

The system begins by initializing the ESP32 microcontroller, which reads data from the connected sensors and transmits it to the server via an internet connection. The sensor readings are displayed in real time on an I2C LCD and can be accessed by users through a web-based interface.

Figure 5 illustrates the system flowchart that describes the operational stages of an IoT-based environmental monitoring system. The process begins with component initialization and sensor validation. If all sensors are successfully validated, the system establishes a network connection. In the event of a sensor error, such as a malfunctioning DHT sensor, an error notification (e.g., "DHT error") will be displayed on the website interface, prompting the user to take corrective action. Once sensor validation is completed and the system is connected to the network, data from all sensors is collected and transmitted to the server. The stored data is then retrieved by the backend and displayed in real-time through a user-friendly web interface. Additionally, users can monitor the data directly via the LCD screen integrated into the device.

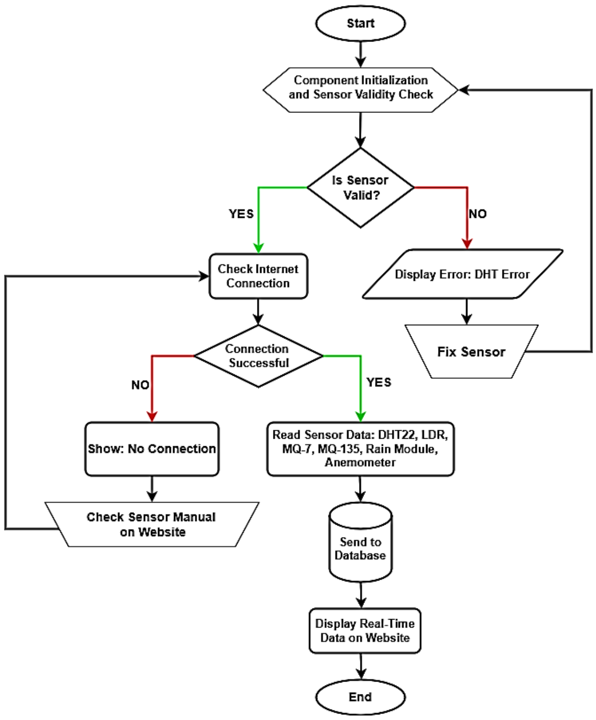


Figure 5. System Workflow Diagram

3.3. Testing and Data Processing

After the system is assembled and operational, testing is conducted to evaluate the sensor performance under real-world conditions, both indoors and outdoors. This testing aims to assess each sensor's responsiveness to environmental changes and to compare the collected data with reference measuring instruments.

Initial testing focused on validating the sensor data generated under various environmental conditions. As shown in Table 1, all sensors responded effectively to environmental changes, producing data characteristics that accurately reflected the observed conditions.

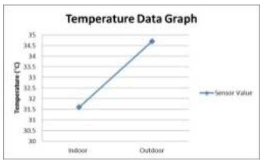
Table 1. Results of Indoor and Outdoor Sensor Testing

No	Sensor Name	Condition	Sensor Value
1.	Dht 22 Temperature	Indoor	31.6 °C
		Outdoor	34.7 °C
	DHT 22 Humidity	Indoor	70.6 %
		Outdoor	59.9 %
2.	Mq135	Indoor	648 PPM
		Outdoor	509 PPM
3.	Mq7	Indoor	17 PPM
		Outdoor	22 PPM
4.	LDR	Indoor	1 (Dark)
		Outdoor	0 (Bright)
5.	Rain	Indoor	1 (Bright)
		Outdoor	1 (Bright)
6.	Anemometer	Indoor	0 m/s
		Outdoor	5.6 m/s

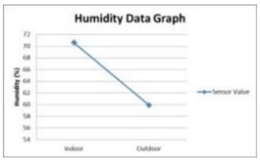
The data in Table 1 are also visualized in a comparison graph shown in Figure 5 to clarify the comparison between indoor and outdoor conditions.

Figure 6 compares sensor measurements under indoor and outdoor conditions, revealing significant variations across each environmental parameter. The DHT22 sensor recorded temperatures of 31.6°C indoors and 34.7°C outdoors, indicating that the outdoor temperature was higher due to direct exposure to sunlight. For humidity, the same sensor measured 70.6% indoors and 59.9% outdoors, suggesting that indoor humidity was higher, possibly due to limited air circulation in enclosed spaces. The MQ135 sensor detected CO_2 concentrations of 648 PPM indoors and 509 PPM outdoors, while the MQ7 sensor measured CO levels of 17 PPM indoors and 22 PPM outdoors. These findings suggest that indoor environments accumulate more CO_2, whereas outdoor areas are more prone to elevated CO levels, potentially due to external factors such as vehicle emissions or open combustion. The LDR sensor reported 1 (dark) indoors and 0 (bright) outdoors, confirming its sensitivity to ambient light intensity. The rain sensor indicated no rainfall, with consistent values of 1 (bright) in both environments, implying that the test was conducted during sunny weather. Additionally, the anemometer recorded wind speeds of 0 m/s indoors and 5.6 m/s outdoors, demonstrating the sensor's ability to detect natural wind movement accurately.

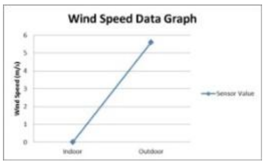
Overall, the test results indicate that all sensors performed reliably and accurately recorded environmental parameters according to their respective characteristics and technical specifications. The visualization presented in Figure 6 complements the data summarized in Table 1, offering a comprehensive overview of sensor performance under varying environmental conditions.



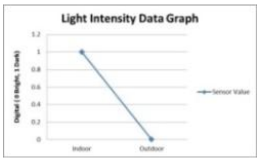
a. Temperature



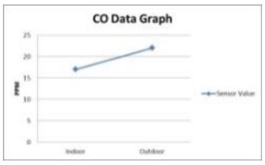
b. Humidity



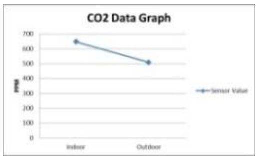
c.Wind Speed



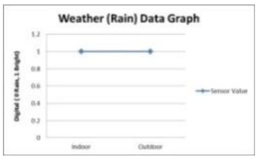
d. Light Intensity



e. CO



f. CO_2



g. Weather

Figure 6. Charts of Indoor and Outdoor Sensor Testing Results

The second stage of testing evaluated the sensors accuracy, stability, and responsiveness to variations in environmental conditions. It involved calculating each parameter's average error and standard deviation and comparing the results with those obtained from standard measuring instruments, such as hygrothermometers. Table 2 presents the performance evaluation results for each sensor under the specified test conditions.

Table 2. Sensor Test Results Data

No	Sensor	Test Condition/ Comparison	Result Sensor	Average	Standard Deviation (SD)/ Error	information
1.	DHT22 (Temperature)	Room Temperature (32.1)	31.9 °C	31.9°C	0.62 %	Compared to the Hygrothermometer
			32.0 °C			
			32.0 °C			
	DHT22 (Humidity)	Room Humidity (78)	77.9 %	77.7 %	0.38 %	
			77.7 %			
			77.7 %			
2.	MQ-7	Normal (No gas)	31	30	1	ADC - unit PPM
			30			
			29			
		There is a lighter gas.	90	96.67	5.77	
			100			
			100			
3.	MQ-135	Normal (No gas)	681	667.67	12.22	ADC - Unit PPM
			665			
			657			
		There's smoke.	1812	1937.33	108.52	
			2000			
			2000			
4.	LDR	There's Light	0	0	-	Digital (0 Bright, 1 Dark)
			0			
			0			
		There is no light.	1	1		
			1			
			1			
5.	Rain module	Bright	1	1	-	Digital (0 Rain, 1 Bright)
			1			
			1			
		Rain	0	0		
			0			
			0			
6;	Anemometer	There's wind.	3.4	5.00	1.49	Wind Speed (m/s)

No	Sensor	Test Condition/ Comparison	Result Sensor	Average	Standard Deviation (SD)/ Error	information
			5.6			
			6.1			
		There is no wind.	0	0	0.00	
			0			
			0			

Table 2 presents the performance evaluation results for each sensor under the specified test conditions. The DHT22 sensor recorded a temperature of 31.9°C, closely aligned with the reference value of 32.1°C, and a humidity reading of 77.7% compared to the reference of 78%. These slight differences demonstrate a high level of precision and consistent sensor performance. The MQ-7 sensor measured a value of 30 under normal conditions (without gas), which increased significantly to 96.67 when exposed to lighter gas, indicating high sensitivity to the presence of carbon monoxide (CO). Likewise, the MQ-135 sensor registered a baseline value of 667.67 under normal conditions and rose sharply to 1937.33 upon detecting smoke, reflecting a strong responsiveness to airborne pollutants.

The LDR sensor produces a digital output of '0' under bright conditions and '1' in the dark, while the rain sensor displays a value of '1' in clear weather and '0' during rainfall. Both sensors demonstrate consistent accuracy in distinguishing binary environmental states. Meanwhile, the anemometer records a wind speed of 5.00 m/s during windy conditions, with individual readings of 3.4 m/s, 5.6 m/s, and 6.1 m/s, and registers 0 m/s without wind. The variation in these measurements highlights the sensor's capability to detect changes in dynamic environmental conditions precisely as can be seen in Figure 7.

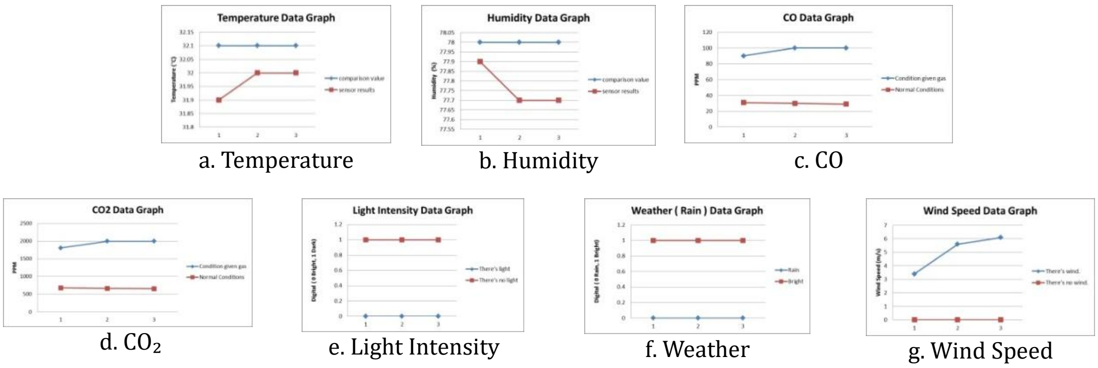


Figure 7. Graph of Phase 2 Testing Data

Figure 7 enhances the interpretation of sensor performance by providing a graphical representation of each tested parameter. The temperature graph displays a reference line at 32.1°C alongside an upward trend in the sensor readings from 31.8°C to 32.0°C, indicating stable and accurate performance. The humidity graph shows consistent sensor readings at 77.7%, closely aligned with the reference value of 78%, reflecting minimal deviation. In the CO and CO_2 graphs, a sharp rise in sensor values upon exposure to gas and smoke demonstrates the sensors' high sensitivity to air pollutants.

The digital graphs for light intensity and rainfall clearly distinguish between the two extremes of light versus dark and sunny versus rainy conditions. The values remain at zero under bright light, 1 in darkness, one during sunny conditions, and zero during rainfall, confirming the reliability of the binary sensor readings. The wind speed graph shows a noticeable increase in values from 3.4 m/s to 6.1 m/s under windy conditions while consistently reading 0 m/s when there is no wind, accurately detecting variations in air movement.

The overall test results demonstrate that the system is capable of delivering stable and accurate data. The DHT22 sensor exhibited minimal deviation in measuring both temperature and humidity, indicating reliable performance. The MQ-7 and MQ-135 gas sensors exhibited significant changes in value when exposed to test substances, indicating strong sensitivity and responsiveness to gas concentrations. These findings are supported by (Azemi et al., 2021), who reported that, based on prototype testing, the DHT22, MQ-135, and MQ-7 sensors performed effectively in detecting variations in environmental parameters, demonstrating high sensitivity and accuracy under changing conditions. Additionally, the LDR and rain sensor produced consistent digital signals with no observed deviation, confirming high detection accuracy. The anemometer successfully distinguished different airflow conditions through logical and accurate variations in wind speed readings, further validating the system's ability to capture environmental dynamics effectively.

The validity of the testing method is further supported by the findings of (Rajani et al., 2023), which demonstrated a high degree of compatibility between microcontroller-based sensors and standard measuring instruments in environmental monitoring applications. Accordingly, the developed multisensor monitoring system has been proven capable of recording and displaying environmental data in real-time, with a high level of accuracy, low data variability, and strong responsiveness to environmental changes, each as a result of the specific function of the corresponding sensor.

Further testing was conducted on a farm over eight hours, with data collected at ten-minute intervals. The objective was to evaluate the overall system performance under real-world conditions and to ensure that all sensors operated optimally and consistently in dynamic environments.

The test data is then visualized in graphical form as in Figure 8 to facilitate analysis of trends, fluctuations, and sensor stability over time. This graphical representation aims to provide a more informative and comprehensive overview of system performance under real environmental conditions.

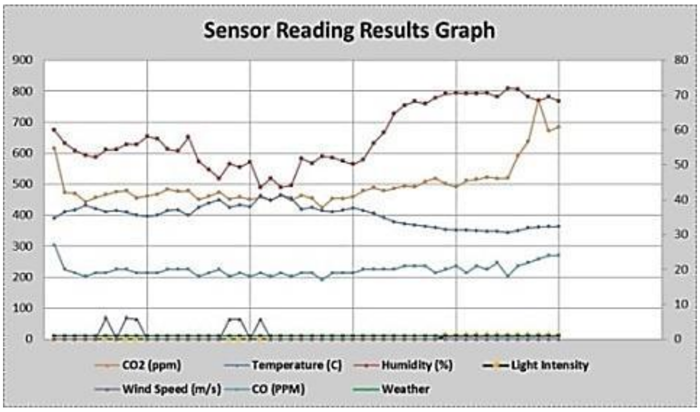


Figure 8. Graph of Sensor Readings Every 10 Minutes

Figure 8 illustrates the monitoring results collected over approximately eight hours, during which the system demonstrated stable, precise, and responsive performance in adapting to changing environmental conditions in open areas.

a. Temperature and humidity

The temperature graph shows a gradually increasing trend from 34.7°C at 11:10 AM, peaking at 41.4°C at 2:50 PM, and then decreasing to 30.6°C by 6:30 PM. The humidity starts at 59.9% at the beginning of the observation, drops to its lowest point of 43.6% between 2:30 and 2:50 PM, and then rises to 71.9% by 6:30 PM. This pattern is consistent with typical daytime solar heating followed by natural cooling in the evening, demonstrating the sensor's ability to capture daily temperature fluctuations accurately. Moreover, the sensor effectively detects dynamic changes in relative humidity by the environmental thermal cycle, aligning with the daily microclimate patterns reported by (Wilberforce, 2025), where an IoT-based system successfully recorded real-time temperature and humidity variations for irrigation optimization.

b. Light Intensity:

The LDR sensor successfully detected dominant lighting conditions as "bright" until approximately 5:30 PM, then transitioned to a "dark" status after sunset. This change demonstrates the system's reliability in recognizing light intensity as a natural time indicator in the field, reflecting accurate and contextual detection capabilities. These findings support the implementation of similar systems in greenhouse environments, where light sensors are used to optimize the cultivation process, as explained by (Wang, 2024).

c. Wind Speed:

Wind speed was generally calm (0 m/s), however, the system successfully detected light wind gusts between 12:00 PM and 2:30 PM, with a maximum speed reaching 6.1 m/s. This confirms the anemometer's sensitivity to subtle variations in air movement, even under weak wind conditions.

d. Air Quality (CO and CO_2):

The CO gas concentration remained stable within the 17–24 ppm range, showing no significant spikes. In contrast, the CO_2 concentration increased markedly after 6:00 PM, reaching 771 ppm by 7:00 PM. This surge is believed to result from reduced air circulation during the evening, leading to gas accumulation in the test area. This observation aligns with nighttime gas buildup patterns reported in the study by (Pérez-Padillo et al., 2022).

e. Weather Conditions:

The rain sensor detected "Bright" conditions throughout the observation period, consistent with the absence of rainfall. Although no extreme weather changes occurred, the system demonstrated its capability to monitor and confirm the stability of weather conditions continuously.

Overall, the monitoring results indicate that the system is capable of accurately recording the dynamics of environmental parameters in real time. The system's stable performance during observations, along with the sensors' responsiveness to natural fluctuations, serves as an indicator of the validity and reliability of the developed system. (Patil, 2023) stated that the integration of IoT and Big Data represents a key approach for real-time agricultural monitoring, offering advantages in optimizing data management from diverse environmental sensors and supporting data-driven decision-making. This aligns with the strengths of the system developed in this study, which integrates multisensors and a web-based platform to enable real-time access. Similarly, research by (Alahmad et al., 2023) emphasized that collecting and analyzing big data from both fixed and mobile sensors is essential for enabling predictive decision-making capabilities in precision agriculture. These findings reinforce the notion that multisensor integration in the present system extends beyond simple data aggregation. It constitutes a strategic step toward making reliable, predictive, and informed decisions on agricultural land.

Compared to previous studies, the system developed in this research demonstrates several advantages, including comprehensive multisensor integration, seamless access to real-time data via a web-based platform, and direct validation in open-field environments. (Seetaram et al., 2024) emphasized that the use of the ESP32 as the central control unit in innovative greenhouse systems enables the integration of multiple sensors, such as temperature, air and soil humidity, and light intensity, while facilitating real-time data transmission via Wi-Fi. In such systems, actuators respond automatically to environmental changes based on predefined threshold values. These findings highlight that the system developed in this study aligns with best practices in multisensor integration and real-time web-based monitoring, both of which are key trends in the advancement of IoT-based precision agriculture. Therefore, the proposed system offers a significant contribution to the application of IoT technologies in agriculture, particularly as a data-driven environmental monitoring solution that supports informed decision-making and risk mitigation in response to microclimatic changes on agricultural land.

4. Conclusion

This study successfully designed and implemented an Internet of Things (IoT)-based environmental monitoring system with multisensor integration, capable of monitoring seven key parameters in real-time: temperature, air humidity, light intensity, rainfall, wind speed, and concentrations of carbon monoxide (CO) and carbon dioxide (CO_2). The system utilizes an ESP32 microcontroller and presents data through both an I2C LCD screen and a user-friendly web dashboard, enabling practical, accurate, and remotely accessible monitoring of environmental conditions. Test results indicate that the system exhibits a high level of accuracy and consistent reading stability, with error percentages and standard deviations falling within the acceptable tolerance range of reference instruments. The system's responsiveness in detecting environmental dynamics demonstrates its effectiveness in supporting early, data-driven decision-making in the agricultural sector. The scientific contribution of this research lies in the integration of IoT technology, embedded systems, and web-based interfaces to build an efficient, adaptive, and energy-efficient environmental monitoring solution. For future development, the system will be enhanced by incorporating machine learning-based artificial intelligence algorithms to enable the prediction of extreme environmental conditions. Additionally, the integration of automatic actuators such as fans, pumps, and sprayers will enable the system to respond in real-time to parameter threshold values. The inclusion of mobile-based notification features will further strengthen the system's early warning capabilities. Through these enhancements, the system is expected to evolve into an intelligent, responsive, and practical monitoring solution for mitigating climate change risks and enhancing agricultural productivity.

Author Contributions

Dwi Ramadhani: Contributed to the conceptualization of the study, design of methodology, data collection, analysis, drafting of the manuscript, and overall revision. Ahmad Taqwa (Corresponding Author): Responsible for supervision, validation, critical evaluation of results, manuscript editing, and journal submission. Ade Silvia Handayani (Corresponding Author): Contributed to data curation, accuracy verification, and supported the evaluation and refinement of research findings. Wahyu Caesarendra: Responsible for data curation and original draft preparation. Nyayu Latifah Husni: Participated in field data acquisition, literature review, and assisted in manuscript formatting and compliance with journal guidelines. Carlos R.S.: Provided technical support for sensor integration, contributed to system implementation and hardware testing, and assisted in reviewing the methodological framework and interpreting technical results. All the authors have read and approved the final manuscript.

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The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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