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IoT-Based Monitoring System for Temperature and pH Control in Cocoa Fermentation

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ABSTRACT

Cocoa fermentation plays a crucial role in cocoa bean production, as it directly influences the taste, aroma, and texture of the final product. Temperature and pH significantly impact microbial activity during fermentation, making their control essential for achieving optimal and consistent results. A promising solution is the implementation of an IoT-based system for temperature regulation and pH monitoring, allowing for real-time data tracking throughout the fermentation process. This study developed a cocoa fermentation box integrated with an IoT system, utilizing a DHT22 temperature sensor and a 4502C pH sensor for precise monitoring. The system enables real-time data access and remote control, improving efficiency and quality while transforming conventional manual observation methods into a standardized, data-driven approach. IoT technology facilitates rapid condition adjustments and predictive analysis, minimizing human error and reducing the risk of fermentation inconsistencies. The experimental results demonstrated high sensor accuracy, with the IoT system successfully enhancing efficiency, control, and cocoa bean quality. In the 1 kg cocoa test, temperatures ranged from 28°C to 35°C, with pH values between 4.0 and 5.3. In the 10 kg experiment, temperatures on the second day ranged from 28°C to 33°C with pH values between 4.3 and 5.9, while on the third day, temperatures ranged from 28°C to 32°C, with pH values stabilizing between 4.0 and 5.3.

Keywords
Cocoa Fermentation, IoT-Based Monitoring, Temperature and pH Control, Real-Time Data Tracking

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INTRODUCTION

Indonesia is the third-largest cocoa producer globally, following Côte d'Ivoire and Ghana, with a production area of 1.73 million hectares [1]–[4]. Cocoa is cultivated across state-owned, private, and smallholder plantations, contributing to the production of dry cocoa beans [5]–[7]. The processing of fresh cocoa beans involves hulling, fermentation, washing, drying, sorting, and storage, all of which are essential for producing high-quality dry cocoa beans used in the food, cosmetics, and pharmaceutical industries [8], [9]. The flavor and aroma of cocoa beans are greatly influenced by the fermentation process [10]–[12]. In Indonesia, many farmers still rely on manual fermentation monitoring using conventional measuring instruments to record temperature and pH, which often results in inaccuracies and inconsistencies. Moreover, remote monitoring technology has not been widely adopted, hampering efficiency and consistency in the fermentation process [13], [14]. To improve cocoa quality, modern fermentation techniques are necessary. Implementing advanced monitoring technologies can enhance accuracy, efficiency, and standardization, ensuring better fermentation outcomes and higher-quality cocoa products.

Farmers generally still rely on manual conventional measuring instruments to monitor the fermentation process of cocoa beans, which is time-consuming and labor-intensive [15]–[18]. This process requires continuous recording of temperature and pH changes, with farmers having to actively regulate temperature to maintain optimal conditions [19]–[22]. However, this method is inefficient and prone to inaccuracies due to human error in manual measurements, which can slow down production and impact cocoa bean quality [23]–[26]. Additionally, the absence of a remote monitoring system forces farmers to be physically present to supervise and regulate fermentation.

To address this issue, researchers have developed a cocoa bean fermentation box integrated with a modern Internet of Things (IoT) system for temperature and pH monitoring. IoT applications in agriculture are widely used for smart irrigation, soil moisture monitoring, plant nutrient management, and early pest detection. Integrating IoT technology into the fermentation process not only enhances efficiency but also enables farmers to make real-time data-driven decisions [27]–[29]. The system displays temperature and pH data on an LCD and supports remote monitoring via mobile devices, allowing farmers to manage fermentation without being on-site constantly. Additionally, the fermentation box is equipped with two cooling fans for automatic temperature regulation, ensuring consistent fermentation conditions. This automated control system improves efficiency, consistency, and overall cocoa bean quality, addressing the limitations of conventional methods.

METHOD

The system design process involves developing a new and improved system to enhance performance and efficiency. To achieve optimal results, the design process references various sources and incorporates several key components, including the system block diagram, system flow diagram, system wiring diagram, and tool product design. The system utilizes sensor inputs to detect changes in physical conditions, which are then processed to generate the required output data. The processing device relies on various software libraries to facilitate data handling, particularly when using ESP32 hardware.

At this stage, software design is implemented by programming the ESP32 MCU Node controller. The program is developed using Arduino IDE and uploaded to the ESP32 board via USB connection. The software development process begins with the creation of a Temperature Controlling & pH Monitoring program, which is then integrated with a data transmission program for real-time monitoring. This combined system enables ESP32 to process and execute monitoring functions efficiently. The flowchart illustrating the Temperature & pH Monitoring system is presented in Figure 1.

Figure 1 illustrates the system workflow, where the ESP32 first establishes a WiFi connection. If the connection is successful, ESP32 then attempts to connect to the Blynk server. In cases where the connection fails, ESP32 will continuously retry until a successful connection to WiFi and Blynk is established. Once connected, the temperature and pH sensors begin reading input data and transmitting it to ESP32. If the temperature exceeds 50°C, the cooling fan is activated to regulate the temperature. When the temperature drops below 50°C, the fan automatically turns off. ESP32 then processes the sensor data from the 4502C Temperature Sensor and pH Sensor and sends the output data to both the I2C LCD display and the IoT system for real-time monitoring. The system block diagram, which illustrates the main components and their interconnections, is presented in Figure 2.

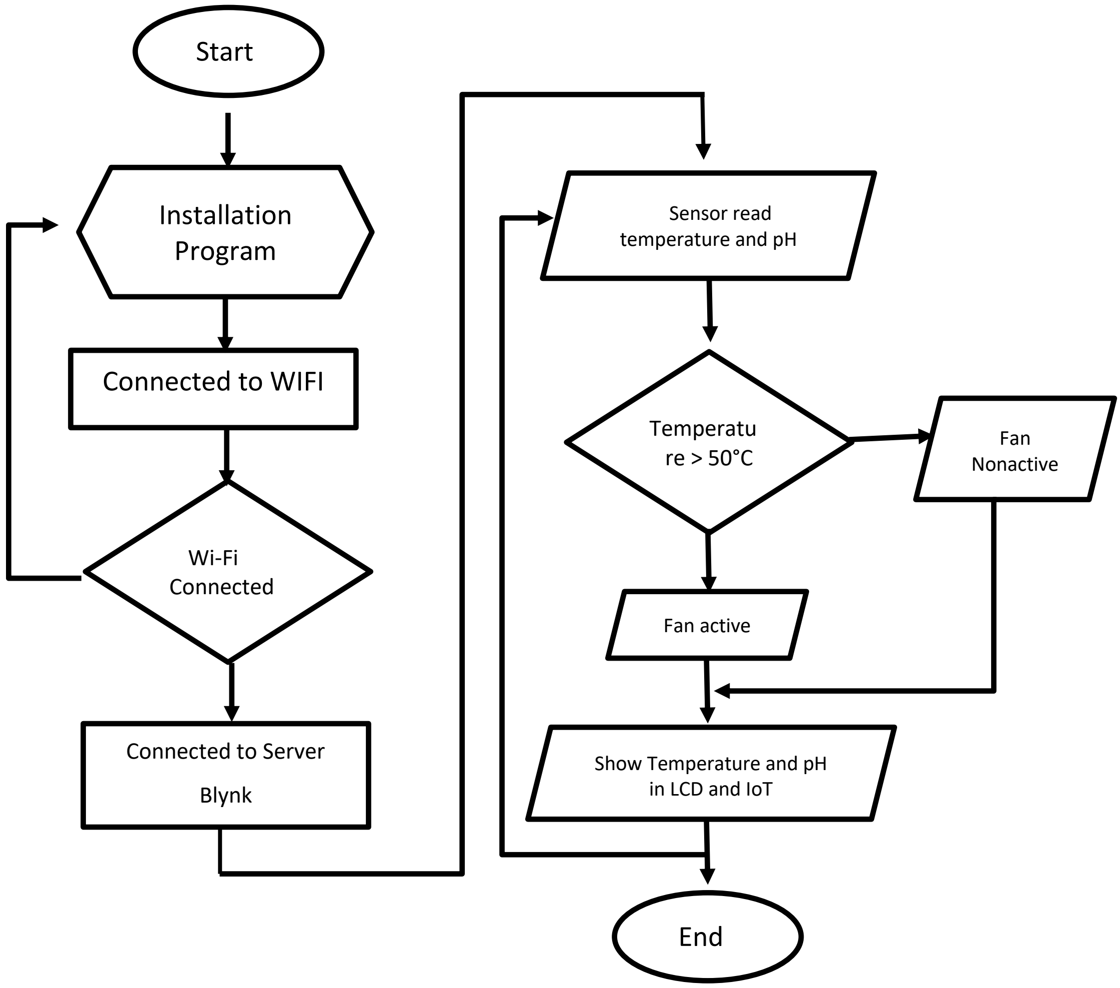

Figure 1. Temperature & pH Monitoring Flowchart

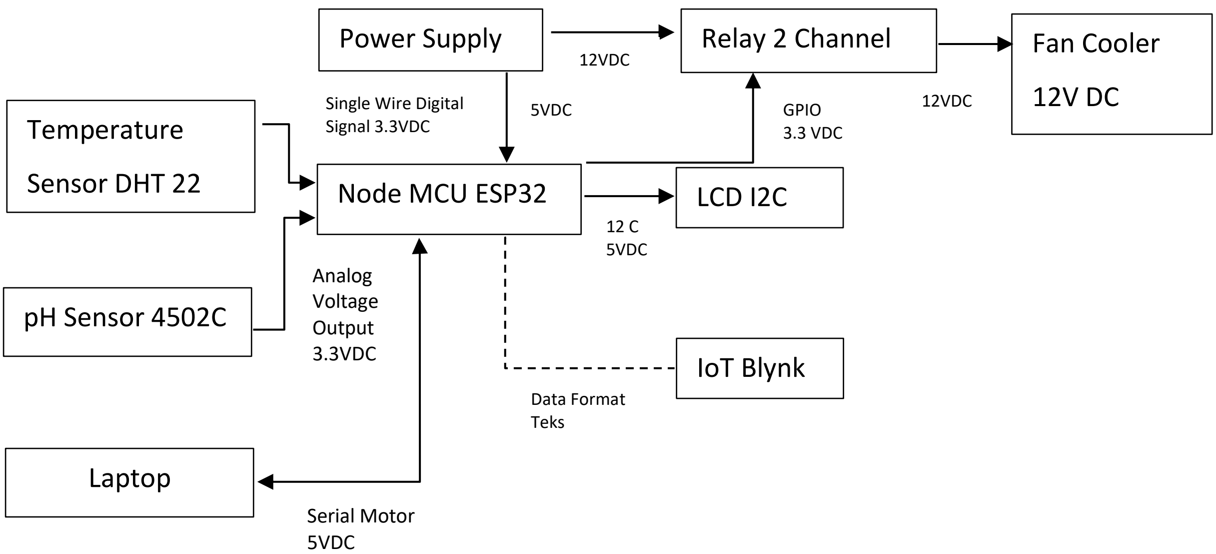

Figure 2. Block Diagram

Figure 2 presents the system block diagram, illustrating the interaction between components. Data from the temperature and pH sensors are transmitted to the ESP32 MCU

Node, which processes the information. The ESP32 then controls the relay module to activate or deactivate the cooling fan based on the detected temperature levels. Additionally, the processed data is sent to the I2C LCD display for on-site monitoring and transmitted to IoT Blynk for remote access. The data is formatted appropriately: temperature readings are sent as digital data, while pH measurements are transmitted as analog data. Through IoT Blynk, users can access the data in text format via a mobile app or website, enabling real-time system monitoring and control. A schematic circuit is designed to visualize the 2D wiring connections, illustrating how each component is linked within the system. Additionally, a 3D model is developed to provide a realistic representation of the system's physical structure, serving as a reference for prototype development. The 3D design results are presented in Figure 3.

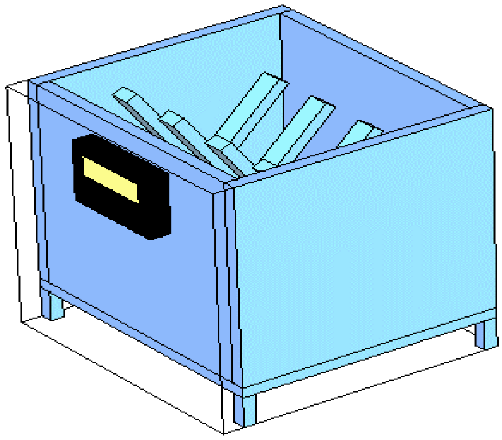

Figure 3. 3D Design

Calibration Data of DHT 22 Sensor and 4502C Sensor

Sensor calibration is conducted to verify the accuracy of the sensors used in the system and to minimize errors during operation. The calibration process utilizes IoT-based data display for real-time monitoring. The calibration procedure involves comparing sensor readings with reference measurements from a digital thermometer for temperature calibration and a pH buffer solution for pH calibration. The accuracy of the sensors is assessed by calculating the difference between the sensor readings and the reference values, using the temperature difference formula (Equation 1) and the temperature error formula (Equation 2). The calculated error values and sensor accuracy results are presented in Figures 4, 5, and 6, illustrating the calibration performance of both sensors.

$$(\Delta T = |\mathrm{T(DHT22)} - \mathrm{T(Termometer)}|) \tag{1}$$

$$\left(\text{Eror Relatif} = \left(\frac{|\mathrm{T(Termometer)} - \mathrm{T(DHT22)}|}{\mathrm{T(DHT22)}}\right) \times 100\%\right) \tag{2}$$

Figures 4, 5, and 6 present the temperature measurement results obtained from the DHT22 sensor and a digital thermometer during three different periods: morning, afternoon, and evening. Measurements were recorded every 10 minutes over a 50-minute period for each time frame. The average relative error was 0.59% in the morning, increasing to 0.72% in the afternoon, and reaching 0.80% at night, indicating minor variations in sensor accuracy across different conditions. For pH calibration, the 4502C pH sensor was tested using a pH meter and buffer solutions with values of 4, 7, and 10. This calibration process involved comparing the sensor’s readings with reference values from the standard buffer solutions. Using the IoT system display, the sensor's output was directly compared to the standard buffer values to assess accuracy and consistency. The calibration results are visualized in Figures 7, 8, and 9, showing the performance and error margins of the pH sensor under different conditions.

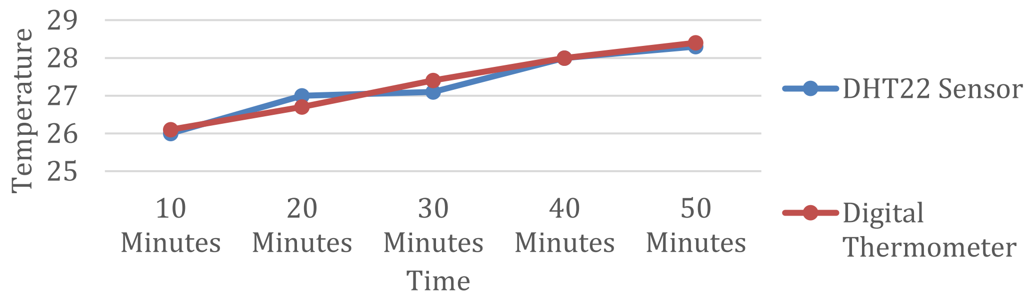

Figure 4. Morning Temperature Graph Data

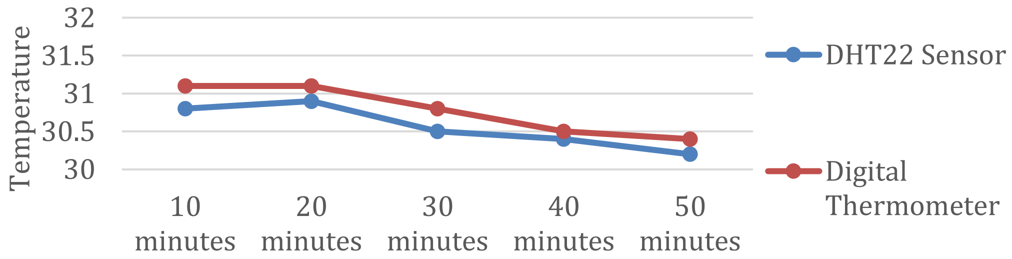

Figure 5. Daytime Temperature Graph Data

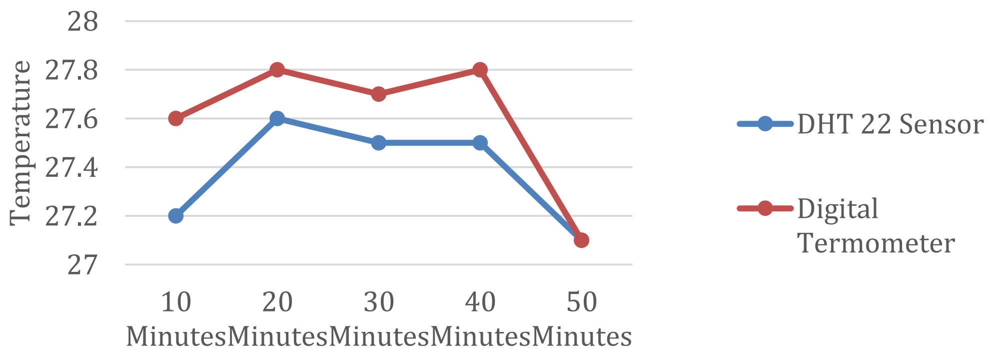

Figure 6. Night Temperature Graph Data

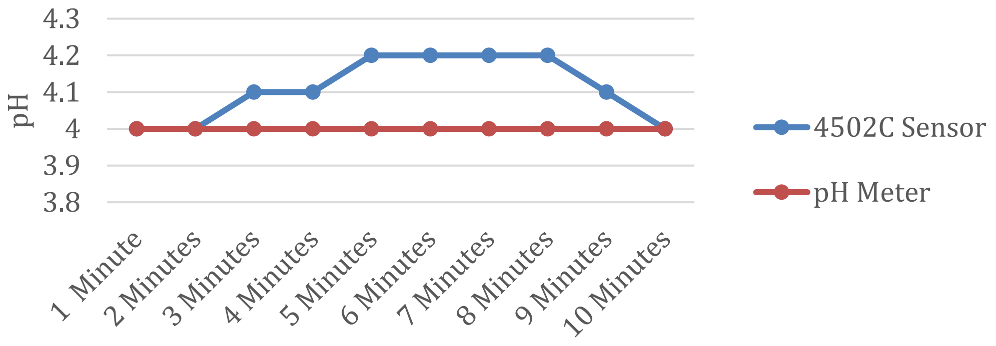

Figure 7. Acid pH graph

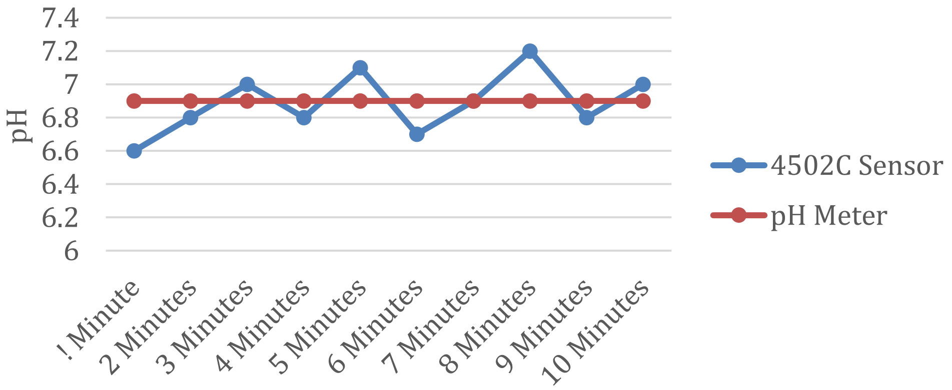

Figure 8. Neutral pH graph

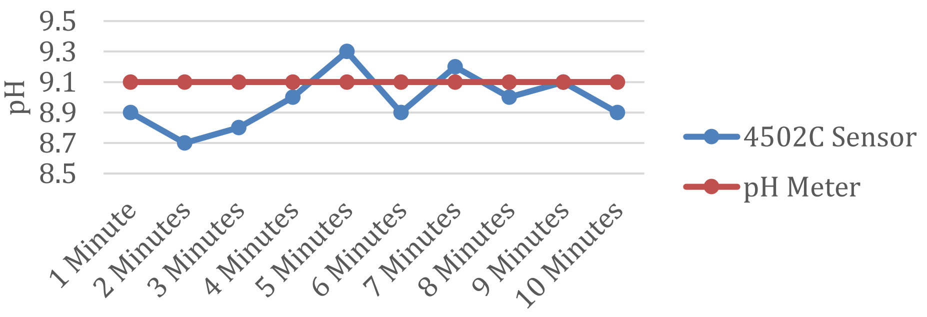

Figure 9. pH Chart of Bases

Figures 7 to 9 illustrate the pH measurement differences between the 4502C pH sensor and the comparison tool. The deviations between the devices are minimal and within an acceptable range. The measurement error of the 4502C sensor is determined based on the total error for acidic, neutral, and alkaline solutions, with an average error of 2.6% for acidic pH, 2.2% for neutral pH, and 2.0% for alkaline pH. Fluctuations in the 4502C sensor readings are likely caused by voltage instability, which can affect measurement accuracy. Sensor accuracy is evaluated by comparing the DHT22 temperature sensor and the 4502C pH sensor against a digital thermometer and pH buffer solutions. The results indicate that the error for each sensor remains below 3%, confirming that the sensors used in this study provide reliable accuracy.

RESULT AND DISCUSSION

Sensor Testing in 1 kg Cocoa Fermentatio

The DHT22 temperature sensor and 4502C pH sensor were tested in a sealed cocoa fermentation box containing 1 kg of cocoa beans. The box is equipped with a fan that automatically activates when the temperature reaches 50°C, ensuring that excess heat is expelled and the internal temperature remains below 50°C. The objective of this test was to monitor real-time temperature and pH variations during fermentation, a critical phase influencing cocoa bean quality. Data was collected 10 times per hour over a 10-hour period, providing a detailed analysis of the fermentation conditions. The DHT22 sensor recorded temperature and humidity, while the 4502C sensor monitored pH fluctuations within the fermentation box. The results of the monitoring process, calculated using the previously defined formulas, are presented in Table 1.

Table 1. Fermentation Monitoring Results on 1 kg cocoa beans

No.	Temperature (°C)	pH	Voltage (V)	Fan
1	30.0	4.6	3.2	OFF
2	35.1	4.7	3.2	OFF
3	33.6	4.7	3.2	OFF
4	33.2	4.8	3.2	OFF
5	33.0	5.0	3.1	OFF
6	34.7	5.3	3.1	OFF
7	32.9	4.7	3.2	OFF
8	31.5	4.3	3.2	OFF
9	29.8	4.0	3.3	OFF
10	28.4	4.0	3.3	OFF

Based on Table 1, the DHT22 sensor recorded temperature fluctuations between 28.4°C and 35.1° cover the 10-hour monitoring period, covering data collection from morning to night. The initial temperature was 30.0°C, gradually decreasing to 28.4°C by the end of the test. These variations are likely influenced by natural temperature changes occurring throughout the day, affecting the internal conditions of the fermentation box. Meanwhile, the 4502C pH sensor recorded pH variations ranging from 4.0 to 5.3 during the same period. The data indicate that the pH initially measured at 4.6 gradually increased to 5.3 before stabilizing at 4.0. This pH fluctuation is likely attributed to microbial activity and biochemical reactions occurring during the fermentation process, which play a key role in the development of cocoa bean quality.

Sensor Testing in 10 kg Cocoa Fermentation

In the second test, fermentation was conducted using 10 kg of cocoa beans, with data collection carried out on the second and third days of the fermentation process. Measurements were recorded every 15 minutes, providing a detailed observation of fermentation dynamics. A total of 15 data points were collected each day to accurately track progress and variations during this period. The second test began in the afternoon and continued into the evening, with data recorded at regular intervals throughout the process. The primary objective was to monitor temperature and pH fluctuations, capturing the real-time impact of fermentation on cocoa bean conditions. The experimental results, including temperature and pH trends, are illustrated in Figures 10 and 11.

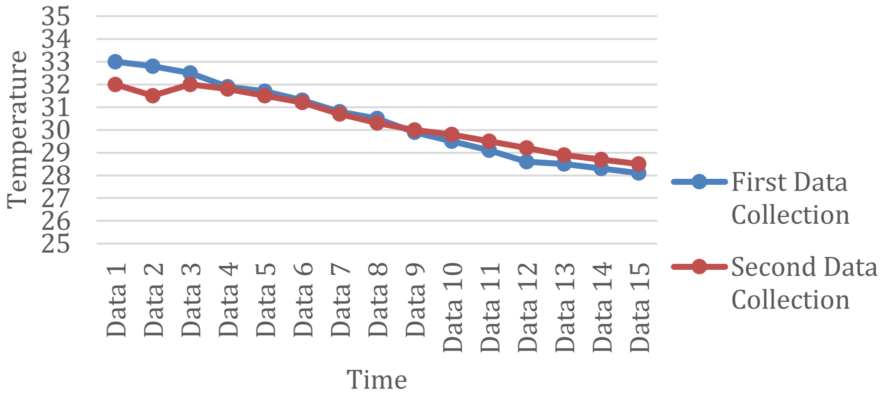

Figure 10. Temperature Comparison Chart of Fermented Cocoa Beans 6 kg

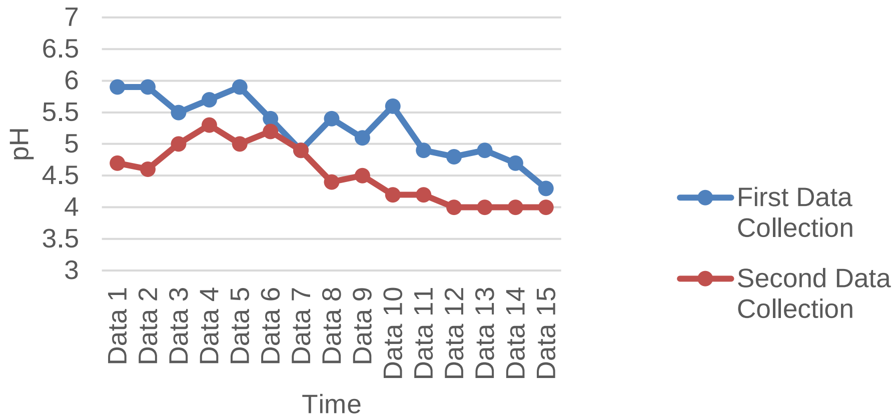

Figure 11. pH Comparison Chart of Fermented Cocoa Beans 6 kg

Based on the monitoring data from the DHT22 and 4502C sensors, collected on the second day (first data collection) and the third day (second data collection) of cocoa bean fermentation, both temperature and pH exhibited a consistent pattern of change. On the second day of fermentation, the temperature gradually decreased from 33.0°C in the afternoon to 28.1°C in the evening. This decline is likely influenced by the transition from afternoon to evening, as ambient temperatures naturally drop. The pH values varied between 4.3 and 5.9, while voltage remained stable between 3.0V and 3.2V. The pH fluctuations indicate possible changes in fermentation conditions, whereas the stable voltage suggests that the 4502C pH sensor operated reliably, providing consistent readings throughout the measurement period.

On the third day of fermentation, the temperature continued to decrease from 32.0°C to 28.5°C, following a similar gradual decline pattern. This trend is also attributed to data collection occurring from late afternoon to evening. The pH remained within the range of 4.0 to 5.3, showing greater stability compared to the second day, indicating more consistent fermentation conditions.

A temperature comparison between the second and third days of cocoa bean fermentation revealed a consistent decrease in temperature from afternoon to evening. On the second day, the temperature dropped from 33.0°C to 28.1°C, with minor fluctuations due to the transition from afternoon to night. In contrast, on the third day, the temperature started at 32.0°C and decreased to 28.5°C, showing a more stable and gradual decline under similar time conditions.

The pH comparison between the second and third days also displayed distinct variations. On the second day, pH values ranged between 4.3 and 5.9, with relatively large fluctuations throughout the data collection period, indicating active fermentation changes. Conversely, on the third day, the pH range narrowed to 4.0–5.3, with smaller fluctuations, suggesting a more stable fermentation process. The pH graph further illustrates that while pH variations were present, the decrease in fluctuation on the third day indicates that fermentation had reached a more stable phase.

Temperature fluctuations recorded in the first test (28.4°C to 35.1°C) may influence the rate and outcome of fermentation. The optimal temperature range for microbial activity in cocoa fermentation is typically 40°C to 50°C. Temperatures outside this range can slow down or inhibit microbial activity, affecting the formation of key organic acids responsible for the flavor and aroma of cocoa. In the second test, the more stable temperature on the third day suggests a more controlled and mature fermentation process, leading to more consistent cocoa bean quality. Meanwhile, the pH values (4.0–5.3) recorded in the second test suggest conditions that could still influence fermentation dynamics. The increase in pH from 4.6 to 5.3 during the first test likely indicates active microbial growth. A more stable pH decrease on the third day of the second test, remaining between 4.0 and 5.3, reflects an optimal and controlled fermentation state.

Overall, well-regulated temperature and pH play a crucial role in determining cocoa bean quality. The implementation of sensor-based IoT monitoring technology, which enables real-time temperature and pH control, ensures that fermentation conditions remain stable and optimal. This technology contributes to the production of higher-quality cocoa beans, with improved taste, aroma, and texture.

Application of The Internet of Things (IoT)

The integration of the Internet of Things (IoT) into the cocoa bean fermentation box was successfully implemented using the Blynk application. This system enables real-time monitoring of fermentation temperature and pH via a smartphone, utilizing an internet connection. With Blynk, users can remotely track fermentation conditions, receive instant notifications of significant parameter changes, and ensure that temperature and pH remain within the optimal range without requiring physical presence at the site. This feature enhances efficiency and convenience, allowing for more precise and controlled fermentation management. The Blynk application interface and settings used in this study are illustrated in Figure 12.

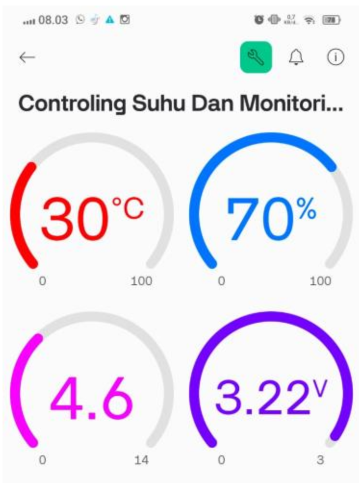

Figure 12. IoT view in Blynk

CONCLUSION AND RECOMMENDATION

Conclusion

This study successfully developed and implemented an IoT-based monitoring system for cocoa bean fermentation, enabling real-time temperature and pH tracking via the I2C LCD and Blynk application. The calibrated sensors provided accurate and reliable data, ensuring effective monitoring of fermentation conditions. The IoT system allowed for efficient remote access, making it easier to track fermentation progress without requiring on-site supervision. In the 1 kg cocoa fermentation test, temperatures ranged from 28°C to 35°C, with pH values between 4.0 and 5.3. In the 10 kg experiment, temperatures on the second day ranged from 28°C to 33°C, with pH values between 4.3 and 5.9, while on the third day, temperatures ranged from 28°C to 32°C, with pH values stabilizing between 4.0 and 5.3. These results confirm that IoT integration significantly enhances fermentation monitoring, ensuring better control over temperature and pH stability, which are crucial for optimizing cocoa bean quality.

Recommendation

Based on these conclusions, several recommendations can be considered. Future developments should focus on enhancing sensor capabilities to measure additional parameters such as oxygen levels and humidity, providing a more comprehensive understanding of fermentation conditions. The findings have significant implications for the cocoa industry, particularly in improving efficiency and consistency in the production of high-quality cocoa beans. Integrating IoT technology with predictive analytics can further optimize the fermentation process, reducing reliance on manual supervision and improving overall product quality. This approach can help minimize waste, enhance flavor, aroma, and texture, and enable remote monitoring from multiple locations, increasing competitiveness in the global cocoa market.

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