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A dual-node ESP32-based cloud-synchronized multi-sensor monitoring platform for vertical greenhouse cultivation of *Brassica rapa subsp.* chinensis

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ABSTRACT

This study presents a cloud-synchronized dual-node ESP32-based multi-sensor monitoring platform for vertical greenhouse cultivation of *Brassica rapa subsp*. chinensis (pak choi). The proposed architecture consists of an ESP32-S3 sensing node and an ESP32-based LCD visualization node synchronized through firebase realtime database using HTTP communication. The sensing node monitored five environmental parameters (air temperature, relative humidity, nutrient solution temperature, nutrient concentration, and light intensity) together with DC and AC electrical parameters. The system was deployed in a four-tower vertical greenhouse for 28 days and generated more than 8,000 timestamped records at approximately 5-min intervals. Experimental results demonstrated stable cloud synchronization, reliable local visualization, and continuous monitoring of both environmental and electrical conditions. The monitored DC branch operated within 12.7–13.8 V with an average power consumption of 0.65 W, whereas the AC operational load ranged from 60.9 to 145 W with a mean power of 138 W. The proposed platform integrates distributed sensing, embedded visualization, and environmental–electrical monitoring within a single internet of things (IoT) framework, providing a practical and energy-aware solution for greenhouse monitoring and future smart agriculture applications.

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1. INTRODUCTION

The rapid growth of urban areas and the continuous decline of available agricultural land have created serious challenges for conventional food production [1]–[3]. To meet the increasing demand for fresh vegetables in a sustainable manner, alternative cultivation methods are required. Vertical greenhouse farming has emerged as a practical solution, allowing crops to be grown in stacked structures under controlled environmental conditions [3], [4]. Leafy vegetables such as *Brassica rapa subsp*. chinensis (pak choi) are particularly well suited for this approach due to their compact form, short growth cycle, and high economic and nutritional value [5], [6].

In vertical greenhouse systems, plant performance is highly dependent on microclimatic factors, including air temperature, relative humidity, light intensity, nutrient solution temperature, and nutrient

concentration [3]. Small deviations from optimal ranges can directly affect physiological processes and result in reduced growth and yield. In many small-scale greenhouse installations, these parameters are still monitored manually. Such practices are time-consuming, prone to human error, and unable to capture rapid environmental changes, making timely intervention difficult [4], [7]. The development of the internet of things (IoT) enables continuous environmental monitoring using low-cost sensors and embedded devices. Combined with cloud services such as firebase realtime database, sensor data can be stored, synchronized, and accessed remotely in real time, providing a lightweight infrastructure suitable for agricultural monitoring applications [7], [8].

This work proposes a cloud-synchronized dual-node ESP32-based multi-sensor monitoring platform for vertical greenhouse cultivation of *Brassica rapa subsp.* chinensis. The system employs a primary ESP32-S3 node for multi-parameter environmental and branch-level electrical sensing, while a secondary ESP32-based LCD node provides cloud-synchronized local visualization within the greenhouse environment. Unlike dashboard-centric greenhouse IoT implementations, the proposed architecture uses firebase realtime database as a lightweight cloud-mediated synchronization layer between embedded nodes, without requiring direct inter-device communication or a dedicated web application. A comparison of the proposed platform with representative existing greenhouse IoT monitoring systems is presented in Table 1. The comparison focuses on the monitoring scope, visualization interface, energy monitoring capability, and renewable energy integration.

Table 1. Comparison of existing greenhouse IoT monitoring systems and the proposed platform

Study	Architecture	Monitoring scope	Visualization interface	Energy monitoring	Renewable energy integration
Danita *et al.* [9]	Raspberry Pi 3 + IoT	Temperature, humidity, soil moisture + automatic climate control	Thingspeak cloud + Web Page	No	No
Heri *et al.* [10]	ATmega328 + Arduino WiFi Shield	Temperature, humidity, soil moisture, and light intensity monitoring with automatic fan, pump, and LED control	Web server (PC/smartphone)	No	No
Putri *et al.* [11]	ESP32 + IoT	Air temperature and humidity monitoring with automatic fan, misting, and shading net control	Blynk application	No	No
Seetaram *et al.* [12]	ESP32 + IoT	Temperature, humidity, and soil moisture monitoring with automatic water pump, cooling fan, exhaust fan, and LED control	Blynk mobile Application + LCD	No	No
Proposed system	Dual-node ESP32 + Firebase (IoT)	Environmental monitoring (temperature, humidity, water temperature, TDS, light intensity) and AC/DC electrical monitoring	Embedded LCD + Firebase realtime database	Yes	PV-battery supported

The main contributions of this work are as follows: i) the development of a dual-node ESP32-based distributed embedded sensing architecture that separates sensing and visualization while maintaining cloud-mediated synchronization; ii) the integration of environmental sensing with representative branch-level DC and AC electrical sensing within a single vertical greenhouse monitoring platform; iii) the implementation of a lightweight cloud-synchronized local visualization interface using an ESP32-LCD node without requiring direct inter-device communication or a dedicated web application; and iv) experimental validation of the proposed platform under practical off-grid vertical greenhouse deployment supported by a photovoltaic-battery subsystem.

2. SYSTEM ARCHITECTURE AND METHODOLOGY

The proposed system is a cloud-synchronized dual-node embedded monitoring platform for vertical greenhouse cultivation. It employs two ESP32-based nodes, in which sensing and visualization are functionally separated and synchronized through firebase realtime database. This distributed architecture follows recent IoT designs that decouple sensing and user interfaces via cloud mediation [13], [14].

Figure 1 illustrates the overall system architecture. The primary ESP32-S3 node acquires environmental and representative electrical data, whereas the secondary ESP32-based LCD node retrieves synchronized data from firebase realtime database for local visualization. The cloud database also enables passive monitoring from external devices without requiring direct inter-device communication.

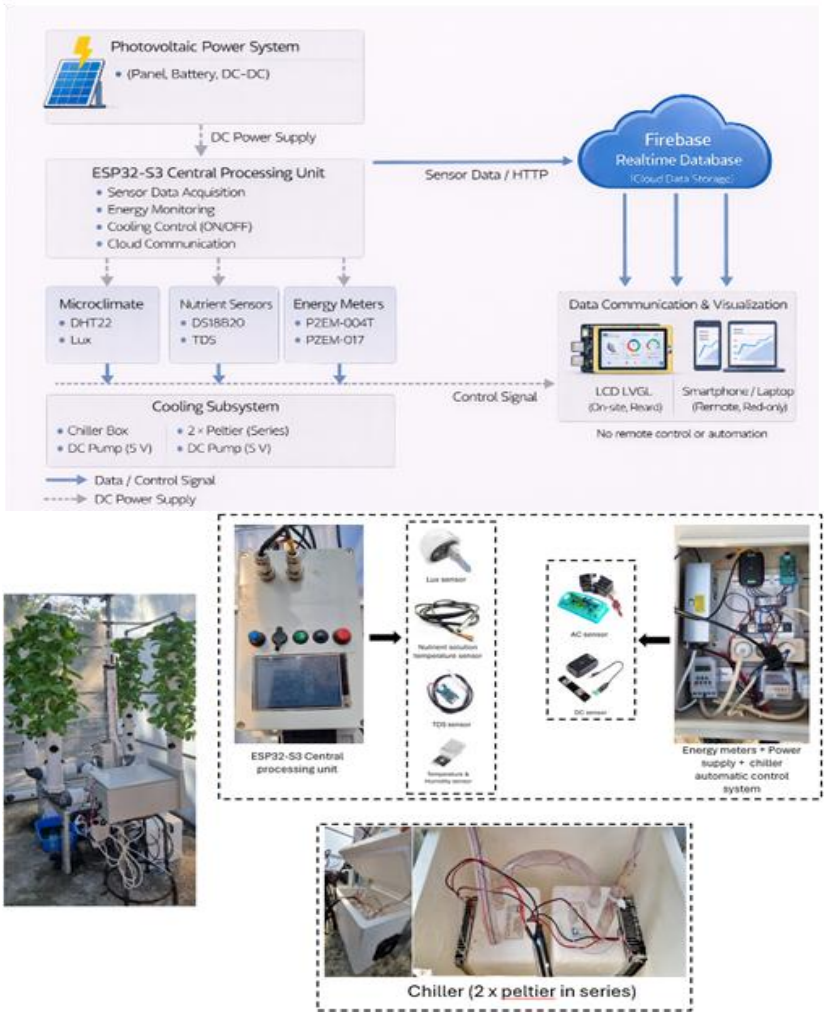


Figure 1. Overall architecture of the proposed cloud-synchronized dual-node monitoring platform

2.1. Hardware configuration

The sensor node is built around an ESP32-S3 microcontroller with integrated Wi-Fi and interfaces with multiple environmental and electrical sensors, including DHT22, DS18B20, gravity TDS, SEN0390, PZEM-017, and PZEM-004T. The complete hardware configuration is summarized in **Error! Reference source not found.**2. All sensors are interfaced with the ESP32-S3 through digital, analog, and serial interfaces. The microcontroller periodically acquires, preprocesses, and uploads sensor data to firebase realtime database [14], [15]. The visualization node consists of an ESP32-based TFT LCD running the LVGL graphical framework, which retrieves synchronized data from firebase for local display. This functional separation enables sensing and visualization to operate independently while remaining cloud-synchronized [16]. All sensors were configured according to the manufacturers' recommended procedures before deployment. The gravity TDS sensor was calibrated using a standard TDS solution, whereas the DHT22, DS18B20, SEN0390, PZEM-017, and PZEM-004T were verified using their factory calibration specifications.

Table 2. Hardware components of the proposed monitoring system

Component	Model/Type	Measured Parameter	Node
Microcontroller	ESP32-S3	–	Sensor node
Temperature & humidity sensor	DHT22	Air temperature, RH	Sensor node
Water temperature sensor	DS18B20	Nutrient solution temperature	Sensor node
Nutrient sensor	Gravity TDS	TDS (ppm)	Sensor node
Light sensor	SEN0390	Light intensity	Sensor node
DC energy meter	PZEM-017	DC voltage, current, power	Sensor node
AC energy meter	PZEM-004T	AC voltage, current, power, power factor	Sensor node
Display	TFT LCD + LVGL	Visualization	Display node

2.2. Communication and cloud integration

Data communication between the sensor node and the cloud is implemented using Wi-Fi and the HTTP REST API provided by firebase. Each measurement cycle produces a structured data packet containing timestamped sensor values. These data are uploaded to firebase realtime database, where they are stored in a hierarchical format [17]. Data transmission and visualization were intentionally configured as periodic cloud-synchronized updates rather than strict hard real-time streaming. Such a design is appropriate for greenhouse monitoring applications, where responsive periodic updates are generally sufficient for environmental observation and operator awareness.

The sensor node periodically uploads timestamped measurements to firebase realtime database throughout the cultivation period, enabling cloud-based synchronization and historical data storage for monitoring and analysis. The visualization node periodically queries firebase to obtain the most recent dataset. Upon reception, the data are parsed and mapped to graphical elements on the LCD, such as numeric indicators and dynamic bars. This mechanism enables periodic cloud-mediated synchronization between the sensing process and local visualization without requiring direct wired or wireless communication between the two ESP32 devices, following cloud-mediated IoT architectures reported in the literature [11], [14]. External devices such as smartphones and personal computers may also access the cloud-stored data for observation purposes. No dedicated web application or remote-control functionality is implemented.

2.3. Power system

To ensure autonomous operation, the proposed monitoring system is supported by a standalone photovoltaic subsystem consisting of a solar panel and battery storage. Within this power architecture, the PZEM-017 module monitors the low-power DC branch supplied by the photovoltaic-battery subsystem, including the embedded sensing, communication, and local display components, while the PZEM-004T monitors the principal AC operational load branch associated with nutrient cooling and hydroponic circulation. Similar energy-aware designs have been shown to improve sustainability in greenhouse IoT systems, underscoring the importance of efficient energy management in sustainable practices [18]. This configuration enables simultaneous observation of environmental conditions and representative electrical behavior on both the low-power embedded branch and the principal operational load branch, providing insight into the practical energy profile of vertical greenhouse operation and supporting more informed resource allocation [18].

2.4. Experimental deployment

The system was deployed in a multi-level vertical greenhouse cultivating *Brassica rapa subsp*. chinensis (pak choi) over a 28-day cultivation cycle. The cultivation setup consisted of four vertical towers, with approximately 10 plants per tower, representing a practical small-scale vertical greenhouse configuration. The sensor node was positioned near the plant canopy and nutrient reservoir to capture representative environmental conditions, in accordance with placement considerations commonly adopted in greenhouse monitoring studies [18], [19]. The visualization node was installed inside the greenhouse for on-site observation of cloud-synchronized measurements. Sensor data were collected continuously to evaluate sensing, cloud synchronization, and local visualization performance under practical operating conditions. The deployment generated more than 8,000 timestamped observations at approximately 5-min intervals, providing sufficient temporal resolution for greenhouse monitoring and trend analysis.

2.5. Data processing and derived electrical parameters

To improve the interpretability of the monitored environmental and electrical variables, temperature-compensated nutrient concentration estimation and representative electrical parameter calculations were implemented. The gravity TDS sensor output was temperature-compensated using the nutrient solution temperature measured by the DS18B20 sensor. The temperature compensation factor was calculated as:

$$C_f = 1 + 0.02(T_w - 25) \quad (1)$$

where C_f is the temperature compensation factor and Tw is the nutrient solution temperature (°C).
The compensated sensor voltage was then calculated as

$$V_c = \frac{V_m}{C_f} \quad (2)$$

where V_m is the measured sensor voltage (V) and V_c is the temperature-compensated voltage (V). The compensated voltage was subsequently converted into TDS concentration using the manufacturer-

recommended third-order polynomial model [20]

$$TDS = 0.5(133.42V_c^3 - 255.86V_c^2 + 857.39V_c) \quad (3)$$

where TDS is the estimated nutrient concentration (ppm). This procedure improves the consistency of nutrient concentration estimation under varying greenhouse conditions. For the low-power DC branch monitored by the PZEM-017 module, the instantaneous DC power was estimated as

$$P_{DC} = V_{DC} I_{DC} \quad (4)$$

where PDC is the DC power (W), VDC is the measured DC voltage (V), and IDC is the measured DC current (A). For the AC branch monitored by the PZEM-004T module, the active power was obtained directly from the sensor module, while the apparent power was calculated as

$$S = V_{AC} I_{AC} \quad (5)$$

where S is the apparent power (VA), VAC is the measured AC voltage (V), and IAC is the measured AC current (A). The power factor of the monitored AC load was determined as

$$PF = \frac{P_{AC}}{S} \quad (6)$$

where PF is the power factor and PAC is the measured active power (W).

Descriptive statistics (minimum, maximum, and mean) were calculated to summarize representative environmental and electrical operating conditions throughout the deployment period. Calibration coefficients of the TDS sensor were stored in non-volatile EEPROM memory to preserve settings after power interruptions, thereby improving long-term operational consistency and reducing recalibration requirements.

3. RESULTS AND DISCUSSION

3.1. System operation and data acquisition performance

The proposed platform was evaluated through continuous operation in a vertical greenhouse cultivating *Brassica rapa subsp*. chinensis. During deployment, environmental and electrical measurements were acquired by the sensing node, synchronized through firebase realtime database, and retrieved by the visualization node. The dual-node architecture functioned as intended, enabling independent sensing and visualization processes without interfering with data acquisition and transmission [21].

3.2. Environmental monitoring and nutrient solution cooling performance

Representative environmental measurements are presented in

Figure 22 and

Figure 3. Air temperature and relative humidity exhibited the expected diurnal variations typical of greenhouse environments, whereas the nutrient solution temperature remained comparatively stable during daytime operation. To moderate daytime temperature increases, a timer-based thermoelectric cooling subsystem operated daily from 06:00 to 18:00 with a 5 min ON/1 min OFF cycle. Although no non-cooled control was included, the relatively stable nutrient temperature profile suggests that the cooling strategy helped limit excessive daytime temperature increases under the monitored operating conditions. Continuous monitoring also enabled the detection of short-term environmental fluctuations that would be difficult to capture through manual observations, supporting more effective greenhouse management [22]–[24].

Error! Reference source not found.3 summarizes the environmental conditions recorded during the 28-day deployment. The monitored variables exhibited the expected greenhouse diurnal variations, while the nutrient solution temperature remained relatively stable under timer-based cooling. Overall, the results confirm that the proposed platform continuously monitored environmental conditions throughout the cultivation period.

Table 3. Summary of environmental and nutrient monitoring parameters

Parameter	Unit	Min	Max	Mean
Air temperature	°C	22.2	41.1	29.67
Relative humidity	%	43.5	100	77.99

Light intensity	lux	0.06	91,771.41	11,585.84
Nutrient solution temperature	°C	18.22	34.94	27.27
Nutrient concentration (TDS)	ppm	900.2	1,842.52	1,221.02

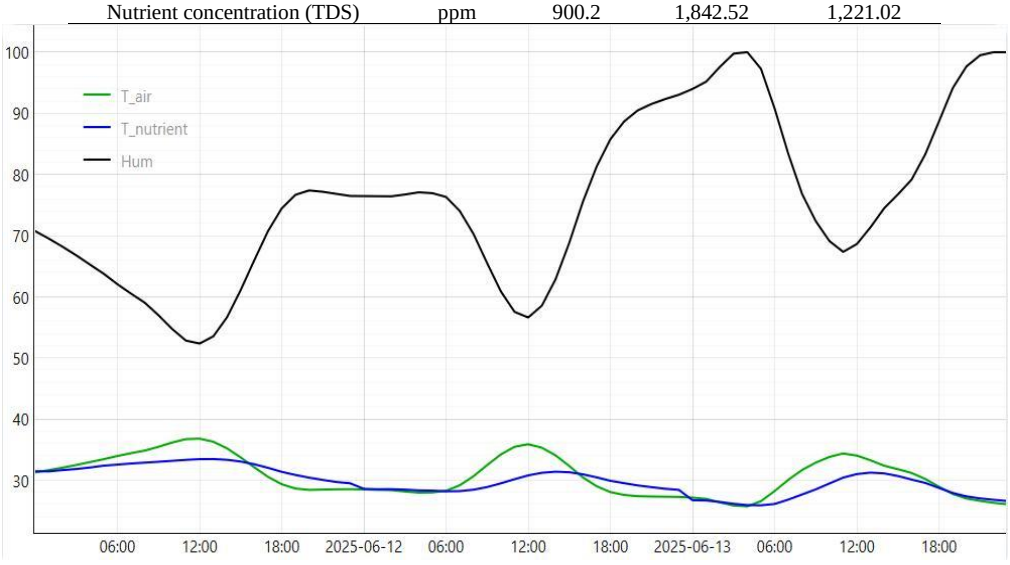


Figure 2. Representative time-series of air temperature, relative humidity, and nutrient temperature

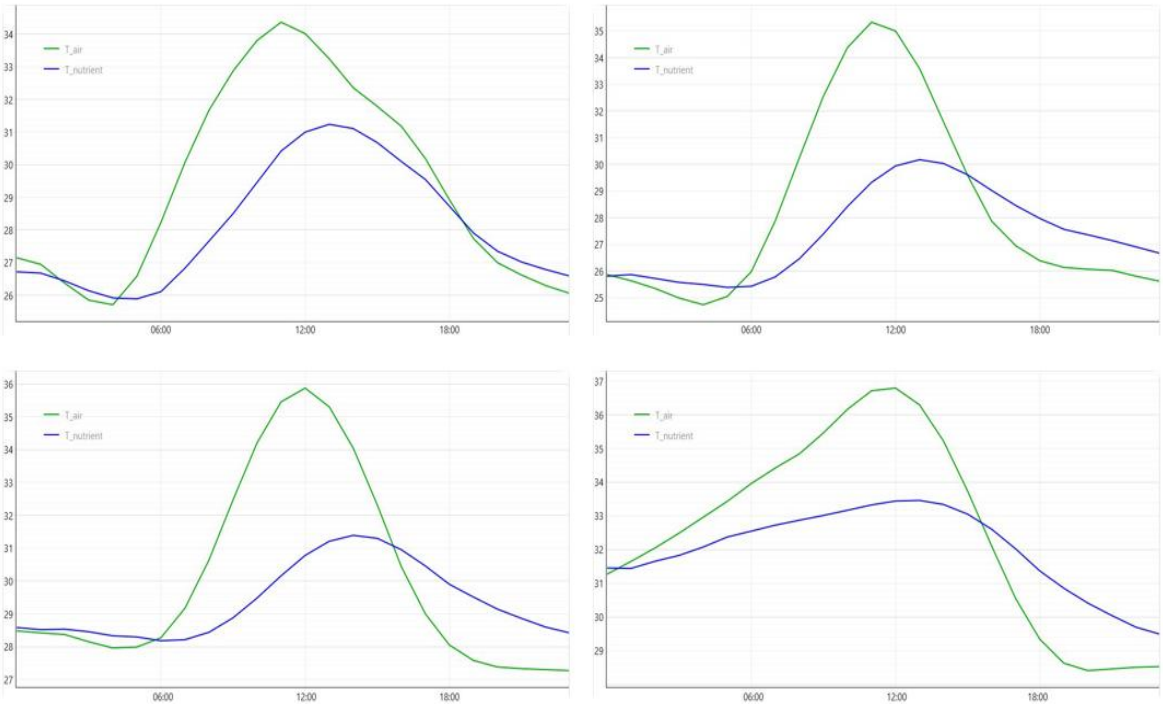
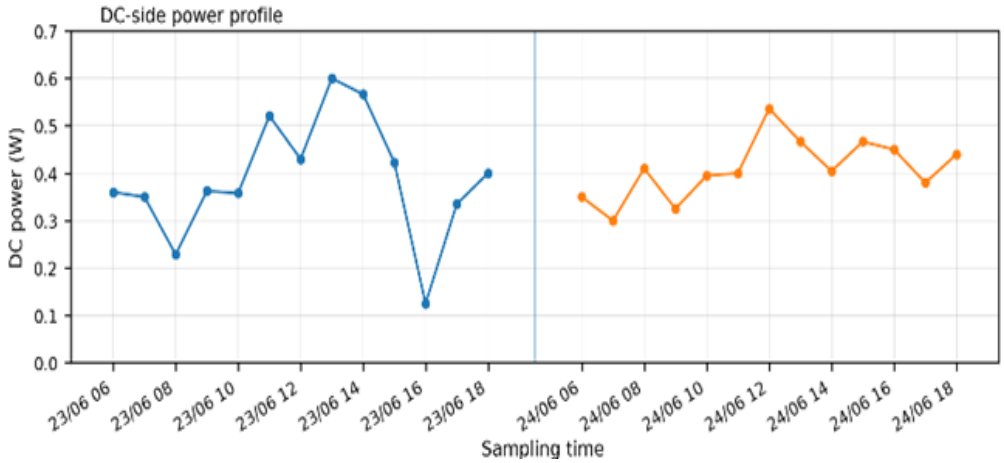


Figure 3. Nutrient solution temperature during daytime operation (06:00–18:00) with timer-based thermoelectric cooling

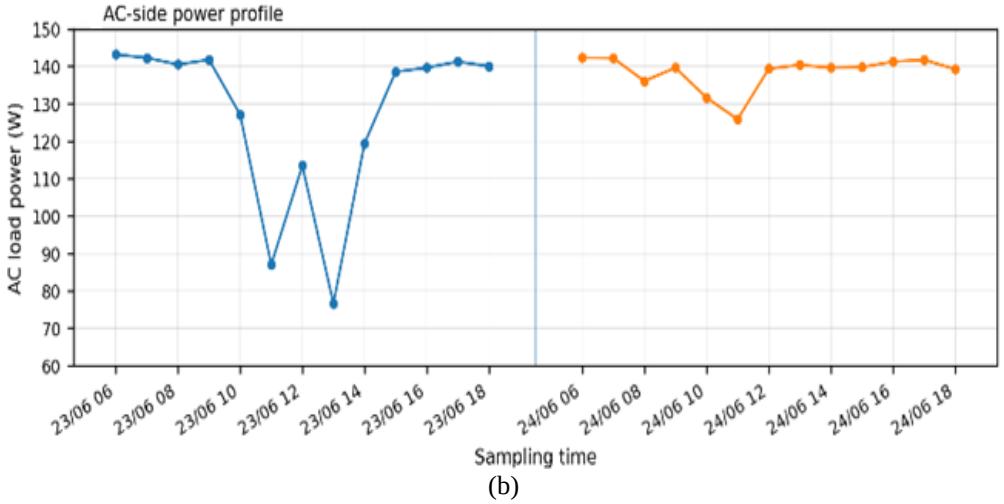
3.3. Representative electrical performance of the monitored system

In addition to environmental conditions, the system continuously monitored electrical energy usage from both DC and AC branches. The DC-side variables were measured using the PZEM-017 module, which recorded voltage, current, and power for the low-power branch supplied by the photovoltaic-battery subsystem. Meanwhile, AC-side electrical parameters, including voltage, current, power, and power factor, were monitored using the PZEM-004T module to characterize the principal operational loads of the hydroponic system.

These results demonstrate the capability of the proposed platform to simultaneously monitor low-power embedded loads and higher-demand greenhouse operational loads, providing an energy-aware perspective for greenhouse management [25]–[27]. As shown in Figure 4 and summarized in Table 4, the monitored electrical behavior clearly distinguished the low-power DC monitoring branch from the higher-demand AC operational branch. Figure 4(a) shows the DC power profile, while Figure 4(b) shows the AC power profile. The DC branch maintained a stable operating voltage close to the nominal 12 V level (mean: 13.0 V) with a low average power consumption of 0.65 W, reflecting the continuous operation of the ESP32-based sensing node, communication module, local LCD display, and auxiliary DC fan supplied by the photovoltaic-battery subsystem. In contrast, the AC branch operated at a mean voltage of 231 V with an average power demand of 138 W, representing the principal operational loads of the greenhouse, including the thermoelectric nutrient cooling subsystem and nutrient circulation equipment. These findings demonstrate that the proposed platform can simultaneously monitor representative electrical characteristics of both the embedded monitoring devices and the primary greenhouse loads, providing useful energy-awareness for practical greenhouse operation.



(a)



(b)

Figure 4. Representative daytime power profiles of the monitored system: (a) DC branch and (b) AC branch

Table 4. Summary of representative electrical parameters during system operation

Parameter	Sensor	Unit	Min	Max	Mean
DC voltage	PZEM-017	V	12.7	13.8	13
DC current	PZEM-017	A	0.02	0.09	0.05
DC power	PZEM-017	W	0.2	1.1	0.65
AC voltage	PZEM-004T	V	218	237	231
AC current	PZEM-004T	A	0.41	0.94	0.89

AC load power	PZEM-004T	W	60.9	145	138
AC power factor	PZEM-004T	–	0.56	0.71	0.67

3.4. Descriptive plant growth performance under monitored and cooled conditions

To complement the environmental and electrical monitoring results, representative plant growth observations were recorded during the cultivation period under the monitored greenhouse conditions. Since the primary objective of this study was the development and validation of the proposed IoT-based monitoring platform, these measurements are presented only as supporting agronomic observations rather than as a comparative treatment analysis. As summarized in Table 5, pak choi cultivated across the four vertical towers achieved average plant heights of 20.77–23.08 cm, produced 13.9–15.6 leaves plant^{-1}, developed canopy areas of 98.66–129.96 cm², and reached root lengths of 14.18–16.95 cm. Although no statistical comparison among towers was performed, the recorded growth parameters indicate consistent vegetative development under the monitored greenhouse conditions, demonstrating that the proposed monitoring platform supported practical crop cultivation throughout the 28-day deployment.

Table 5. Summary of final vegetative growth parameters of pak choi under monitored and cooled vertical greenhouse cultivation

Tower	Plant height (cm)	Number of leaves	Canopy area (cm²)	Root length (cm)
A	23.08	15.6	106.24	16.95
B	21.97	15.1	102.33	16.42
C	20.77	13.9	98.66	16.16
D	21.58	14.9	129.96	14.18

3.5. Performance of cloud-based visualization

The visualization node, consisting of an ESP32 microcontroller and an LCD driven by the LVGL graphical framework, successfully retrieved the most recent sensor data from the firebase realtime database and displayed them locally inside the greenhouse. This interface served as the primary human–machine interaction-point for on-site observation. Unlike many IoT greenhouse platforms that rely on web-based dashboards as the main user interface [14], [28], [29] the proposed system avoids the need for a dedicated web application or server infrastructure. This design choice reduces system complexity and simplifies deployment, making it particularly suitable for environments with limited technical resources. Although smartphones and personal computers were able to access the same cloud-stored data, these devices were used only for observation purposes. No remote control or automation functionality was implemented, in line with the monitoring-oriented objective of this study.

3.6. Discussion

The experimental results demonstrate that the proposed cloud-synchronized dual-node monitoring platform provides reliable distributed sensing and local visualization for vertical greenhouse applications. By separating sensing and visualization into two independent ESP32 nodes synchronized through firebase realtime database, the proposed architecture minimizes functional coupling between sensor acquisition, wireless communication, and graphical rendering while eliminating direct inter-device communication. This architectural separation contributes to stable cloud-mediated monitoring in resource-constrained embedded systems [14].

Compared with previous greenhouse IoT systems employing Raspberry Pi, Arduino, or ESP32 platforms for environmental monitoring and automation [11], [12], the proposed platform additionally integrates representative AC/DC electrical monitoring within a cloud-synchronized embedded architecture. This combined sensing capability extends conventional greenhouse monitoring by providing operational insight into both environmental conditions and electrical behavior, making the system particularly suitable for photovoltaic-supported and energy-constrained greenhouse applications [21]. The 28-day deployment confirmed stable cloud synchronization and continuous acquisition of more than 8,000 timestamped observations. firebase realtime database successfully served as a lightweight synchronization layer between the sensing and visualization nodes without requiring dedicated server infrastructure or web-based dashboards. Throughout the deployment period, no manual restart or reconfiguration of either ESP32 node was required, indicating stable long-term operation under practical greenhouse conditions. These findings demonstrate the feasibility of lightweight cloud-mediated synchronization for embedded agricultural monitoring and provide a practical foundation for future intelligent greenhouse management and feedback-based control [30], [31].

Several limitations should be acknowledged. Quantitative communication metrics, including synchronization latency, packet loss, and communication reliability, were not experimentally evaluated

because the primary objective of this study was the development and practical validation of a cloud-synchronized monitoring platform rather than communication benchmarking. In addition, long-term statistical evaluation of sensor accuracy and comparative benchmarking against alternative synchronization architectures were beyond the scope of this work. Plant growth observations were also presented only as supporting evidence of practical deployment rather than as a controlled agronomic experiment. Nevertheless, these limitations do not diminish the primary contribution of this work, namely the development, integration, and practical validation of a cloud-synchronized multi-sensor embedded monitoring platform for greenhouse applications.

4. CONCLUSION

This study presented the design and practical deployment of a cloud-synchronized dual-node ESP32-based multi-sensor monitoring platform for vertical greenhouse cultivation of *Brassica rapa subsp*. chinensis. The proposed system was implemented as a distributed embedded sensing architecture in which environmental and representative electrical measurements were acquired by a primary ESP32-S3 sensing node and periodically transmitted through firebase realtime database to a secondary ESP32-based LCD visualization node.

Experimental deployment over a 28-day cultivation cycle demonstrated continuous multi-sensor data acquisition, practical cloud-mediated data synchronization, local real-time visualization, and simultaneous monitoring of both environmental conditions and representative electrical behavior from the low-power DC branch and the principal AC operational load branch. The deployment generated more than 8,000 timestamped environmental and electrical observations, indicating the capability of the proposed platform to support long-term greenhouse monitoring under practical operating conditions. Compared with conventional greenhouse IoT implementations that primarily emphasize environmental monitoring and dashboard-based visualization, the proposed platform integrates environmental sensing, branch-level electrical monitoring, cloud-mediated synchronization, and embedded local visualization within a single distributed architecture.

This combination provides a practical and energy-aware monitoring framework that is particularly suitable for small-scale and off-grid greenhouse applications. Future work will focus on quantitative communication performance evaluation, long-term sensor stability assessment, comparative benchmarking with alternative synchronization architectures, and the integration of feedback-based control and edge-level analytics to further enhance system intelligence and operational autonomy.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are available from the corresponding author, O. Saputra, upon reasonable request.

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