Design and development of an IoT-integrated solar water-heated drying system for macadamia nuts

Minh Tan Le[1*], Xuan Thao Ngo[2], Tuan Nguyen[2], Tan Sy Nguyen[2]

(1.Faculty of Natural Science and Technology, Tay Nguyen University, 63161, Vietnam;
2. Faculty of Agriculture, Tay Nguyen University, 63161, Vietnam)

Abstract: This paper presents the design, development, and testing of an IoT-integrated solar-powered macadamia nut drying system for small to medium-scale farmers. Utilizing a solar water heating system as the primary heat source, it switches to grid electricity as needed. IoT technology allows real-time monitoring and control of temperature, humidity, hot water flow and the moisture content of the macadamia nuts, optimizing drying while conserving energy. The dryer was evaluated over three days in the rainy season in Vietnam's Highlands, comparing performance with and without IoT control. The results indicated that without a set temperature threshold, chamber temperatures reached 42.1°C and 45.1°C on days one and two, respectively. However, with a temperature threshold set at 38°C on the third day, chamber temperatures stabilized between 37.5°C and 39°C from 10:08 to 19:27, leading to a 16.7% reduction in energy use compared to the first day. Testing with 5.04 kg of macadamia showed energy savings of 32.6% compared to traditional electric dryers, even in cloudy conditions, while maintaining high drying quality and reducing costs. This innovation boosts efficiency and supports sustainable agriculture.

Keywords: IoT control systems, renewable thermal energy, post-harvest drying of macadamia nuts, sustainable agriculture, energy efficiency

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1 Introduction

Macadamia nuts are among the most nutritious nuts, rich in vitamins, omega fatty acids, protein, and minerals such as magnesium, phosphorus, and iron, along with healthy fats. They play a vital role in preventing cardiovascular disease, diabetes, and cancer, while also supporting brain and bone health and assisting in weight management (Marks, 2024). In Vietnam, the macadamia industry is growing rapidly, particularly in the Central Highlands, where about 2 363 hectares are currently under cultivation. The national goal is to increase the planting area to 130 000-150 000 hectares by 2030, with the Central Highlands aiming for approximately 45 000 hectares. By 2050, this area could expand to around 250 000 hectares. Significant investments are being made in processing facilities to increase value, with projected export revenues reaching $400 million by 2030 and up to $2.5 billion by 2050 (Vietnam Agriculture, 2022, 2023). Given the economic importance of macadamia nuts, it is crucial to enhance their quality and improve post-harvest preservation methods. The crop ripens and is harvested from June to August, during heavy rains that make drying challenging. Currently, farmers preserve harvested macadamia nuts through two drying methods: sun drying and artificial drying.

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*Corresponding author:**Minh Tan Le, Ph,D.,** Faculty of Natural Science and Technology, Tay Nguyen University, Vietnam 63161, Tel:+84935318151, E-mail: lmtan@ttn.edu.vn.

Sun drying exposes the nuts to UV rays and high heat, which can compromise quality, making traditional methods inefficient and time-consuming. The traditional drying process involves spreading nuts in thin layers on mats or paved surfaces and exposing them to sunlight and wind, leading to quality declines due to dust contamination, insect infestations, enzymatic reactions, and microbial infections (Weiss and Buchinger, 2012). In large-scale production, artificial drying typically uses low-temperature drying at around 30°C for 2-3 days, gradually increasing to 38°C for 1-2 days, then 45°C for another 1-2 days, and finally reaching 50°C until the moisture content (wet basis) is approximately 1.5%. A high-temperature roasting phase follows, lasting a few minutes to a few hours (Guangzhou Shuntec Dryer Machinery Co., LTD., 2021).

Macadamia nuts are particularly sensitive to moisture loss, requiring careful post-harvest handling. Studies suggest storing harvested nuts at high moisture levels (7%-17%) and low temperatures (7°C-17°C) to maintain quality, with proper ventilation crucial to prevent mold during storage. Other research suggests that drying macadamia nuts to a moisture level of 7.5%-10% within two weeks of harvest is ideal, with temperatures kept below 30°C to prevent quality degradation and browning of the nut kernel (Hong et al., 1996; Quinlan et al., 2008; Susilowati et al., 2019). Additionally, research by Rajagopal et al. (2014) and Umayal Sundari et al. (2014) shows that solar dryers equipped with evacuated tube collectors can significantly reduce drying times while maintaining product quality. However, these systems face challenges in heat retention during cloudy weather or at night. Integrating IoT technology to monitor and control drying parameters could help mitigate these issues.

Thus, many farmers still rely on traditional sun-drying techniques for post-harvest macadamia nut drying. While these methods are effective for small quantities, they are slow and inconsistent for larger volumes. Industrial electric dryers powered by 220 V grid electricity are often used for large-scale drying, but their high operational costs and energy consumption present significant challenges.

To enhance efficiency and safety in modern agriculture, particularly in India, issues such as product quality, safety, and environmental pollution must be addressed. Drying is a vital preservation method that requires specific temperature and humidity conditions. Although hybrid solar dryers are preferred, they can be costly and only operate during the day. Automating these dryers with IoT technology allows for remote monitoring and control, necessitating energy requirement estimates for optimizing these advanced systems (Harischandrakar et al., 2023).

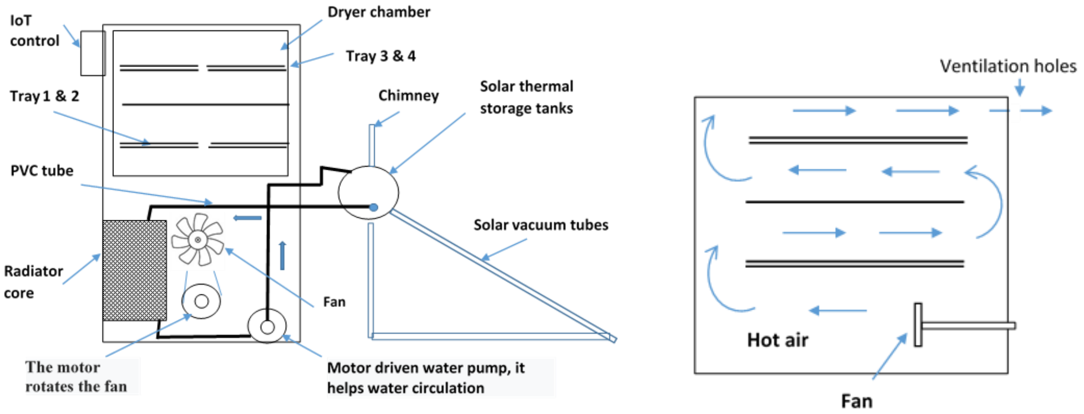
This study aims to develop an IoT-based macadamia nut dryer that uses hot water from a solar thermal storage tank, with grid electricity as a backup. The system maintains stable drying by utilizing heat from solar-heated water, even during periods of fluctuating sunlight. The IoT integration enables real-time monitoring and control, optimizing quality and conserving energy. A test run is conducted to evaluate the dryer's effectiveness.

2 Material and methods

2.1 Prototype development

The macadamia nut dryer consists of four key components: solar thermal storage tank with vacuum tubes, a heatsink device, a drying chamber, and an IoT control system. These elements work together to harness solar energy, convert it into heat, and distribute it effectively inside the drying chamber (Figure 1).

A prototype dryer was built according to the design specifications. The drying chamber is constructed from 5 mm thick stainless steel sheets and thick plastic sheets, with a layer of foam insulation in between. This construction ensures that the heat inside the chamber is retained, maximizing energy efficiency. Inside the chamber, there are four drying trays positioned in two tiers. The trays allow the hot air to circulate evenly around the macadamia nuts, ensuring uniform drying. The dryer's dimensions are 113 cm in height, 113 cm in width, and 60 cm in depth, providing ample space for drying large batches. The drying chamber has dimensions of 100 cm × 64 cm × 60 cm and is fitted with four trays, each designed to hold a maximum of 5 kg of macadamia nuts. Within the chamber, hot air circulates in a zigzag pattern, as illustrated in Figure 1(b).



(a) the front diagram of the dryer (b) the side diagram of the dryer

Figure 1 Schematic diagram of the dryer

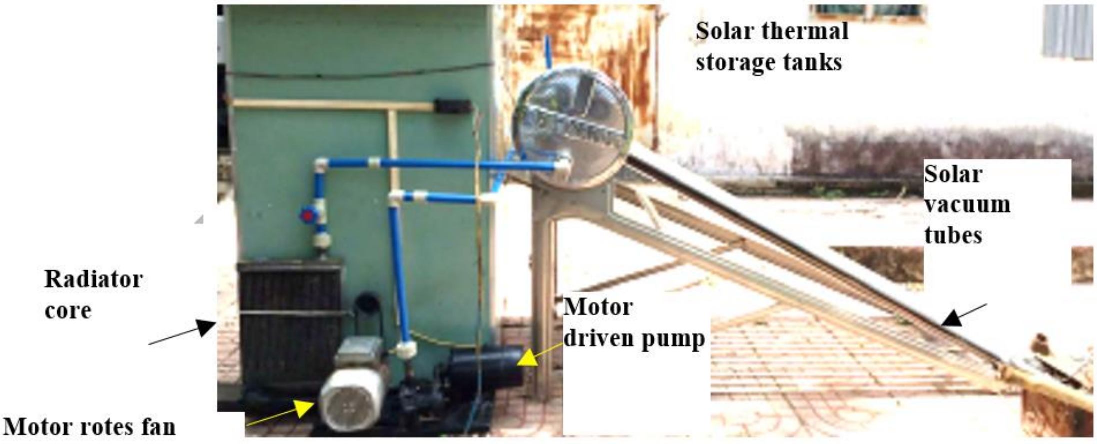


Figure 2 The image of the dryer

The dryer's solar vacuum tubes are its primary source of energy. There are 12 vacuum tubes installed, each designed with an outer layer that shields the system from environmental elements like rain and dust. The inner layer absorbs sunlight, converting it into heat that warms the water inside the tubes. A vacuum exists between the two layers, providing insulation that prevents heat loss and allows the water inside to heat rapidly. The heated water is stored in the solar thermal storage tank, which is well-insulated to maintain temperature for longer periods (Solar Tribune, 2011).

The hot water is then circulated through the system, and pumped into a radiator core, which is a metal component measuring 45 cm × 32 cm × 5.5 cm. The radiator core is made of a large metal block containing cooling fins made of copper, allowing the hot water to quickly dissipate heat into the air inside the chamber. To distribute this heat, a fan powered by a motor draws the hot air from the radiator core and blows it into the drying chamber, ensuring consistent air circulation throughout the chamber. There is a chimney to exhaust hot air for the hot water storage tank (Figure 1a).

The system is positioned along a north-south axis with the front facing south to maximize exposure to sunlight during the day. This strategic orientation ensures the solar vacuum tubes receive the highest possible amount of solar radiation, making the system highly efficient in capturing and utilizing solar energy.

An essential part of the dryer is its IoT control system, which is designed to monitor and optimize the drying process. This control system is designed to manage essential parameters such as temperature, hot water flow, and humidity levels within the drying chamber.

2.2 IoT control system setup

The IoT control system efficiently oversees the drying process by gathering data from various sensors and managing the drying chamber's environment through relays, heater, blower, and fan (Figure 3). Users can monitor key parameters in real-time using the Blynk and ThingSpeak interfaces, allowing for adjustments and emergency stops. Figure 4 displays the control panel with a keypad, indicator lights, and an LCD screen. The keypad sets the drying program by temperature, and the red, green, and yellow indicator lights indicate the status of the motor-driven fan, motor-driven pump, and air heater, respectively. The system's components and their specifications are detailed in Table 1.

2.2.1 Central control components

The system is built around the Arduino Mega 2560, which serves as the main microcontroller. It features 54 digital I/O pins and 16 analog input pins for collecting data from sensors and controlling relays. The NodeMCU ESP8266 communicates with the Arduino via UART, ensuring efficient data transmission for remote monitoring. The NodeMCU handles wireless data transfer, connecting to IoT platforms like Blynk and ThingSpeak (Figure 6) to allow remote access and control of relays based on set temperature thresholds.

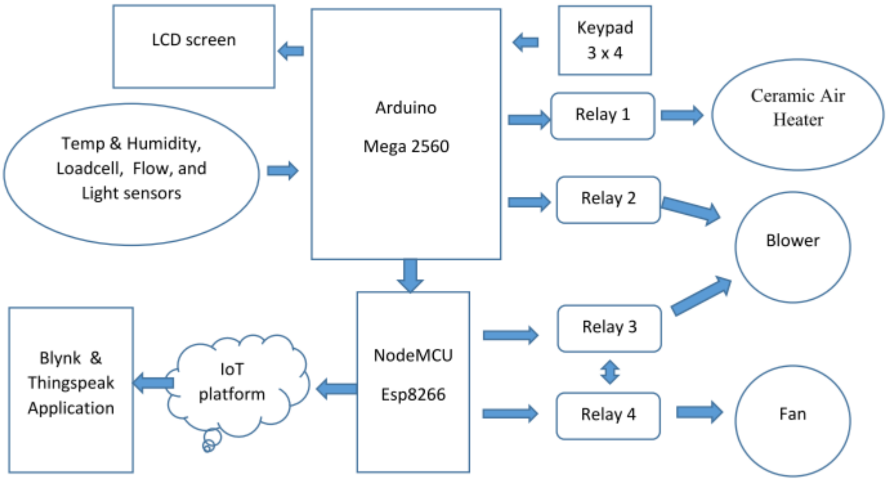


Figure 3 Block diagram of IoT control systems

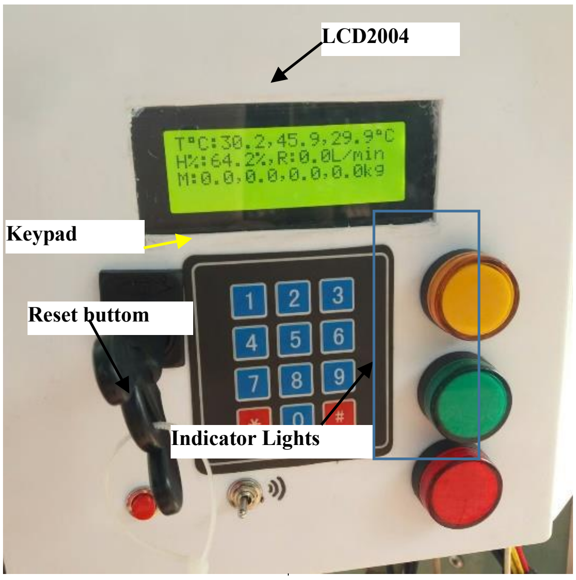


Figure 4 Circuit box

Table 1 List of components of IoT and controlling systems

No.	Sensors	Quantity	Parameters
1	Arduino Mega 2560	1	Main Microcontroller: ATmega2560 IC. Programming and UART communication: CH340. Power supply 5 -12VDC. Number of Digital I/O pins: 54 (15 of which can output PWM signals). Number of Analog Input pins: 16. DC Current per I/O pin: 20 mA
2	NodeMCU Esp8266 CP2102	1	Main IC: ESP8266. Firmware version: NodeMCU Lua. Programming and UART communication: CP2102. Power supply: 5 VDC. GIPO operates at 3.3 VDC.
3	LCD 2004 with I2C driver	1	5 VDC power supply, I2C standard communication
4	DS18B20 Temperature Senso	3	Operating voltage: 3.3 – 5.5 V. Communication standard: Digital TTL 1-Wire. Temperature range: -55°C ~125°C. Accuracy: ±0.5°
5	SHT30 Sensor	1	Model: SHT30 V2 I2C. Communication standard: I2C. Signal level: TTL 3.3-5.5VDC. Temperature range: -40°C ~ 125°C, accuracy ±0.2°C. Humidity range: 0~100% RH, accuracy ±2% RH. Built-in 10K pull-up resistor and noise filter capacitor.
6	BH1750FVI Light Sensor	1	Operating voltage: 5VDC. Communication: I2C. Input light range: 1-65535 lx. Peak sensitivity wavelength: 560n
7	YF-B1 Flow Sensor	1	Flow rate: 1-25 L min^{-1}. Operating voltage: 5 → 15 V DC. Water pressure: 1.75 MPa.
8	Load cell sensor	8	Load capacity: 20 kg. Rated output (mV V^{-1}): 1.0 ± 0.15. Linearity error: 0.05%. Operating voltage: 5 V. Zero balance point %RO: ±0.1.
9	PTC Ceramic Air Heater	1	Heating material: PTC. Voltage: 220 VAC. Power: 1200 W. Wire material: high-temperature resistant wire.
10	Relay	4	Power supply: 5 V, high-level trigger, maximum current 10 A
11	AC-DC Converter 1	1	Maximum current: 2 A. Rated power: 24 W; Input: 220 V, Output: 12 VDC
12	AC-DC Converter 2	1	Maximum current: 2 A. Rated power: 10 W Input: 220 V, Output: 5 VDC
13	Motor rotating the fan	1	Power supply: 220 ACV, power: 1 HP
14	Motor rotating the blower	1	Power supply: 220 ACV, power: 0,5 HP

2.2.2 Sensors and measurement

Three DS18B20 temperature sensors measure temperatures inside and outside the drying chamber and at the solar thermal storage tank outlet. The SHT30 sensor monitors humidity, while load cells track the weight of nut trays to indicate moisture loss. A BH1750FVI light sensor measures sunlight intensity, allowing for adjustments in the drying process, as light intensity in lux is directly proportional to solar radiation in W m^{-2}, with 1 000 W m^{-2} roughly equating to 120 000 lux (Michael, 2019). Additionally, a YF-B1 flow sensor monitors hot water flow rates to optimize energy transfer in the solar thermal system, and user input for drying temperatures is facilitated through a 3×4 keypad.

2.2.3 Output control modules and user interface

The system features four relays to manage key components: one for activating the ceramic air heater, and two for controlling motor-driven pump and fan motors based on temperature conditions, with a fourth relay providing an emergency stop function. User interaction occurs through an LCD 2004 screen displaying system status and parameters, alongside IoT platforms like Blynk (Figure 5) and ThingSpeak (Figure 6) for real-time monitoring and historical data access. The ceramic air heater, powered by a 220 V source, maintains consistent temperatures in the drying chamber. AC-DC converters supply necessary voltage levels for various components, ensuring stable operation.

Figure 5 Blynk interfaces for displaying dryer parameters

2.2.4 Arduino control system for heating management

We developed the Arduino program. It allows users to select operating modes via a keypad (0-4) and displays the information on an LCD.

(1) Keypad Input: Pressing a key overwrites the previous selection and updates the display.

(2) Controlling hot circulating water with a pump

Key 0: Turn off the water pump.

Key 1: Set the threshold to 32°C.

Key 2: Set the threshold to 38°C.

Key 3: Set the threshold to 44°C.

Key 4: Set the threshold to 50°C.

The water pump operates when the temperature falls below the threshold and stops when it rises above.

(3) Flow Rate Condition: If the flow rate exceeds 1 m s^{-1} and the temperature is below the threshold:

Key 0: Turn off the water pump and ceramic air heater.

Keys 1-4: Activate the air heater according to the selected temperature.

Default Condition: The air heater remains off if no conditions are met.

Using the Wi-Fi capabilities of the NodeMCU in conjunction with the Arduino, users can monitor the parameters of the dryer remotely and adjust the temperature settings through a mobile application.

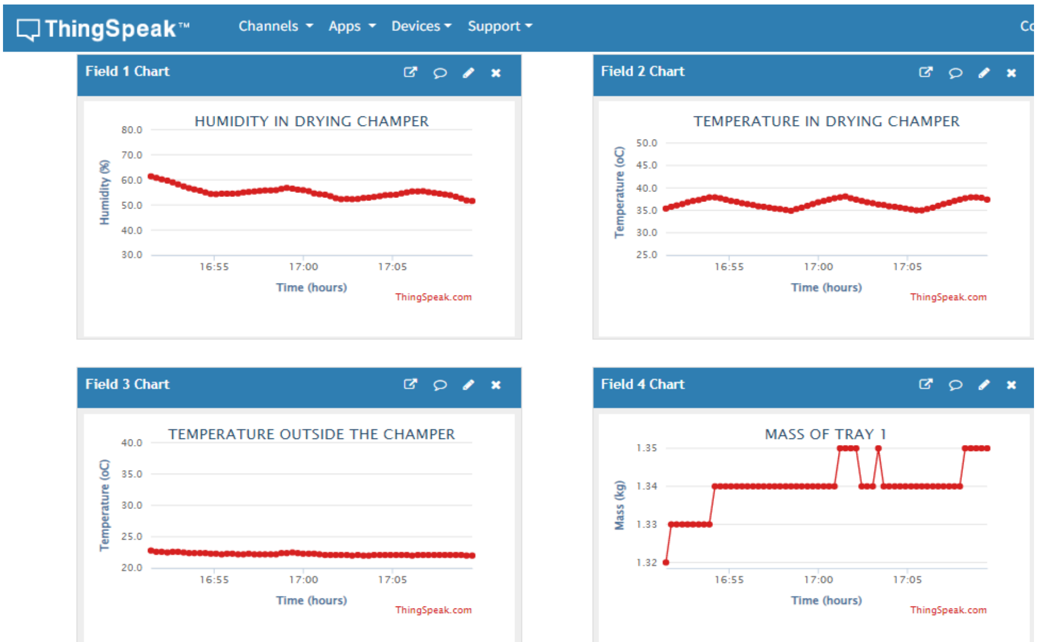


Figure 6 ThingSpeak interfaces for displaying and storing dryer parameters

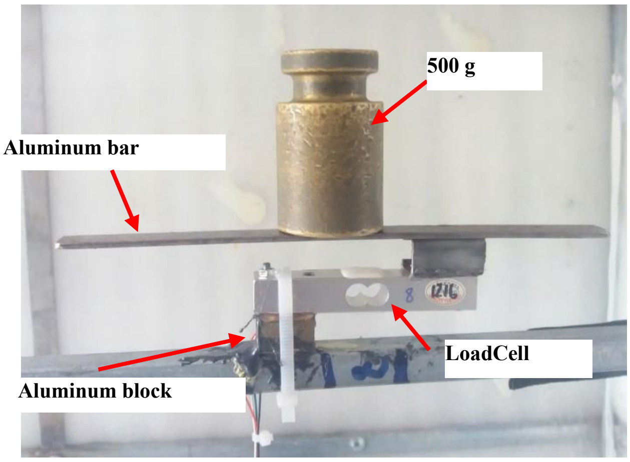


Figure 7 Object being weighed on the sensor

2.3 Sensor calibration

We installed 8 load cells for four macadamia drying trays, calibrating the sensors in sequence from 1 to 8. An aluminum bar, measuring 20 cm × 2 cm × 1 cm, is mounted onto a small aluminum block, 1.5 cm thick, which matches the width of the load cell. This aluminum block is placed between the sensor and the aluminum bar, with all parts secured by screws (Figure 7).

We followed the calibration method outlined in Instructables (2020). The loadcells were connected to the Arduino pins, while the sensor received power from an external supply. When activated, the sensor initially shows a weight reading of 0.00. To perform the calibration, a 500 g object is placed on the sensor, and adjustments are made using the values "a" to increase or "z" to decrease the displayed weight in the Serial Monitor of the IDE until the reading accurately represents the 500 g mass of the object. Once the calibration process is complete, the calibration factors are integrated into the code.

After calibrating the sensors, we weighed objects in increments of 500 g, ranging from 500 g to 3000 g, to assess the measurement error (Table 2).

Table 2 Accuracy test of tray sensors

	Object weight (g)						
Tray	500	1000	1500	2000	2500	3000	Relative error (%)
1	498	997	1478	1961	2383	2872	0.3 – 4.7
2	482	978	1457	1997	2545	3095	1.5 – 3.6
3	498	996	1494	1990	2487	2986	0.4 – 0.52
4	511	1019	1533	2038	2550	3058	1.9 – 2.2

Each macadamia drying tray is placed on two sensors. After placing tray 1 on sensors 1 and 2, tray 2 on sensors 3 and 4, tray 3 on sensors 5 and 6 and tray 4 on sensors 7 and 8, weigh the objects on the tray. Measure objects sequentially from 500 g to 3000 g. The relative errors in measuring the sample masses for trays 1 to 4 are 0.3% – 4.7%, 1.5% – 3.6%, 0.4% – 0.52%, and 1.9% – 2.2%, respectively.

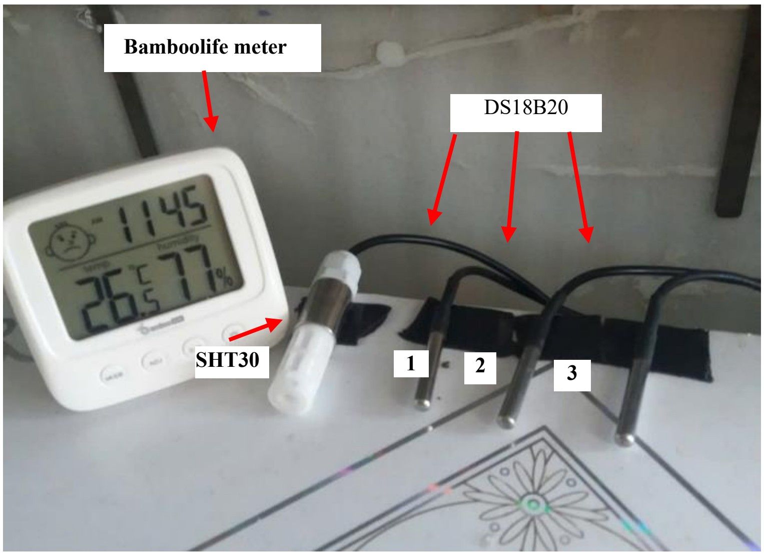


Figure 8 Calibration for DS18B20 and SHT30 sensors using the Bamboo Life meter

Temperature and humidity sensors are placed at four corresponding positions, consisting of three temperature sensors and one humidity sensor. Temperature sensor 1 measures the temperature in the drying chamber, sensor 2 measures the temperature at the outlet of the solar thermal storage tank to monitor water heating, and sensor 3 measures the temperature of the environment (Figure 8).

Use the Bamboo Life electronic temperature and humidity meter to calibrate the DS18B20 temperature sensor and the SHT30 sensor. Position the meter and sensors close to each other in the air. Every two minutes, observe and record the readings from both the meter and the sensors for a total of 10 measurements. Organize the data in a table to calculate the differences between the sensor readings and the meter, as shown in Table 3 and Table 4. In Table 3, ΔT_1, ΔT_2, and ΔT_3 represent the temperature differences measured between the Bamboo Life meter (T_b) and the DS18B20 sensors (T_1, T_2, T_3). We obtained average temperature deviations of 0.01°C, 0.5°C, and 0.3 °C, respectively.

Table 3 Comparison of the temperature from DS18B20 sensors with the Bamboo Life meter

Test No.	T_b (°C)	T_1 (°C)	ΔT_1 (°C)	T_2 (°C)	ΔT_2 (°C)	T_3 (°C)	ΔT_3 (°C)
1	26.4	26.6	-0.2	26.4	0	26.4	0
2	26.3	26.4	-0.1	26.0	0.3	26.1	0.2
3	26.2	26.2	0	25.7	0.5	25.9	0.3
4	26.1	26.1	0	25.6	0.5	25.8	0.3
5	26.0	25.9	0.1	25.3	0.7	25.6	0.4
6	25.9	25.8	0.1	25.2	0.7	25.5	0.4
7	25.8	25.7	0.1	25.2	0.6	25.4	0.4
8	25.8	25.7	0.1	25.1	0.7	25.3	0.5
9	25.7	25.7	0	25.1	0.6	25.4	0.3
10	25.8	25.8	0	25.2	0.6	25.6	0.2
Average temperature difference			0.01		0.5		0.3

Table 4 Comparison of humidity readings between the SHT30 sensor and the Bamboo Life meter

Test No.	Bamboo life Humidity (%)	SHT30 Humidity (%)	Humidity Difference (%)
1	75	70,2	4.8
2	75	70,3	4.7
3	75	72,2	2.8
4	75	72,5	2.5
5	76	73.0	4.5
6	76	73.6	2.4
7	76	74.3	1.7
8	76	74.4	1.6
9	76	75.0	1.0
10	77	75.7	1.3
Average humidity difference			2,7

After calculating the difference coefficient among the sensors, including the SHT30 sensor, the DS18B20 sensors, and the Bamboo Life industrial meter, adjust the program's code by adding this coefficient to align the data between the sensors and the industrial meter.

2.4 Experimental procedure

The moisture loss of the drying product was measured every hour using the formula below (Gatea, 2011),

$$M_L = M_t - M_d \tag{1}$$

Where, M_t (g) represents the initial mass and M_d (g) the final mass of samples, both recorded with load cells.

The moisture content represents the amount of moisture in a material on a wet basis, expressed as a percentage. The moisture content, M_{wb} (%) on a wet basis was calculated using Equation 2.

$$M_{wb} = \frac{M_L}{M_t} \times 100 \tag{2}$$

This procedure was repeated at hourly intervals until the drying process was complete. The drying rate (*DR*) is proportional to the difference in moisture content between the material to be dried and its equilibrium moisture content (Mohanraj and Chandrasekar, 2009).

$$DR = \frac{dM_{wb}}{dt} \tag{3}$$

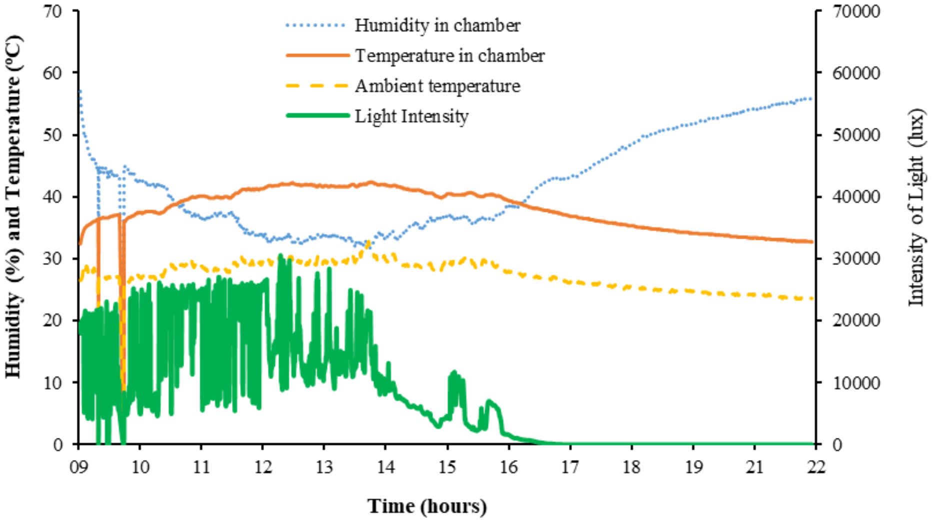
Here, *DR* is the drying rate, d_{Mwb} is the mass loss of the crop, and *dt* is the drying time.

To calculate the moisture content of macadamia nuts, you can use the Equation 2, which represents the moisture content on a wet basis

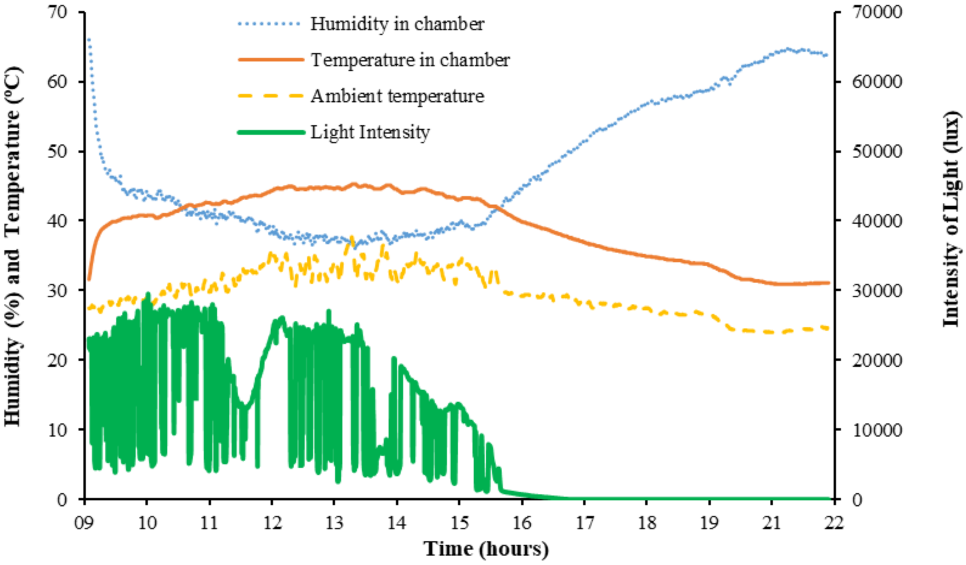
3 Results and discussions

3.1 Testing the dryer under conditions with and without IoT control

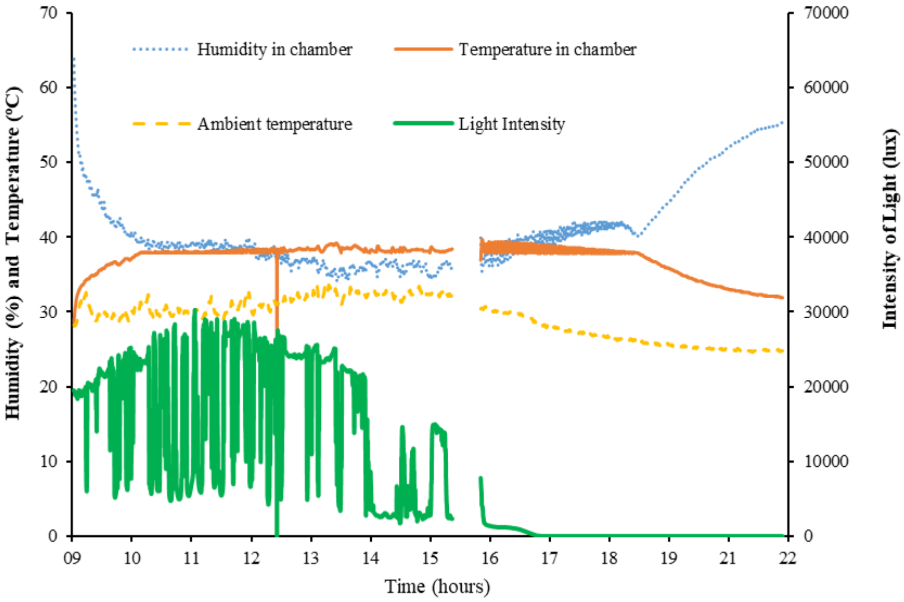
The temperature changes of the dryer were recorded over 3 days in October 2024 to evaluate the dryer's performance. The dryer operated from 9:00 to 22:00. The fan operates at an airflow speed of 2 m s^{-1} (measured by Windmaster2 with an accuracy of ±4%, ±1 digit). The flow rate of the recirculating water is adjusted to 5.5 liters per minute. The water flow rate is adjusted to be suited to weather conditions using a water valve.



(**a**) Day 1: Testing without a temperature threshold



(b) Day 2: Testing without a temperature threshold



(3) Day 3: Testing with a set temperature threshold

Figure 9 Variations in temperature, humidity, and light intensity parameters during dryer testing

Under the bad weather conditions of the first day, which was mostly cloudy with 89% cloud cover, the drying chamber temperature reached a maximum of 42.1°C, and the chamber humidity reached a minimum of 32.5% (Figure 9a). After 10:00, the temperature inside the drying chamber was approximately 9°C to 14.6°C higher than the ambient temperature outside. Once it was fully dark, the drying chamber temperature reached 37°C and gradually dropped to 32.7°C by 22:00. The temperature in the drying chamber varied from 38.0°C to 42.1°C between 10:33 and 17:11. We used a KWS-AC300-100A digital power meter to measure the energy consumption of the dryer system, which recorded an electricity usage of 12 kWh during operation. The measured light intensity varied according to cloud cover and the sun’s angle of incidence. During the day, due to the high cloud cover, the light intensity recorded by the sensor fluctuated significantly, while the temperature changed gradually in response to the sun's angle.

On the second day, with only 30% cloud cover, the temperature in the drying chamber varied from 32.2°C to 45.1°C between 9:05 and 20:21, from 38.0°C to 45.1°C between 9:15 and 17:20 and specifically, from 44.0°C to 45.1°C between 10:10 and 15:11. During testing period, humidity decreased to a minimum of 36.8% at 14:19 (Figure 9a).

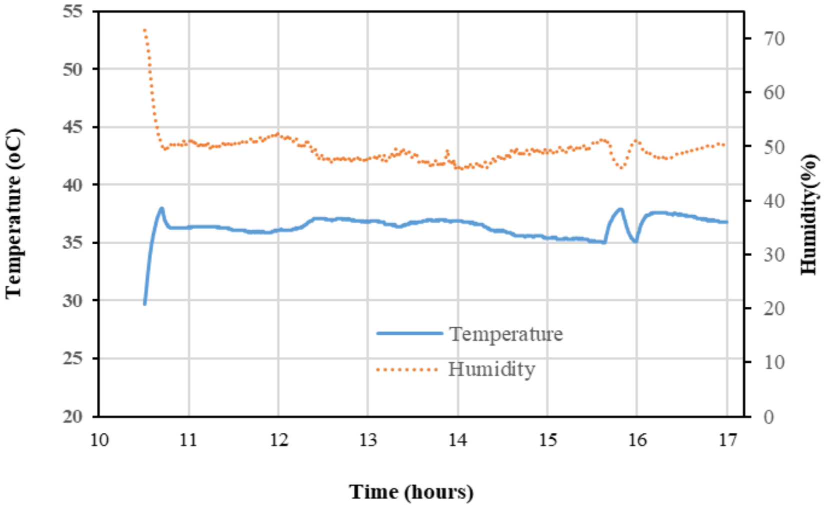
On the third day, we operated the dryer from 9:00 to 22:00 (Figure 9c) with a temperature threshold set at 38°C through the IoT controller. On the second day, with 87% cloud cover, the light intensity graph indicated that the weather conditions were similar to those of the first day. In the afternoon, as seen in Figure 9, clouds appear increasingly, the intensity of light fluctuates rapidly, and the amplitude decreases significantly. During the drying process from 10:08 to 19:27, the chamber temperature fluctuated slightly in the range of approximately 37.5°C – 39°C, and the chamber humidity varied from 35% to 40.7%. The temperature inside the chamber was 5 to 11.6°C higher than the ambient temperature outside the drying chamber during this period. After dark, the temperature gradually dropped, reaching 31.9°C by 22:00. The electricity consumption for the dryer’s operation was 10 kWh, saving approximately 16.7% energy. Therefore, the drying machine operates with the involvement of an IoT controller, which stabilizes the temperature, reduces energy for the water recirculation system, and consequently saves more energy compared to when the dryer runs continuously without the control of this system.

Thus, under high cloud cover conditions (87%) and without supplementary heating from a ceramic air heater, the dryer operated at a temperature threshold of 38° C, maintained for more than 9 hours. In the case of setting the temperature threshold, the drying chamber stays above 38°C for 3 hours longer than if the threshold is not set in both test cases, the chamber temperature maintained around 32°C at 22:00. This indicates that setting a drying temperature threshold of 32°C and 38°C can ensure the drying of macadamia nuts under adverse weather conditions.

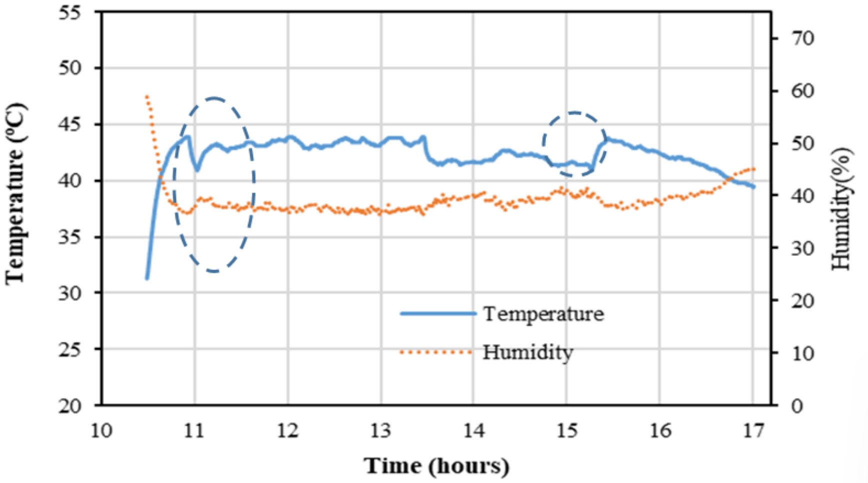
3.2 Macadamia drying test

We used trays 3 and 4 to dry macadamia nuts, weighing 2.73 kg and 2.31 kg, respectively, from 23 – 25 October 2024, from 10:24 to 17:00 each day. Prior to the drying experiments, the macadamia nuts were shelled and subjected to natural air-drying under ambient conditions for two weeks. After this pre-drying phase, the nuts had a moisture content of approximately 15%. During the drying process, cloud cover was 81%, 32%, and 68% over the three days. Despite the significant cloud cover on the third day, sunlight filtered through the cumulus clouds, enabling the solar dryer to effectively absorb a considerable amount of energy.

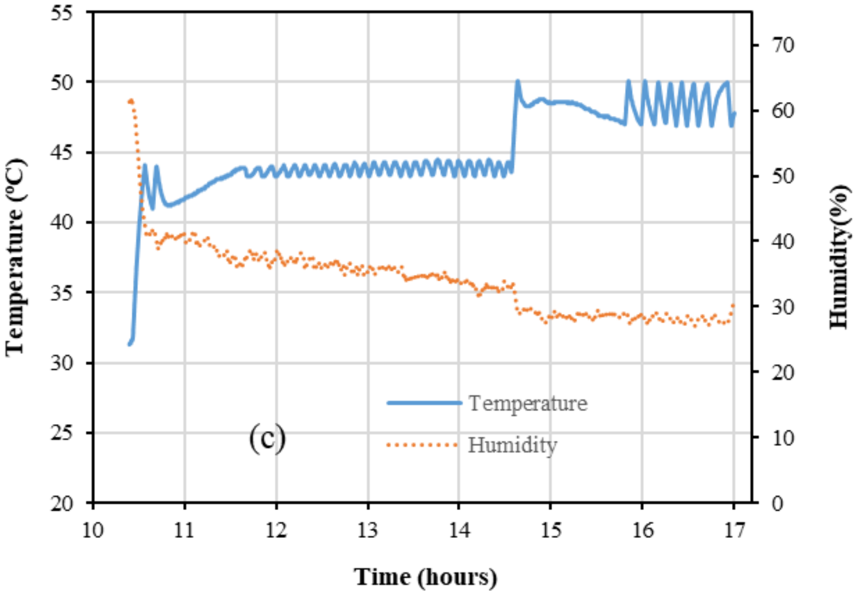
The control system was set to operate at temperature thresholds of 38°C, 44°C, and 50°C. On the third day, the temperature setting was adjusted to 55°C at 14:30 due to the observed equilibrium moisture level in the nuts at 44°C, as indicated by the dashed vertical lines in Figure 9c and Figure 10c. Because of the cloudy conditions for three days, we activated the automatic heating element to provide additional heat to the drying chamber. This PTC ceramic air heater has a capacity of 600 kW.



(a) Threshold temperature set at 38 °C

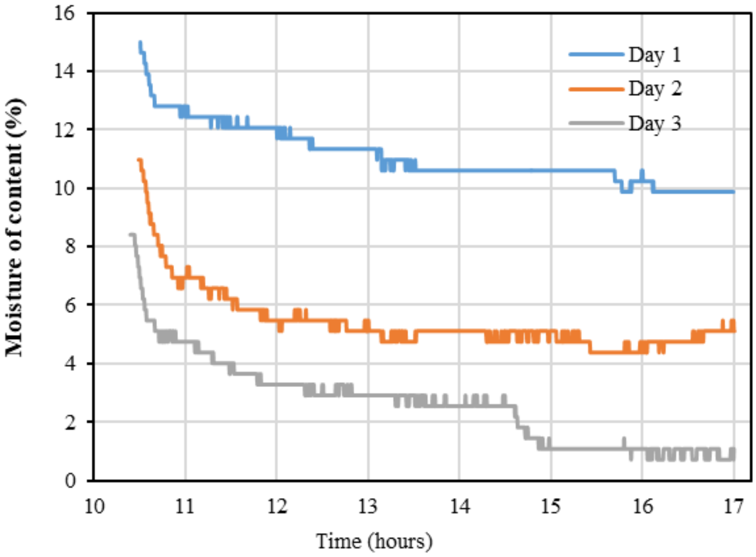


(b) Threshold temperature set at 44 °C

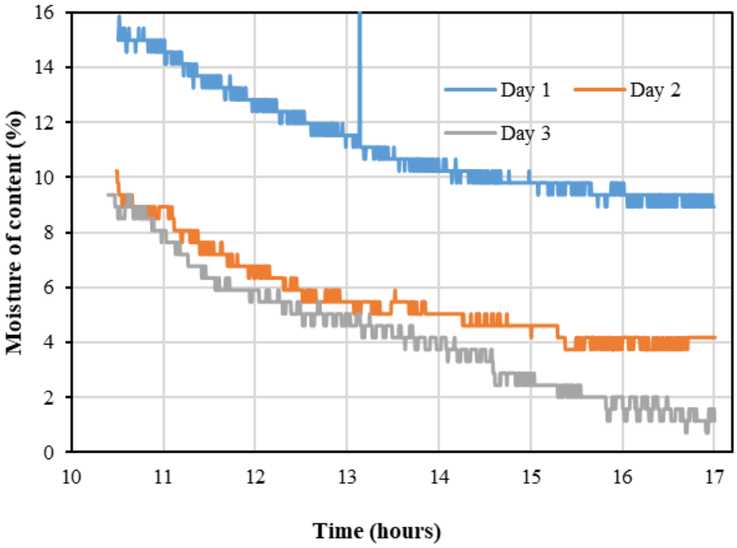


(c) Threshold temperature set at 55 °C

Figure 10 Temperature and humidity variations within the drying chamber during the drying process



(a) Tray 3, thresholds: 38°C, 44°C, and 50°C



(b) Tray 4, thresholds: 38°C, 44°C, and 50°C

Figure 11 Changes in moisture content (wet basis) of macadamia nuts at different temperature thresholds

On the first day, the heating element activated at 10:30 and 15:37, operating for 12 and 11 minutes when the temperature was below 35°C, with chamber humidity ranging from 46.6% to 51.9%. On the second day, the heater operated twice, at 10:30 and 16:12, with temperatures around 41°C, for about 90 and 58 minutes. Humidity on the second day ranges from 36% to 45%. On the third day, the heater ran more frequently, activating whenever the temperature dropped below 47°C and running for a total of 6 hours. Chamber humidity ranged from 27.6% to 29%, with temperatures between 47°C and 50°C. This humidity level is consistent with the drying requirements for macadamia nuts as outlined in Quinlan et al. (2008).

During drying, temperatures were around 38°C for 7 hours, 44°C for 11 hours, and 50°C for 4 hours and 30 minutes. The moisture content of macadamia nuts on tray 3 decreased from 15% to approximately 1% (Figure 11a), and on tray 4 from 15% to 1.15% (Figure 11b), reaching moisture equilibrium. The dryer system consumed a total of 22 kWh of energy over 22.5 hours. In comparison, a local industrial grid-powered dryer capable of processing 15-20 kg per batch, with a power rating of 1.5 kW (SUNSAY, 2021), would consume approximately 33.75 kWh over the same period. Consequently, this prototype demonstrated energy savings of 32.6% under predominantly cloudy conditions.

4 Conclusion

The IoT-integrated solar-powered macadamia nut drying system utilizes a solar water heating system and supports remote monitoring of temperature, humidity, hot water flow, light intensity, and nut moisture content. Users can adjust the drying temperature and control the system remotely. This capability improves operational efficiency, optimizes drying conditions, and reduces energy consumption.

Testing conducted over three days during the rainy season in Vietnam's Highlands, with cloud cover ranging from 30% to 89%, showed clear performance differences. On the first two days, without a temperature threshold, the dryer chamber reached peak temperatures of 42.1°C and 45.1°C, with minimum humidity levels of 32.5% and 36.8%, respectively. On the third day, with 86% cloud cover and a 38°C temperature threshold, a stable range of 37.5°C to 39°C was maintained from 10:08 to 19:27, resulting in a 16.7% reduction in energy consumption. Even under 87% cloud cover and without supplementary heating, the dryer maintained the 38°C threshold for over 9 hours. Setting the threshold allowed the drying chamber to remain above 38°C for 3 additional hours compared to operation without it.

Over three drying days with 5.04 kg of macadamia nuts and cloud cover ranging from 32% to 81%, the moisture content dropped from 15% to approximately 1%, resulting in 32.6% energy savings compared to conventional industrial dryers.

By integrating solar energy and thermal energy from a hot water tank, this dryer substantially reduces operational costs and environmental impact, promoting sustainable agriculture. These findings underscore the dryer's scalability and adaptability, offering strong potential for farmers in diverse climates.

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