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Web-Based Monitoring System for Automatic Coffee Drying in a Smart Dryer Dome

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ABSTRACT

This study designed and implemented a web-based monitoring system to automate the coffee drying process in a Smart Dryer Dome (SDD). The system enables real-time monitoring and control of temperature, humidity, and light intensity to improve post-harvest efficiency. A microcontroller is integrated with environmental sensors and operates actuators (fans and heating lamps) automatically based on temperature thresholds of 45–50 °C and humidity of 20–40% relative humidity. Sensor data are transmitted using the MQTT protocol and visualized via a Laravel-based dashboard for remote monitoring. System evaluation was conducted during an eight-hour daytime test under overcast conditions. Results showed that the system responded to environmental changes and operated actuators according to control logic. However, the average temperature reached only 33.33 °C (standard deviation: 2.40), and humidity 54.93% relative humidity (standard deviation: 5.40), indicating suboptimal conditions. The average light intensity was 1,367.35 lux (standard deviation: 479.25). Despite these deviations, the system demonstrated stable operation in maintaining the drying environment. The integration of solar energy further supports the sustainability aspect of the design. Future work should include full-cycle drying tests and evaluation of final product quality, particularly the moisture content of dried beans, to validate long-term performance and system effectiveness in post-harvest coffee processing.

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1. INTRODUCTION

Indonesia, the world's largest archipelagic country and a major global coffee producer, faces significant challenges in the post-harvest drying phase. In 2023, national coffee production reached 758,730 tons, with *Robusta* accounting for approximately 90% and 279,940 tons exported [1], [2], [3], [4]. This commodity plays a strategic role in the national economy and serves as a primary livelihood for millions of farmers. However, most farmers still rely on traditional drying methods that depend on direct sunligh [5], This dependence makes the drying process vulnerable to unpredictable weather, such as rain, which slows moisture reduction, promotes fungal growth, and decreases coffee bean quality.

The final product quality is directly influenced by drying conditions. Drying duration varies depending on the coffee type and processing method, ranging from 7–15 days for *kopi parutan* (pulped coffee), 12–21 days for *kopi mucilage*, and up to 30–45 days for *kopi ceri* (whole cherry coffee) [6], [7]. Temperature fluctuations whether too low or too high can deteriorate the physical and sensory quality of the beans [8], [9]. The moisture content of coffee beans must be maintained below 12% to prevent the growth of pathogenic fungi such as *Penicillium*, *Aspergillus ochraceus*, and *Aspergillus niger* [10], [11]. However, at the farm level, moisture content often exceeds 16% and may reach up to 20% in certain regions [10], indicating the need for a more controlled drying method.

The development of the *Smart Dryer Dome* (SDD) aims to provide stable drying conditions. This semi-enclosed structure utilizes natural airflow and ambient temperature to create an optimal microclimate, thereby reducing reliance on sunlight and minimizing contamination risks [12]. The SDD can also be applied in remote areas without access to conventional electricity. Accurate and real-time monitoring of temperature and humidity is essential to ensure the quality of dried coffee [13], [14], [15], [16], [17], [18], [19], [20]. The *International Coffee Organization* (ICO) reports that approximately 70% of global coffee drying still uses natural methods [21]. The ICO standard recommends a drying temperature of 49–60 °C with a maximum final temperature of 55 °C. Higher drying temperatures (60 °C) can reduce processing time by up to 65% compared to lower temperatures (45 °C) [7], [22]. Environmental control limits of 45–50 °C and 20–40% RH were selected to balance energy efficiency with product quality during the drying process [23].

The advancement of the *Internet of Things* (IoT) has enabled real-time environmental monitoring. Several automated agricultural systems have been developed [17], [24], [25], [26], but many are not yet integrated with *Smart Dryer Dome* structures or lack a complete web interface. Most previous systems only offer basic monitoring with user interfaces that are not optimized for field conditions.

This study proposes a web-based monitoring system connected to an ESP32 microcontroller, RN-GZWS-RS485 sensor, and automated actuators. The system measures temperature, humidity, and light intensity and displays them in real time through a Laravel-based interface using MQTT and Modbus communication protocols [27], [28], [29]. This approach is expected to improve control accuracy, facilitate remote monitoring, and support sustainable application in rural areas.

The research aims to develop an automated monitoring system for the *Smart Dryer Dome* to maintain temperature and humidity within the ideal range in real time, while evaluating its performance stability in a semi-enclosed environment. However, evaluation of final product quality, such as the moisture content of dried beans, has not yet been comprehensively conducted.

2. RESEARCH METHOD

This section outlines the methodology employed in the development and evaluation of the web-based automated coffee drying monitoring system. The main stages include system design, hardware and software integration, and system performance testing.

2.1. Design and Research Object

The research object was a *Smart Dryer Dome* (SDD) located at SMK Negeri 1 Jarai. The dome structure was designed to create a controlled drying environment by optimizing natural airflow and utilizing solar energy. Figure 1(a) shows the exterior view of the dome, while Figure 1(b) presents the interior, which includes multi-level drying racks, heating lamps, and a system control box.



(a) (b)

Figure 1. Exterior and interior views of the Smart Dryer Dome

2.2. System Architecture

The automatic control system consists of three main components: input, processing, and output, as shown in Figure 2. The RN-GZWS-RS485 sensor measures temperature, humidity, and light intensity. Data is sent to the ESP32 microcontroller via RS-485 to TTL for processing. The ESP32 applies control logic based on predefined thresholds. The actuators include six incandescent lamps and two exhaust fans, activated automatically through relays to stabilize drying conditions.

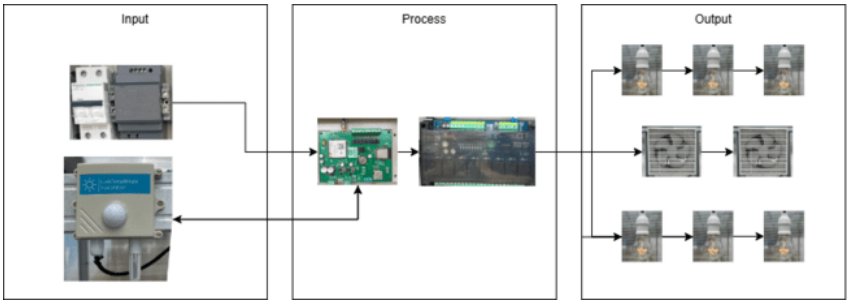


Figure 2. Block diagram of the automated coffee drying control system.

The overall structure of the monitoring system is illustrated in Figure 3. The system includes a solar panel that supplies power to a battery via a charge controller, which is then converted into alternating current (AC) by an inverter. This renewable energy source enables independent operation of the microcontroller, sensors, and actuators without relying on conventional grid power. Environmental parameters are transmitted to the server using the MQTT communication protocol. The received data is processed and visualized through a Laravel-based web interface, allowing remote monitoring and control of the system by the operator.

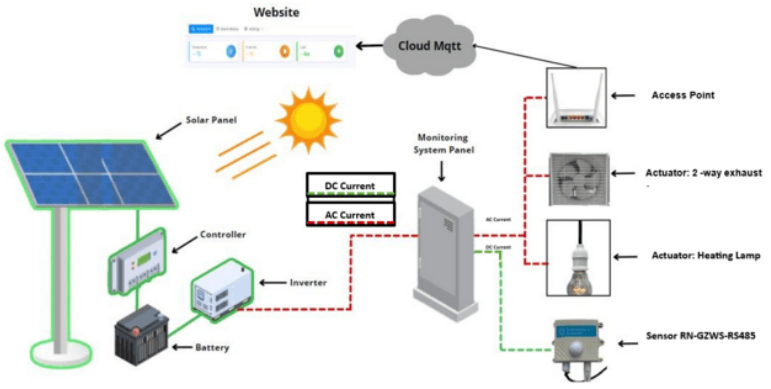


Figure 3. Architecture of the automated coffee drying monitoring system

The communication and control flow is depicted in Figure 4. Environmental parameters are sensed and transmitted to the ESP32 microcontroller, where the data is processed based on predefined control logic. Output signals are then sent to the relay module to regulate the actuators according to the current conditions. Simultaneously, the microcontroller connects to an access point and forwards the data to a cloud platform using the MQTT protocol, enabling online monitoring via a web-based dashboard.

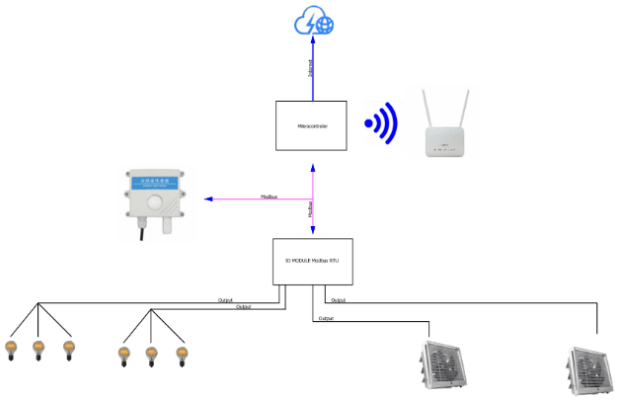


Figure 4. Communication and control diagram of the web-based system

2.3. Automatic Control Logic

The automatic control logic of the system is illustrated in Figure 5, showing the flow from sensor data acquisition to actuator operation. The RN-GZWS-RS485 sensor detects temperature, humidity, and light intensity, transmitting the data to the ESP32 microcontroller via an RS-485 connection.

The microcontroller executes control decisions based on predefined environmental thresholds. The decision-making mechanism includes three main conditions:

1) When the temperature is below 45 °C and/or the relative humidity exceeds 40% RH, the heating lamps are activated to raise the temperature and reduce humidity.
2) When the temperature exceeds 50 °C and/or the humidity drops below 20% RH, the exhaust fans are activated or the lamps are turned off to lower the temperature and stabilize humidity.
3) When both temperature and humidity are within the optimal range of 45–50 °C and 20–40% RH, the system remains in monitoring mode without activating any actuators.

The entire process operates autonomously without manual intervention. Sensor readings are transmitted to the web interface, where real-time data is visualized in the form of graphs, digital indicators, and historical logs. This presentation enables comprehensive monitoring and system performance evaluation.

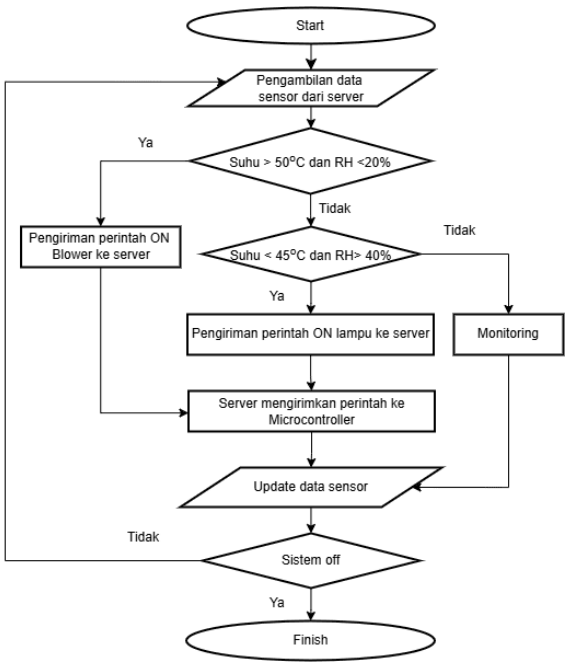
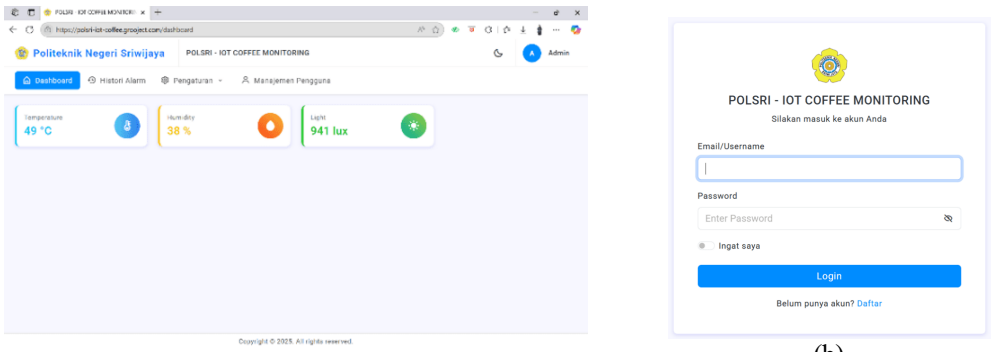


Figure 5. Flowchart of the automatic control logic in the coffee drying system.

2.4. System Software and User Interface

The web interface was developed using the Laravel framework and serves as the central platform for real-time system monitoring. The dashboard provides comprehensive information on temperature, humidity, light intensity, and actuator status, as shown in Figure 6.

Figure 6(a) displays real-time data visualization integrated with an environmental parameter observation database. This feature enables users to efficiently access both current conditions and historical records. Figure 6(b) shows the authentication module implemented to ensure user data security and integrity. Through this interface, users can monitor drying conditions, review historical data, and remotely control the system with flexibility.



(a) (b)

Figure. 6 Coffee drying monitoring and control dashboard interface

2.5. Testing Procedure and Data Analysis

System testing was conducted over an eight-hour period, from 09:26 to 16:26 Western Indonesia Time (WIB), during the rainy season. Overcast conditions predominated the test location at SMK Negeri 1 Jarai, significantly affecting the solar panel's power availability. As a result, actuator performance particularly the heating lamps was suboptimal due to limited energy supply.

The testing scope did not include a full drying cycle, which typically spans several days to weeks. Seasonal variations and drying loads were also not included in this phase. Nevertheless, temperature, humidity, and light intensity data were consistently collected using the RN-GZWS-

RS485 sensor. All data were transmitted to the server via the MQTT protocol and stored automatically in a database for analysis.

System performance was evaluated based on its ability to maintain environmental parameters within the ideal thresholds of 45–50 °C for temperature and 20–40% RH for humidity. The following key metrics were used:

1) Percentage of time each environmental parameter remained within the ideal range
2) Mean and standard deviation values of each parameter (temperature, humidity, and light intensity)

The analysis employed the following formulas:

Mean value:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \quad [30]$$

where *Xi* is the individual data point and n is the total number of observations.

Standard deviation:

$$\sigma x = \sqrt{\frac{1}{n-1}}\sum_{i=1}^{n} (X_i - \bar{X})^2 \quad [31]$$

The percentage of data falling within the ideal range was calculated to determine the duration during which temperature and humidity stayed within the predefined setpoints. This approach follows measurement and control methodologies outlined in previous studie [32], [33]. Percentage within ideal range:

$$P = (\frac{F}{N})\, x\, 100\% \quad [34]$$

where *F* is the number of data points within the ideal range, and *N* is the total number of data points.

This analytical approach was applied to assess system stability in maintaining drying chamber conditions near the target values. The results served as the basis for evaluating the effectiveness of automatic control and identifying operational limitations.

3. RESULTS AND DISCUSSION

System testing focused on evaluating the role of the web-based monitoring platform in automating the coffee drying process. The assessment included the system's ability to monitor and regulate environmental conditions specifically temperature, humidity, and light intensity within the drying chamber. Testing prioritized the accuracy of actuator responses to predefined control logic and the system's performance in maintaining environmental parameters within the target range.

Data analysis addressed three core aspects: (1) the stability of temperature and humidity control, (2) system responsiveness to environmental fluctuations, and (3) the accuracy of automated control actions relative to threshold values.

3.1. Sensor Data Visualization

The real-time monitoring interface was developed using the *Laravel* framework, which presents environmental data captured from the RN-GZWS-RS485 sensor. This includes temperature, relative humidity, and light intensity within the Smart Dryer Dome. As shown in Figure 7, the dashboard recorded a temperature of 49 °C, relative humidity of 38%, and light intensity of 941 lux at the time of observation.

The system is designed to maintain temperature within 45–50 °C and relative humidity between 20–40%. Although the displayed snapshot may not fully represent the broader dataset analyzed in subsequent sections, it demonstrates the interface's real-time responsiveness and visualization capabilities. With remote access via an internet connection, users can continuously monitor environmental conditions and intervene promptly when deviations occur. This feature

enhances the operational reliability of the system, particularly in semi-supervised or remote drying environments.

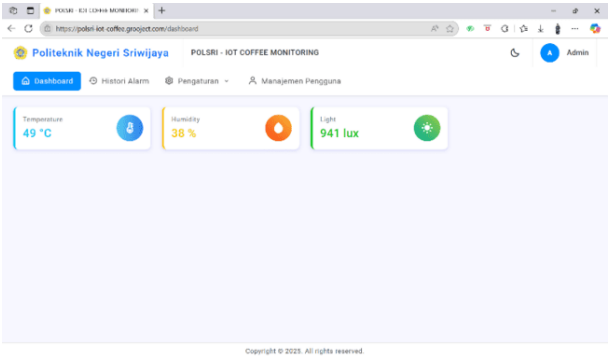


Figure 7. Web interface displaying real-time temperature, humidity, and light intensity

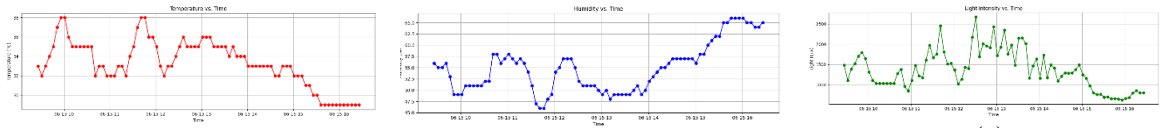
3.2. Environmental Parameter Trends

The RN-GZWS-RS485 sensor provided real-time data on temperature, relative humidity, and light intensity within the drying chamber. The recorded trends are visualized in Figure 8 and were used to evaluate the system's capability to regulate environmental parameters near the defined thresholds and to assess its responsiveness to dynamic changes in the chamber conditions.

Figure 8(a) shows the internal temperature profile throughout the testing period. Temperature values frequently fell below the lower threshold of the ideal setpoint range (45–50 °C), suggesting insufficient thermal input. In response, the control system automatically activated incandescent heating lamps to increase the chamber temperature.

Figure 8(b) illustrates the trend of relative humidity (RH). Initial RH readings ranged between 50% and 56%, exceeding the targeted range of 20%–40%. This condition triggered the system's drying mechanism. The control logic prioritized temperature evaluation to determine whether to activate the exhaust fans or maintain heating to balance both temperature and humidity.

Figure 8(c) presents the light intensity fluctuations inside the chamber. Although this parameter was not directly involved in the actuator control logic, it was monitored as a reference to assess environmental stability, particularly regarding natural thermal contributions from solar radiation.



(a) (b) (c)

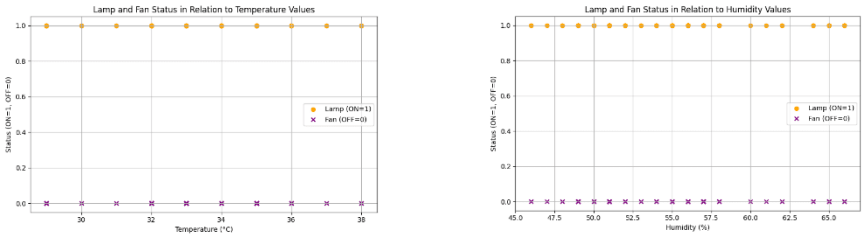
Figure 8. Trends of environmental parameters during the drying process.

3.3. System Response and Actuator Behavior

Sensor readings depicted in Figure 8 reveal that the temperature within the drying chamber frequently remained below the ideal range of 45–50 °C, while relative humidity often exceeded 40% during the observation period. These deviations from the target thresholds indicate that the environmental conditions were suboptimal for effective coffee drying. In response, the automated system triggered the heating lamps to increase ambient temperature and facilitate humidity reduction.

Figure 9 illustrates the actuator behavior relative to environmental parameters. In Figure 9(a), the actuator status is plotted against temperature values. When the temperature fluctuated between 29 °C and 35 °C, the heating lamps remained active (ON = 1), while the exhaust fans stayed inactive (OFF = 0). This pattern indicates that additional heating was required and that ventilation was unnecessary at these temperature levels.

Figure 9(b) shows actuator activity in relation to relative humidity. During periods when RH ranged from 47% to 65%, the heating lamps continued to operate, whereas the exhaust fans remained off. This suggests the system prioritized heat generation to accelerate drying as the humidity levels remained outside the desired 20–40% RH range. The selective activation of the lamps, combined with the delayed engagement of the fans, reflects the system's adherence to its control logic initiating cooling mechanisms only when upper thresholds were approached or exceeded.



(a) (b)

Figure 9. Actuator response in relation to environmental conditions.

3.4. Environmental Parameter Fluctuations During Daily Cycle

Environmental measurements collected over a complete daytime cycle within the drying chamber are visualized in Figure 10. The figure simultaneously presents temperature, relative humidity, and light intensity trends recorded at five-minute intervals from 09:26 to 16:26. This sampling resolution allowed accurate observation of microclimate fluctuations corresponding to natural daylight progression

Light intensity exhibited the most dynamic variation among the three measured parameters. The session began with an intensity of approximately 1300 lux, which steadily rose between 12:30 and 13:30 and reached a peak exceeding 2600 lux. Toward the end of the period, the intensity gradually declined to around 700 lux. This trend mirrored the natural cycle of solar radiation intensifying around midday and decreasing toward the afternoon.

Temperature showed a similar upward trend, starting from 32 °C and peaking slightly above 36 °C around 13:00. In contrast, relative humidity decreased from initial values of 55%–58% RH to approximately 47%–49% RH during midday, followed by a minor increase in the later hours. These patterns reflected the thermal response of the semi-enclosed structure to solar exposure and internal airflow dynamics.

Parameter interdependence remained evident throughout the session. Increases in light intensity and temperature were consistently accompanied by reductions in humidity, aligning with the expected thermodynamic behavior of air in enclosed drying systems. The automated control system responded appropriately to these shifts. Its real-time decision-making, guided by predefined logic thresholds, enabled stabilization of internal conditions to support the drying process without requiring manual intervention.

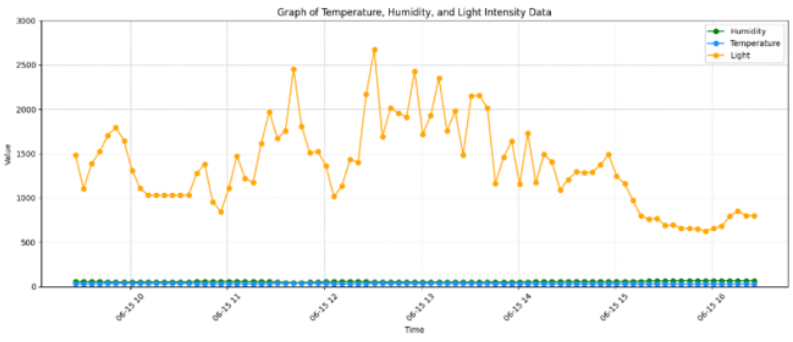


Figure 10. Temperature, humidity, and light intensity trends during a single daytime cycle recorded at five-minute intervals.

3.5. Statistical Analysis of Environmental Parameters

Maintaining environmental stability in the drying chamber requires accurate regulation of temperature, humidity, and light intensity. A statistical analysis was performed using recorded sensor data to evaluate the system's ability to maintain these parameters within operational thresholds. The analysis included calculations of mean values, standard deviations, and the percentage of observations within the ideal ranges.

Control thresholds were defined as 45–50 °C for temperature and 20–40% relative humidity (RH), aligning with the system's embedded logic. Table 1 summarizes the statistical results obtained from the monitoring session.

Table 1. Statistical Summary of Environmental Parameters

Parameter	Mean	Standard Deviation	% Within Ideal Range
Temperature (°C)	33.33	2.40	71.76%
humidity (%)	54.93	5.40	64.71%
Light (Lux)	1367.35	479.25	68.24%

Temperature data showed relatively stable thermal behavior, with a standard deviation of 2.40 °C. Although the average temperature (33.33 °C) remained below the target range of 45–50 °C, the system maintained temperatures within the ideal range for 71.76% of the monitoring period. This outcome demonstrates the effectiveness of the automatic control mechanism in responding to fluctuating thermal conditions by activating heating elements when necessary.

Humidity analysis revealed an average value of 54.93% RH and a standard deviation of 5.40%. The average humidity exceeded the desired range, indicating consistent moisture presence within the chamber. Despite this, the system maintained humidity within the ideal threshold for 64.71% of the observation period. This was achieved through coordinated operation of the heating lamps and exhaust fans, which reduced moisture levels during high-humidity intervals.

Light intensity had an average of 1367.35 lux with a standard deviation of 479.25 lux. While light was not actively used in the control logic, it played a supplementary role in supporting the thermal balance of the chamber by contributing passive solar energy. A significant proportion of measurements fell within a range beneficial for maintaining internal stability.

Statistical outcomes across all three parameters confirmed the system's ability to maintain near-target environmental values under varying external conditions. Low standard deviations indicated minimal fluctuations, while adaptive responses enabled consistent environmental control throughout the drying process. These findings demonstrate that integrating sensors, automated logic, and a web-based interface enables a more reliable and responsive coffee drying system.

3.6. Implications and Research Limitations

Experimental results confirmed that the system maintained environmental parameters temperature, humidity, and light intensity close to their designated target ranges. Low standard deviation values across measured variables indicate stable microclimatic control throughout the drying process, demonstrating the effectiveness of sensor integration, automated logic, and the web-based interface.

However, several limitations emerged during the study. The testing phase was limited to an 8-hour daytime session under overcast weather conditions. As such, the system's performance was not evaluated across a complete drying cycle, which typically spans 15 to 45 days. Furthermore, the research did not assess the final quality of the dried coffee beans particularly the moisture content therefore, compliance with standards (<12% moisture) remains unverified.

Additional limitations include the absence of seasonal variation trials, varying load conditions, and formal feedback from end users such as farmers or cooperative staff. These aspects are essential for understanding the usability and operational impact of the monitoring dashboard on daily agricultural workflows.

Despite these constraints, anecdotal use of the system at SMKN 1 Jarai showed promising results. During an informal 10-day drying session under predominantly cloudy weather, the drying chamber consistently maintained temperatures within the range of 43–49 °C. This outcome

suggests the system's potential viability under real-world conditions, especially if supported by more reliable energy sources or enhanced heating element designs.

These limitations provide clear directions for future research, including extended-duration trials, quality assessment of dried coffee, multi-site validation, and user-centered studies. Addressing these aspects will be critical for evaluating the system's scalability, sustainability, and broader acceptance among agricultural communities.

4. CONCLUSION

This study successfully designed and implemented an Internet of Things (IoT)-based automatic monitoring system to support the coffee drying process in a Smart Dryer Dome (SDD). The system is capable of measuring temperature, humidity, and light intensity in real time, and autonomously controlling fans and heating lamps based on predefined environmental thresholds (45–50 °C for temperature and 20–40% RH for humidity). Measurement data are visualized through a Laravel-based web interface that enables remote monitoring.

Testing results showed that the system maintained temperature within the target range for 71.76% of the observation period, while humidity remained within the ideal threshold for 64.71% of the time. Low standard deviation values indicate the system's stability in maintaining environmental parameters. These findings support the study's objective of delivering a responsive automated drying solution, particularly for locations with limited access to conventional electricity.

The average recorded temperature was 33.33 °C, while relative humidity reached 54.93% RH, indicating that the solar panel's power supply was insufficient to fully support heating functions during overcast weather conditions. The limited 8-hour testing period did not represent a complete drying cycle, preventing a comprehensive evaluation of the final coffee bean quality, particularly moisture content.

Further system development should include long-term testing under various seasonal conditions, quantitative analysis of final drying quality, and field trials in real agricultural environments. Integrating predictive features based on historical data, mobile-friendly user interfaces, and multi-node architecture is expected to enhance system flexibility and scalability. This system holds strong potential as an adaptive and sustainable automation solution for post-harvest processing in remote areas lacking access to conventional electricity.

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