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Design and Pilot Implementation of a Low-Cost IoT-Based Temperature Monitoring System for Cacao Fermentation Optimisation

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Abstract

Cacao fermentation is a critical post-harvest process that strongly influences cocoa bean quality and farmer income, yet it is commonly managed using fixed time-based rules that fail to reflect real-time microbial activity. This results in inconsistent fermentation outcomes, particularly for smallholder producers. This paper presents the system design and pilot implementation of a low-cost Internet of Things (IoT)-based cacao fermentation monitoring device that uses continuous temperature sensing to guide fermentation management. The system employs a PT100 platinum resistance temperature detector (RTD) interfaced with a MAX31865 RTD-to-digital converter, managed by an ESP32 Wi-Fi microcontroller, and transmitting data to a Blynk cloud dashboard for remote monitoring and automated alerts. A rule-based algorithm incorporating an exponential moving average (EMA) signal to smooth temperature data identifies characteristic temperature rise and peak patterns associated with microbial phase transitions, enabling timely notifications for aeration (bean turning) and the progression of the fermentation cycle. The complete firmware architecture, hardware integration, signal-processing approach, and cloud-communication framework are documented. Pilot deployment under real fermentation conditions confirmed that the device reliably captured temperature profiles consistent with established phase transitions in fermentation. The total hardware cost of approximately 3,680 Thai Baht (approximately USD 105) demonstrates the feasibility of sensor-driven fermentation guidance as a scalable, affordable approach to improving post-harvest cacao management for smallholder producers.

Keywords
Cacao fermentation, IoT, Temperature monitoring

1. Introduction
Cacao fermentation is widely recognised as the first critical post-harvest step in chocolate production, during which microbial activity drives the formation of flavour precursors and reduces astringency through biochemical changes initiated after the seed embryo dies (Schwan and Wheals 2004). Reviews characterise cacao fermentation as a spontaneous process dominated by a microbial succession of yeasts, lactic acid bacteria (LAB), and acetic acid bacteria (AAB), accompanied by systematic changes in temperature and acidity (De Vuyst and Weckx 2016; De Vuyst and Leroy 2020). The exothermic metabolic activity of these microbial populations generates a characteristic temperature rise that serves as a practical indicator of fermentation progress, with reported fermentation temperatures commonly reaching 40-50 degrees Celsius (Schwan and Wheals 2004; Calvo et al. 2021).

Despite the recognised relevance of temperature as a process indicator, routine monitoring in smallholder and small-batch contexts remains intermittent and subjective. Most producers rely on fixed timelines, visual cues, and tactile assessment rather than objective data, leading to highly variable fermentation outcomes (Kongor et al. 2016). In Thailand, dried fermented cacao beans range from 120 to 300 Thai Baht per kilogram, depending on quality, meaning that fermentation variability alone can determine whether a farmer receives premium or bulk-grade pricing. This inconsistency creates a structural barrier: premium chocolate makers are willing to pay more for well-fermented beans, but farmers lack the tools to reliably meet quality standards.

Internet of Things (IoT) architectures offer a promising approach to addressing this gap. Smart agriculture surveys identify continuous monitoring, remote data access, and automated alert generation as core capabilities of IoT applications (Farooq et al. 2019; Quy et al. 2022). For cacao fermentation specifically, several recent studies have explored IoT-based monitoring. Saguidon et al. (2024) developed an Arduino-based system using DS18B20 temperature sensors to automate cacao fermentation control. Sabila et al. (2025) tested IoT monitoring with DHT22 and pH sensors at small scales. Singbua et al. (2025) deployed nine DS18B20 sensors and an ESP32 microcontroller to support community cocoa producers in Thailand. However, these systems generally employ consumer-grade digital temperature sensors with limited accuracy and do not incorporate signal smoothing or sophisticated firmware state management for robust field operation.

1.1 Research Objectives

This paper's objective is to present the design and pilot implementation of a low-cost IoT-based cacao fermentation temperature monitoring system that addresses several limitations of existing approaches. The system uses a PT100 platinum resistance temperature detector (RTD) with a MAX31865 RTD-to-digital converter for higher measurement precision, an ESP32 Wi-Fi microcontroller with a structured firmware state machine for reliable field operation, exponential moving average (EMA) signal smoothing for noise reduction, and a Blynk cloud platform for real-time remote monitoring with automated fermentation stage alerts. The paper documents the complete system architecture, firmware design, hardware integration, signal-processing methodology, bill of materials, and observations from the pilot deployment under real fermentation conditions. The scope is intentionally limited to the engineering design and implementation of the monitoring device; analysis of bean quality outcomes is reserved for a separate study.

2. Literature Review

This review examines the existing research surrounding cacao fermentation dynamics and the application of Internet of Things (IoT) technologies in agricultural monitoring.

2.1 Cacao Fermentation Microbiology and Temperature Dynamics

Cacao fermentation involves a well-characterised microbial succession. During the initial anaerobic phase (approximately 0 to 48 hours), yeasts ferment pulp sugars into ethanol and carbon dioxide, contributing to pulp degradation and creating conditions for subsequent bacterial activity (Schwan and Wheals 2004; De Vuyst and Weckx 2016). As fermentation progresses and oxygen availability increases through natural pulp drainage and deliberate turning (aeration), LAB and AAB become dominant. AAB oxidise ethanol to acetic acid in a strongly exothermic reaction that generates substantial heat, driving internal temperatures upward (De Vuyst and Leroy 2020). This heat, combined with acid diffusion, kills the bean embryo and initiates internal physicochemical changes that produce precursors of chocolate flavour.

Field studies consistently report characteristic temperature profiles. Camu et al. (2008) observed internal heap temperatures rising from approximately 25 degrees Celsius at the start to approximately 45.6 degrees Celsius during fermentation in Ghana, noting that turning affected the timing of maximum temperature. Calvo et al. (2021) tracked temperature across three Colombian fermentation sites and reported average temperatures ranging from 36.9 to 39.9 degrees Celsius, indicating that temperature and pH are the primary parameters to monitor. A Thai fermentation study reported temperatures reaching 40-45 °C over multi-day fermentations in wooden containers (Tikapunya 2021). The International Cocoa Organization describes temperature rising to 40-45 degrees Celsius during the first 48 hours and identifies turning as a mechanism to increase aeration and bacterial activity (ICCO 2024).

2.2 IoT Systems in Agriculture and Fermentation Monitoring

IoT architectures for agriculture typically follow a layered model comprising perception (sensors), network (communication), processing (cloud or edge computing), and application (dashboards and alerts) layers (Farooq et al. 2019; Quy et al. 2022). Wireless sensor networks (WSNs) have been applied across diverse agricultural and food industry contexts, including field crop monitoring, cold chain management, and greenhouse environmental control (Ruiz-Garcia et al. 2009). In smallholder contexts, studies have identified affordability, reliability under intermittent connectivity, and ease of deployment as critical design requirements (Bayih et al. 2022; Devkota et al. 2023).

Within fermentation monitoring, IoT approaches have been applied to beer brewing (Buonocore et al. 2021), wine production (Kontogiannis et al. 2025), and cacao processing. Adeleke et al. (2023) conducted a bibliometric review of IoT applications in food fermentation, confirming growing research activity but noting that most cacao-specific systems remain at the prototype stage. Guillermo et al. (2019) developed a WSN architecture for monitoring cacao crops in Ecuador, while Abijaude et al. (2022) combined IoT sensors with blockchain to record tamper-proof fermentation data in Brazil. For rule-based agricultural decision support, Mazon-Olivo et al. (2018) presented a rules engine framework for processing IoT sensor streams and triggering automated alerts, and Muangprathub et al. (2019) demonstrated a complete IoT system with rule-based control and data analytics.

2.3 Hardware and Software Components for IoT Sensing

The ESP32 microcontroller, manufactured by Espressif Systems, integrates a dual-core processor with 2.4 GHz Wi-Fi and Bluetooth connectivity, making it a widely adopted platform for IoT sensor applications (Hercog et al. 2023). Correa-Quiroz et al. (2025) demonstrated an ESP32-based smart irrigation system that achieved a 35 percent reduction in water consumption, while Galon et al. (2025) combined ESP32 with the Blynk IoT platform for greenhouse monitoring and control. The Blynk platform provides cloud-based dashboards, mobile application interfaces, device provisioning, and over-the-air (OTA) firmware updates, and its suitability for agricultural monitoring has been validated by Serikul et al. (2018).

For temperature measurement, platinum resistance temperature detectors (RTDs) are standard instruments in temperature metrology, offering superior accuracy, stability, and repeatability compared to thermistors and digital sensors (Sarkar 2018). The Analog Devices MAX31865 is a dedicated RTD-to-digital converter that supports PT100 and PT1000 sensors in 2-wire, 3-wire, and 4-wire configurations, communicates via SPI, and includes integrated fault detection with input protection (Analog Devices 2024). For signal conditioning in embedded systems, the exponential moving average (EMA) filter provides a computationally efficient noise-reduction approach suitable for resource-constrained microcontrollers, with performance characterised in comparative studies by Varshavskiy et al. (2019, 2020). The structured finite state machine (FSM) design pattern provides a robust framework for managing the multiple operational modes required in IoT devices (Samek 2008).

3. Methods

This section describes the hardware integration and sensor configurations used to monitor the cacao fermentation process. It details the system architecture, component selection for high-precision data acquisition, and the firmware-level signal processing implemented to ensure data reliability in field conditions.

3.1 System Architecture Overview

The monitoring system follows a four-layer IoT architecture: perception (temperature and pH sensors), network (ESP32 Wi-Fi via mobile hotspot), processing (Blynk cloud platform), and application (mobile dashboard with automated alerts). The core hardware comprises a PT100 RTD probe interfaced via a MAX31865 breakout board, an ADS1115 16-bit analogue-to-digital converter for the pH sensor, a Wemos D1 R32 ESP32 development board, status LEDs, a manual reset button, and a ZTE MF79U mobile Wi-Fi hotspot for connectivity in field locations without fixed internet infrastructure. All components are housed in a weatherproof plastic enclosure (NANO 22W), powered by a 100W GaN USB charger that provides a stable 5V supply.

3.2 Sensor Selection and Interface Design

The PT100 RTD was selected over consumer-grade digital sensors (such as the DS18B20 or DHT22) for several reasons. Platinum RTDs conform to the IEC 60751 standard, which defines the temperature-resistance relationship for industrial platinum resistance thermometers (IEC 2008). The PT100 offers accuracy of ±0.15 degrees Celsius at 0 degrees Celsius (Class A), excellent long-term stability, and resistance to drift, which are important properties for sustained monitoring in the humid, acidic environment of a fermentation box. The MAX31865 RTD-to-digital converter handles the resistance measurement, linearisation, and fault detection through an SPI interface, eliminating the need for external instrumentation amplifiers or analogue front-end circuits (Analog Devices 2024).

The sensor is configured in 3-wire mode with a 430-ohm reference resistor, as implemented in the firmware configuration. A pH sensor module connected through an ADS1115 16-bit ADC provides supplementary acidity measurements. The ADS1115 communicates via I2C (SCL on GPIO 22, SDA on GPIO 21) and is configured with two-thirds gain to accommodate the sensor output voltage range. pH calibration uses a two-point linear mapping derived from buffer solutions at pH 4.01 and pH 9.18, with corresponding voltage readings stored as firmware constants.

3.3 Hardware Integration and Wiring
The ESP32 serves as the central controller, managing all sensor interfaces, cloud communication, LED indicators, and button inputs. The MAX31865 communicates via software SPI using GPIO 18 (SCK), GPIO 19 (MISO), GPIO 23 (MOSI), and GPIO 5 (CS), powered from the 3.3V rail. The ADS1115 ADC connects via I2C on GPIO 21 (SDA) and GPIO 22 (SCL), powered from 5V. Two status LEDs provide local visual feedback: a green LED on GPIO 27 indicates normal running operation, and a red LED on GPIO 16 signals an alarm state (fermentation cycle completed, turning required).

A configuration status LED on GPIO 14 indicates the Blynk connectivity state. A physical push button on GPIO 12 enables manual alarm acknowledgement via a 3-second press-and-hold, and a second button on GPIO 13 allows configuration reset. USB cooling fans provide ventilation within the enclosure to prevent overheating of the electronics in tropical ambient conditions. GX16 aviation connectors provide robust, weatherproof connections for the external PT100 and pH sensor probes.

3.4 Firmware Architecture
The firmware is developed in C++ for the Arduino/ESP32 platform and follows a structured state-machine architecture based on Blynk.Edgent framework (Blynk 2024a). The state machine manages nine operational modes: WAIT_CONFIG (awaiting initial provisioning), CONFIGURING (active Wi-Fi credential entry), CONNECTING_NET (establishing Wi-Fi connection), CONNECTING_CLOUD (authenticating with Blynk servers), RUNNING (normal sensor acquisition and cloud publishing), OTA_UPGRADE (receiving over-the-air firmware updates), SWITCH_TO_STA (transitioning from access point to station mode), RESET_CONFIG (clearing stored credentials), and ERROR (fault recovery with automatic restart). This structured approach ensures that the device gracefully handles real-world conditions such as power interruptions, Wi-Fi dropouts, and cloud connectivity failures, automatically recovering to the RUNNING state when conditions permit (Samek 2008).

During normal operation (RUNNING mode), the main control loop executes the following sequence at one-second intervals: (1) read the PT100 temperature via MAX31865, (2) read the pH value via ADS1115, (3) apply EMA smoothing to both readings, (4) publish smoothed values to the Blynk cloud, (5) evaluate the fermentation logic rules, and (6) update local LED indicators. The Blynk real-time clock (RTC) synchronisation ensures accurate timestamping, with periodic resynchronisation every 3600 seconds to prevent clock drift.

3.5 Signal Processing: Exponential Moving Average
Raw sensor readings from the PT100 and pH sensor contain measurement noise arising from electrical interference, quantisation effects, and environmental fluctuations. The firmware applies an exponential moving average (EMA) filter to smooth these readings while maintaining adequate responsiveness to genuine temperature changes during fermentation. The EMA is defined as:

$$S(t) = alpha * X(t) + (1 - alpha) * S(t-1)$$

where S(t) is the smoothed output at time t, X(t) is the raw sensor reading, and alpha is the smoothing factor between 0 and 1 (Varshavskiy et al. 2019). A higher alpha value provides faster response but less smoothing, while a lower value provides greater noise reduction at the cost of increased lag. The firmware uses alpha = 0.4 for both the PT100 temperature and the pH ADC readings, selected to balance noise suppression and responsiveness, appropriate for the relatively slow thermal dynamics of cacao fermentation (typical temperature change rates of 1 to 3 degrees Celsius per hour). This value was determined through iterative bench testing, observing the trade-off between signal stability and tracking fidelity across the operating temperature range.

3.6 Fermentation Logic and Alert System
The core fermentation monitoring logic implements a rule-based algorithm designed to detect temperature peak-and-decline patterns that indicate when microbial activity in the current aeration cycle has diminished and the beans require turning (aeration) to restart aerobic bacterial activity. The algorithm operates as follows. During the initial anaerobic phase (approximately 0 to 48 hours), the system monitors temperature passively without issuing turning alerts,

consistent with standard fermentation practice that recommends no disturbance during the initial yeast-dominated stage (ICCO 2024). After the initial phase, the system enters active monitoring mode.

In active monitoring mode, the algorithm records the temperature at the start of each monitoring interval (configurable via the Blynk dashboard) and compares subsequent readings against this baseline. When the timer expires, the system checks whether the current temperature has fallen below the recorded baseline. If the temperature has declined, this is counted as one confirmation interval toward a configurable threshold (the alarm count parameter). Once the required number of consecutive declining intervals is reached, the system concludes that the temperature has peaked and is falling, triggers a turning alert via the Blynk event notification system, increments the cycle counter, and records the maximum temperature observed during that cycle. If the temperature has not declined (that is, it is still rising or stable), the confirmation counter resets to zero and the baseline updates to the current temperature, reflecting ongoing microbial heat generation.

Two additional termination conditions supplement the primary peak-detection logic. First, a configurable cycle time limit automatically triggers a turning alert if no temperature decline is detected within a maximum duration, preventing indefinitely prolonged cycles. Second, a configurable cycle-end temperature threshold triggers an alert if the temperature reaches a specified upper limit, providing protection against overheating. All parameters (monitoring interval, alarm count, cycle time limit, and temperature threshold) are remotely adjustable via the Blynk dashboard, enabling the operator to adapt the system to different cacao varieties, batch sizes, and environmental conditions without modifying the firmware.

3.7 Cloud Platform and Remote Monitoring

The Blynk IoT platform provides the cloud infrastructure for data storage, visualisation, and user notification (Blynk 2024a). The device publishes sensor data to virtual pins on the Blynk cloud, which are displayed on a mobile dashboard application. The dashboard presents: real-time temperature and pH readings (V1, V2), countdown timers showing time remaining until the next evaluation (V6), cycle progress indicators (V4, V10), alarm status with LED widgets (V8, V9), and the maximum temperature recorded in the current cycle (V18). When a turning alert is triggered, the Blynk event system sends push notifications to the operator's mobile device with a descriptive message including the cycle number, maximum temperature, and trigger condition.

The system supports over-the-air (OTA) firmware updates through the Blynk.Air service, enabling remote deployment of firmware improvements and bug fixes without physical access to the device (Blynk 2024b). The OTA process downloads the firmware binary via HTTPS, verifies integrity using MD5 checksums, applies the update, and reboots the device. This capability is important for devices deployed at remote farm locations where physical access for manual firmware updates would be impractical.

3.8 Bill of Materials and Cost Analysis

A primary design objective was to maintain a total hardware cost suitable for smallholder adoption. Table 1 presents the complete bill of materials for one monitoring unit, with all components sourced from local Thai electronics suppliers.

Table 1. Bill of Materials for One Monitoring Unit

No.	Component	Qty	Unit Price (THB)	Shipping (THB)	Total (THB)	Function
1	100W GaN USB Charger	1	484	29	513	Power supply
2	120mm USB Cooling Fan	1	60	35	95	Enclosure ventilation
3	Fan Guard Grill	1	13	35	48	Fan protection
4	MAX31865 Breakout Board	1	199	35	234	RTD-to-digital converter
5	PT100 RTD Probe (Waterproof)	1	249	35	284	Temperature sensing
6	Wemos D1 R32 ESP32	1	155	29	184	Microcontroller (MCU)

7	pH Sensor Module	1	610	0	610	Acidity measurement
8	ZTE MF79U Mobile Hotspot	1	1,029	29	1,058	Field Wi-Fi connectivity
9	Plastic Enclosure (NANO 22W)	1	105	48	153	Weatherproof housing
10	ADS1115 16-bit ADC	1	110	35	145	pH sensor interface
11	GX16 Aviation Connectors	1	27	29	56	Probe connectors
12	Misc. (LEDs, buttons, wires, standoffs)	1	300	0	300	Assembly components
	Total				3,680	Approx. USD 105

The total unit cost of approximately 3,680 THB (approximately USD 105 at prevailing exchange rates) is substantially below the cost of industrial fermentation monitoring systems, which typically exceed USD 5,000 (Guillermo et al. 2019). The mobile hotspot is the single most expensive component and may be shared across multiple devices in a cooperative deployment model, further reducing the effective per-unit cost.

4. Data Collection

Pilot deployment of the monitoring system was conducted under real cacao fermentation conditions in Thailand. The device was installed in a fermentation setup processing approximately 200 kilograms of fresh cacao beans in a plastic cooler container. The PT100 probe was inserted into the centre of the bean mass to a depth of approximately 15 centimetres, secured using the GX16 aviation connector through a hole drilled in the container wall. The ZTE mobile hotspot provided Wi-Fi connectivity via the Thai 4G cellular network, enabling continuous cloud data transmission throughout the fermentation period.

The system operated continuously for approximately 5.5 days, recording temperature and pH readings at 1-second intervals. Data was published to the Blynk cloud platform and logged for subsequent analysis. The Blynk dashboard was monitored remotely, and push notification alerts were received on the operator's mobile device when the fermentation logic determined that bean turning was required. During the pilot, the system completed five aeration cycles based on the temperature peak-detection algorithm, with alerts generated for each cycle transition. All system parameters (monitoring interval, alarm count thresholds, cycle time limits) were configured remotely via the Blynk dashboard prior to fermentation and adjusted during the process as needed.

5. Results and Discussion

This section evaluates the performance of the monitoring system over the pilot fermentation.

5.1 System Performance

The monitoring system operated continuously throughout the 5.5-day pilot fermentation without hardware failures, connectivity dropouts lasting more than 5 minutes, or firmware crashes requiring a manual restart. The structured state machine architecture proved effective for handling transient Wi-Fi disconnections: when connectivity was temporarily lost, the device automatically transitioned from RUNNING to CONNECTING_NET, re-established the Wi-Fi link, reconnected to the Blynk cloud, and resumed data publishing. Over the entire fermentation period, estimated data completeness was high, with brief gaps attributable to periodic Wi-Fi reconnection events. The OTA firmware update capability was verified during development by remotely deploying incremental firmware revisions, confirming that the device could be maintained without physical access.

5.2 Temperature Profile Observations

The temperature profile recorded during the pilot fermentation exhibited patterns consistent with the established literature on cacao fermentation dynamics. During the initial anaerobic phase (0 to approximately 48 hours), the temperature rose gradually from approximately 27 degrees Celsius to approximately 35 degrees Celsius, reflecting the onset of yeast-driven metabolic activity and pulp degradation. Following the first aeration event (bean turning), the temperature rose more sharply, consistent with the transition to aerobic conditions that favour the activity of acetic acid bacteria and the associated exothermic ethanol oxidation (De Vuyst and Leroy 2020).

Across the five monitored aeration cycles, the system recorded a global maximum temperature of approximately 51.37 degrees Celsius, consistent with the upper range reported in field studies (Schwan and Wheals 2004; Camu et al. 2008). Each successive cycle exhibited a local maximum temperature, and the duration of each cycle decreased progressively as fermentation progressed, which aligns with the expected pattern of diminishing substrate availability and microbial population dynamics in later fermentation stages. In all five cycles, the temperature peak-detection algorithm correctly identified the temperature decline, indicating the need for aeration.

The EMA smoothing with alpha = 0.4 effectively reduced high-frequency noise in the temperature readings while preserving the overall trend shape. Visual comparison of raw and smoothed temperature traces confirmed that the EMA filter did not introduce sufficient lag to delay the detection of temperature peak events, which is critical for timely alert generation. The one-second sampling interval combined with the EMA filter provided a smooth, responsive signal suitable for the rule-based decision logic.

5.3 Proposed Improvements

Several improvements are proposed based on the pilot deployment experience. First, the current system uses a single PT100 probe per device to measure temperature at a single point within the bean mass. Given that fermentation temperature can vary spatially (Camu et al. 2008; Papalexandratou et al. 2011), future versions could incorporate multiple probes at different positions and depths to provide a more representative temperature profile. Second, reliance on a mobile hotspot for connectivity introduces recurring costs and a potential single point of failure. Integration of a local data logger with SD card storage would provide data redundancy in the event of connectivity loss. Third, the rule-based algorithm could be augmented with adaptive threshold learning, where the system adjusts its peak-detection parameters based on historical batch data, reducing the need for manual parameter tuning. Fourth, power consumption could be reduced by implementing sleep mode during the less dynamic initial anaerobic phase, extending battery life for deployments where mains power is unavailable.

5.4 Comparison with Existing Systems

Table 2 compares the key specifications of the proposed system with recently published IoT-based cacao fermentation monitoring systems.

Table 2. Comparison with Existing IoT-Based Cacao Fermentation Monitoring Systems

Feature	This Work	Saguidon et al. (2024)	Sabila et al. (2025)	Singbua et al. (2025)
MCU	ESP32	Arduino Uno	ESP32	ESP32
Temp. Sensor	PT100 + MAX31865	DS18B20	DHT22	DS18B20 (x9)
Accuracy	+/- 0.15 C (Class A)	+/- 0.5 C	+/- 0.5 C	+/- 0.5 C
pH Sensor	Yes (ADS1115)	No	Yes	No
Cloud Platform	Blynk	Blynk	Not specified	LINE Notify
Alert Logic	Peak-detection rule-based	Threshold	Threshold	Manual
Est. Cost (USD)	~105	Not reported	Not reported	~145

The proposed system offers several advantages over existing approaches. The use of a PT100 RTD with MAX31865 provides approximately three times better temperature accuracy than DS18B20- or DHT22-based systems. The structured nine-state firmware state machine with automatic recovery from connectivity failures provides more robust field operation than simpler firmware architectures. The EMA signal smoothing reduces noise-induced false triggers in the peak-detection algorithm. The OTA update capability enables continuous firmware improvement without physical device recovery. These features collectively represent a more mature engineering solution compared to existing prototypes, while maintaining a competitive cost below USD 110.

6. Conclusion

This paper presented the design and pilot implementation of a low-cost IoT-based temperature monitoring system for cacao fermentation optimisation. The system integrates a PT100 platinum RTD with a MAX31865 digital converter, an ESP32 Wi-Fi microcontroller, EMA signal smoothing, a rule-based fermentation stage detection algorithm, and the Blynk cloud platform for remote monitoring and automated alerts. The complete firmware architecture employs a nine-state finite-state machine to enable robust field operation, with automatic recovery from connectivity disruptions and support for over-the-air firmware updates.

Pilot deployment during a 5.5-day cacao fermentation confirmed that the system reliably captured temperature profiles consistent with established fermentation phase transitions documented in the literature. The peak-detection algorithm successfully identified all temperature decline events in aeration cycles, triggering timely turning alerts to the operator. The total hardware cost of approximately 3,680 THB (approximately USD 105) demonstrates that precision temperature monitoring for cacao fermentation is achievable at a price point accessible to smallholder producers and cooperatives, particularly given that the mobile hotspot component can be shared across multiple devices.

The contributions of this work include: (1) the integration of industrial-grade PT100 RTD sensing with cloud-based IoT monitoring for cacao fermentation, providing higher accuracy than consumer-grade sensors used in comparable systems; (2) the implementation of EMA signal smoothing with a characterised smoothing factor for fermentation temperature data; and (3) a peak-detection algorithm that provides adaptive, biology-informed turning guidance rather than fixed-schedule or simple threshold alerts. Future work will focus on multi-probe deployments for spatial temperature profiling, adaptive threshold learning from historical batch data, and extended field trials across multiple fermentation sites and cacao varieties.

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References

Adeleke, I. T., et al., Internet of Things (IoT) in the food fermentation process: A bibliometric review, Journal of Food Process Engineering, vol. 46, no. 3, article e14321, 2023.

Abijaude, J., Sobreira, P., Santiago, L., and Greve, F., Improving data security with blockchain and Internet of Things in the gourmet cocoa bean fermentation process, Sensors, vol. 22, no. 8, article 3029, 2022.

Analog Devices, MAX31865 RTD-to-Digital Converter Datasheet, Available: https://www.analog.com/en/products/max31865.html, Accessed March 2026.

Bayih, A. Z., Salau, A. O., Sewnet, E., et al., Utilization of Internet of Things and wireless sensor networks for sustainable smallholder agriculture, Sensors, vol. 22, no. 9, article 3273, 2022.

Blynk Documentation, Blynk.Edgent overview, Available: https://docs.blynk.io/en/blynk.edgent/overview, Accessed March 2026. (2024a)

Blynk Documentation, Over-the-air firmware updates (OTA), Available: https://docs.blynk.io/en/blynk-library-firmware-api/ota-updates, Accessed March 2026. (2024b)

Buonocore, D., Ciavolino, G., di Caro, D., and Liguori, C., An IoT-based beer fermentation monitoring system, Proceedings of the 2021 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), pp. 263-267, 2021.

Calvo, A. M., Botina, B. L., Garcia, M. C., Cardona, W. A., Montenegro, A. C., and Criollo, J., Dynamics of cocoa fermentation and its effect on quality, Scientific Reports, vol. 11, article 16746, 2021.

Camu, N., et al., Influence of turning and environmental contamination on the dynamics of populations of lactic acid and acetic acid bacteria involved in spontaneous cocoa bean heap fermentation in Ghana, Applied and Environmental Microbiology, vol. 74, no. 1, pp. 86-98, 2008.

Correa-Quiroz, J. J., Toribio-Barrueto, M. A., and Castro-Vargas, C., IoT system with ESP32 for smart drip irrigation and climate monitoring in greenhouses, Emerging Science Journal, vol. 9, no. 3, pp. 1133-1157, 2025.

De Vuyst, L., and Leroy, F., Functional role of yeasts, lactic acid bacteria and acetic acid bacteria in cocoa fermentation processes, FEMS Microbiology Reviews, vol. 44, no. 4, pp. 432-453, 2020.

De Vuyst, L., and Weckx, S., The cocoa bean fermentation process: From ecosystem analysis to starter culture development, Journal of Applied Microbiology, vol. 121, no. 1, pp. 5-17, 2016.

Devkota, R., et al., Design and implementation of Internet of Things (IoT) platform targeted for smallholder farmers: From Nepal perspective, Agriculture, vol. 13, no. 10, article 1900, 2023.

Farooq, M. S., Riaz, S., Abid, A., Abid, K., and Naeem, M. A., A survey on the role of IoT in agriculture for the implementation of smart farming, IEEE Access, vol. 7, pp. 156237-156271, 2019.

Galon, M. L. Q., Tumaliwan, M. V. R., and Sejera, M. M., Automated monitoring and control system of solar greenhouse using ESP32 and Blynk application, Engineering Proceedings, vol. 92, no. 1, article 57, 2025.

Guillermo, J. C., Garcia-Cedeno, A., Rivas-Lalaleo, D., Huerta, M., and Clotet, R., IoT architecture based on wireless sensor network applied to agricultural monitoring: A case of study of cacao crops in Ecuador, Advances in Intelligent Systems and Computing, vol. 893, Springer, 2019.

Hercog, D., Lerher, T., Truntic, M., and Tezak, O., Design and implementation of ESP32-based IoT devices, Sensors, vol. 23, no. 15, article 6739, 2023.

International Cocoa Organization (ICCO), Harvesting and post-harvest, Available: https://www.icco.org/harvesting-post-harvest-new/, Accessed March 2026. (2024)

International Electrotechnical Commission (IEC), IEC 60751:2008 Industrial platinum resistance thermometers and platinum temperature sensors, 2008.

Kongor, J. E., Hinneh, M., Van de Walle, D., Afoakwa, E. O., Boeckx, P., and Dewettinck, K., Factors influencing quality variation in cocoa (Theobroma cacao) bean flavour profile: A review, Food Research International, vol. 82, pp. 44-52, 2016.

Kontogiannis, S., Tsoumani, M., Kokkonis, G., Pikridas, C., and Kotseridis, Y., Proposed SmartBarrel system for monitoring and assessment of wine fermentation processes using IoT nose and tongue devices, Sensors, vol. 25, no. 13, article 3877, 2025.

Mazon-Olivo, B., Hernandez-Rojas, D., Maza-Salinas, J., and Pan, A., Rules engine and complex event processor in the context of Internet of Things for precision agriculture, Computers and Electronics in Agriculture, vol. 154, pp. 347-360, 2018.

Muangprathub, J., Boonnam, N., Kajornkasirat, S., et al., IoT and agriculture data analysis for smart farm, Computers and Electronics in Agriculture, vol. 156, pp. 467-474, 2019.

Papalexandratou, Z., et al., Species diversity, community dynamics, and metabolite kinetics of the microbiota associated with traditional Ecuadorian spontaneous cocoa bean fermentations, Applied and Environmental Microbiology, vol. 77, no. 21, pp. 7698-7714, 2011.

Quy, V. K., Van Hau, N., Van Anh, D., et al., IoT-enabled smart agriculture: Architecture, applications, and challenges, Applied Sciences, vol. 12, no. 7, article 3396, 2022.

Ruiz-Garcia, L., Lunadei, L., Barreiro, P., and Robla, J. I., A review of wireless sensor technologies and applications in agriculture and food industry: State of the art and current trends, Sensors, vol. 9, no. 6, pp. 4728-4750, 2009.

Sabila, L., Dwiyono, L., Hakim, A., Karuana, A., and Hakika, D., IoT-based monitoring system for temperature and pH control in cocoa fermentation, MOTIVECTION: Journal of Mechanical, Electrical and Industrial Engineering, vol. 7, no. 1, pp. 1-12, 2025.

Saguidon, J. R., Dellosa, J., and Mendoza, R. N., Internet-of-Things (IoT)-based automated temperature monitoring and control system for enhanced cacao fermentation quality, Proceedings of the 2024 IEEE Conference, 2024.

Samek, M., Practical UML Statecharts in C/C++: Event-Driven Programming for Embedded Systems, 2nd Edition, CRC Press, New York, 2008.

Sarkar, S., Platinum RTD sensor based multi-channel high-precision temperature measurement system for temperature range -100 C to +100 C using single quartic function, Cogent Engineering, vol. 5, no. 1, article 1558687, 2018.

Schwan, R. F., and Wheals, A. E., The microbiology of cocoa fermentation and its role in chocolate quality, Critical Reviews in Food Science and Nutrition, vol. 44, no. 4, pp. 205-221, 2004.

Serikul, P., Nakpong, N., and Nakjuatong, N., Smart farm monitoring via the Blynk IoT platform: Case study: Humidity monitoring and data recording, Proceedings of the 2018 16th International Conference on ICT and Knowledge Engineering, IEEE, pp. 1-6, 2018.

Singbua, P., Oajsalee, S., Traisom, P., et al., Development of an IoT-based temperature monitoring and display system for cocoa bean fermentation, Journal of Vongchavalitkul University, vol. 38, no. 2, pp. 115-128, 2025.

Tikapunya, T., Changes in physico-chemical and microbiological properties in Thai cocoa bean fermentation, Walailak Journal of Science and Technology, 2021.

Varshavskiy, I. E., Krasnova, A. I., and Polivanov, V. V., Efficiency estimation of the noise digital filtering algorithms, Proceedings of the 2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), pp. 724-727, 2019.

Varshavskiy, I. E., Dmitriev, I. A., Krasnova, A. I., and Polivanov, V. V., Selection of sampling rate for digital noise filtering algorithms, Proceedings of the 2020 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), pp. 932-935, 2020.

Biography

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