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DESIGN OF AN *IOT*-BASED *GREENHOUSE* MICROCLIMATE MONITORING SYSTEM WITH *REAL-TIME* NOTIFICATION AND *THRESHOLD ALERT*

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ABSTRACT
Greenhouse microclimate monitoring is essential to maintain plant productivity, yet it is still commonly performed manually or with poorly integrated systems. This research designs and implements an IoT-based Greenhouse microclimate monitoring system using an ESP32 microcontroller integrated with five sensors (DHT22, BMP280, DS18B20, BH1750, and MQ-135), equipped with an LCD display, MicroSD data storage, a web dashboard, and real-time notifications via Telegram and buzzer as threshold alerts. Testing was carried out through sensor calibration/comparison against standard instruments, functional testing, and a 7-day field test at Hydroponic Greenhouse of KWT Mawar 8, Tangerang City, with most sensors well calibrated against the standard instruments. The field test shows high system reliability, with 98.81% data completeness and no significant downtime, and successfully detected microclimate conditions outside the ideal range, particularly air and water temperature during the day and humidity at night, which could potentially cause heat stress, root rot, and fungal disease risk in lettuce plants. The threshold alert feature via Telegram and buzzer is validated to function properly in providing early warnings under real operating conditions.

Keywords: IoT, Greenhouse, microclimate monitoring, ESP32, threshold alert, Telegram

Abstrak
Pemantauan kondisi mikroklimat pada Greenhouse merupakan aspek penting dalam menjaga produktivitas tanaman, namun pada praktiknya masih banyak dilakukan secara manual atau menggunakan sistem yang kurang terintegrasi. Penelitian ini merancang dan mengimplementasikan sistem monitoring mikroklimat Greenhouse berbasis Internet of Things (IoT) menggunakan mikrokontroler ESP32 yang terintegrasi dengan lima sensor (DHT22, BMP280, DS18B20, BH1750, dan MQ-135), dilengkapi tampilan LCD, penyimpanan data pada MicroSD, dashboard web, serta notifikasi real-time melalui Telegram dan buzzer sebagai threshold alert. Pengujian dilakukan melalui kalibrasi/komparasi sensor terhadap alat standar, pengujian fungsional sistem, serta pengujian lapang di Greenhouse hidroponik KWT Mawar 8, Kota Tangerang, dengan sebagian besar sensor terkalibrasi baik terhadap alat standar. Pengujian lapang menunjukkan keandalan sistem yang tinggi dengan kelengkapan data sebesar 98,81% tanpa downtime signifikan, serta berhasil mendeteksi kondisi mikroklimat yang berada di luar rentang ideal, terutama suhu udara dan suhu air pada siang hari serta kelembaban pada malam hari, yang berpotensi menimbulkan heat stress, root rot, dan risiko penyakit jamur pada tanaman selada. Fitur threshold alert melalui Telegram dan buzzer tervalidasi berfungsi dengan baik dalam memberikan peringatan dini pada kondisi operasional nyata.

Kata kunci: IoT, Greenhouse, monitoring mikroklimat, ESP32, threshold alert, Telegram

INTRODUCTION

Modern agriculture faces serious challenges due to global climate change, which is causing environmental conditions to become increasingly unstable and unpredictable. One widely adopted solution to address these issues is the use of Greenhouses, which enable the control of microclimate parameters such as temperature, humidity, air pressure, light intensity, water temperature (growing medium), and CO_2 concentration. Effective environmental control within Greenhouses has been shown to significantly

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improve the productivity and quality of horticultural crops (Rais, Aidah, & Nurlia, 2025).

An accurate microclimate measurement and monitoring system is required to ensure that conditions inside the Greenhouse remain at the ideal levels required by the plants. However, in practice, environmental monitoring is still largely carried out manually or using monitoring systems that lack integration. This results in limited data accuracy and delays in responding to changes in environmental conditions, which can ultimately have a negative impact on plant growth and health and reduce Greenhouse productivity (Kurniawan, Ristiono, & Sulistiadi, 2021).

Advances in Internet of Things (IoT) technology offer significant opportunities to improve the efficiency of agricultural environmental monitoring. Various sensors, such as the DHT22 for temperature and humidity, the BMP280 for air pressure, the DS18B20 for the temperature of the growing medium, the BH1750 for light intensity, and the MQ-135 for air quality and CO_2 concentration, can be integrated into an IoT system to generate real-time and accurate microclimate data (Suci & Rohmah, 2025). An IoT-based monitoring system not only enables continuous monitoring of environmental conditions but can also be developed with threshold alert features and automatic notifications via Telegram, as well as buzzer alerts. The addition of these features is crucial for providing early warnings when microclimate parameters fall outside ideal conditions, enabling Greenhouse managers to take corrective action swiftly to maintain environmental stability and prevent damage to crops (Rabbani, 2025).

Several prior studies have developed IoT-based Greenhouse monitoring systems, yet each remains limited in scope. Rabbani (2025) designed a smart Greenhouse monitoring and notification system using an ESP32, a DHT22 sensor, soil moisture, and soil pH with the MQTT protocol, but did not include CO2 or light-intensity sensing and lacked integration with Telegram or a web dashboard. Kurniawan et al. (2021) designed a real-time microclimate monitoring system using an ESP32 connected to the Thingspeak platform, but did not provide automatic notification or a local LCD indicator. Regita, Nasution, & Nasution (2024) developed a Greenhouse monitoring system with an ESP32, DHT22, and soil moisture sensor, but did not incorporate growing-medium temperature or air-quality sensing, nor any notification mechanism. Unlike these studies, the present research integrates six microclimate parameters simultaneously (air temperature, humidity, air pressure, light intensity, water temperature, and CO2) within a single system, combines dual real-time alerting channels (Telegram and buzzer) with a configurable three-tier threshold (lower alert, optimal range, upper alert), and validates the complete system from sensor-level calibration through a 7-day continuous field deployment on an operating hydroponic Greenhouse, rather than a laboratory bench test alone. This combination of parameter breadth, dual-channel alerting, and end-to-end field validation has not been jointly demonstrated in the studies reviewed above. This research designs a Greenhouse microclimate monitoring system integrated with real-time notifications and threshold alert, covering six microclimate parameters simultaneously (air temperature, humidity, air pressure, light intensity, water temperature, and CO_2), with outputs in the form of an LCD for local data display, web dashboard for remote monitoring, MicroSD storage for data backup from database, and Telegram and buzzer notifications. The system is then tested through sensor calibration, functional testing, and field testing at an NFT hydroponic Greenhouse of Kelompok Wanita Tani (KWT) Mawar 8, Tangerang.

This research offers three categories of contribution. Methodologically, it presents an integrated calibration to deployment protocol that combines traceable sensor calibration against standard instruments with dual-channel (Telegram and buzzer) threshold-alert mechanism covering six microclimate parameters simultaneously, rather than treating calibration and alerting as separate, unvalidated design choices. Empirically, it provides quantified accuracy and reliability evidence, including per-sensor correction values, the MQ-135's limited correlation with a reference gas analyzer ($r = 0.400$), and a 98.81% field data-completeness rate over seven continuous days, that has not been jointly reported for this sensor combination in a hydroponic Greenhouse context. Practically, the system was deployed and validated on an operating smallholder hydroponic Greenhouse (KWT Mawar 8) rather than under laboratory conditions, demonstrating a low-cost, farmer-operable design that can inform future deployments for small-scale horticultural producers.

The theoretical basis covers the main concepts and components used as a reference in designing the IoT-based Greenhouse microclimate monitoring system in this research.

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Greenhouse and Hydroponics

A Greenhouse is a building with a light-transmitting roof and walls that functions to manipulate environmental factors so that plants can grow optimally from the seedling stage to production, with the main environmental parameters including air temperature, air humidity, light intensity, air circulation, water availability, and CO_2 concentration$_2$ (Ernawati et al., 2021). Hydroponics is a plant cultivation method without soil, in which plant roots obtain nutrients directly from a nutrient solution dissolved in water. This system allows more precise control of the growing environment, efficient use of water and nutrients, and minimizes pest and disease disturbances from the soil (Mulyani, Hermanto, Natalliasari, & Khairul A, 2021). The success of a hydroponic system is heavily influenced by the microclimate conditions inside the Greenhouse; therefore, the hydroponic system in this research was integrated with an IoT-based monitoring system to maintain optimal growing conditions (Kurniawan et al., 2021).

Greenhouse Microclimate

A microclimate is a set of climatic conditions occurring within a very small area that has a direct influence on climatic elements such as air temperature, humidity, radiation and wind speed near the soil surface and vegetation (Fitri, 2023). Microclimates have a significant impact on plant physiology in the context of protected cultivation (Greenhouses), such as the rate of photosynthesis, transpiration, and oxygen availability in the root zone; consequently, the control of temperature, humidity, radiation, and gas concentrations is key to plant productivity and health (Purbakawaca, Roidelindho, Maulizar, & Hardyanto, 2025). Six microclimate parameters that influence plant growth in Greenhouses include:

1. Air Temperature
   Air temperature significantly affects plant photosynthesis, respiration and transpiration; excessively high temperatures cause plants to wilt, whilst excessively low temperatures slow growth, with an optimal range of 24–35°C for horticultural crops in general (Satmoko, Sumarni, & Sulistyo, 2025).
2. Air Humidity
   Air humidity (RH) affects the rate of plant transpiration; low humidity causes water stress, whilst high humidity increases the risk of fungal and bacterial diseases, with an optimal range of 50–80% RH (Priyonggo et al., 2023).
3. Air Pressure
   Practically, monitoring air pressure serves as an indirect indicator of ventilation system performance and impending weather changes, a sudden pressure drop often precedes rain or storm events, allowing the system to signal operators to close ventilation openings or take protective action, with an optimal range of 1000 - 1020 hPa (Liang et al., 2022)
4. Light Intensity
   Light intensity is the primary energy source for photosynthesis; excessively high intensity triggers photoinhibition, whilst excessively low intensity inhibits photosynthesis and causes etiolation. with an optimal range of 10,000 - 50,000 lux for horticultural crops in general (Almajdi, Ika Uktoro, 2025)
5. Water Temperature
   In hydroponic systems, water temperature determines the solubility of dissolved oxygen and root activity; inappropriate temperatures cause root stress and reduce plant growth. With an optimal range of 18 - 30°C (Puspitahati, Kelana, & Aulia, 2025)
6. CO_2 Concentration
   CO_2 is the primary raw material for photosynthesis; levels that are either too low or too high can inhibit growth, making its monitoring an indicator of Greenhouse ventilation efficiency. With an optimal range of 400 - 1000 ppm (Yusuf, Al-Yahya, Saleh, & Abdel-Ghany, 2025)

These six parameters were selected because they represent the microclimate variables most consistently identified in the Greenhouse and hydroponic cultivation literature as directly limiting to plant physiological processes such as photosynthesis, transpiration, respiration, and root-zone nutrient/oxygen uptake

Table 1. The Effect of Microclimate Parameters in Greenhouses

Microclimate Parameter	Effect on the Greenhouse
Air temperature	Affects plant growth and stress level
Air humidity	Affects transpiration and disease risk
Air pressure	Affects circulation and ventilation stability

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Light intensity	Affects the plant photosynthesis process
Water temperature	Affects root growth and condition
CO_2 concentration	Affects photosynthesis process and efficiency

Internet of Things (IoT)

Internet of Things (IoT) is a technological concept that allows various physical devices to be interconnected through the internet network to collect, send, and process data automatically without direct human interaction, generally consisting of sensors, actuators, microcontrollers, and communication modules working in an integrated manner (Radouan Ait Mouha, 2021). The application of IoT in a Greenhouse system enables continuous monitoring of microclimate parameters, where data obtained from sensors can be stored, analyzed, and presented to users in the form of visual information or early warning notifications if an unsuitable condition occurs (Purbakawaca et al., 2025).

ESP32 Microcontroller

ESP32 is a low-cost microcontroller equipped with integrated Wi-Fi and Bluetooth for wireless communication in IoT applications. This microcontroller uses a dual-core Tensilica Xtensa LX6 processor with a frequency of up to 240 MHz, equipped with internal SRAM, support for SPI, I2C, UART, ADC, DAC, PWM communication, and flexible GPIO, so it is often used as the control center in IoT monitoring systems, including microclimate parameter monitoring (Yacub, 2025).

DHT22 Sensor

The DHT22 sensor is a digital temperature and humidity sensor that uses a capacitive humidity sensor and NTC thermistor to measure the surrounding air and output a digital signal on the data pin. The capacitive humidity sensor detects capacitance changes in a moisture-reactive material to measure relative humidity, while the NTC thermistor measures temperature through changes in resistance. Both quantities are converted by an internal 8-bit microcontroller into a digital signal sent through a single-wire data line (Setyanto & Salahuddin, 2022).

BMP280 Sensor

BMP280 is a digital barometric sensor that measures absolute pressure in the range of ±300-1100 hPa with an accuracy of ±0.12 hPa, low power consumption, and I2C/SPI communication (Bosch, 2021). The internal piezo-resistive element undergoes a change in resistance when the pressure changes, which is then converted into digital air pressure data by the internal ADC.

BH1750 Sensor

BH1750 is a 16-bit ambient light sensor that produces a direct digital output in lux units, and is already factory-calibrated, although that it was still need comparison test because factory calibration certifies the bare sensor die under standardized laboratory conditions, not its as-installed accuracy after PCB assembly, enclosure integration, and exposure to field conditions (Setyanto & Salahuddin, 2022). The sensor uses a photodiode with a spectral response close to human eye sensitivity; the resulting photocurrent is converted into voltage by an internal transimpedance amplifier, then converted into digital data through a 16-bit ADC.

DS18B20 Sensor

DS18B20 is a silicon-based semiconductor digital temperature sensor with a 1-Wire communication protocol, so it only requires one data line besides the power supply and ground. Voltage changes in the temperature-sensitive semiconductor element are converted by the internal ADC into digital data with up to 12-bit resolution (Maxim integrated, 2019). In this research, the DS18B20 is used to measure the temperature of the growing medium (nutrient water) in the NFT hydroponic system.

MQ-135 Sensor

MQ-135 is a gas sensor based on SnO_3 semiconductor material used to detect air quality in the range of 10-1000 ppm, including CO_2, NH_3, CO, benzene, and other volatile compounds, with an analog voltage output (Umbu, 2023). The MQ-135 is specifically used to measure CO_2 because it is one of the key parameters that influence photosynthesis and plant growth in greenhouses. The sensor resistance decreases as the gas concentration increases, producing a voltage change in the voltage divider circuit that is read by the microcontroller ADC.

Threshold Alert and Telegram Bot

A threshold alert is an environmental parameter value limit used as a reference to determine normal (optimal) conditions or warning (alert) conditions in a monitoring system. If the parameter value is outside the optimal range, the system activates a

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warning notification via buzzer or a message in the monitoring application (Priyonggo et al., 2023). Telegram is a cloud-based instant messaging application that provides the Telegram Bot API to send automatic messages to users without manual interaction, used in this research as a real-time notification medium when microclimate conditions exceed the threshold (Yacub, 2025)

RESEARCH METHODS

This research was carried out in several stages, including system design, determination of threshold alert values, system working principles, and testing plans.

System Design

System design was carried out by creating a circuit schematic using the Fritzing software. Figure 1 shows the circuit schematic of the IoT-based Greenhouse microclimate monitoring system.

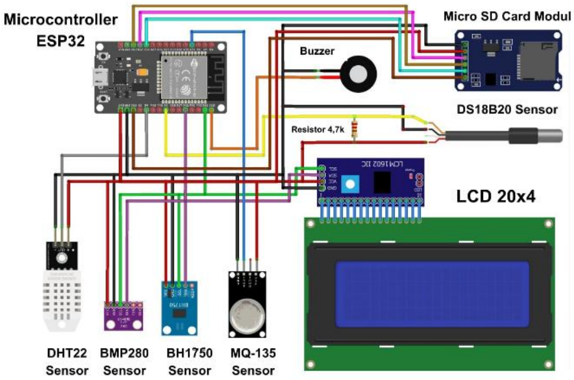

Figure 1. System Circuit Schematic

The system block diagram in Figure 2 illustrates the workflow and the relationships between components. On the input side, each sensor converts the physical quantity of each measured parameter into an electrical signal or digital data sent to the ESP32 microcontroller as the processing center. The ESP32 then compares the data with the threshold value for each parameter and prepares the data to be sent through the Wi-Fi network to the web server. On the output side, data is displayed locally via the LCD and stored on the MicroSD, while also being sent to the web server to be stored in the database and displayed on the dashboard. If the environmental condition is outside the ideal limit, the system generates a warning in the form of a Telegram notification and a buzzer sound.

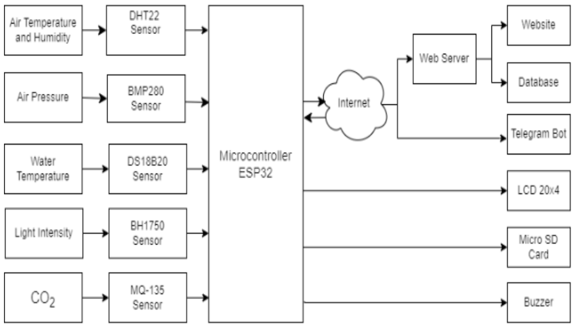

Figure 2. System Block Diagram

Microclimate Parameter Threshold Alerts

The Greenhouse microclimate monitoring system in this research utilises six parameters with three condition categories: lower alert, optimal range, and upper alert. Table 2 shows the thresholds and the parameters that influence them, which serve as a reference for the ESP32 in evaluating microclimate conditions and triggering Telegram notifications and the buzzer.

The threshold values in Table 2 are derived directly from the microclimate parameter ranges reviewed in the preceding subsection (Greenhouse Microclimate), each supported by the cited literature; the lower and upper alert boundaries were set at the lower and upper bounds of the optimal range reported in those sources.

Table 2. Microclimate Parameter Alert Thresholds for General Horticultural Crops

Parameter	Lower Alert	Optimal Range	Upper Alert
Air Temperature	< 24°C	24 - 35°C	> 35°C
Humidity	< 50%	50 - 80% RH	> 80%
Air Pressure	< 1000 hPa	1000 - 1020 hPa	> 1020 hPa
Light	< 10,000 lux	10,000 - 50,000 lux	> 50,000 lux
Water Temperature	< 18°C	18 - 30°C	> 30°C
CO_2	< 400 ppm	400 - 1000 ppm	> 1000 ppm

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System Flowchart

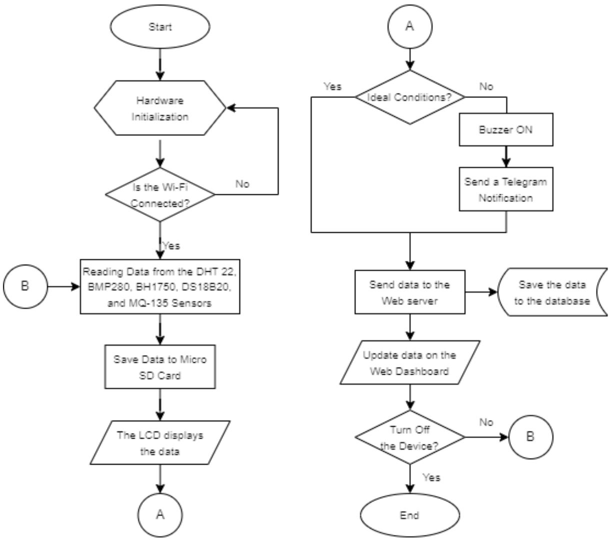

Figure 3. System Flowchart

Figure 3 is the system flowchart that explains how the designed device works. The monitoring process begins with hardware initialization and Wi-Fi connection by the ESP32, followed by reading the microclimate parameters using the DHT22, BMP280, BH1750, DS18B20, and MQ-135 sensors. The measurement results are stored locally on the MicroSD and displayed on the LCD, then compared with the predetermined threshold value. If a parameter is outside the ideal limit, the system activates the buzzer and sends a notification via Telegram. Subsequently, the data is sent to the web server, stored in the database, and displayed on the web dashboard for real-time monitoring. This process repeats continuously as long as the device remains operating.

System Working Principle

The overall working principle of the system is to place the prototype in the Greenhouse to observe six microclimate parameters using five sensors. Data from the sensors is processed by the ESP32 through an evaluation mechanism against the predetermined threshold, after which the processed data is displayed on the LCD and stored on the MicroSD Card as a backup medium. The system then sends the observation data through the Wi-Fi network to the web server to be stored in the database and displayed on the dashboard online. If a microclimate parameter exceeds the specified limit, the ESP32 activates the buzzer as a local warning and sends an HTTP request to the Telegram Bot API to send a notification to the user.

RESULTS AND DISCUSSION

This section discusses the results of sensor calibration/comparison, functional system testing, and field testing conducted at the research location.

System Implementation

During the system implementation phase, all components, both hardware and software were assembled, installed and integrated into a real-time Greenhouse microclimate monitoring system with a threshold alert mechanism.

Figure 4. Hardware Implementation

The DHT22, BMP280, and BH1750 sensors were placed in a Stevenson case, while the DS18B20 was placed on the hydroponic growing medium and the MQ-135 was installed in the box logger. The system is also equipped with a 20×4 LCD, buzzer, and MicroSD as the display, warning, and data storage media, so that the measurement, storage, and data transmission process can be carried out in real-time

Figure 5. Monitoring Website Display

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Figure 6. Telegram Bot Interface

Figures 5 and 6 show the results of the software implementation in the form of a monitoring website and a Telegram bot as system monitoring tools. The website displays microclimate parameter data in real time along with measurement history graphs, whilst the Telegram bot is used to display information on the Greenhouse's condition via the /status command and to send automatic warning notifications when measured parameters fall outside the predefined threshold limits.

Sensor Testing

Sensor testing was carried out by calibrating and comparing the measured values of each sensor against a traceable reference standard instrument at the BMKG Central Calibration Laboratory, Kemayoran. Temperature sensors (DHT22 and DS18B20) were calibrated using a Fluke-Hart Scientific 5627A thermometer at three set points (20°C, 30°C, and 40°C) inside a Kambic environmental chamber. The DHT22 humidity element was calibrated against a Vaisala HMT 333 digital thermohygrometer at three set points (40%, 50%, and 60% RH). The BMP280 pressure sensor was calibrated against a Vaisala PTB330 barometer using the Sequence C method, in which pressure was increased from 851 hPa to 1051 hPa across five set points (851, 900, 950, 1000, and 1051 hPa) and then decreased back to 851 hPa, allowing both an ascending (M1) and descending (M2) reading to be obtained at each point to check for hysteresis. The BH1750 light sensor was compared against an AS803 luxmeter under three natural lighting conditions (morning, midday, and afternoon), with five paired readings taken under each condition (n = 15 total comparisons). The MQ-135 gas sensor was compared continuously against a Picarro G2401 NDIR reference analyzer over a 50-hour monitoring period at Kemayoran Meteorological Station. Table 3 shows a summary of the sensor calibration results.

Table 3. Sensor Test Results

Sensor	Standard Instrument	Correction
DHT22 Temperature Sensor	Fluke-Hart 5627A	+0.22 °C
DHT22 Humidity Sensor	Vaisala HMT333	-10.29 %
BMP280 Sensor	Vaisala PTB330	-1.1 hPa
DS18B20 Sensor	Fluke-Hart 5627A	+0.29 °C
BH1750 Sensor	Luxmeter AS803	-0.65 %
MQ-135 Sensor	Picarro G2401	+1.77 ppm

Functional System Testing

Functional testing included testing of the LCD display, MicroSD storage, Website display, database, and threshold alert notifications on Telegram and the buzzer. The test results show that the 20x4 LCD successfully displayed all parameters in real-time and was updated according to the transmission interval, sensor data was successfully stored on the MicroSD in CSV format sequentially, the Website dashboard displayed data consistent with what was stored in the database, and the Telegram and buzzer notifications were consistently active every time a parameter exceeded the threshold, both in controlled testing and field conditions.

System Field Testing

Field testing of the system was carried out for 7 days (6-12 July 2026) in the KWT Mawar 8 Greenhouse on NFT Hydroponic Lettuce (Lactuca Sativa) with a data recording interval of every 5 minutes. Descriptive statistics of the microclimate parameters during the test are shown in Table 4.

Table 4. Statistics of Microclimate Parameters from the Field Test Results

Parameter	Minimum	Maximum	Average
Air Temperature (°C)	24.0	39.9	29.89
Humidity (%)	28.2	87.0	64.74
Air Pressure (hPa)	1007.4	1013.8	1011.10
Light (lux)	0	19396	2993.6
Water Temperature (°C)	24.0	36.9	28.73

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CO_2 (ppm)	438	475	454.2

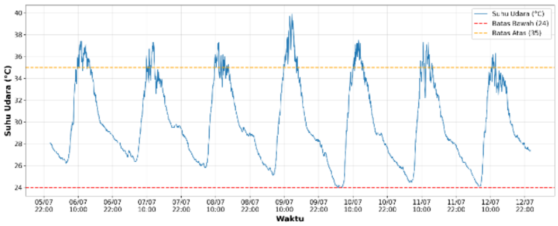

Figure 7. Air Temperature Graph During Testing

Air temperature showed a regular daily fluctuation pattern, rising from morning to midday and falling toward evening, with values of 24.0-39.9°C. Temperature exceeded the upper limit of 35°C during peak midday hours (12:00-14:00) for 11.8% of the test time (calculated as the proportion of 5-minute-interval logged readings during the 7-day test period in which the value exceeded the respective threshold). This condition has the potential to trigger heat stress in lettuce plants, increase excessive transpiration rates, and increase the risk of bolting, which reduces the quality of the consumed leaves.

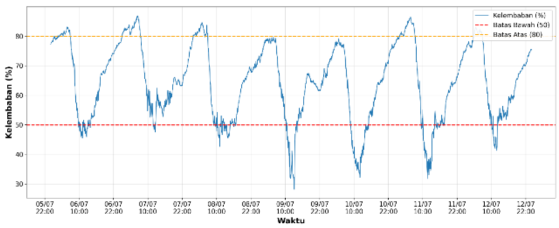

Figure 8. Humidity Graph During Testing

Humidity showed an inverse pattern to air temperature, with a range of 28.2-87.0%. Humidity was below the lower limit of 50% during the day (14.7% of the time) and above the upper limit of 80% at night/early morning (14.0% of the time). Low humidity increases the rate of water evaporation from the leaves, putting the plant at risk of wilting, while high humidity at night increases the risk of fungal diseases such as downy mildew and Botrytis.

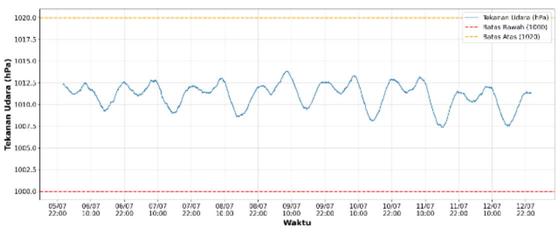

Figure 9. Air Pressure Graph During Testing

Air pressure was relatively stable throughout the test (1007.4-1013.8 hPa) and remained entirely within the ideal range of 1000-1020 hPa without ever exceeding the upper or lower limit, indicating a stable atmospheric condition that did not have a significant impact on the microclimate or plant growth.

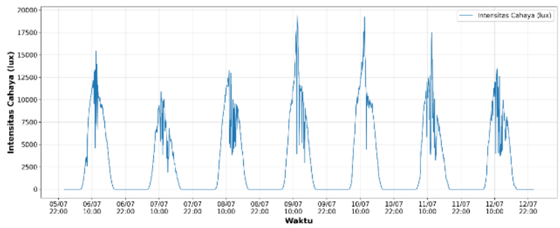

Figure 10. Light Intensity Graph During Testing

Sunlight was first detected at an average of 06:10 and ended at an average of 17:47, with an effective illumination duration of ±11.6 hours/day consistently over the 7 days, and an average peak at 10:00 (±11,499 lux). Nevertheless, the light intensity inside the Greenhouse was generally low relative to the ideal range, consistent with the characteristics of the UV plastic roof that dampens most of the solar radiation. This condition can inhibit the rate of photosynthesis and trigger etiolation if it continues over a long period.

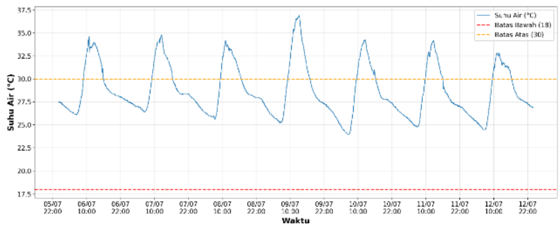

Figure 11. Water Temperature Graph During Testing

Water temperature showed a daily pattern following the air temperature trend with a smaller amplitude (24.0-36.9°C), exceeding the upper limit of 30°C from midday to evening for 29.1% of the test time, the highest proportion among the other parameters. Nutrient solution temperatures exceeding 30°C reduce dissolved oxygen solubility in the NFT solution, increase the risk of root rot due to Pythium sp., and reduce the efficiency of nutrient uptake by the roots.

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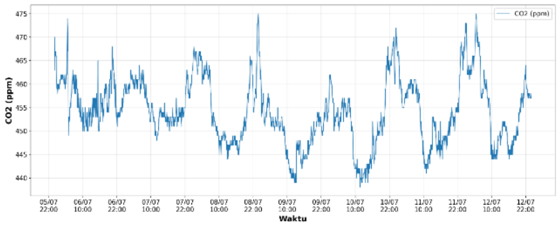

Figure 12. CO_2 Concentration Graph During Testing

CO_2 concentration was relatively stable in the range of 438-475 ppm throughout the test, remaining entirely within the ideal range of 400-1000 ppm, indicating that air circulation inside the Greenhouse was quite good without significant CO_2 accumulation or deficiency.

Discussion

Overall, the IoT-based microclimate monitoring system that was built has successfully achieved its main objective, namely monitoring the microclimate conditions of the hydroponic Greenhouse in real-time, accurately for most parameters. The system not only functions as a data logging tool but also successfully produces information that can be directly used for cultivation decision-making. The operational reliability of the system during field testing is shown in Table 5 and Figure 13.

Table 5. Operational Reliability of the System During Testing

Reliability Parameter	Value
Effective test duration	7 days
Logging interval	5 minutes
Expected number of data points	2,016
Actual number of data points	1,992
Data completeness	98.81%
Downtime events (>15 minutes)	0
Longest recording gap	7 minutes

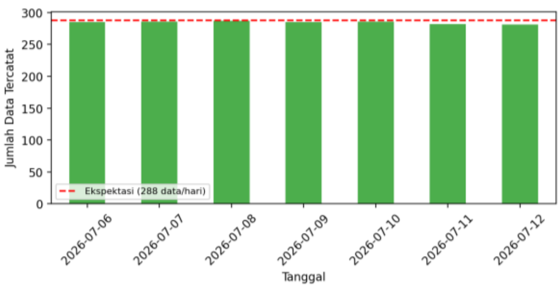

Figure 13. Daily Data Logging Completeness During Testing

The system successfully recorded 1,992 out of 2,016 expected data points (98.81%) without significant downtime, with the longest recording gap being only 7 minutes. This result shows that the data acquisition mechanism on the ESP32, including storage to the MicroSD and transmission to the web dashboard, ran reliably without significant failure during the seven consecutive days of operation under actual field conditions.

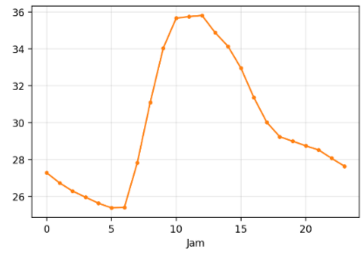

Figure 14. Diurnal Pattern Graph of Air Temperature

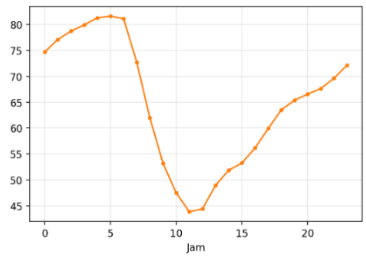

Figure 15. Diurnal Pattern Graph of Humidity

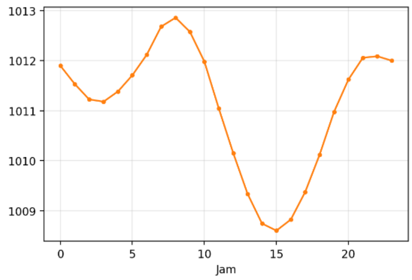

Figure 16. Diurnal Pattern Graph of Air Pressure

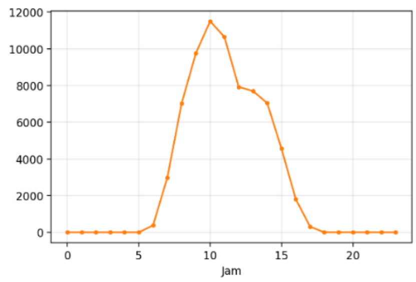

Figure 17. Diurnal Pattern Graph of Light Intensity

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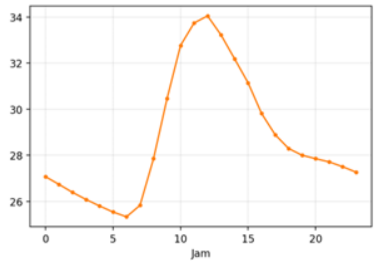

Figure 18. Diurnal Pattern Graph of Water Temperature

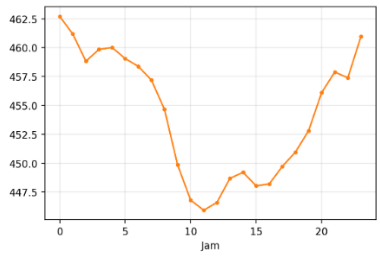

Figure 19. Diurnal Pattern Graph of CO_2 Concentration

The consistency of the diurnal pattern over the seven days of testing can be seen in the graph above (Figure 14). The graph shows that all sensors were able to capture the dynamics of the Greenhouse microclimate in a stable and repeatable manner, so the system is considered suitable for long-term monitoring.

CONCLUSIONS AND SUGGESTIONS

Conclusion

An IoT-based Greenhouse microclimate monitoring system with real-time notification and threshold alert has been successfully designed and implemented using an ESP32 integrated with the DHT22, BMP280, DS18B20, BH1750, and MQ-135 sensors. Calibration results show that most sensors have good accuracy, with errors below 1.2% against the standard instrument (BMP280 0.13%; BH1750 0.64%; DHT22 temperature 0.81%; DS18B20 0.97%), except for the DHT22 humidity sensor (error 20.77%) and the MQ-135 sensor, which shows low correlation (r = 0.400) due to the limited sensitivity of the semiconductor gas sensor.

The 7-day field test demonstrates high system operational reliability with 98.81% data completeness and no significant downtime, and successfully detected microclimate conditions outside the ideal range, particularly light intensity (90.7% of the time below 10,000 lux due to the UV plastic roof) and water temperature (29.1% of the time above 30°C). The threshold alert feature via Telegram and buzzer is proven to function properly in providing early warnings in real-time, both in controlled testing and actual operational field conditions.

Suggestion

Further development can be directed toward adding an automatic control system (closed-loop control) using actuators, an automatic calibration mechanism in the firmware, especially for the DHT22 (RH) and MQ-135 sensors, backup connectivity (GSM/LoRa) and backup power supply, a user-configurable threshold via the dashboard, predictive analytics capability, and multi-node sensor support for application at a larger Greenhouse scale.

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