

Study on Drying Characteristics and Color of Aromatic Bananas using Heat Pump and Resistance Hybrid Drying Mode

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ABSTRACT

In Vietnam, the primary technologies employed for banana processing and preservation are drying methods, predominantly used for soft-dried and crispy-dried banana products. However, no prior studies have focused on the drying of whole bananas using advanced heat pump systems. This study aims to determine the optimal drying regime for whole aromatic bananas through experimental investigation utilizing a hybrid drying system that combines heat pump technology with electrical resistance heating. The results reveal that the optimal drying process consists of three distinct stages, each defined by specific temperature and humidity parameters. Among the tested modes, the hybrid heat pump-resistance drying method demonstrated the lowest energy consumption, achieving energy savings of approximately 37% and 24% compared to the standalone resistance and heat pump drying modes, respectively, under identical conditions (i.e., mass, input moisture content, and target product moisture content). The total drying time using the hybrid method was 35 hours, with the drying agent's relative humidity having been maintained between 20% and 25%, and the energy consumption having been measured at 2.13 kWh per kg of raw material.

Keywords-drying mode; heat pump; resistance; aromatic banana

I. INTRODUCTION

Bananas are among the most widely consumed agricultural products globally [1]. However, bananas are prone to bruising and rapid spoilage during transportation and consumption, which leads to significant post-harvest losses [2] and contributes to CO₂ emissions. As a result, drying has emerged as a practical solution to reduce post-harvest losses [3], extend shelf life, and mitigate environmental impact, especially in the

case of bananas. Various advanced drying methods are currently in use for agricultural products, including microwave vacuum drying [4], sublimation vacuum drying [5], and hot air drying [6]. Among these, heat pump drying has gained attention as an energy-efficient and controllable method [7]. Based on the principle of the reverse Carnot cycle [8], heat pump dryers can recover energy from exhaust air and independently regulate air temperature and humidity, making them especially suitable for temperature-sensitive, high-value

products like fruits. Studies have shown that heat pump dryers consume 60–80% less energy compared to conventional dryers while delivering superior sensory qualities [9]. For example, authors in [10] reported minimal quality loss in herbs dried using heat pump technology, while authors in [11] determined that heat pump drying for grape pomace consumed 51% less energy than a convective dryer. Similarly, authors in [12] showed that the heat pump drying of pineapple consumed less energy than vacuum drying. Furthermore, the combination of heat pump and Electrohydrodynamic (EHD) drying in sliced bananas reduced drying time by 40 minutes [13].

In Vietnam, banana drying remains a primary method for processing and preserving bananas [14], resulting in products, such as soft-dried and crispy-dried bananas. Traditional drying techniques, such as sun drying and fuel-based hot air drying, are still widely practiced, especially in small-scale facilities. These methods typically utilize energy sources, like firewood, rice husks, or coal. However, they suffer from several drawbacks: high drying temperatures (typically 60–100 °C), long drying times, energy inefficiencies, residual high product moisture content (15–20%), and deterioration in the color and appearance of the final product.

In contrast, the heat pump drying technology offers a promising alternative. It is gaining traction in Vietnam's agricultural and food industries due to its lower energy requirements and ability to preserve product quality, including nutritional value, texture, and color. Several studies have already been conducted on heat pump drying in Vietnam. For instance, authors in [15] investigated rice seed drying, achieving a final moisture content of 13.2%. In [16], turmeric starch that was dried at 55 °C for 10 hours yielded the highest product quality. Additionally, authors in [17] studied mango drying using heat pump technology with a drying temperature of 30 °C, and authors in [18] explored infrared-assisted heat pump drying of lime slices, identifying 110–300 W/m² as the optimal radiation range.

However, no prior studies in Vietnam have examined the drying of whole bananas using a hybrid heat pump drying system. This research addresses that gap by investigating the drying regime of whole aromatic bananas using a combined heat pump and resistance heating system. The goal is to develop an optimized drying process that meets Vietnamese food safety standards and offers practical applicability for small and medium-sized banana processing enterprises in the country.

II. METHODOLOGY

A. Raw Materials

Figure 1 illustrates the experimental setup and raw materials used in the drying process. The selected raw material was aromatic bananas with a uniform ripeness level of approximately 80% to ensure consistency throughout the experiment. The bananas had an average diameter of 20 ± 0.5 cm, and their initial moisture content was 82%.

A total of 25 kg of fresh bananas were used, and after peeling the outer skin, the net weight of raw material was 15 kg. The peeled bananas were evenly distributed onto five

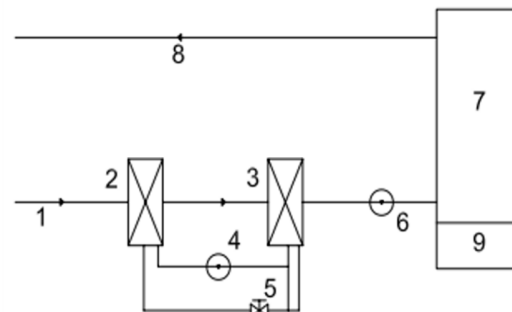
stainless steel trays, each measuring 500×500 mm, and perforated to facilitate air circulation. Each tray contained 3 kg of raw material, ensuring uniform load distribution during the drying process.



Fig. 1. Aromatic bananas in several stages of the experimental setup.

B. Laboratory Equipment

The experimental study uses a heat pump dryer combined with resistance, as shown in Figure 2.



- 1: Outside air; 2: Evaporator; 3: Condenser;
4: Compressor; 5: Expansion; 6: Fan;
7: Drying chamber; 8: Moisture release valve; 9: Resistance

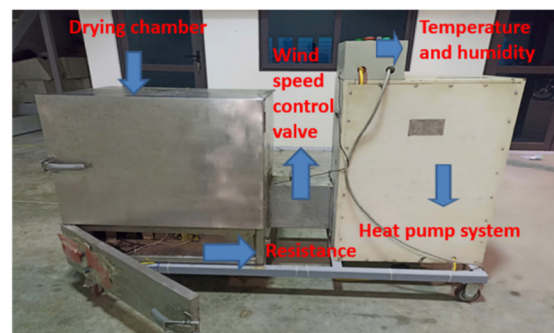


Fig. 2. Heat pump dryer combined with resistance.

The drying equipment operates based on a closed-loop heat pump system that combines controlled airflow and refrigerant circulation to achieve efficient moisture removal. The process can be described through two primary pathways:

- **Airflow Pathway:** Ambient air is first passed through an evaporator, where it is dehumidified, transforming it into dry air. This air is then directed through a condenser, where it undergoes heat exchange, raising its temperature from ambient levels to approximately 45 °C. The heated air is

subsequently supplied to the drying chamber, where its temperature is maintained within the range of 30–45 °C and relative humidity is controlled between 70% and 20%. Within the chamber, the air interacts with the drying material, initiating the evaporation of water from the material through heat and mass transfer.

- **Refrigerant Pathway:** The refrigerant circulates in a closed loop within the refrigeration system. The compressor draws in refrigerant vapor from the evaporator and compresses it adiabatically, increasing its temperature and pressure. This high-temperature, high-pressure refrigerant is then passed through the condenser, where it releases heat into the air before undergoing throttling to reduce its temperature and pressure. The cooled refrigerant then returns to the evaporator, completing the cycle.

In this heat pump drying system, the main driving force for moisture removal is the difference in water vapor pressure between the drying material and the drying agent. By lowering the humidity of the drying air, the vapor pressure at the material's surface becomes lower than that within the material, thus enhancing moisture migration from the interior to the surface. Additionally, the temperature gradient—where the outer surface is cooler than the interior—works in harmony with the vapor pressure gradient, promoting rather than inhibiting moisture transfer. Unlike traditional hot air drying, where the surface can become overly hot and slow moisture movement, this method allows for accelerated internal moisture transport even when surface temperatures are below 0 °C. The technical parameters during drying were monitored using the following equipment:

- A Precisa XM 60-HR moisture analyzer (Switzerland) for moisture content measurement.
- An EMIC CV140 20(80)A single-phase power consumption meter (Vietnam) to record energy usage.
- An AWD weighing scale (China) to determine the input and output mass of the material.
- An STC-3028 (China) control device for continuous monitoring and regulation of temperature and humidity within the drying chamber.

C. Research Method

The initial moisture content of aromatic bananas is determined by [18]:

$$\omega_0 = \frac{G_0 - G_c}{G_0} 100\% \quad (1)$$

where G_0 is the initial mass of the material (kg), and G_c is the mass of material after drying (kg).

The moisture content of dried material is calculated as:

$$\omega_t = \frac{G_{ni}}{G_i} 100\% \quad (2)$$

where G_{ni} is the mass of water in the material (kg), and G_i is the mass of the material at the time of the measurement (kg).

The amount of moisture removed is calculated by the Specific Moisture Extraction Rate (SMER):

$$\text{SMER} = \left(\frac{G_0 - G_c \left(\frac{100 - \omega_0}{100 - \omega_t} \right)}{E} \right) [\text{kg}_{\text{H}_2\text{O}} / \text{kWh}] \quad (3)$$

where ω_0 is the initial moisture content of the drying material (%); ω_c is the final moisture content of the drying material (%); G_0 is the initial mass of the drying material (kg); E is the total power consumption (kWh).

To evaluate the performance of the heat pump–resistance hybrid drying method, a comparative analysis was conducted against independent heat pump drying and resistance drying methods. The assessment focused on the energy consumption and sensory quality of the final dried product. The specific energy consumption e for each drying method was determined using:

$$e = \frac{E}{G_c} [\text{kWh}/\text{kg}] \quad (4)$$

In addition, the sensory evaluation method was applied to assess the changes in the characteristic color of the dried product at different temperatures and under various drying technologies. This evaluation was conducted by an expert panel using a sensory scoring system developed in accordance with Vietnamese Standard TCVN 3215-79 [19]. Each panelist independently assessed specific indicators using a standardized score sheet and having assigned integer scores on a 6-point scale ranging from 0 to 5, where higher scores indicated better sensory quality. The aromatic banana drying process using the heat pump–resistance heating hybrid mode is displayed in Figure 3. This process consists of four main steps: preparation of the raw banana, preparation for drying, drying process, involving three consecutive temperature stages, and product completion.

In Stage 1 ($t_1 = 35$ °C; $\omega_1 = 25\%$; $\tau_1 = 12$ h), the goal is to shape and stabilize the outer surface structure of the material, thereby facilitating more efficient moisture evaporation in the subsequent stages. Stage 2 ($t_2 = 45$ °C; $\omega_2 = 20\%$; $\tau_2 = 12$ h) is characterized by the highest evaporation rate, reaching 0.49 kg H₂O/h. In Stage 3 ($t_3 = 50$ °C; $\omega_3 = 20\%$; $\tau_3 = 11$ h), heat is supplied to accelerate the evaporation of internal moisture, enabling the material to reach the target moisture level more rapidly while maintaining product color and quality.

For comparison, independent experimental studies were also conducted for heat pump drying and resistance drying, each operated under its maximum achievable temperature:

- In the resistance drying mode, the drying temperature was set at 50 °C, with the drying agent humidity being maintained at ambient level (70%).
- In contrast, the heat pump drying mode operated at a maximum temperature of 45 °C, with the drying agent humidity being reduced to 25% - a condition enabled by the dehumidification function of the heat pump.

Throughout the drying processes, key parameters, such as drying time, energy consumption, and final product quality were recorded. These metrics were used to evaluate the energy efficiency and sensory performance of each drying method, providing a comprehensive basis for comparison.

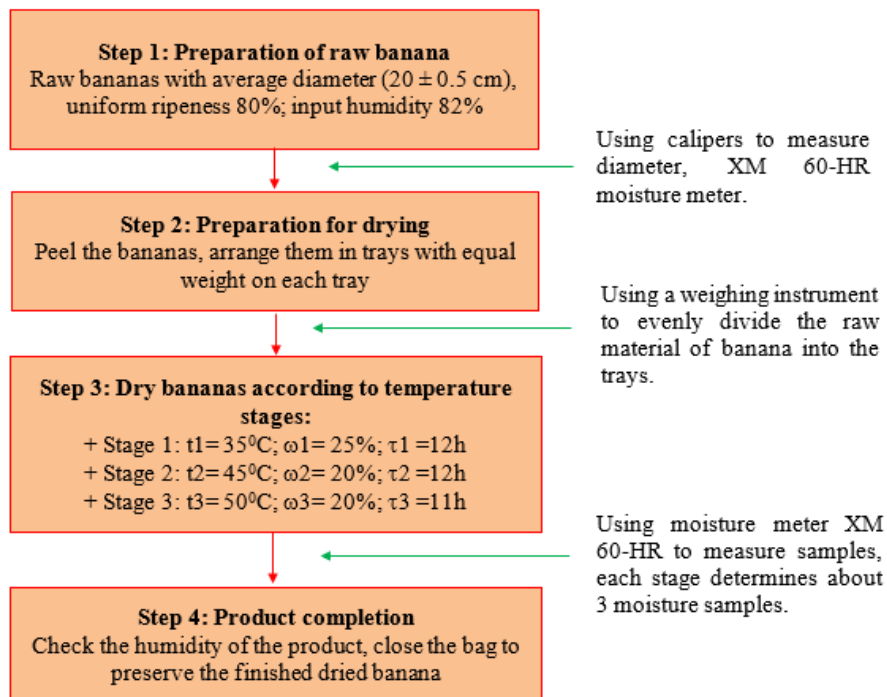


Fig. 3. Aromatic banana drying process in the heat pump and resistance hybrid drying mode.

III. RESULTS AND DISCUSSION

The paper presents drying experiments conducted in three different drying modes using the same dryer. These modes include: the heat pump with resistance hybrid drying mode, the resistance drying mode, and the heat pump drying mode, all applied to the same quantity of products, specifically 15 kg per batch.

A. Temperature and Humidity in Resistance Drying Mode

In the resistance drying mode, the drying temperature is maintained consistently at 50°C throughout the entire drying process, with the humidity of the drying agent being equal to the ambient humidity of 70%. The heat source is provided by the resistance heater. The effect of the drying time on the process is portrayed in Figure 4.

At the end of Stage 1, with a drying temperature of 50°C , the product's moisture content dropped significantly from the initial level to 56.3%. During Stage 2, the evaporation rate decreased compared to Stage 1, with the moisture content further reducing from 56.3% to 39.5%. However, in Stage 3, the surface of the raw material began to gelatinize, resulting in a slower evaporation of water. It took 19 hours to reduce the moisture content from 39.5% to 11.3%. The experimental analysis indicates that Stage 1 had the highest water evaporation rate, with an average evaporation of 2.14% per hour, while Stage 3 had the slowest evaporation rate, averaging only 1.16% per hour.

Additionally, the total electricity consumption during the drying process was 55 kW, yielding a final product mass of 4.4

kg at a moisture content of 11.3%. Consequently, the electricity consumption per kg of raw material was 3.66 kWh/kg.

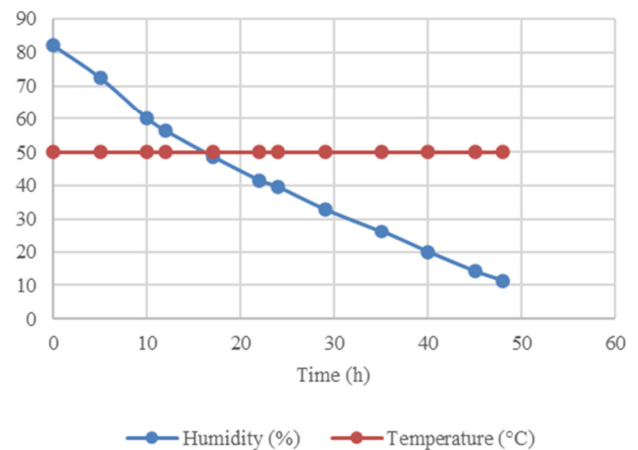


Fig. 4. Temperature and humidity in resistance drying mode.

B. Temperature and Humidity in Heat Pump Drying Mode

In the heat pump drying mode, as shown in Figure 5, the drying temperature is fixed at 45°C throughout the drying process.

In Stage 1, the humidity of the product decreased by 23.8%. During Stage 2 of the drying cycle, the evaporation rate intensified, with the product's humidity dropping from 58% to 30.5%. In Stage 3, the product's humidity further decreased from 30.5% to 11.3%. The analysis of the drying process

revealed that the most intense water evaporation occurred in Stage 2, with an average evaporation rate of 2.5% per hour. In contrast, Stage 1 exhibited the lowest evaporation rate, with an average of 1.65% per hour.

The total electricity consumption during the drying process was 46 kW, yielding a final product mass of 4.4 kg with a moisture content of 11.3%. Therefore, the electricity consumption per kg of raw material was 3.07 kWh/kg.

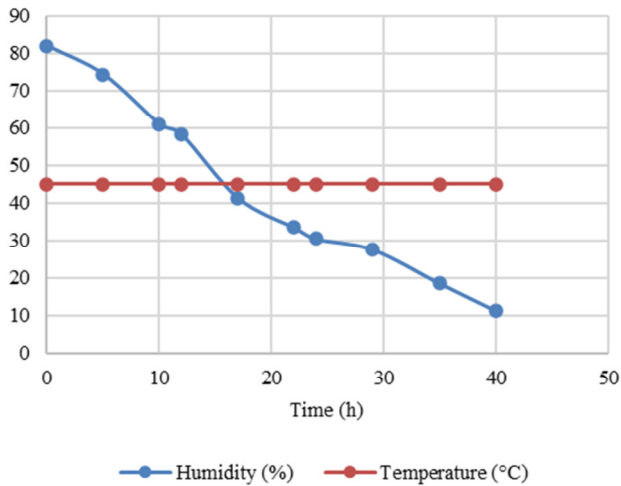


Fig. 5. Temperature and humidity in heat pump drying mode.

C. Temperature and Humidity in Heat Pump and Resistance Hybrid Drying Mode

In the heat pump and resistance heating hybrid mode, as depicted in Figure 6, the most intense water evaporation in the raw material occurs during Stage 2. The average evaporation rate in this stage is 1.83 times higher than in Stage 1 and 3.43 times higher than in Stage 3, respectively. The average evaporation rate over the entire drying process is 0.3 kg H₂O/h.

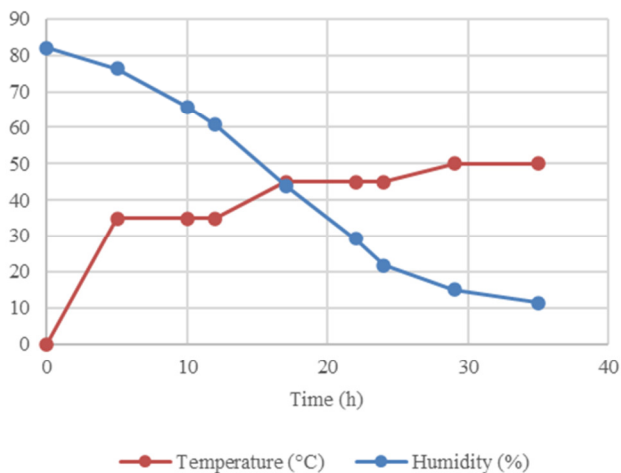


Fig. 6. Temperature and humidity in heat pump and resistance hybrid drying mode.

The total electricity consumed during the drying process is 32 kW, and the final mass of the product obtained is 4.4 kg with a moisture content of 11.3%. Consequently, the electricity consumed per kg of evaporated water is 3.2 kW/kg, while the electricity consumed per kg of raw material is 2.13 kWh/kg. The energy consumption rate for 1 unit of product is 7.28 kWh/kg.

D. Product Moisture in the Three Drying Modes

According to the results, illustrated in Figure 7, in Stage 1, the resistance drying mode exhibits the fastest evaporation rate, reducing the moisture content from 82% to 56%, a decrease of 25.7%. In contrast, the heat pump and resistance hybrid drying mode shows the slowest evaporation rate, reducing moisture by only 21.27%. This difference is due to the resistance drying mode operating at 50°C, accelerating the evaporation process.

In Stage 2, as the temperature of both the heat pump and resistance hybrid drying modes rises to 45°C, the evaporation rate increases significantly. The heat pump and resistance hybrid mode evaporates 39.01% of the moisture, while the resistance drying mode only removes 17.5%. This slower evaporation in the resistance drying mode is caused by the formation of a film on the banana surface, which slows down moisture separation.

In Stage 3, the heat pump and resistance hybrid drying mode increases the temperature to 50 °C, requiring 11 hours to reduce the moisture content from 21.72% to 11.3%. In comparison, the heat pump drying mode takes 16 hours to evaporate moisture from 38% to 11.3%, and the resistance drying mode requires 24 hours to reduce moisture from 39.5% to 11.3%. The prolonged drying time in the resistance drying mode is due to the gelatinization of the banana surface starting in Stage 2, which forms a hard film that hinders the movement of moisture from the center of the product to the surface, slowing down the moisture release compared to the other two drying modes.

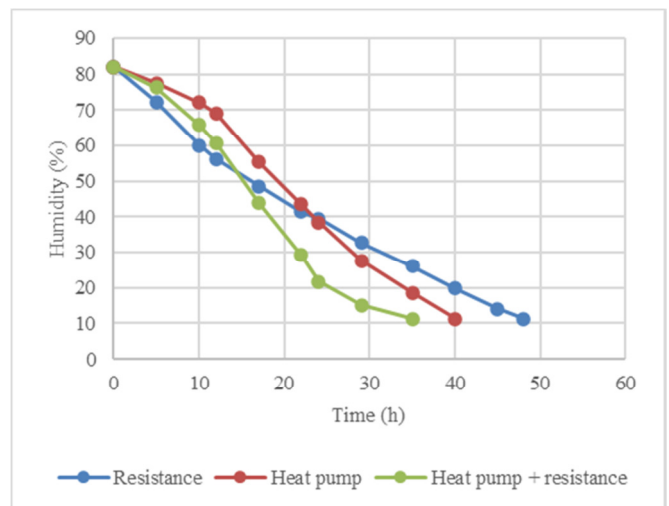


Fig. 7. Drying speed curve chart of the three drying modes.

E. Evaluation of Time and Power Consumption in Three Drying Modes

As shown in Figure 8, the heat pump and resistance hybrid drying mode demonstrated the fastest drying time, being 25% and 10% faster than the resistance drying mode and the heat pump drying mode, respectively.

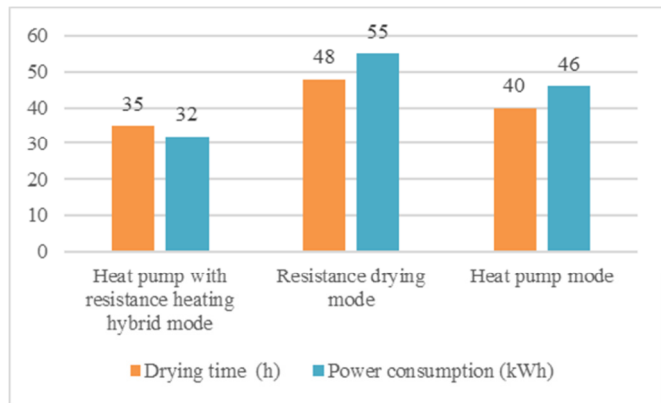


Fig. 8. Drying time and power consumption chart for three different drying modes.

In terms of energy consumption, the heat pump and resistance hybrid drying mode exhibited savings of 37% and 24% compared to the resistance drying mode and the heat pump drying mode, respectively, with identical input mass and output product moisture content. The power consumption efficiency for each drying mode per kg of raw aromatic banana is as follows: 2.13 kW/kg for the heat pump and resistance hybrid drying mode, 3.66 kW/kg for the resistance drying mode, and 3.07 kW/kg for the heat pump drying mode.

TABLE I. EVALUATION OF PRODUCT COLOR IN DRYING MODES

Drying mode	Color	Image
Heat pump and resistance hybrid drying mode	7.5	
Heat pump drying	7.2	
Resistance drying	6.0	

F. Evaluation of Product Quality of Three Drying Processes

The results of the sensory evaluation of dried aromatic banana products in different drying modes are presented in Table I. The sensory evaluation revealed distinct differences in the quality of the aromatic banana products across the drying modes. In the heat pump and resistance hybrid drying mode, the color received the highest preference score of 7.5, compared to the other modes. In contrast, the resistance drying mode received the lowest color evaluation score of 6.0. This difference is attributed to the fact that the drying process at a lower temperature, which takes longer, promotes the conversion of sugars, leading to the formation of unwanted color pigments.

IV. CONCLUSION

This study demonstrates that the hybrid heat pump and resistance drying mode offers a compelling advantage over conventional resistance and heat pump drying techniques, especially in the context of whole banana drying. Specifically, the hybrid mode reduced drying time by 25% compared to resistance drying and by 10% compared to heat pump drying, all while maintaining identical input mass and achieving the target product humidity. This reduction in processing time directly contributes to enhanced throughput and operational efficiency. Energy consumption in the hybrid system was measured at 2.13 kWh per kg of raw material, marking a significant improvement in energy efficiency, saving approximately 37% and 24% compared to traditional resistance and standalone heat pump drying modes, respectively. These savings are particularly meaningful in small- and medium-sized banana processing enterprises, where energy costs can be a critical factor. Importantly, the hybrid drying mode also delivered superior product quality. In sensory evaluations focused on visual appeal, products dried using the hybrid method achieved the highest color preference score of 7.5, compared to the lowest score of 6.0 in the resistance-only mode. This confirms that the hybrid system not only optimizes process performance, but also better preserves the aesthetic and potentially nutritional qualities of the final product.

In the Vietnamese context, where traditional drying techniques often compromise both energy efficiency and product quality, the adoption of a hybrid heat pump and resistance drying system represents a viable, scalable solution. It aligns with national efforts to modernize agricultural practices, reduce post-harvest losses, and ensure compliance with food safety standards, paving the way for more sustainable and value-added banana processing.

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