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Experimental Study and Energy Evaluation of Heat Pump–Solar Hybrid Drying of Bitter Melon

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Abstract: ***This study experimentally investigates the performance of a hybrid drying system that integrates a heat pump with solar thermal energy, aiming to improve energy efficiency in the drying of bitter melon (Momordica charantia). The research focuses on the effects of slice thickness on drying time, Specific Energy Consumption (SEC), and the quality of the dried product. Drying trials were conducted using slices of bitter melon of three different thicknesses: 1 mm, 2 mm, and 3 mm. The hybrid system employed a flat-plate solar collector to preheat the inlet air before it entered the heat pump drying chamber. Results show that slice thickness had a significant effect on drying kinetics. Slices with 1 mm thickness reached the target moisture content in 4 hours, whereas 3 mm slices required up to 5.5 hours. The integration of solar preheating reduced total electrical energy consumption from 4.3 kWh to 2.7 kWh per batch, yielding an energy savings of approximately 37.2%. The SEC was also reduced, from 5.73 to 3.60 kWh/kg of evaporated water. In addition to energy improvements, the hybrid system helped retain favourable product characteristics, including a final moisture content of 10–12%, natural green colour, aroma, and essential bioactive compounds such as momordicin and flavonoids. These outcomes demonstrate the hybrid system's potential as a sustainable solution for small- to medium-scale agricultural drying. A slice thickness of 1–2 mm is recommended for optimizing both drying efficiency and product quality. The findings support further research on the drying parameters that affect nutrient retention and the physical properties of dried agricultural products.***

Keywords: Bitter Melon Drying; Hybrid Drying System; Solar Energy; Heat Pump; Drying Kinetics; Energy Efficiency; Product Quality.

Abbreviations:
SEC – Specific Energy Consumption.

I. INTRODUCTION

Drying is an essential agricultural preservation method used to extend shelf life, reduce post-harvest losses, and facilitate processing [1]. According to a study by Grover and Yadav (2004), among nutrient-rich and medicinal foods, bitter melon (Momordica charantia) is widely used in both traditional and modern medicine due to its benefits in supporting diabetes treatment and enhancing overall health [2]. However, because of its high moisture content, bitter melon is highly perishable if not processed promptly. Therefore, drying is a critical step to ensure the quality and usability of the product.

Traditional drying systems using electrical resistance heaters have the advantage of ease of operation but consume a large amount of energy and have difficulty in precisely controlling temperature and humidity, which negatively affects product quality (Belessiotis & Delyannis, 2011) [3]. In contrast, heat pump drying systems have gained increasing appreciation for their energy-saving capabilities, stable operation, and flexible control of drying conditions. Notably, integrating renewable energy sources such as solar energy represents a sustainable approach that utilizes clean and abundant energy, especially suitable for tropical monsoon climates like Vietnam (Hii et al., 2012) [4].

Currently, there is a limited number of experimental studies evaluating the energy efficiency of hybrid drying systems, particularly for bitter melon. Therefore, this study was conducted to assess the energy-saving potential and performance of a hybrid heat pump and solar energy drying system during bitter melon drying, thereby proposing an effective and environmentally friendly solution for drying agricultural products.

II. MATERIALS AND METHODS

A. Material

The material used in this study was fresh bitter melon (*Momordica charantia*), purchased from a commercial supplier in Hoài Đức district, Hanoi, Vietnam. The raw materials were carefully selected to ensure freshness, uniform size, and absence of pest infestation or damage. After harvesting, the bitter melons were sorted, thoroughly washed with water, drained, and then sliced evenly across the horizontal axis with thicknesses of 1 mm, 2 mm, and 3 mm. The slice thickness was measured using a Syntek 150 mm digital calliper to ensure accuracy and uniformity. Slices that did not form uniform circular shapes or did not meet the size requirements were discarded. All qualified slices were weighed and evenly arranged on drying trays in preparation for the experimental process.

The initial moisture content of the bitter melon was determined following the standard AOAC method (2019) [5] by drying samples at 105 °C for 24 hours. The results showed that the initial moisture content of the raw material was approximately 77.5% on a wet basis on average.

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[Fig.1: Fresh Bitter Melon Slices Prepared for the Drying Experiments]

B. Drying Equipment

The equipment used in this study consisted of a heat pump drying system and a solar water heating unit. The system comprised key components, including a heat pump unit, a heat exchanger utilising solar-heated water, a centrifugal fan, and a temperature controller installed inside the drying chamber. The drying material was arranged on drying trays to ensure uniform energy absorption by the bitter melon slices. The entire system was operated and controlled via an HMI interface integrated with a PLC (Programmable Logic Controller), allowing for adjustment and monitoring of technical parameters throughout the drying process. The drying air temperature can be flexibly controlled within the range of 25°C to 60°C to meet the requirements of different drying modes. Photographs and simulations of the actual system are presented in Figures 2 and 3.

[Fig.2: Actual View of the Heat Pump Drying System Used in the Experiment]

[Fig.3: 3D Schematic Model of the Heat Pump–Solar Hybrid Drying System]

Before conducting the main experiments, the system was fully installed, a trial run was conducted, and operational parameters were calibrated. Measurements of variables such as voltage, current consumption, compression pressure, evaporation pressure, humidity, and temperature inside the drying chamber indicated stable system operation, with discrepancies between design specifications and experimental data all below 10%

III. RESULTS AND DISCUSSION

A. Parameter Determination Methods

i. *Moisture Content of Bitter Melon:* In this study, it is assumed that the entire mass loss during drying is due to water evaporation. The moisture content of fresh bitter melon at any given time was calculated using the formula from Nguyen Van May (2004) [6]:

$$\omega_1 = \frac{m_1 - m_2}{m_1} . 100\% \quad \dots \quad (1)$$

Where:

- ω_1 is the moisture content (% wet basis),
- m_1 is the initial mass at time t (g),
- m_2 is the dry mass after drying (g), determined according to the AOAC method.

Procedure:

- A sample of 100 uniform thin slices of bitter melon with precise initial mass m1 was taken.
- The samples were placed in a drying oven at 105 °C for 24 hours.
- After drying, the samples were weighed again to determine the dry mass m2 due to water evaporation.

ii. Specific Energy Consumption (SEC):

$$\text{SEC} = \frac{\text{Electric energy consumption (kWh)}}{\text{Amount of water evaporated (kg)}} \qquad (2)$$

B. Experimental Procedure

The experiment was conducted to evaluate the energy-saving potential of a heat pump drying system combined with solar energy by drying sliced bitter melon with three different thickness levels. The initial drying material mass for each trial was 1 kg, with an average initial moisture content of approximately 77.5%. The final moisture content after drying was determined to be 10% (wet basis). For each drying condition, the experiment was repeated independently three times, and the presented results are the average values of the three trials.

The bitter melon slices were dried under an average ambient temperature of 28.4 °C. The drying system operates by combining energy from the heat pump and solar energy. The drying air was preheated to 45 °C by the solar water heating system, and then further heated to 55 °C by the heat pump heater. The air temperature inside the drying chamber was maintained steadily at approximately 50 ± 3 °C throughout the drying process. The total electricity consumption recorded during each drying cycle was 2.7 kWh.

The three drying modes were conducted as follows:

- **Mode 1:** Bitter melon slices with a thickness of 1 mm were dried for 1 hour using combined solar energy (45 °C) and heat pump energy (55 °C).
- **Mode 2:** Bitter melon slices with a thickness of 2 mm were dried under the same conditions as Mode 1.
- **Mode 3:** Bitter melon slices with a thickness of 3 mm were dried under unchanged drying conditions.

Data collected during each experiment included the average drying air temperature, the average relative humidity of the drying medium inside the chamber, the drying time, the remaining mass of the drying material, and the electricity consumption. These data formed the basis for evaluating energy indicators such as Specific

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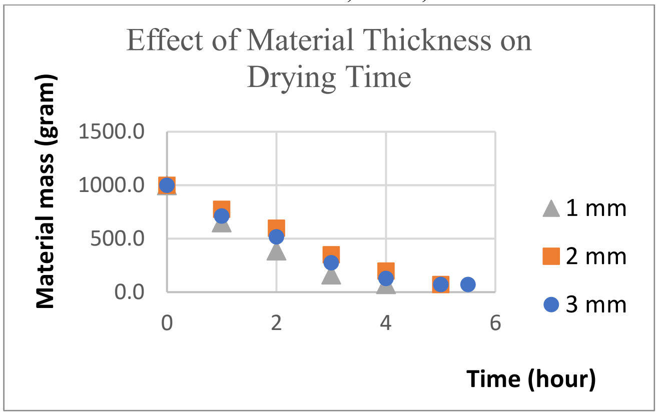
Energy Consumption (SEC), thermal efficiency, and drying kinetics.

C. Experimental Results

i. *Effect of Material Thickness on Drying Time*

The experimental results indicate that the thickness of bitter melon slices significantly affects the drying rate and the time required to reach the desired moisture content. Figure 4 illustrates the change in material mass during drying at three different thickness levels: 1 mm, 2 mm, and 3 mm.



[Fig.4. Effect of Material Thickness on Drying Time]

As the slice thickness decreases, the drying rate significantly increases. Specifically, the 1 mm slices exhibited the fastest mass reduction, reaching near-complete dryness after approximately 4 hours. In contrast, the 2 mm slices required about 5 hours to achieve a similar mass, while the 3 mm slices reached complete dryness after 5.5 hours of drying.

This phenomenon is attributed to the fact that thicker materials increase the resistance to moisture diffusion from the interior to the surface, thereby slowing down the moisture removal process. Consequently, this leads to extended drying times and increased energy consumption.

These results are consistent with the heat and mass transfer theory during the drying of porous materials, where the moisture diffusion rate is inversely proportional to the material thickness. Hence, selecting an appropriate slice thickness is a crucial factor in optimising drying efficiency and energy savings.

ii. *Evaluation of Energy Savings*

The energy-saving performance of the drying system was assessed by comparing the electricity consumption and Specific Energy Consumption between two drying methods: conventional heat pump drying and hybrid drying using a heat pump combined with solar thermal energy.

iii. *Electricity Consumption Calculation*

The dry matter content remains constant during the drying process and was calculated as:

$G_k = G_0 * (1-\omega_1) = 1*(1 - 0,775) = 0,225$ kg

Final product mass after drying:

$G_{dried} = G_k/(1 - \omega_2) = 0,225/(1 - 0,10) = 0,25$ kg

Mass of water evaporated:

$m_2 = G_0 - G_{dried} = 1 - 0,25 = 0,75$ kg

iv. *Heat Pump Drying (Conventional)*

- Total electrical energy consumed:

$E_{HP} = 4,30$ kWh

- Specific Energy Consumption:

$SEC_{HP} = 4,3/0,75 = 5,73$ kWh/kg of water evaporated

v. *Hybrid Heat Pump + Solar Energy Drying*

- Total electrical energy consumed:

$E_{hybrid} = 2,7$ kWh

- Specific Energy Consumption

$SEC_{Hybrid} = 2,7/0,75 = 3,6$ kWh/kg of water evaporated

vi. *Electricity Savings*

% Savings = (4,3 – 2,7)/4,3 *100 =37,21 %

To evaluate the effectiveness of electrical energy use during the drying process of bitter melon, the authors conducted a comparative analysis between two methods: conventional heat pump drying and hybrid solar-assisted heat pump drying. The comparison criteria included the mass of dry matter, amount of evaporated moisture, electrical energy consumption, and Specific Energy Consumption (SEC). The detailed results are presented in Table 1.

Table-1: Comparison of Energy Consumption Between the Two Drying Methods

Indicator	Conventional Heat Pump Drying	Hybrid Heat Pump – Solar Drying
Initial material mass (G_0), kg	1.00	1.00
Initial moisture content (ω_1), %	77.5	77.5
Final moisture content (ω_2), %	10	10
Dry matter mass (G_k), kg	0.225	0.225
Final dried product mass (G_{dried}), kg	0.25	0.25
Evaporated water mass (m_2), kg	0.75	0.75
Electrical energy consumption (E), kWh	4.30	2.70
Specific energy consumption (SEC), kWh/kg H_2O	5.73	3.60
Electricity saving ratio compared to the conventional system, %	–	**37.21**

Table 1 illustrates a significant difference in energy consumption between the two drying methods. The hybrid heat pump–solar system consumed markedly less energy (2.70 kWh) compared to the conventional heat pump drying system (4.30 kWh), resulting in an electricity saving ratio of 37.21%. Additionally, the specific energy consumption (SEC) decreased from 5.73 to 3.60 kWh/kg H_2O, demonstrating the superior energy efficiency of the hybrid drying system.

IV. DISCUSSION

The research results demonstrate that the slice thickness of the material has a significant impact on the drying kinetics. As thickness decreases, the moisture diffusion resistance from the interior to the surface is reduced, thereby increasing the drying rate. Specifically, one mm-thick bitter melon slices reached the target moisture content after 4 hours, faster than the 5 hours (2 mm) and 5.5 hours (3 mm) required for thicker slices. This result is consistent with the principles of moisture transfer in porous materials as described by Keey et al. (2012) [7], stating that the moisture diffusion rate is inversely proportional to material thickness.

The energy efficiency of the hybrid drying system is demonstrated through the SEC

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indicator and electrical energy consumption. The system utilises solar energy to preheat the drying air, significantly reducing the load on the heat pump and resulting in 37.2% lower electricity consumption compared to the conventional heat pump drying method. The specific energy consumption dropped from 5.73 to 3.60 kWh/kg of evaporated water, confirming the effectiveness of the integrated solution. This finding aligns with the study by Fudholi et al. (2014) [8], which highlighted that solar-assisted drying systems can substantially reduce electrical energy consumption and improve overall drying efficiency, especially in tropical climates.

Compared with the study by M. Fatouh et al (2006). [9], in which herbal drying using a heat pump at 55 °C took 2 to 6 hours, the drying time of 4–5.5 hours for bitter melon in this study falls within an acceptable range. Similarly, Abdelwahab [10] reported that drying sliced onions using a heat pump dryer at 50 °C took up to 6 hours, indicating that the system used in this research performs equally or even better than some previously developed drying systems.

Notably, the electrical consumption results align with the findings of Shaikh and Kolekar (2015) [11], who stated that hybrid solar-heat pump drying systems can significantly reduce energy use, depending on daily solar radiation intensity. In tropical climates like Vietnam, the use of solar energy is both feasible and highly practical.

In addition to time and energy efficiency, the quality of the dried product was also maintained. The dried bitter melon retained its natural colour, characteristic aroma, and important bioactive compounds such as momordicin and flavonoids, enhancing both the nutritional and commercial value of the product. This aligns with findings from Thi-Van-Linh Nguyen et al. (2020) [12], who demonstrated that low-temperature microwave-assisted drying preserved both vitamin C and total phenolic content (a proxy for flavonoids) in bitter melon slices, with vigorous antioxidant activity remaining [13]. Moreover, studies on the drying of wild bitter gourds have shown that microwave-assisted convective drying effectively maintains total phenolic and flavonoid contents, while minimising colour degradation. Research by Pal et al. [14] also indicated that heat-pump drying effectively retained volatile aroma compounds in sliced fruits and vegetables, supporting the preservation of aroma in our product

In summary, integrating solar energy into a heat pump drying system not only reduces operational costs but also aligns with the trend of green technology development, contributing to carbon emission reduction and improving sustainability for small and medium-sized agricultural processing facilities. Such integrated systems, which deliver efficient energy use and high-quality output, demonstrate strong potential for environmentally friendly industrial adoption.

V. CONCLUSIONS

This study conducted experimental drying of bitter melon slices at three different thicknesses (1 mm, 2 mm, and 3 mm) using a heat pump drying system combined with solar energy, aiming to evaluate the effect of slice thickness on drying time and specific energy consumption (SEC). The key findings are as follows:

- Slice thickness significantly influences drying time: thinner slices (1 mm) reduce drying time to 4 hours, while thicker slices (3 mm) require up to 5.5 hours to reach the desired final moisture content.
- The hybrid system effectively reduced electrical energy consumption from 4.3 kWh to 2.7 kWh, corresponding to an energy savings of approximately 37.2% compared to the standalone heat pump dryer. The SEC decreased from 5.73 to 3.60 kWh/kg of evaporated water, confirming the efficiency improvements brought by integrating solar preheating.
- The dried product retained favourable qualities, including a moisture content of 10–12%, natural colour, aroma, and valuable bioactive compounds such as momordicin and flavonoids, meeting food storage standards.
- The combined heat pump and solar energy drying system demonstrated energy-saving effectiveness, environmental friendliness, and suitability for small to medium-scale agricultural drying applications in Vietnam.

Based on these findings, it is recommended to use slice thicknesses in the range of 1–2 mm to optimize drying time and energy consumption. Future research should extend the evaluation to product quality parameters, including colour, nutrient retention, and crispness, to refine the optimal drying process for bitter melon and similar agricultural products.

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DECLARATION STATEMENT

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Nguyen Thi Viet Linh, born on November 11, 1988, in Hai Duong, Vietnam, graduated with an engineering degree in 2011 from Hanoi University of Industry and a Master's degree in 2014 from Hanoi University of Science and Technology. I work at the Department of Energy, School of Electrical and Electronics Engineering, Hanoi University of Industry. I have been teaching and researching at the school since 2019. My major is in the field of thermal engineering technology. I have 14 years of experience in the field of thermal technology and equipment. I have researched and collaborated with research groups in areas such as evaluating the replacement of refrigerants in refrigeration systems with banned refrigerants using environmentally friendly alternatives, as well as heat pump drying systems with integrated solar energy and Fluidised bed drying systems. I have written reference books, such as "Refrigeration Safety" and "Practice of Civil Air Conditioning."

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