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A Low-Cost IoT-Based Environmental Monitoring and Sensor Validation Framework for Controlled-Environment Agriculture

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Abstract

Reliable environmental monitoring is essential for controlled-environment agriculture to ensure suitable environmental conditions for crop growth and resource efficiency. This study aims to develop and validate a low-cost Internet of Things (IoT)-based environmental monitoring system for indoor hydroponic farming. The system consists of an MG811 carbon dioxide sensor, Durian Uno microcontroller, DHT22 temperature and humidity sensor, ESP8266 Wi-Fi module, and the Blynk Console dashboard for monitoring the carbon dioxide concentration, temperature, and relative humidity. The experiment was carried out at the indoor plant factory of Universiti Tun Hussein Onn Malaysia using green coral lettuce as the test crop over a 30-day growth cycle. The findings indicate that the CO_2 concentration fluctuated between 540 ppm and 1225 ppm, with an average of 789.63 ppm. The temperature and humidity were stable, ranging from 20.2°C to 21.2°C, with an average of 20.8°C, and the relative humidity ranged from 78% to 81%, with an average of 79.3%. The validation using the Kimo Instruments AMI310 handheld with a DHT22 sensor showed consistent temperature and humidity readings with small average differences of 0.28°C and 1.5%, respectively. However, the MG811 sensor showed a larger deviation in CO_2 measurements, indicating the need for further calibration or replacement with a more reliable CO_2 sensor. Overall, the proposed system demonstrates the viability of low-cost IoT-based monitoring for indoor farming and underscores the importance of sensor validation in controlled-environment agriculture.

1. Introduction

Currently, food security issues have been widely discussed among the global community due to population growth, rapid urbanization, limited agricultural land, and the growing pressure on natural resources [1]. In Malaysia, agriculture-related causes of food insecurity are often linked to production limitations, socioeconomic factors, and policy challenges. Previous studies have reported that food insecurity arises from limited land and investment, import dependence, and climate impacts on staple crops [2] – [4]. In addition, climate-sensitive production constraints and governance arrangements may further contribute to food security challenges [3] – [5].

Collectively, these factors continue to challenge the conventional agricultural sector as demand for fresh food increases each year. Therefore, alternative farming approaches such as indoor hydroponic farming have become relevant for supporting more stable and efficient crop production, especially in areas with limited land availability.

Indoor farming is a controlled-environment agriculture approach that grows plants in enclosed or semi-enclosed facilities under controlled growing conditions. This system allows the main environmental parameters such as carbon dioxide concentration, temperature, relative humidity, lighting, water, and nutrients to be monitored and managed effectively compared to conventional open-field farming [6] – [11]. In recent years, indoor farming has become a popular approach in contributing to the stability of crop production in areas where land is scarce, reducing reliance on external weather conditions and improving resource efficiency [12], [13]. In addition, indoor farming approaches such as hydroponics help address soil-related cultivation challenges by enabling better control of crop nutrition [14], [15]. Thus, indoor farming has given a practical solution for supporting sustainable and efficient crop production, especially in areas with limited land availability.

Although indoor farming allows for greater control over crop production, its effectiveness depends on the ability to maintain suitable environmental conditions during the cultivation period. The main environmental parameters, such as carbon dioxide (CO_2) concentration, air temperature, and relative humidity, are closely related to crop growth and development [16] – [19]. For example, lettuce cultivation needs consistent monitoring of these parameters due to their influence on photosynthetic activity, carbon dioxide uptake, plant metabolic performance, transpiration rate, and water balance. Without proper monitoring of these conditions, crop consistency and effectiveness with controlled-environment agriculture can be affected by environmental changes [18]. Manual monitoring is often used in indoor farming; however, it is limited due to its reliance on periodic human observation, which is time-consuming, inconsistent, and unable to provide continuous real-time data on sudden environmental changes [20] – [25]. Thus, integrating Internet of Things (IoT) technology provides a practical solution for real-time environmental monitoring in an indoor farming system. Through an IoT-based monitoring system, environmental data can be continuously collected, transmitted, and visualized remotely, enabling users to remotely monitor indoor farming conditions and respond more efficiently to environmental changes.

Several IoT-based monitoring systems have been developed for agriculture and indoor farming applications. However, many of these systems focus primarily on real-time data visualization without adequately evaluating sensor reliability [26] – [30]. In controlled-environment agriculture, inaccurate sensor readings may affect monitoring decisions, trigger false alerts, and reduce the effectiveness of environmental management. This issue is particularly important for sensors, as their performance may be influenced by calibration limitations, environmental sensitivity, and measurement instability. Therefore, there is a need to develop an IoT-based monitoring system that is capable not only of real-time data acquisition and visualization but also of being validated against a reference device to evaluate measurement deviation and sensor reliability [31].

Therefore, this study aims to develop and validate a low-cost IoT-based environmental monitoring system for indoor hydroponic farming through real-time analysis of CO2 concentration, temperature, and relative humidity, and by comparing results with a handheld reference device. This study was conducted at the indoor plant factory of Universiti Tun Hussein Onn Malaysia using low-cost components to develop the proposed IoT-based monitoring system. This study contributes to the development of an affordable indoor farming monitoring solution while also emphasizing the need for sensor validation to improve the reliability of low-cost IoT-based systems.

2. Materials & Method

This section describes the materials and methods used in this study, including the experimental setup, hardware and software configuration, IoT-based monitoring system design, data collection procedure, and validation approach.

2.1 Experimental Setup

Table 1 presents the experimental setup for this study, including the experimental location, type of farming system, crop, experimental period, monitoring parameter, and supporting equipment.

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Table 1 *Indoor farming experimental setup*

Parameters	Description
Experimental location	Indoor plant factory at the UTHM Center of Energy and Industrial Environment Studies (CEIES)
Type of farming system	Indoor hydroponic farming
Crop	Green coral lettuce
Experimental period	30 days
Monitoring parameter	Carbon dioxide (CO_2), temperature, and humidity
Supporting equipment	Air conditioner, water pump, LED lighting, CO_2 gas cylinder, plant rack, and Wi-Fi adapter

The experimental work for this study was conducted in the indoor hydroponic farming facility at the CEIES UTHM, and green coral lettuce was selected as the test crop due to its short growth cycle and suitability for controlled-environment agriculture. The plants were cultivated under artificial light in a low-energy plant factory environment where environmental parameters influencing plant growth could be monitored.

The indoor farming system consists of several supporting facilities, including an air conditioner, a water pump, LED lighting, a CO2 gas cylinder, a plant rack, and a Wi-Fi adapter that is used to maintain the indoor farming environment and support the hydroponic cultivation system. The main environmental parameters monitored in this study were carbon dioxide concentration, temperature, and relative humidity. These parameters were selected because they directly impact plant growth, indoor air quality, and environmental stability in a controlled farming system. The monitoring period covered one completed crop growth cycle of 30 days. During this period, environmental data was collected to observe variations in carbon dioxide, temperature, and humidity within the indoor farming area.

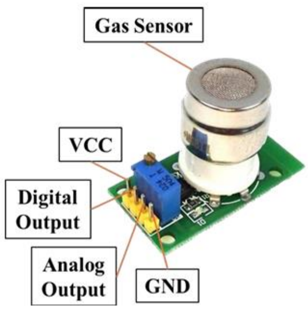
2.2 Hardware and Software Configuration

In this study, several hardware and software components were used to develop a low-cost IoT-based environmental monitoring system. The hardware components consist of sensors, a microcontroller, and a wireless communication module, while the software components were used for the system programming, cloud connectivity, and real-time data visualization. The selection of these components enables the system to collect, process, and transmit the environmental data to the end user.

2.2.1 Hardware Components

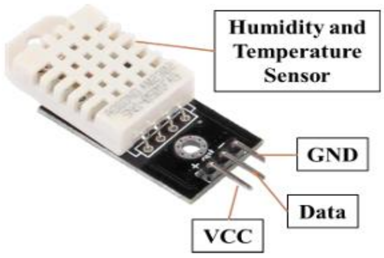
Table 2 presents the hardware components used to develop the low-cost IoT-based environmental monitoring system in this study. The selection of these components is based on their functions in sensing environmental parameters, processing sensor readings, and transmitting data to the cloud platform.

Table 2 *List of hardware components used*

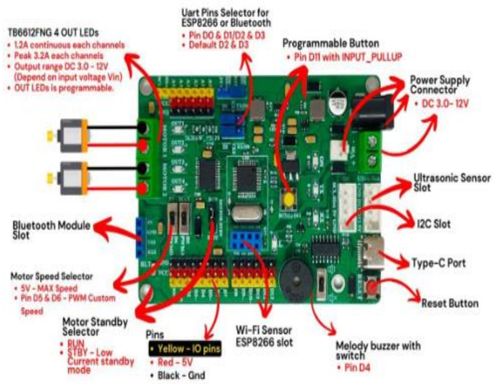
Components	Description	Picture
MG811 Sensor	• A gas sensor used to detect carbon dioxide (CO_2) concentration in the air • Detection range between 350 ppm and 10,000 ppm	

<table>
<tr><th>Components</th><th>Description</th><th>Picture</th></tr>
<tr><td>DHT22 sensor</td><td>

- Used to detect temperature and relative humidity
- Temperature measurement ranges from -40°C to 80°C and relative humidity between 0% and 100% RH

</td><td>
</td></tr>
<tr><td>Durian Uno</td><td>

- Upgrade version of Arduino Uno
- Acts as the main microcontroller used to collect and process data from the sensors before sending the data to the Wi-Fi module for cloud transmission

</td><td>
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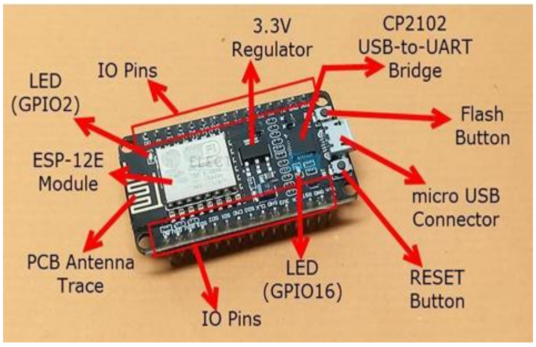
<tr><td>ESP8266 Wi-Fi Module</td><td>

- Used to transmit data to the cloud platform (Blynk)

</td><td>
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2.2.2 Software Components

Table 3 presents the software components used for programming, data transmission, and real-time visualization of the low-cost IoT-based environmental monitoring system.

Table 3 *List of software used*

Components	Description
Arduino IDE	• Used to write, compile, and upload program code to the Durian Uno microcontroller. • Enable the system to read data from the sensor, process and transmit the data to the Blynk Console through the ESP8266 Wi-Fi Module. • The programming language used is C++.
Blynk console	• An IoT cloud-based platform used to display the real- time environmental data through gauges and charts.

Fig. 1 shows the physical prototype design of the low-cost IoT-based monitoring system. The main components of this prototype include the MG811 and DHT22 sensors, a Durian Uno microcontroller, and an ESP8266 Wi-Fi module, which are built into a single monitoring unit. The prototype was built in a compact enclosure to protect the electronic components and enable practical installation in indoor farming settings.

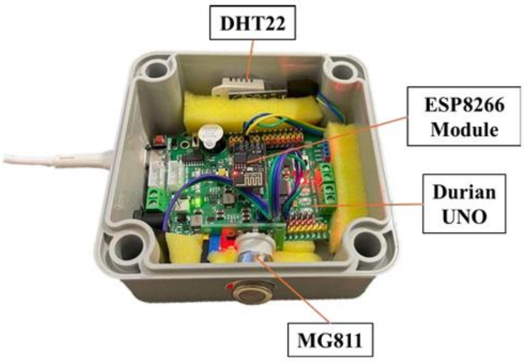

Fig. 1 *IoT- based environmental monitoring system prototype*

2.3 IoT- Based Monitoring System Design

This study develops a low-cost IoT-based monitoring system to enable real-time acquisition, transmission, and visualization of environmental data in the indoor hydroponic farming system. The system was divided into four functional units that include the sensing unit, the processing and communication unit, the cloud platform, and the visualization interface. Each unit performed a specific function to ensure that the monitored environmental parameters could be collected, processed, and accessed remotely.

Under the sensing unit, the MG811 sensor measured carbon dioxide concentration, and the DHT22 sensor measured air temperature and relative humidity. Both sensors were connected to the Durian Uno microcontroller, which functions as the main processing unit for receiving and processing the sensor readings. Next, the processed data were sent to the cloud platform via the ESP8266 Wi-Fi module. This module enables wireless communication between the prototype and the Blynk Cloud, which allows environmental data to be uploaded and monitored remotely.

The monitored parameters are then displayed on the Blynk Console dashboard using gauge and chart widgets, which allow the user to observe carbon dioxide concentration, temperature and relative humidity in real time. This monitoring design enables users to remotely monitor environmental conditions and observe data trends throughout cultivation periods. The overall design and data flow of the low-cost IoT-based monitoring system are illustrated in Fig. 2.

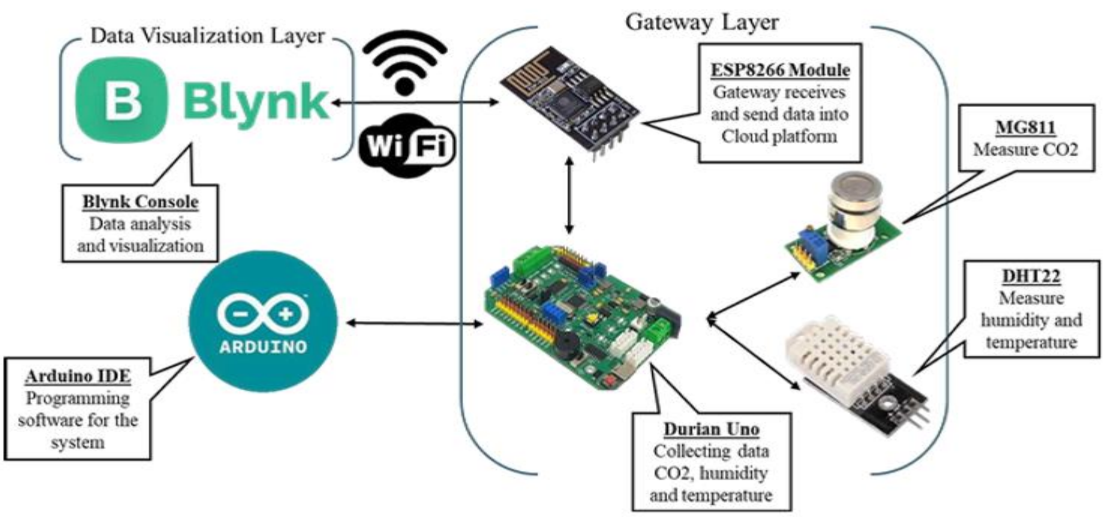

Fig. 2 *Block diagram of IoT environmental monitoring system*

2.4 Data Collection Procedure

For this study, the data were collected over a 30-day lettuce growth cycle to evaluate environmental conditions within the indoor hydroponic farming system. Carbon dioxide concentration, temperature, and relative humidity were selected as the main monitoring parameters due to their influence on photosynthetic activity, plant metabolic performance, and transpiration balance. The readings were recorded daily throughout the monitoring periods, and the observations were made during morning, afternoon, and evening sessions to improve measurement consistency. The dataset recorded in the Blynk Console dashboard was tabulated and analyzed using minimum, maximum, and average values to identify environmental fluctuations across cultivation periods. The minimum and maximum values obtained indicated the range of environmental fluctuations, while the average value represented the general condition of the indoor farming environment throughout the cultivation period.

2.5 Validation Approach

The performance of the developed IoT-based monitoring system was validated by comparing the readings obtained from the Blynk dashboard with a handheld device known as Kimo Instruments AMI310. The comparison focuses on three environmental parameters, which are carbon dioxide concentration, temperature, and relative humidity, with the selected observation periods. The purpose of this validation is to evaluate the measurement deviation between the proposed IoT monitoring and the handheld device.

3. Result & Discussion

This section presents the findings from the proposed IoT-based monitoring system and discusses the analysis of three environmental parameters evaluated in this study. The results are presented based on the environmental monitoring data collected throughout the cultivation period. In addition, the validation of the proposed system is discussed in this section by comparing the sensor readings obtained from the proposed system with those from the handheld device.

3.1 Environmental Monitoring Data

Table 4 presents the environmental data collected using the proposed IoT–based monitoring system over a 30-day lettuce growth cycle. The parameters monitored were CO_2 concentration, temperature, and relative humidity. The readings were taken from the Blynk Console dashboard and summarized in a table to assess the indoor hydroponic farming system's environment. The data were analyzed using minimum, maximum, and average values to determine the fluctuations in the monitored parameters during the cultivation period.

Table 4 *Environmental data from proposed IoT-based monitoring system*

Day	Date	Carbon dioxide (PPM)	Temperature (°C)	Humidity (%)
1	30/11/2023	659	21.0	79
2	1/12/2023	798	20.7	80
3	2/12/2023	901	20.2	78
4	3/12/2023	1083	20.9	78
5	4/12/2023	666	20.6	79
6	5/12/2023	882	20.8	81
7	6/12/2023	567	20.7	80
8	7/12/2023	936	21.0	80
9	8/12/2023	700	20.9	79
10	9/12/2023	540	21.1	80
11	10/12/2023	1024	20.7	78
12	11/12/2023	926	20.6	79
13	12/12/2023	705	21.2	81
14	13/12/2023	676	20.7	78
15	14/12/2023	555	20.8	79
16	15/12/2023	609	21.2	80
17	16/12/2023	800	21.1	79
18	17/12/2023	590	20.6	78
19	18/12/2023	607	20.9	78
20	19/12/2023	593	20.4	79
21	20/12/2023	752	21.1	81
22	21/12/2023	1205	20.2	80
23	22/12/2023	884	20.3	79

Day	Date	Carbon dioxide (PPM)	Temperature (°C)	Humidity (%)
24	23/12/2023	657	21.0	80
25	24/12/2023	999	20.6	80
26	25/12/2023	892	21.1	78
27	26/12/2023	789	21.0	79
28	27/12/2023	692	20.7	80
29	28/12/2023	1225	20.8	81
30	29/12/2023	777	20.5	78
Total		23689	623.3	2379
Average		789.63	20.8	79.3

From Table 4, the CO_2 concentration ranges from 540 ppm to 1225 ppm with an average of 789.63 ppm over the 30 days. Based on the observation, the average temperature was relatively stable at 20.8°C, ranging from 20.2°C to 21.2°C throughout the monitoring period. Meanwhile, the relative humidity ranges from 78% to 81% with an average value of 79.3%. Overall, these results indicate that temperatures and humidity are more stable compared with the CO_2 concentration, which fluctuated throughout the cultivation period.

3.1.1 Carbon Dioxide Concentration

Fig. 3 illustrates the carbon dioxide (CO_2) concentration recorded by the proposed IoT-based monitoring system throughout the 30-day lettuce growth cycle. The recorded CO_2 levels were between 540 ppm and 1225 ppm, with an average of 789.63 ppm throughout the monitoring period. The results indicate that CO_2 concentration changes significantly over the period due to the indoor farming environment experiencing different atmospheric conditions at different times. Higher CO_2 levels were recorded on Day 4 (1083 ppm), Day 22 (1205 ppm), and Day 29 (1225 ppm). While the lowest CO_2 levels were recorded on Day 10 (540 ppm) and Day 15 (555 ppm).

Several factors can be considered for the difference in CO_2 concentration, such as plant respiration, air circulation, ventilation conditions, and the sensor response. Since CO_2 is an important parameter for photosynthesis activity, continuous monitoring is needed to detect sudden changes in the indoor farming environment and support better environmental management. Moreover, the general trend of CO_2 changes during the growth cycle was captured by the MG811 sensor. However, the larger fluctuation values recorded by the sensor indicate that its performance is affected by calibration limitations, environmental sensitivity, or measurement instability. Therefore, the MG811 sensor can serve as an economical option for relative CO_2 trend observation but needs to be further calibrated and compared with a reference device to improve measurement accuracy.

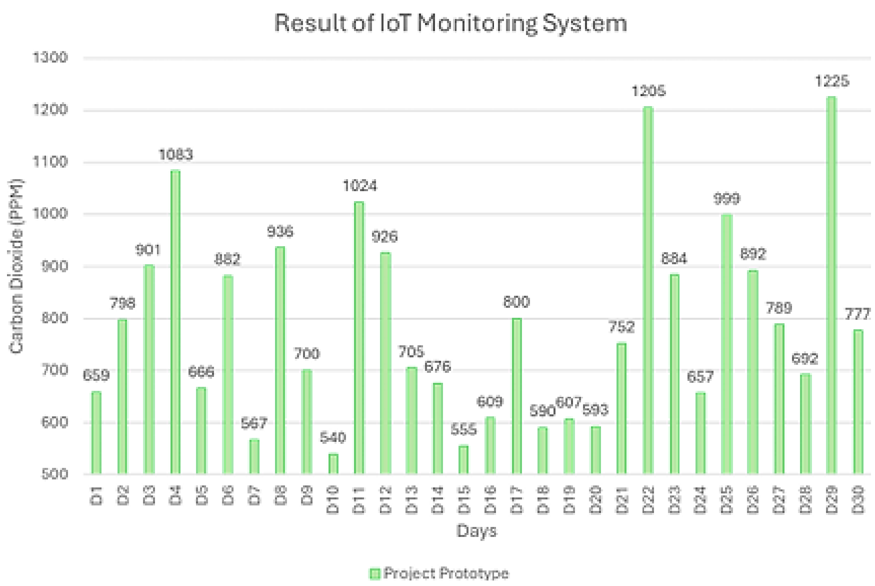

Fig. 3 *Carbon dioxide concentration trends from proposed IoT-based monitoring system*

Overall, Fig. 3 indicates that CO_2 concentration shows greater fluctuations than the other monitored parameters. This highlights the importance of real-time monitoring in indoor farming environments, as manual monitoring cannot effectively detect sudden changes in CO_2 concentration. In addition, the results indicate that low-cost CO_2 sensors such as the MG811 can be beneficial for trend monitoring; however, the readings need to be verified for reliability in controlled-environment agriculture applications.

3.1.2 Temperature Variation

Fig. 4 presents the temperature recorded by the proposed IoT-based monitoring system throughout the cultivation period. The recorded temperatures ranged from 20.2°C to 21.2°C with an average value of 20.8°C. The smaller temperature range indicates that the indoor hydroponic farming environment maintains relatively stable thermal conditions during the cultivation period. The highest temperature of 21.2°C was recorded on several days, while the lowest temperature of 20.2°C was recorded at specific points throughout the monitoring period. The overall temperature variation indicated minimal fluctuation throughout the monitoring period.

The stable temperature trend observed in this study is related to the controlled indoor environmental conditions and the use of an air-conditioning system in the plant factory. The indoor farming temperature needs to be monitored as it can affect the plant's metabolic activity, transpiration, and growth performance. Sudden temperature fluctuations can induce environmental stress and affect crop development in an indoor hydroponic farming system. In this study, the DHT22 sensor used in the proposed IoT-based monitoring system can detect minor daily temperature changes and provide continuous data for real-time monitoring. However, the reliability of the temperature data needs to be verified by comparing it with the handheld device for sensor performance.

Overall, the temperature data showed the most stable trend among the parameters. The difference between the minimum and maximum values indicates that the indoor farming environment maintained consistent thermal conditions throughout the cultivation period. Thus, this finding supports the usefulness of an IoT-based monitoring system for assessing temperature stability in controlled-environment agriculture.

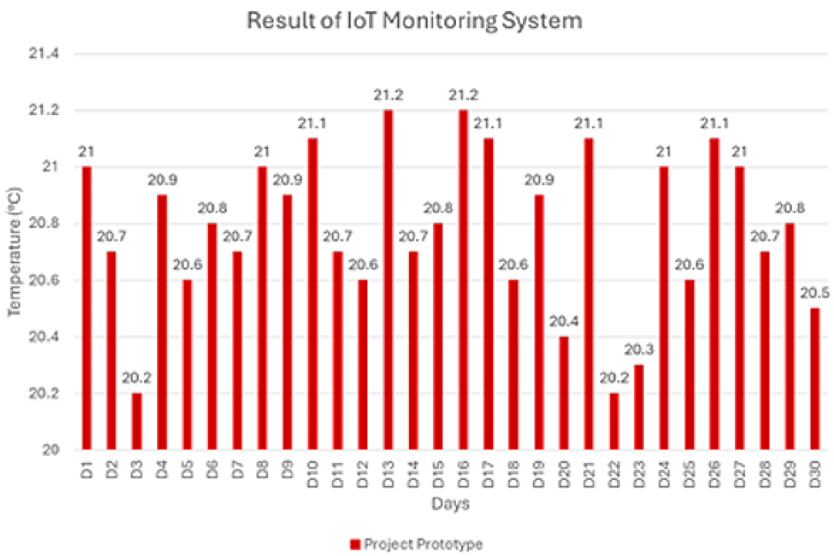

Fig. 4 *Temperature trends from proposed IoT-based monitoring system*

3.1.3 Relative Humidity Variation

Fig. 5 presents the relative humidity data collected by the proposed IoT-based monitoring system throughout the lettuce's growth period. The humidity readings obtained range from 78% to 81%, with an average value of 79.3%. The smaller range of variation indicates that the indoor hydroponic farming environment maintained relatively stable humidity conditions during the growing period. The maximum humidity recorded was 81% on several days, and the lowest was 78% at different points during the monitoring period. However, the difference between the maximum and minimum values is only 3%, indicating that humidity fluctuations are relatively low. Stable humidity is important in the indoor farming environment because relative humidity affects plant transpiration, water balance, and overall crop production. Humidity fluctuations can cause abnormal physiological responses in crops and destabilize the environment in controlled-environment agriculture.

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In addition, the findings indicate that the DHT22 sensor in the proposed IoT-based monitoring system can detect minor changes in relative humidity during the growth cycle and provide useful data for real-time environmental monitoring. However, the reliability of the humidity reading needs to be further evaluated by comparing the findings obtained with a reference device to ensure the sensor's performance. It can be concluded that the humidity data reflected the moisture level of the indoor farming system and were consistent with having a suitable environment for cultivating lettuce.

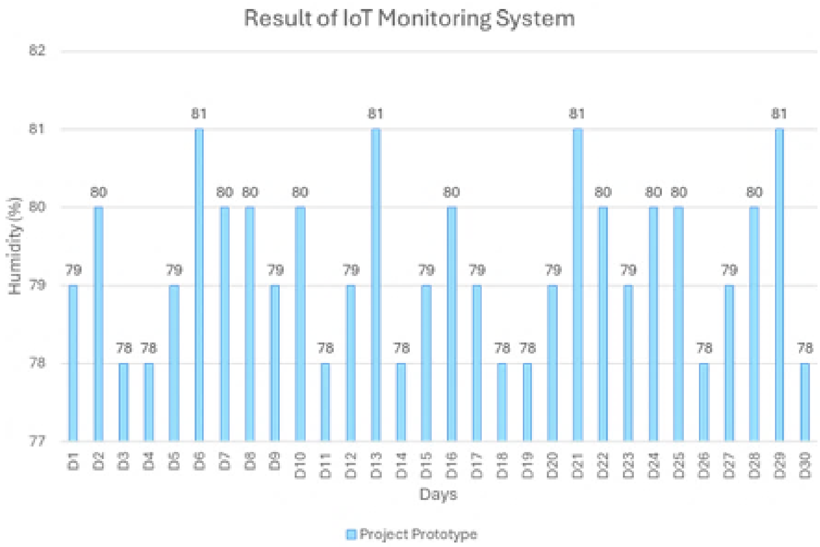

Fig. 5 *Humidity trends from proposed IoT-based monitoring system*

3.2 Comparison with Handheld Device

Table 5 presents the environmental data obtained from the Kimo Instruments AMI310 handheld device for the selected four-day observation period. The monitoring period is from 4/12/2023 to 7/12/2023. From the data recorded in Table 5, the CO_2 concentration ranged from 502 ppm to 533 ppm with an average of 520.3 ppm. The temperature data obtained were relatively stable, ranging from 20.3°C to 20.6°C, with an average temperature of 20.5°C. Additionally, the handheld device measured relative humidity between 78% and 79%, with an average of 78.5%. The findings show that the environmental parameters measured by the handheld device remained stable during the observation period and served as the reference device for comparison with the proposed IoT-based monitoring system.

Table 5 *Environmental data obtained from the handheld device*

Date	Carbon Dioxide (PPM)	Temperature (°C)	Humidity (%)
4/12/2023	502	20.3	78
5/12/2023	529	20.5	79
6/12/2023	533	20.4	78
7/12/2023	517	20.6	79
Total	2081	81.8	314
Average	520.3	20.5	78.5

Fig. 6 presents the comparison of the proposed IoT-based monitoring system (Project Prototype) with the Kimo Instruments AMI310 handheld device (Device Handheld) for carbon dioxide concentration, temperature, and relative humidity. The comparison was conducted over a selected four-day observation period to evaluate the measurement deviations between the prototype and the handheld device. Overall, the prototype devices recorded higher values than the handheld device for all environmental parameters. However, the magnitude of deviation varied between the parameters.

For carbon dioxide (CO_2) concentration, the proposed IoT-based monitoring system showed greater variation than the handheld device. The prototype recorded an average CO_2 value of 762.75 ppm, while the handheld device recorded an average value of 520.3 ppm. This indicated that the MG811 sensor tended to overestimate CO_2 concentration during the observation period. The larger deviation could be due to calibration limitations, the sensitivity of sensor detection, interference from the environment, or measurement instability. Even though the MG811 sensor can be used to observe CO_2 trends, further calibration or the use of a more reliable CO_2 sensor is required to improve measurement accuracy.

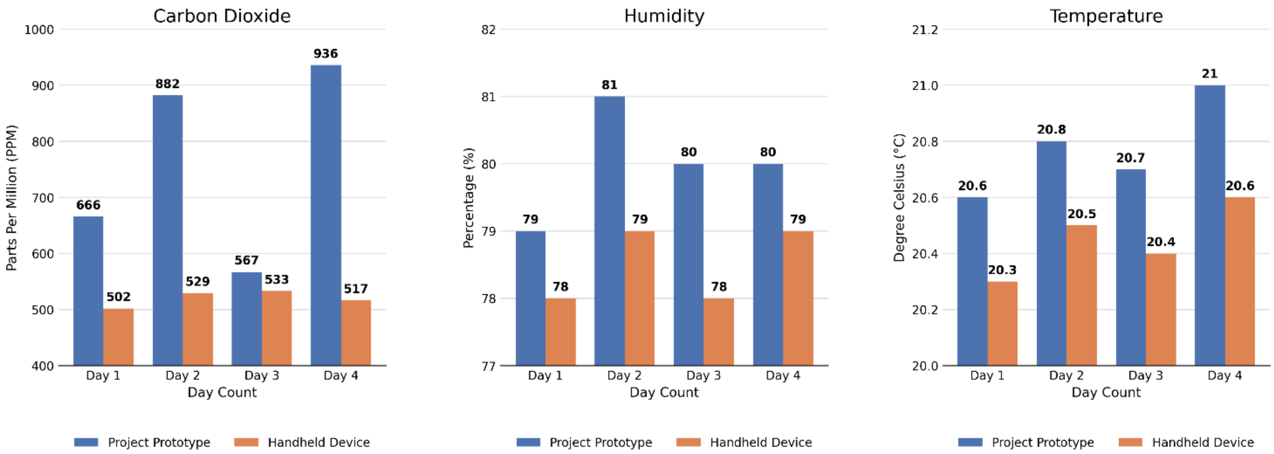

Fig. 6 *Comparison data between handheld device and proposed IoT-based monitoring system*

In contrast, the temperature readings from both the prototype and handheld devices show a smaller difference. The prototype recorded an average temperature of 20.78°C, while the handheld device recorded 20.5°C, resulting in an average difference of only 0.28°C. This indicates that the DHT22 sensor is relatively stable in measurement during the validation period. Similarly, the humidity readings from the handheld devices and the prototype differ slightly, with the prototype recording an average humidity of 80.0% compared to the handheld devices' 78.5%. The average difference of 1.5% suggests that the DHT22 sensor provided consistent relative humidity readings for real-time monitoring.

Table 6 *Environmental data obtained from the handheld device*

Parameter	Sensor	Mean (Prototype)	Mean (Handheld)	RMSE	MAE	% Error	Paired t-test (p)
Carbon Dioxide (ppm)	MG811	762.75	520.25	286.45	242.50	46.71%	p = 0.071
Humidity (%)	DHT22	80.00	78.50	1.58	1.50	1.91%	p = 0.014*
Temperature (°C)	DHT22	20.78	20.45	0.33	0.33	1.59%	p = 0.001**

*Significant at α = 0.05; **significant at α = 0.01. RMSE = root-mean-square error; MAE = mean absolute error. Paired t-test conducted using matched daily readings (prototype − handheld).

Table 6 quantifies the agreement between the IoT prototype and the handheld reference device across the four days on which both instruments were sampled concurrently. The DHT22-based humidity and temperature readings show small absolute errors (RMSE of 1.58% and 0.33°C, corresponding to percentage errors of 1.91% and 1.59%, respectively), and the paired t-test confirms that these small offsets are statistically significant ($p = 0.014$ and $p = 0.001$). Because the offset is both small and highly consistent across days, this indicates a systematic calibration bias rather than random measurement noise — the DHT22 is precise and repeatable but reads slightly higher than the reference instrument on every sampled day.

The Bland-Altman analysis in Fig. 7 reinforces the pattern shown in the paired-difference statistics: the DHT22-based humidity and temperature readings show a small, consistent positive bias relative to the handheld reference (+1.50% and +0.33 °C, respectively), with all four data points falling well within tight 95% limits of agreement (0.37–2.63% for humidity; 0.23–0.42 °C for temperature). This tight clustering indicates that the prototype's error relative to the handheld device is systematic rather than random — the DHT22 consistently reads slightly higher than the reference instrument, which points to a fixed calibration offset that could likely be corrected with a simple additive calibration factor rather than reflecting poor sensor precision. The MG811 CO2 sensor tells a very different story: the mean bias is large (+242.50 ppm), and the limits of agreement are extremely wide (-102.59 to 587.59 ppm), spanning nearly 700 ppm around the mean bias. Unlike the DHT22, the CO2 differences also show no consistent pattern across the mean concentration (ranging from +34 ppm at D7 to +419 ppm at D8), suggesting the MG811's error is not a stable offset, but varies unpredictably with concentration —

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consistent with the sensor's known non-linear voltage-to-ppm response and sensitivity to baseline drift discussed elsewhere in this paper. Taken together, the plots support treating the DHT22 as precise but in need of better calibration, and the MG811 as a fundamentally imprecise one under the tested conditions (a more serious limitation for practical deployment).

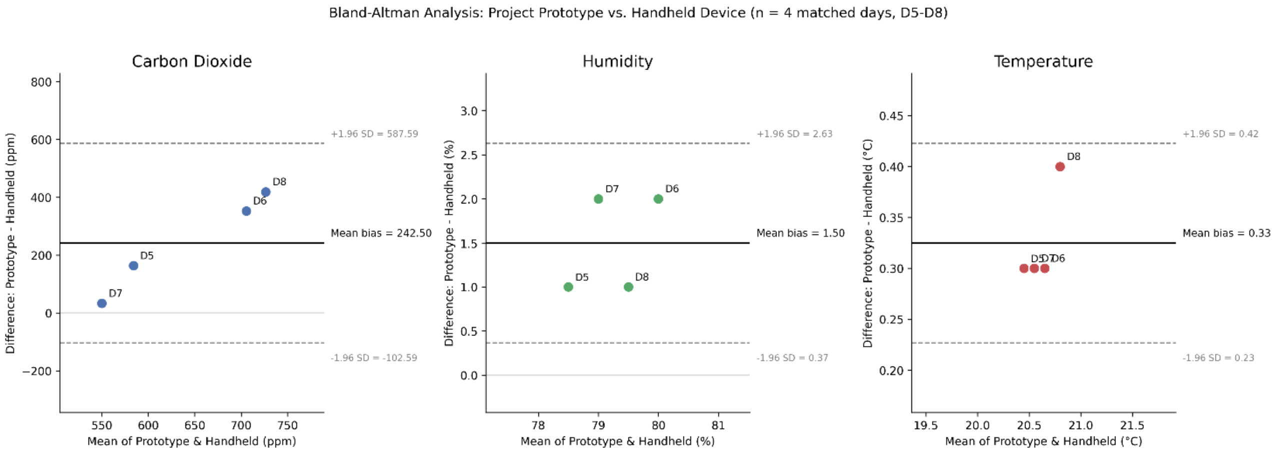

Fig. 7 *Bland-Altman limits of agreement between the handheld device and the project prototype*

Overall, the validation results show that the proposed IoT-based monitoring system is suitable for real-time indoor temperature and relative humidity monitoring. However, improvements are needed for CO_2 concentration monitoring due to the larger deviation observed from the MG811 sensor. Additionally, these findings highlighted the importance of validating low-cost sensors against the handheld device for decision-making in controlled-environment agriculture.

4. Conclusion

In conclusion, the low-cost IoT-based environmental monitoring system for indoor hydroponic farming was successfully developed and validated in this study. The proposed system comprises an MG811 CO_2 sensor, a DHT22 temperature and humidity sensor, a Durian Uno microcontroller, an ESP8266 Wi-Fi module, and a Blynk Console dashboard to collect, transmit, and visualize real-time environmental data. The system was implemented at the indoor plant factory of Universiti Tun Hussein Onn Malaysia and evaluated over a 30-day growth cycle of green coral lettuce. The results showed that the system was able to monitor carbon dioxide concentration, temperature, and relative humidity continuously throughout the cultivation period. The trends for temperature and relative humidity were relatively stable, with averages of 20.8°C and 79.3%, respectively. The concentration of CO_2 shows greater variation, ranging from 540 ppm to 1225 ppm, with an average of 789.63 ppm. The finding shows that real-time monitoring is important in indoor farming environments, especially for detecting environmental changes that are not effectively captured through manual observation.

The validation with the Kimo Instruments AMI310 handheld reference device showed that the DHT22 sensor provided relatively consistent temperature and humidity readings. The results showed that the average temperature difference between the prototype and the handheld device was 0.28°C, and the average relative humidity difference was 1.5%, both within acceptable limits for real-time monitoring. However, the MG811 sensor showed a larger deviation in CO_2 measurements, with the prototype recording higher CO_2 values than the handheld device. This indicates that the CO_2 measurement is influenced by calibration limitations, sensor sensitivity, environmental interference, or measurement instability.

Overall, the findings demonstrate the potential of low-cost IoT technology for supporting environmental monitoring in controlled-environment agriculture. The system can help users remotely monitor indoor farming conditions, enhancing the efficiency of crop management and environmental monitoring through data. The study also emphasizes that low-cost sensors need to be validated before being used for decision-making in indoor farming systems. In future work, the MG811 sensor can be replaced with a Non-Dispersive Infrared (NDIR) CO_2 sensor to improve measurement accuracy and reduce the possibility of false alerts in the indoor farming system. By improving the accuracy of these sensors and enabling continuous validation, the IoT-based monitoring system can help improve the accuracy of indoor farming.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contributions to the paper as follows: ***study conception and design:*** *A.N. Mohammed;* ***data collection:*** *M.H.M. Rizal;* ***analysis and interpretation of results:*** *A.N. Mohammed, M.H.M. Rizal;* ***draft manuscript preparation:*** *A.N. Mohammed, M.H.M. Rizal; All authors reviewed the results and approved the final version of the manuscript.*

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