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ESP-NOW based multi-node internet of things system for agricultural solar dryers with hybrid offline-online monitoring

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ABSTRACT

Existing internet of things (IoT) systems for agricultural solar dryers rely on continuous internet connectivity, limiting deployment in remote rural areas with unreliable infrastructure. This study develops and validates a multi-node IoT architecture using ESP-NOW peer-to-peer communication that enables infrastructure-independent operation with optional ThingSpeak cloud synchronization. The system integrates ESP32 nodes, SHT41 sensors, relay-controlled actuators, and a hybrid solar-battery-grid power supply, deployed at a cocoa processing facility in South Sulawesi, Indonesia. Field evaluation confirmed: >95% packet delivery at 50 m, <10 ms latency, 94.3% cloud synchronization reliability, and 96% upload timing precision within ±2 s (σ=0.96 s). The dual-mode architecture sustained continuous local monitoring and actuator control during all network outages, with autonomous cloud reconnection requiring no manual intervention. Drying trials showed a 40–57% reduction in cocoa drying duration (3–4 days vs. 5–7 days baseline) through automated chamber control (40–60 °C; RH <60%). Energy analysis yielded an intensity of 0.12–0.17 kWh/kg dried output, with the IoT subsystem consuming less than 1% of total drying energy. The validated architecture provides a deployable, offline-capable, and energy-efficient solution for post-harvest monitoring in infrastructure-constrained environments, with applicability to diverse crop drying and storage scenarios.

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1. INTRODUCTION

Post-harvest management of agricultural products remains a critical challenge in developing countries, particularly in regions with unreliable power grids and inadequate internet infrastructure [1], [2]. Traditional open-sun drying methods are highly susceptible to weather variability, resulting in inconsistent product quality and significant post-harvest losses [3]. Solar drying systems offer a more controlled and eco-friendly alternative; however, their full potential is realized only when augmented with automated monitoring and control mechanisms [4], [5].

Advances in internet of things (IoT) technology have enabled sophisticated precision agriculture systems capable of real-time environmental monitoring and autonomous control [6]. However, the vast majority of existing IoT-based agricultural solutions depend on continuous internet connectivity, which severely limits their applicability in remote rural areas where network infrastructure is unreliable or absent [7]. This connectivity dependency creates a critical deployment gap, particularly in developing regions where smart farming solutions are most urgently needed [8], [9].

Industrial IoT deployments have increasingly adopted edge computing and local data buffering to mitigate connectivity interruptions [10], [11]. Agricultural contexts, however, impose distinct constraints: cost sensitivity, energy efficiency, scalability, and user-friendly interfaces operable by non-technical farmers [12], [13]. Furthermore, the spatially distributed nature of farming necessitates multi-node architectures capable of maintaining synchronization during network outages [14]. Despite these recognized needs, existing IoT solar dryer systems such as those reviewed by Kumar *et al.* [15] and Sharma *et al.* [16] either rely on continuous cloud connectivity or implement single-node monitoring without peer-to-peer redundancy. While recent literature features various ESP32-based agricultural monitoring solutions, the majority utilize ESP-NOW solely as a simple wire-replacement strategy without integrating automated cloud failover or actuator synchronization. None of the existing systems simultaneously address true infrastructure independence, autonomous multi-node synchronization, and continuous hybrid offline-online operation within a low-cost embedded framework suitable for smallholder farming contexts. This gap motivates the present work.

To address these gaps, this study proposes and validates a multi-node IoT architecture for agricultural solar dryers in infrastructure-constrained environments. The system targets three measurable technical objectives: i) achieving greater than 95% wireless packet delivery using ESP-NOW peer-to-peer communication without WiFi infrastructure; ii) maintaining continuous monitoring and control during internet outages with seamless automatic cloud reconnection; and iii) sustaining uninterrupted 24-hour operation via a hybrid solar-battery-grid power system. The architecture integrates ESP-NOW for inter-node communication, embedded local web servers for offline access, ThingSpeak-based cloud connectivity, and relay-controlled actuators for thermal management.

The proposed system was deployed and field-evaluated at an operational cocoa processing facility in South Sulawesi, Indonesia, under actual agricultural conditions. Results confirm the system capability to maintain continuous operation across varying network conditions, with reliable environmental monitoring and automated actuator control regardless of internet availability [17]. The dual-mode architecture ensures critical drying data remains accessible at all times, while the scalable multi-node design allows straightforward expansion as operational requirements evolve [18], [19].

2. RESEARCH METHOD

2.1. System architecture overview

The proposed multi-node IoT architecture consists of three primary layers: the sensing layer, the communication layer, and the application layer. The complete system architecture is shown in Figure 1, which shows how all the parts fit together. The sensing layer is made up of sensor nodes that are spread out, and each has an SHT41 temperature and humidity sensor. They can also process data on their own. The communication layer uses a mixed networking strategy that uses WiFi for internet access and the ESP-NOW protocol for communication between nodes. There are two ways to monitor the application layer: a built-in web server for local access and a cloud-based platform for remote access.

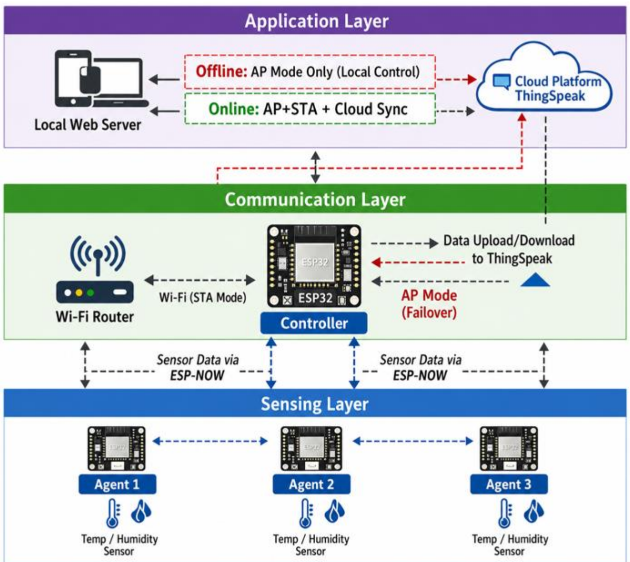
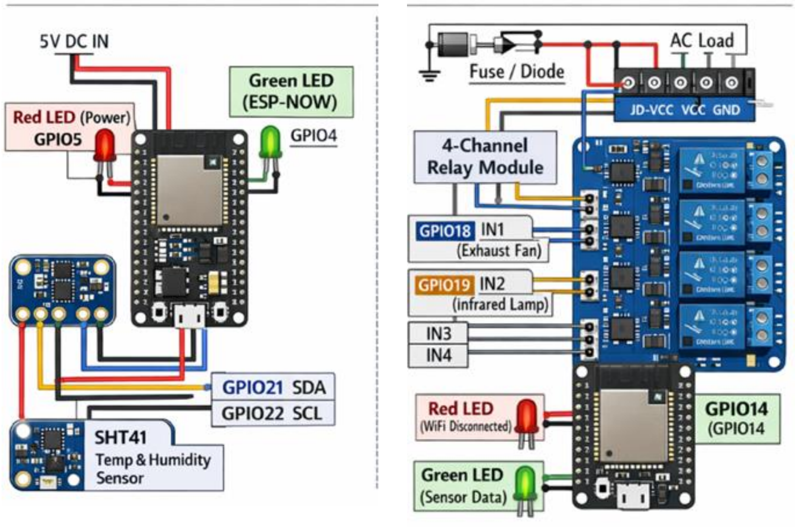


Figure 1. Multi-node IoT system architecture

Based on Figure 1, each sensor node has a dual-mode WiFi setup (AP+STA mode), which means it can do two things: it can act as an access point for direct local connections and a station that tries to connect to existing WiFi networks. This setup is very important because it makes sure that people can always access the site from their own computers, even if the internet goes down. The central controller node is in charge of the primary operations of the system. It collects data from sensors, controls actuators like infrared heaters and exhaust fans, and makes sure that data is synced with cloud services whenever a reliable connection is made.

Figure 2 illustrates the hardware configuration of the proposed multi-node IoT system, consisting of an agent node and a controller node. Specifically, Figure 2(a) depicts the agent node, which integrates an SHT41 temperature and humidity sensor, an ESP32 microcontroller, and LED status indicators for visual feedback on communication state. Figure 2(b) shows the controller node, which houses the ESP32 central processor, a 4-channel relay module for actuator switching, and the power management circuit responsible for distributing energy from the hybrid solar-battery-grid supply to the system loads.

The agent node is responsible for sensing environmental parameters using the SHT41 temperature and humidity sensor, while the controller node manages data aggregation, communication, and actuator control through a relay-based interface. To provide a clearer overview of the system implementation, Table 1 summarizes the main hardware components used in the proposed system along with their key specifications.



(a) (b)

Figure 2. Hardware configuration diagram; (a) agent node with SHT41 sensor, ESP32, and LED indicators and (b) controller node with ESP32, 4-channel relay module, and power management circuit

Table 1. Main hardware components and specifications of the proposed system

Component	Specification
Microcontroller	ESP32 dual-core 240 MHz, WiFi/BLE
Temperature sensor	SHT41, ±0.2 °C accuracy, I2C interface
Infrared heater	6 units Philips incandescent 150 W each
Solar panel	4×665 Wp (2660 Wp total capacity)
Battery storage	2×200 Ah (400 Ah total capacity)
Inverter	Hybrid inverter with grid connection

2.2. Multinode communication protocol

The ESP-NOW protocol is a key part of how the architecture's nodes talk to each other. Espressif made this protocol for direct WiFi communication, which lets one ESP32 device talk to another without needing to connect to a regular WiFi router. This method has a number of clear benefits over standard WiFi-based IoT setups.

These include low latency, less power use, a much easier network setup, and the most important feature: the ability to keep working even when there is no internet connection. Figure 3 illustrates the complete communication flowchart showing the ESP-NOW packet transmission and reception process.

Every 4 seconds, each sensor node sends data packets that include information about temperature, humidity, and the sensor's status. The data structure is a C struct that is always the same size (9 bytes total: 4 bytes for the float temperature, 4 bytes for the float humidity, and 1 byte for the boolean sensor status). This ensures that packets are consistently formatted in the same way and that memory is used efficiently. The 4 seconds transmission interval strikes a good balance between receiving data updates quickly and conserving power. To handle incoming ESP-NOW packets, the controller node registers a callback function called OnDataRecv. This function extracts sensor data and updates the system state simultaneously to prevent race conditions.

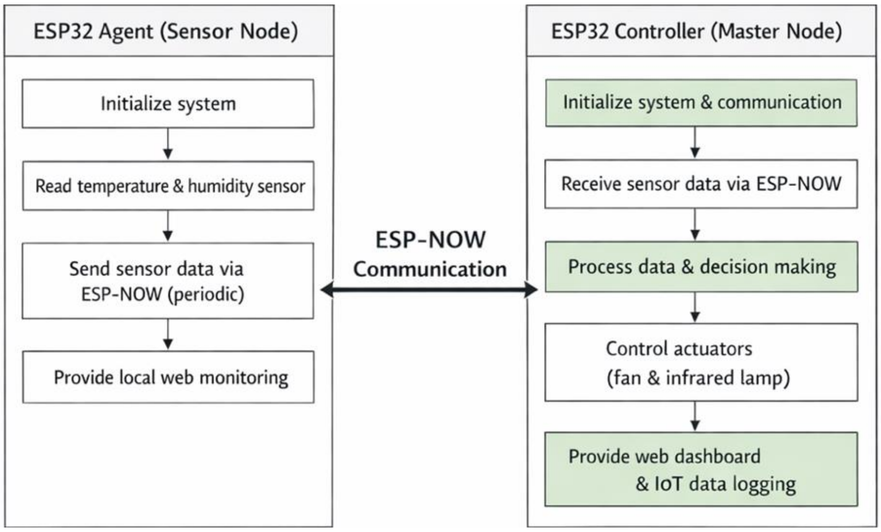


Figure 3. Multinode communication protocol for smart solar dryer system

To ensure the system's reliability, data validation is performed at multiple levels. The controller will not accept packets with temperature values that are too low (below -40 °C or above 85 °C, as the SHT41) or humidity values that are too high (above 100% RH). The sensor_ok boolean flag also provides the system with clear information about the sensor node's validation status, allowing the system to distinguish between valid low readings and sensor problems.

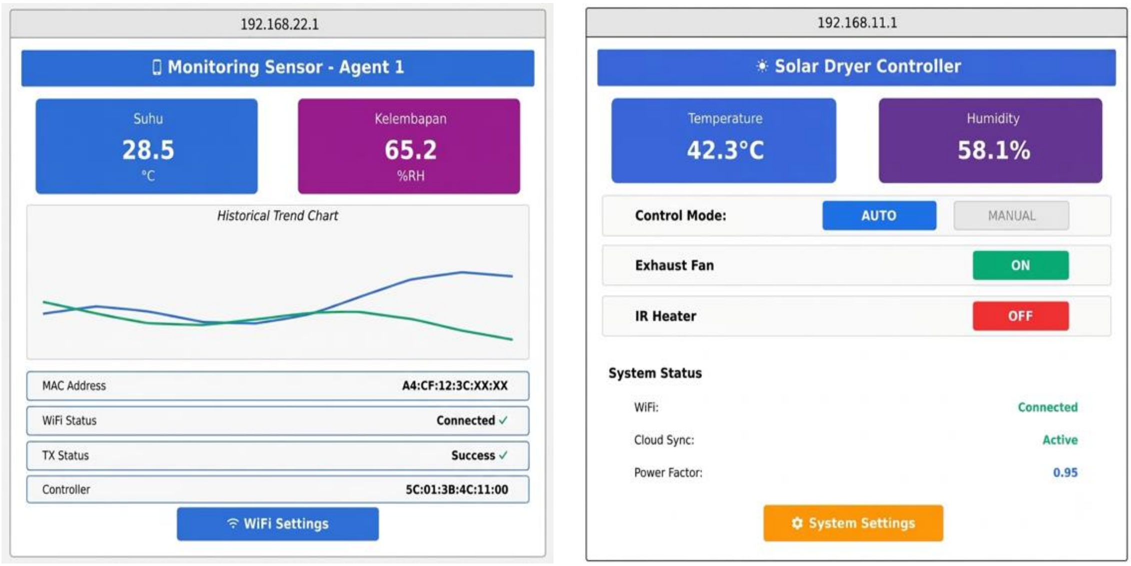
The system uses a star network topology, with the controller as the central node and sensor agents as peripheral nodes. Each sensor node is set up with the controller's MAC address (stored as const uint8_t controllerMac[]), which makes it possible to send data directly to the controller. The controller maintains a list of registered sensor nodes that can communicate with each other, but it does not require bidirectional communication between them. This makes network management easier and reduces communication overhead. LED lights show the status of communication. For example, the green LED lights up for 800 milliseconds when a packet is sent successfully. The red LED shows the system's power status, so operators can quickly check that the system is working without having to go to the web interface.

Regarding security of the ESP-NOW communication layer: by default, ESP-NOW transmits data as plaintext, exposing the system to potential eavesdropping or packet injection within radio range. The current implementation mitigates this through MAC address filtering at the controller node, restricting transmissions to pre-registered sensor nodes only. Application-layer data validation (temperature: -40 to 85 degrees C; humidity: 0-100%; sensor status flags) provides an additional integrity layer. While sufficient for the current low-risk agricultural monitoring context, future commercial deployments should consider AES-128 encryption at the application layer, natively supported by the ESP32 hardware security module, together with periodic MAC address rotation to reduce the attack surface.

2.3. Dual-mode monitoring system

The proposed system adopts a hybrid monitoring approach that integrates locally hosted embedded web servers with cloud-enabled remote connectivity. Each ESP32 device operates its own internal web server, which can be accessed directly through the node’s access point IP address. In this configuration, the sensor nodes are reachable at 192.168.22.1, whereas the central controller is assigned the address 192.168.11.1. The user interface is developed as a responsive single-page web application, allowing consistent access and usability across various platforms, including desktop computers, tablets, and smartphones. The overall interface layout for both sensor agents and the controller is illustrated in Figure 4.

Specifically, Figure 4(a) illustrates the agent node's local dashboard, which displays real-time temperature and humidity metrics directly sourced from the connected SHT41 sensor. This specific view allows field operators to verify individual sensor calibration directly on-site visually. Conversely, Figure 4(b) presents the controller node interface, providing an aggregated master view of all connected sensor agents, along with manual toggle controls for the system's actuators (exhaust fans and infrared heaters). This separation of interfaces ensures that operators can execute immediate manual overrides securely from the master controller node without needing to access individual sensing endpoints.



(a) (b)

Figure 4. Web interface design; (a) agent node local dashboard displaying real-time sensor metrics and (b) controller node interface showing aggregated data and actuator status

At the node side, the embedded web server is mainly used to display environmental conditions directly from the device [20]–[22]. Temperature and humidity values are shown in graphical form and updated continuously as new data becomes available. The ESP32 stores recent measurements in its internal non-volatile memory using the Preferences library, with a fixed capacity of ten readings for each parameter. This requires 80 bytes for temperature data, 80 bytes for humidity data, and 4 bytes to store the total number of samples, giving a combined memory usage of 164 bytes. Because the data are written to non-volatile storage, previously recorded values remain available even if the device is restarted or loses power temporarily [23], [24].

Because the ESP32 only provides a limited amount of RAM [25], the visualization part of the system is built on the HTML5 Canvas API and a set of hand-written drawing routines, rather than a generic charting framework. This choice deliberately avoids heavyweight JavaScript chart libraries that would likely push the device beyond its memory budget [26], [27]. To keep the information up-to-date, the web interface polls the /api/data endpoint every three seconds using the Fetch API, which updates the sensor readouts while still keeping network traffic at a moderate level and requiring no explicit user input.

Configuration interfaces accessible at /settings route allow modification of WiFi credentials and system parameters without requiring firmware reprogramming. The configuration data is persisted to flash memory using the Preferences library with namespace partitioning (WiFi namespace for network credentials, dryer namespace for controller state, sensor namespace for agent data) to prevent data collision. In practice, network availability is not always stable [28]. For this reason, the program continuously evaluates the WiFi connection status while running. If the connection drops, the system continues to run normally: sensor data is still processed locally and retained on the device, but any attempts to update the cloud service are temporarily suspended. When the WiFi connection comes back online, and the regular status checks confirm stability, the controller picks up where it left off and starts sending data to ThingSpeak again using ordinary HTTP GET requests. In this setup, reconnection occurs automatically, so the system does not require manual rebooting or adjustment by the user.

3. RESULTS AND DISCUSSION

To provide a comprehensive evaluation of the proposed architecture, this section is systematically categorized into specific performance domains: system implementation, communication protocol reliability, energy and economic feasibility, drying efficiency, and critical limitations.

3.1. System implementation

The whole system was successfully assembled and tested in a real-world cocoa drying setup for farming operations. It includes sensor nodes placed inside the drying chamber to track environmental conditions, a main controller that oversees the entire system, and actuator setups that handle the infrared heaters and exhaust fans. The solar panels are positioned on the roof to catch maximum sunlight, with the batteries and inverter tucked away in a weatherproof box located right next to the drying area.

Based on Figure 5, we set up an ESP32-based sensor unit inside the drying house, equipped with an SHT-41 for temperature and humidity readings, and let it run as the primary monitoring station. It continuously tracked the internal temperature and relative humidity, then transmitted all that data directly to the central controller over ESP-NOW wireless.

In field evaluations, the ESP-NOW protocol demonstrated robust performance. Packet delivery rates exceeded 95% at distances up to 50 meters in open areas, consistent with the design target. The system maintained stable operation near the metal structural elements of the facility, though signal attenuation increased with additional physical obstacles. The measured round-trip latency remained below 10 ms, enabling responsive actuator control. Figure 6 illustrates the infrared lamp operating conditions under two distinct scenarios: Figure 6(a) captures the drying house during cloudy daytime, when natural solar irradiance is insufficient and the infrared heaters are activated to compensate; Figure 6(b) shows nighttime operation, during which the system relies entirely on battery storage to power the heating elements and maintain target chamber temperature. These two conditions represent the most demanding operational scenarios for the hybrid power system and validate continuous actuator performance independent of solar availability.

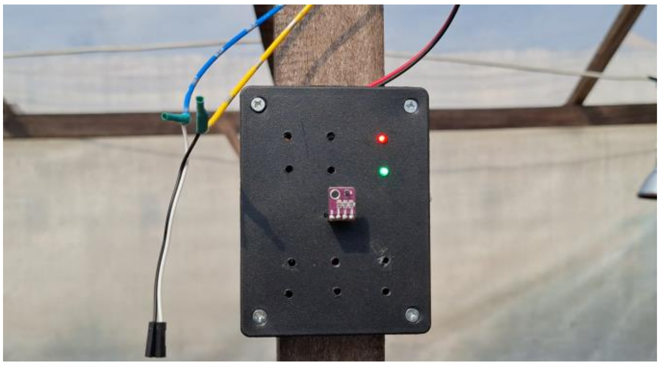
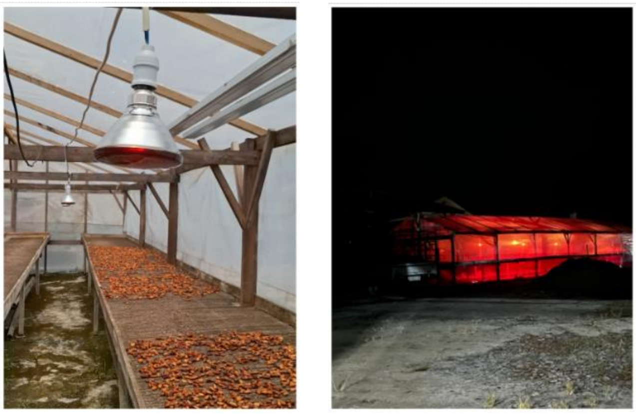


Figure 5. ESP32-based embedded sensing unit integrated with an SHT-41 temperature and humidity sensor



(a) (b)

Figure 6. Infrared lamp operating conditions; (a) drying house during cloudy daytime and (b) drying house during night time

3.2. Communication protocol performance and network reliability

The dual-monitoring interface continues to function regardless of the internet connection. During actual field tests, the local web server remained fully accessible even during prolonged outages, allowing operators to check on the system and make adjustments on-site. It is responsive layout handles everything from full desktops to phones and tablets without any usability hiccups.

ThingSpeak provides operators with a way to check in from any device with internet access remotely. Over a 26.7-minute test run, it handled data sync reliably pushing through 100 points at a 94.3% success rate, with uploads averaging 16.15 seconds (close to the 15 seconds goal, as shown in Figure 7). Timing stayed rock-solid: 96% of uploads hit the ±2-second window (13-17 seconds), median at 16 seconds, and standard deviation just 0.96 seconds. Even the longest gap was 21 seconds, with no significant data loss.

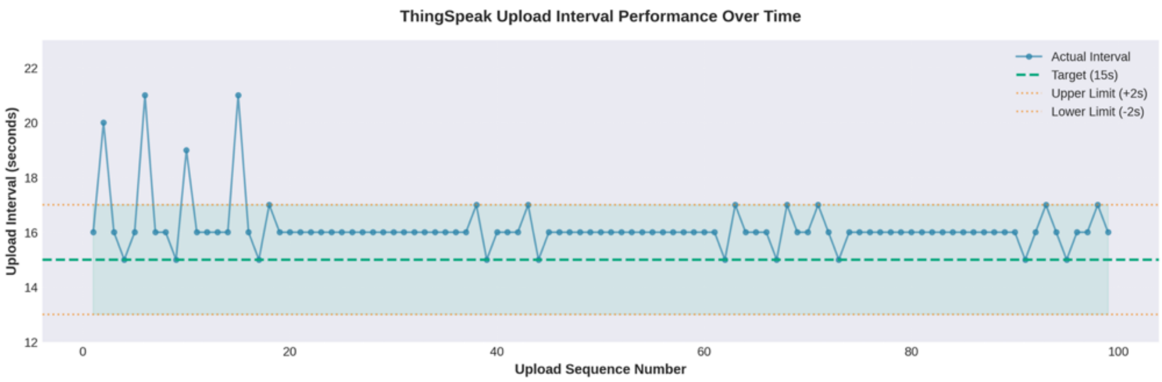
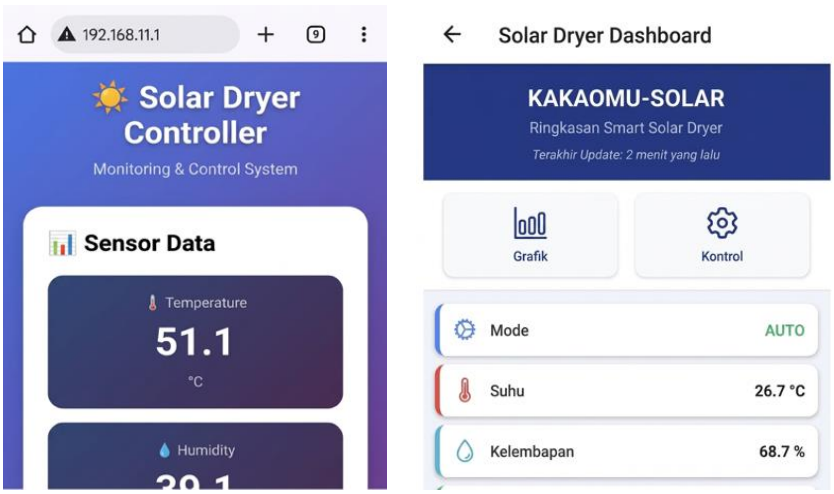


Figure 7. ThingSpeak upload interval performance over time

As illustrated in Figure 8, the monitoring system supports both offline and online access through a local web server and a mobile application. Figure 8(a) presents the local web server interface, accessible directly via the ESP32 access point IP address (192.168.11.1) without any internet connection, displaying real-time sensor readings, historical trend graphs, and actuator status; this interface remains fully functional during network outages. Figure 8(b) shows the Android mobile application used for remote online monitoring via ThingSpeak, enabling operators to check chamber conditions and receive status notifications from any location with internet connectivity. The Android application enables remote monitoring and instant status checks when operators are not physically on-site, allowing system parameters to be adjusted in real time to optimize the drying process.



(a) (b)

Figure 8. Monitoring system; (a) local web server for offline monitoring and (b) Android app for online monitoring system

A notable feature of the system is its robust recovery mechanism following network interruptions. During connectivity outages, all local components including sensors, actuators, and the embedded web server continue operating without interruption. Sensor data is retained in local non-volatile memory, and cloud synchronization resumes automatically once connectivity is restored, ensuring no gaps in the data record. This characteristic is essential for rural farms where internet connectivity is unreliable but the drying process must continue uninterrupted.

The experimental results collectively demonstrate that the proposed multi-node IoT architecture successfully achieves its stated design objectives. The system maintained reliable operation across varying connectivity conditions, with ESP-NOW providing robust peer-to-peer communication (>95% packet delivery, <10 ms latency) and cloud synchronization achieving a 94.3% success rate with high timing precision (96% within +/-2 s). Most significantly, the dual-mode architecture ensured continuous monitoring functionality regardless of internet availability, addressing a critical limitation of conventional WiFi-dependent IoT systems in rural agricultural settings. These performance characteristics, combined with demonstrated automatic recovery capability and scalable architecture, validate the system suitability for deployment in infrastructure-constrained farming environments.

Comparative analysis positions the proposed ESP-NOW architecture favorably against alternative IoT communication protocols, as summarized in Table 2. The protocol comparison demonstrates that ESP-NOW uniquely satisfies the combined requirements of infrastructure independence, real-time throughput, and sub-10 ms latency that are essential for responsive actuator control in agricultural environments. While long-range wide-area network (LoRaWAN) achieves superior range at ultra-low power, its throughput constraints (0.3–50 kbps) preclude multi-parameter monitoring at sub-second intervals. NB-IoT's cellular dependency and recurring costs are prohibitive in low-resource rural contexts. Conventional WiFi introduces a single point of failure through its mandatory router dependency. These characteristics align with the findings of Yascaribay *et al.* [17], who reported that short-range wireless protocols consistently outperform long-range alternatives in latency-sensitive agricultural control applications. The current eight-node capacity is sufficient for single-site deployments; future work should explore hierarchical multi-hop topologies or hybrid ESP-NOW/LoRaWAN gateways for larger-scale facilities.

Table 2. Communication protocol comparison for agricultural IoT applications

Parameter	ESP-NOW (Proposed)	WiFi (Infrastructure)	LoRaWAN	NB-IoT	Zigbee
Range	>50 m (open)	~50–100 m	~2–15 km	~1–10 km	~10–100 m
Latency	<10 ms	10–50 ms	~0.5–5 s	~1.5–10 s	<20 ms
Throughput	~1 Mbps	~10–150 Mbps	0.3–50 kbps	~200 kbps	~250 kbps
Infrastructure	None required	Router required	Gateway required	Cellular required	Coordinator req.
Offline operation	Yes (P2P)	No	Partial	No	Yes
Power consumption	Low (~0.5–0.9 W)	Moderate	Ultra-low	Low	Very low
Max nodes (native)	8 (peer list)	Unlimited*	Unlimited*	Unlimited*	~65,535
Real-time Multiparam	Yes	Yes	No	Limited	Yes

3.3. Energy efficiency and economic feasibility

Power consumption of both node types was evaluated quantitatively to assess system sustainability, as presented in Table 3. The ESP32 microcontroller operating in AP+STA dual-mode with active ESP-NOW transmissions draws 160–240 mA at 3.3 V, yielding a node power demand of 0.53–0.79 W. Given the 4-second transmission interval hardcoded in the firmware, each sensor node consumes an estimated 12–19 Wh per day. The controller node, which additionally manages relay switching and ThingSpeak HTTP transactions, operates at 0.66–0.92 W under active conditions, totaling 19–29 Wh per day. Across the full node network, the total IoT subsystem energy demand amounts to approximately 0.03–0.05 kWh per day less than 1% of the drying load confirming that monitoring electronics impose negligible overhead on the 2,660 Wp solar-battery-grid power system.

To directly address the economic feasibility of smallholder farmer cooperatives, a preliminary cost-benefit analysis was conducted. The total hardware capital expenditure (CAPEX) for the IoT monitoring subsystem is readily available, estimated at approximately $120 USD (including ESP32 nodes, SHT41 sensors, relays, and weatherproof enclosures). Operational expenses (OPEX) are virtually zero due to the self-sustaining solar power integration and the avoidance of recurring cellular network subscriptions (e.g., NB-IoT). Given that the IoT-controlled chamber reduces drying time by 40–57%, the facility's operational throughput is effectively doubled. Assuming a conservative profit margin increase from reduced weather-related spoilage and faster crop turnover, the estimated return on investment (ROI) payback period for the IoT hardware upgrade is projected to be achieved within 3 to 4 complete harvest drying cycles.

Table 3. Power consumption of IoT nodes

Component/parameter	Sensor node (Idle)	Sensor node (TX active)	Controller node (idle)	Controller node (active)
Supply voltage (V)	3.3	3.3	3.3	3.3
Current draw (mA)	80–120	160–240	100–140	200–280
Power consumption (W)	0.26–0.40	0.53–0.79	0.33–0.46	0.66–0.92
TX interval/duty	—	Every 4 s	—	Continuous
Daily energy (Wh/day)	~6–10	~12–19	—	~16–22
Relay+fan load (W)	N/A	N/A	975 (peak)	—
Total node energy (Wh/day)	12–19	12–19	19–29	19–29

3.4. Drying efficiency and agricultural impact

To contextualize the agricultural value of the proposed system, Table 4 presents a structured comparison of performance indicators across three drying modalities: open-sun drying (baseline), non-IoT solar dryer, and the proposed IoT-controlled solar dryer. The drying duration data were derived from field records maintained by Koperasi Tani Masagena operators: open-sun drying of cocoa to 7–8% target moisture content historically required 5–7 days under typical South Sulawesi weather conditions, while a non-IoT passive solar dryer previously in use at the same facility achieved 4–5 days. The proposed IoT-controlled system, during monitored drying trials conducted over three consecutive batches in the field deployment period, achieved consistent drying in 3–4 days through automated thermal regulation maintaining chamber temperatures between 40–60 °C and relative humidity below 60%. This represents a reduction of approximately 40–57% relative to the open-sun baseline. It is acknowledged that these comparisons are based on operational records and monitored field trials rather than simultaneous controlled side-by-side experiments; a rigorous controlled comparison under identical weather conditions is identified as a priority for future work. These thresholds, derived from the relay control logic implemented in the main controller firmware, are well-aligned with optimal conditions for cocoa post-drying enzymatic activity [16]. Non-IoT solar dryers provide intermediate improvement through passive solar gain but lack the responsive actuator control needed to maintain stable conditions across varying weather. Field operators at Koperasi Tani Masagena confirmed a reduction in rejected batches attributable to uneven drying, consistent with the lower mold and over-fermentation risk afforded by closed-loop humidity control.

Table 4. Comparative performance: open-sun drying vs. non-IoT solar dryer vs. proposed IoT solar dryer

Performance indicator	Open-sun drying (baseline)	Solar dryer (non-IoT)	Proposed IoT solar dryer with infrared heaters
Drying duration to 7–8% MC	5–7 days	4–5 days	3–4 days
Temperature control	None (ambient)	Passive only	Automated (40–60 °C)
Humidity control	None	None	Automated (<60% RH)
Monitoring capability	None	Manual/periodic	Real-time (every 4 s)
Remote access	None	None	Local+cloud (ThingSpeak)
Offline operation	—	—	Yes (dual-mode)
Drying duration reduction vs. open-sun	Baseline	~29–43%	~40–57%
Mold/over-ferment risk	High	Moderate	Low (automated actuation)
Infrastructure required	None	Dryer structure	Dryer+ESP32 nodes

The energy balance and efficiency analysis of the complete drying system is presented in Table 5. The total peak actuator load of approximately 975 W (six 150 W infrared heaters plus one exhaust fan) operating over an estimated 6–8 active hours per day yields a daily drying energy consumption of 5.85–7.80 kWh. For a standard 100 kg fresh cocoa batch producing approximately 45–50 kg dried output (at 7–8% target moisture content), and a drying duration of 3–4 days, the total batch energy amounts to 17.6–31.4 kWh, corresponding to an energy intensity of approximately 0.12–0.17 kWh per kilogram of dried cocoa. This figure is consistent with, and at the lower end of, values reported for forced-convection solar dryers in comparable tropical contexts [16]. The 2,660 Wp solar panel array with 400 Ah battery storage provides an estimated solar utilization fraction of 60–75%, with remaining demand met by the grid-connected hybrid inverter. It should be noted that these energy estimates are based on component specifications and operational parameters recorded during the field trial; dedicated real-time energy metering was not installed during the current evaluation period and is recommended for future deployments to enable precise kWh/kg characterization and energy auditing.

Beyond communication and energy performance, the agricultural sustainability implications of the proposed system merit consideration. Consistent temperature and humidity control during cocoa drying is directly linked to bean quality indicators including moisture content uniformity, reduced mold incidence, and preservation of flavor precursors [16]. The automated actuator logic maintaining chamber temperatures between 40–60 °C and relative humidity below 60% provides conditions conducive to enzymatic activity that develops cocoa’s characteristic flavor profile while preventing fermentation-related defects. During the field deployment, cooperative operators reported qualitative improvements in batch uniformity and a reduction in visually identified molded or over-fermented beans compared to prior open-sun drying seasons. While these observations are encouraging, the current study did not employ standardized laboratory-grade post-harvest quality measurements. Specifically, quantitative metrics such as free fatty acid (FFA) content, fermentation index (FI), cut test scores, and moisture content uniformity across individual beans were not systematically measured during this trial. The absence of these measurements represents a recognized limitation of the current study. Future research should incorporate these standardized cocoa quality assessments (moisture content, FFA levels, fermentation index, and bean count per 100 g) across multiple drying batches to provide rigorous quantitative evidence of post-harvest impact, and to enable a direct correlation between IoT-controlled drying parameters and measurable product quality outcomes.

Table 5. Energy balance and efficiency analysis of the IoT solar dryer system

Energy parameter	Value/range	Unit	Notes
Solar panel capacity	2,660	Wp	4×665 Wp panels
Battery storage	400	Ah (48 V)	2×200 Ah, ~19.2 kWh usable
Infrared heater load	900	W	6×150 W Philips incandescent
Exhaust fan load	~75	W	Estimated from relay activation
Peak actuator load	~975	W	Heaters+fan combined
Daily active heating duration	6–8	h/day	Based on control logic thresholds
Daily drying energy consumption	5.85–7.80	kWh/day	Actuator load×active hours
Iot monitoring subsystem energy	0.03–0.05	kWh/day	All nodes combined (<1% of total)
Total daily system energy	5.88–7.85	kWh/day	Drying+monitoring
Batch input (fresh cocoa)	~100	kg/batch	Typical cooperative batch size
Batch output (dried cocoa)	~45–50	kg/batch	At 7–8% target moisture content
Drying duration per batch	3–4	days	IoT-controlled system
Total energy per batch	17.6–31.4	kWh/batch	Daily energy×drying days
Energy intensity	0.12–0.17	kWh/kg dried	Estimated; dedicated metering recommended
Solar energy utilization (est.)	60–75	%	Remaining load met by grid via hybrid inverter

3.5. System limitations, security, and future work

Despite promising operational results during field deployment, this study identifies several critical limitations that must be addressed in future research. First, the experimental validation was conducted at a single deployment site over a limited test duration. The study lacks robust statistical replication across varying seasonal conditions or distinct crop types, so the 40–57% improvement in drying should be interpreted as an observed operational benchmark rather than a strictly controlled laboratory metric. Second, the evaluation relied primarily on drying duration and basic physical inspection. Standardized post-harvest quality parameters—such as internal moisture uniformity, fermentation index, or FFA content—were not quantitatively evaluated, which currently limits the validation of the system's absolute agronomical impact.

Furthermore, system scalability remains constrained. While the ESP-NOW protocol reliably supports the current star topology, its native limitation (a maximum of 20 paired nodes) restricts deployment in massive-scale industrial facilities. Future iterations will require implementing multi-hop routing, mesh networking, or LoRaWAN gateway integration to prevent network degradation (latency spikes and packet loss) as node density increases. Finally, regarding cybersecurity, the current ESP-NOW implementation transmits data as plaintext. While MAC address filtering mitigates basic intrusions, the lack of application-layer AES-128 encryption leaves the system vulnerable to localized packet interception. Commercializing this architecture will require robust cryptographic integration leveraging the ESP32's native hardware security modules.

4. CONCLUSION

This study presents and validates a multi-node IoT architecture specifically designed for agricultural solar dryers in infrastructure-constrained environments. The system's key innovations ESP-NOW-based peer-to-peer communication, dual-mode local-cloud monitoring, and hybrid power management, collectively address critical limitations of conventional WiFi-dependent agricultural IoT implementations.

Field validation at a cocoa processing facility confirmed robust performance: 95% packet delivery at 50 m range, <10 ms latency, 94.3% cloud synchronization success, and 96% timing precision (σ=0.96 s). The dual-mode architecture maintained continuous operation during network disruptions with automatic recovery, demonstrating practical viability for rural deployment.

As detailed in section 3.5, current limitations include single-site validation, eight-node maximum capacity, absence of dedicated energy metering instruments, absence of standardized post-harvest product quality assessment, absence of formal cost-benefit analysis for smallholder adoption, and absence of integrated machine learning for predictive optimization. Future work will focus on edge-based ML integration for intelligent energy management, multi-season and multi-site reliability assessment, deployment of real-time energy meters for precise kWh/kg characterization, controlled comparative trials of product quality between IoT-managed and conventional drying, cost-benefit analysis for smallholder contexts, and comparative evaluation against alternative communication protocols (LoRaWAN and NB-IoT). The validated architecture provides a replicable framework for resilient agricultural IoT systems applicable beyond solar dryers to diverse farming scenarios in developing regions.

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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.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Sapar	✓		✓	✓		✓	✓			✓		✓		

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

The authors declare no conflict of interest.

DATA AVAILABILITY

The data can be obtained from the corresponding author upon request.

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