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Research Article

Techno-economic Analysis of Heat Pump Assisted Solar Dryer for Krajood

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ABSTRACT

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This study applies solar energy-assisted heat pumpdryer for Krajood. The prototype solar-assisted heat pump drying system was designed to evaluate heat transfer efficiency and to conduct economic analysis for potential implementation. In the study, temperatures of 45°C, 55°C, and 65°C were investigated. Experimental results indicated that the optimal drying temperature was 55°C, achieving a balance between energy efficiency and product quality. The solar-assisted heat pump drying system exhibited a specific energy consumption of 2.67 kWh/kg and a thermal efficiency of 22.13%. The drying time with the solar-assisted heat pump dryer (22 hours) for 10 kg of Krajood was proven to be shorter compared to open solar drying of Krajood (batch 24 h or 3 days). An economic analysis employing Net Present Value and payback period revealed significant economic benefits over a 5-year lifespan. The payback period for Krajood drying (2.9 years) aligned well with previous studies. These findings demonstrate the economic feasibility and potential of solar-assisted heat pump dryer for reducing postharvest losses of Krajood, particularly in developing countries.

1. Introduction

Krajood trees are an important economic crop in the southern region of Thailand with significant growing areas such as Phru Kuan Kreng in Cha-uat District, Nakhon Si Thammarat Province, Taley Noi in Khuan Khanun District, Phatthalung Province and Khlong U-Taphao area in Singhanakhon District, Province Songkhla. Phru Kuan Kreng is known for its Krajood products, especially weaving, which is an essential household item for daily life. Knowledge of Krajood handicraft has been passed down through generations, particularly in southern communities. Krajood handicraft produces various products for everyday use, such as mats, boat sheets, ropes, food bags and other items. The characteristics of products in each province vary depending on the type of raw materials, local customs, cultures, preferences and uses. Krajood handicraft is culturally significant and a vital occupation for the people of the southern region (Community development department, 2024). Entrepreneurs often use Krajood to dry them for use in weaving and making various products such as bags and various tools. The process of Krajood weaving includes four main steps:

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raw material preparation, Krajood threading, product decoration and product preservation (Sompoangeon and Kongsom, 2021). Problems arise in the Krajood handicraft process, from the extraction of the Krajood trees to the manual harvesting, which can result in uneven or non-standard tree felling. Challenges during the drying phase include longer drying times, difficulties during the rainy season and the risk of fungal growth due to inadequate drying. Finally, pressing Krajood is a labor-intensive and equipment-dependent process that can lead to inconsistent yields. Inadequate drying or pressing may necessitate reprocessing with smaller presses or additional drying, causing delays, repetition, and ultimately, lower output.

Heat pump drying technology has been developed to address the issue of drying heat-sensitive materials such as bioactive food and pharmaceutical products (Masud *et al*., 2020). This technology is well recognized as one of the energy-efficient ways to achieve this drying at comparatively low temperatures. In addition, solar energy combination technology can be used in heat pump drying because of energy efficiency, reduced reliance on weather conditions and improved product quality (Sabarez, 2020). While solar drying methods such as indirect and direct drying through solar radiation have been explored, recent research on hybrid heat pump dryers is exploring how heat pumps can be further combined with various technologies to improve the drying process (EL-Mesery *et al*., 2022; Zhou *et al*., 2022). The indirect sunlight approach was chosen for this study because it minimally affects the color of the woven Krajood products compared to direct sunlight. Due to the southern region's hot and humid climate caused by year-round monsoons, this research prioritizes a hybrid approach utilizing heat pumps for their efficient moisture removal and indirect solar radiation for additional drying power (Zhou *et al*., 2022). Based on previous research, Qiu *et al*. (2016) a method of heat recovery with drying systems that use primary thermal energy from heat pumps. To increase the power coefficient and drying efficiency. In addition, the concept of heat recovery was developed for dryers that mainly use solar energy. Naemsai *et al*. (2019) have proposed drying Krajood using solar dryers combined with heat pumps, using the thermal conductivity method left over from room drying. The condenser is used in a lower temperature chamber, the evaporator chamber, which has been proven to reduce drying time and provide significantly better efficiency than traditional drying methods (Do *et al.*, 2018). While research on heat pumps often prioritizes performance improvement, economic analysis, particularly payback periods, is equally crucial for solar dryers. Economic evaluation reveals whether a proposed dryer is cost-effective, sustainable, and likely to be adopted by users. This information is vital for encouraging investment in and widespread adoption of this technology. Combining energy analysis with economic considerations allows for selecting dryer operating conditions that are both efficient and commercially viable. Expanding upon the findings of Rulazi *et al*. (2024), this research validates the efficacy and sustainability of Solar-Assisted Heat Pump Dryers (SAHPDs) in the dehydration of fruits and vegetables. By substantially curtailing drying times and energy consumption relative to conventional methods, SAHPDs demonstrate significant potential for agricultural applications. The prototype evaluated in this study attained a commendable Coefficient of Performance (COP) of 3.4 and a thermal efficiency of 54%. Moreover, the economic viability of the technology is underscored by calculated payback periods of merely 3 years for tomato drying and 2.6 years for carrot dehydration. These results suggest SAHPDs are a viable solution for developing countries to minimize post-harvest losses and reduce reliance on harmful biomass fuels. Recently, Deymi-Dashtebayaz *et al.* (2024) explored the potential of integrating solar energy storage, heat exchangers, and heat pumps into food waste drying systems. Their research evaluated the dryer's performance with a 100 kg load and a moisture removal rate of 71.42 kg/h under various weather conditions. They also discussed the dryer's potential application in future food production systems, focusing on its ability to improve energy efficiency and reduce carbon dioxide emissions. Moreover, the effective performance of SAHPDs demonstrated in previous studies (Yu *et al*., 2024;

Loemba *et al*., 2024) is further confirmed in this research through its application to agricultural products.

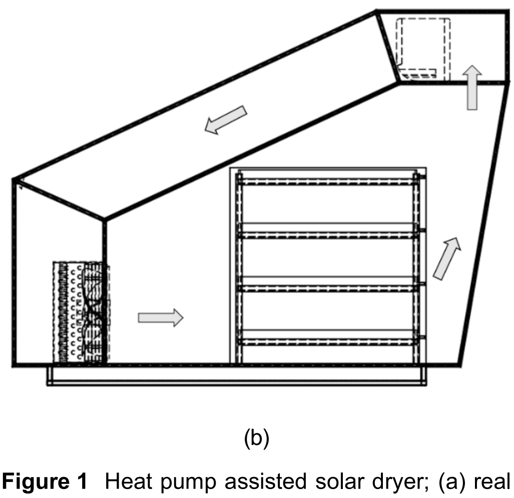
A review of existing literature reveals a scarcity of research exploring the application of indirect solar radiation, in combination with heat pumps and heat recovery, for drying agricultural woven products, particularly Krajood. To fill this gap, this study designed and built a Heat Pump Assisted Solar Dryer (HPASD) specifically for drying Krajood products. The performance of the HPASD is analyzed to assess its efficiency and potential benefits. Moreover, this study investigates the techno-economic feasibility of using a HPASD for drying Krajood. This initiative seeks to address the knowledge translation gap between academic research and practical solutions applicable to community enterprises in southern Thailand. By demonstrating the economic viability of HPASD technology, this study aims to facilitate the widespread adoption of HPASD thereby promoting sustainable energy use and contributing to social development within the region.

2. Materials and Methods

2.1 Materials and experimental setup

The samples of Krajood (*Lepironia articulata*) with an average size (length, 1 m; diameter, 2 cm; thickness, 3 mm) were collected from a Khlong U-Taphao area in Singhanakhon District, Songkhla, Thailand. Approximately 5 kg of fresh fruit was used in each experiment. The samples were cleaned and all foreign matter was removed. The average moisture content of fresh red Krajood was controlled to be about 233.33% (dry basis) before the drying process. An HPASD was designed and installed in Songkhla, Thailand. The dryer uses a combined solar thermal and heat pump system. The drying chamber itself is made of black box steel for durability. The walls are made of polycarbonate panels, which make up about 20% of the total area, to allow some light transmission and possible solar heat gain. A 0.78 kW heat pump unit with the environmentally friendly refrigerant R32 serves as the primary heating source. This unit works with a control system to maintain the desired drying conditions in the chamber. To complement the solar and heat pump system, an additional 500W infrared heater is available if additional heat is needed. The drying chamber offers space for five 0.6 x 0.6 meter drying trays designed to hold baskets with the products to be dried. In addition, as shown in Figure 1(a), the drying system operates as a closed loop with heat recovery. The drying air circulates in the system at a wind speed of 3 m/s, so there is no need to extract or resupply air from the outside environment. This design enables efficient heat recovery by capturing both latent heat (humidity) and sensible heat (temperature) from the exhaust air exiting the evaporator after drying. A key advantage of this system is its independence from external weather conditions such as temperature and relative humidity. This enables reliable operation regardless of the prevailing weather. The airflow characteristics of the system are shown in Figure 1(b).

(a)

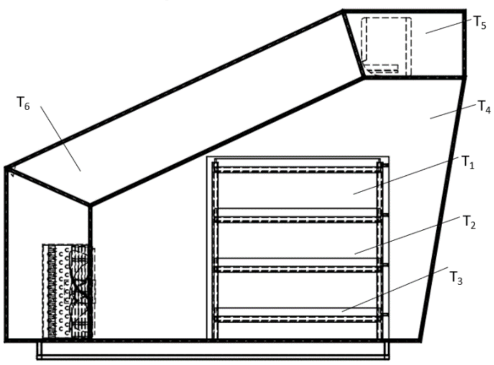


(b)

Figure 1 Heat pump assisted solar dryer; (a) real machine and (b) schematic diagram

2.2 Experimental procedure

In the experiment, three drying temperatures were evaluated in the experiment: 45 °C, 55 °C and 65 °C. The experiments were carried out on cloudy days during the rainy season with a quasi-constant relative humidity of 50% relative humidity. The Krajood samples were dried horizontally. Temperature data were collected using Chromel-Alumel (Type K) thermocouple cables with an uncertainty of 0.5°C. Relative humidity was measured using a Primus brand HM-005-01 detector with an uncertainty of 0.5%. Electricity consumption was monitored using a Schneider Electric PM 2100 series device with an uncertainty of 0.1 kWh. The temperature measurement points in the dryer are shown in Figure 2. T_1 through T_3 represent temperature readings at different shelf levels in the dryer. T_4, T_5, and T_6 measure room temperature, inlet temperature, and outlet temperature, respectively. The dryer was positioned in a north-south direction for a period of six hours (9:00 a.m. - 5:00 p.m.). The moisture content was determined to analyze energy consumption. One kilogram of fresh Krajood was oven-dried in a 3,000 W Binder electric incubator at 103 °C for 48 h to determine its dry weight (approximately 0.35 kg). For each experiment, the condenser temperature controller was set to a maximum of 65 °C. A temperature difference of 50°C was maintained with the evaporator set at 18°C to avoid extreme operating temperatures for the heat pump. All experimental cases were tested at least three times to ensure statistical accuracy. Furthermore, the open sun method dried fresh Krajood for six hours daily (9:00 AM - 5:00 PM), a timeframe that overlaps with the operating hours of the HPASD.



(a)

(b)

Figure 2 Temperature positioning for the experiment, (a) schematic diagram and (b) real positioning in the machine

2.3 Techno-economic Analysis

HPASD performance was evaluated by determining the moisture content (*MC*), weight of water evaporated from the product (m_{out}), Specific Energy Consumption (*SEC*) and thermal efficiency of the drying system (η_{th}). The thermal efficiency or drying efficiency is a crucial factor in evaluating the energy consumption. This research analyzed energy use by first calculating the moisture content removed from the product during drying. Equation (1) is used for this calculation.

$$m_{out} = m_i - m_f \quad (1)$$

where m_{out} is weight of water evaporated from the product m_i is weight of the initial product and m_f is weight of the final product

The moisture content in dry basis was determined by using the gravimetric oven drying method, in which 1 kg of Krajood was accurately weighed in a clean, dry petridish and the weight of the sample was recorded. The percentage of moisture content was calculated using Equation (2).

$$MC_{db} = \frac{m_W - m_D}{m_D} \times 100 \quad (2)$$

where MC_{db} is moisture content on a percent basis, m_W is weight of the wet product and m_D is weight of the dried product

The total energy consumption in the drying system is calculated from Equation (3).

$$E_t = GA_c + E_e t \tag{3}$$

where E_t is the total energy consumed in the drying system, A_C is the sunlight-absorbed area, G is the solar radiation, E_e is the electrical energy in the drying system and t is the drying time.

Specific energy consumption (SEC) is the ratio of energy consumed in a drying system to the moisture evaporated from the material during the drying process. It is calculated from equation (4). The thermal efficiency of the drying system was determined by using Equation (5)

$$SEC = \frac{E_t}{m_{out}} \tag{4}$$

$$\eta_{th} = \frac{m_{out} h_{fg}}{E_t} \tag{5}$$

where h_{fg} is heat of vaporization

Color changes are a crucial variable in consumers' food purchasing decisions. To comprehensively evaluate the influence of drying temperature on color quality, this study employed a colorimeter to quantify the color shift of Krajood samples dried for 24 h at various temperatures compared to open sun drying. Using CIE L*a*b* coordinate system provided a precise and objective method for color measurement. Within this system, L represents lightness, ranging from 0 (black) to 100 (white). Values of a range from -a* (green) to +a* (red), indicating variations on the green-red axis. Similarly, b* values range from -b* (blue) to +b* (yellow), reflecting changes on the blue-yellow axis. By measuring these L*, a*, and b* values, the study could assess the impact of drying temperature on the perceived lightness, green-red hue, and blue-yellow hue of the dried Krajood compared to the sun-dried samples.

Moreover, the economic analysis of the HPASD was evaluated using two standard economic methods, namely net present value and payback period. To conduct an economic analysis of the dryer, several key parameters were established based on Thai economic conditions and previous research findings. The solar dryer's lifespan was assumed to be five years, aligned with industry standards. Average inflation rates of 0.5% were derived from the Bank of Thailand's monthly economic report. (Bank of Thailand, 2024) An annual interest rate of 7% was applied. Given the HPASD's low maintenance requirements, maintenance costs and residual value were estimated at 5% of the annual capital cost. Table 1 provides a comprehensive overview of these parameters. When designing the drying system, it is very important to consider the economics. The payback period (*PP*) depends on the capital (or investment) cost (*CC*) and profit (*PR*) according to the following equation (6).

$$PP = \frac{CC}{PR} \tag{6}$$

where the *CC* consists of the construction material cost and the construction labor cost, the *PR* is defined as the difference between total sales and expenses. The economic analysis also took into account the net present value (*NPV*) was also considered for the economic analysis as it is the difference between the value of cash inflow and the value of cash outflow during a given period. Net present value is used in capital budgeting to analyze the profitability of an investment, which can be calculated from Equation (7)

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{C}{(1+r)^t} \tag{7}$$

where $-C_0$ is total initial investment costs, C is net cash inflow during the period t, r is the discount rate, t is a number of time periods. A positive net present value means that the projected returns of a project or investment exceed the expected costs. Typically, an investment of a positive NPV results in a profit, while a negative NPV results in a net loss.

3. Results and Discussion

This section analyzes the experimental results obtained from drying jute using the solar-combined heat pump dryer. The goal is to identify the most suitable drying conditions for producing jute with qualities fit for different end products. Data from various test cases will be compared to determine the optimal drying parameters. Details of the test procedures and corresponding results are presented below.

3.1 Optimal temperature for Krajood drying kinetics

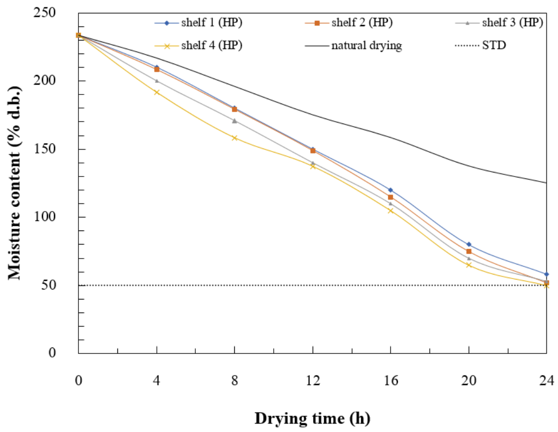
The experiments were conducted over a period of 24 h each (or any specific duration that applies) during the rainy season in southern Thailand, between December 2023 and March 2024. Solar radiation ranged from 90 W/m^2 to 910 W/m^2. Minimum radiation was observed in the morning and evening, while maximum radiation was observed around midday. This case study investigated the effect of drying temperature on the drying performance of Krajood. Three drying temperatures were tested: 45°C, 55°C, and 65°C (Zhou *et al*., 2022). Open sun drying was also included as a comparison point. The experiments were conducted during a period of solar energy availability, from 9:00 AM to 5:00 PM (8 h). A data logger recorded moisture content readings every 10 minutes. After drying, the final moisture content of the Krajood samples was conducted to compared with the standard moisture content of commercial Krajood, which is 50% (dry basis).

The moisture contents at different drying temperatures were shown in Figure 3. The moisture content of the Krajood samples varied depending on the shelf position under the drying temperature in the initial state of the drying process (during 12 h). It was indicated that the top shelf (shelf 1) generally exhibited higher moisture content compared to the lower shelf (shelf 4). This suggested that the weight of water evaporated from the product was greater on the top shelf. The reason for this result could be that heating sources in dryers, such as heating elements or air vents, may not distribute heat evenly throughout the drying chamber. Top shelves might receive more direct heat, leading to faster initial moisture removal and potentially lower final moisture content compared to lower shelves as shown in Figure 2. Even with a modest temperature difference of about 3°C between the top (T_1) and bottom (T_3) of the drying chamber (Figure 3a), the final *MC* of the dried Krajood exhibited minimal variation. The maximum difference observed was only 10% (dry basis) at a drying temperature of 45°C. Notably, the final *MC*s at other drying temperatures were all lower than the standard moisture content of commercial Krajood products.

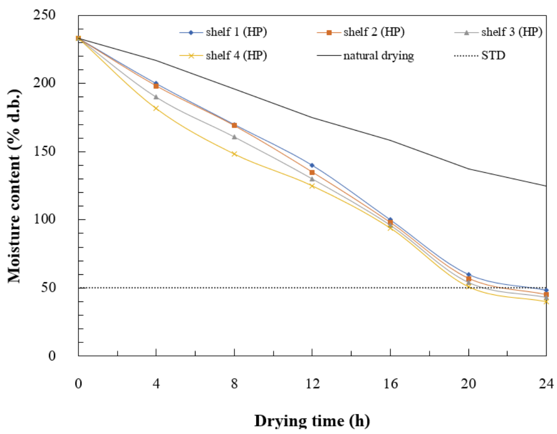
Table 1 Summary of parameters for economic analysis of the HPASD

S/n	Parameters	Value
1	Capital investment cost	62,500 THB
2	Maintenance cost 5% of annual capital cost	5% of annual capital cost
3	Salvage value	5% of annual capital cost
4	Inflation rate	0.5%
5	Dryer life span	5 years
6	Cost of fresh Krajood	50 THB/kg
7	Selling price of the dried Krajood	500 THB/kg
8	Interest rate	7%
9	Dryer drying capacity	5 kg/batch/day
10	Cost for electricity	4.5 THB/kWh

Therefore, Krajood drying times decreased with increasing drying temperature, reaching the desired moisture content in 24, 22, and 21 h at 45°C, 55°C, and 65°C, respectively. The drying trend matched the previous works (Naemsai *et al.*, 2019; EL-Mesery *et al.*, 2022; Zhou *et al.*, 2022). Furthermore, all drying temperature conditions provided the faster drying time than the that of open sun condition, as depicted in Figure 3. The HPASD demonstrated promising results as an alternative to open sun drying for Krajood. However, to definitively establish its superior performance, a detailed analysis of the drying efficiency is necessary.



(a)



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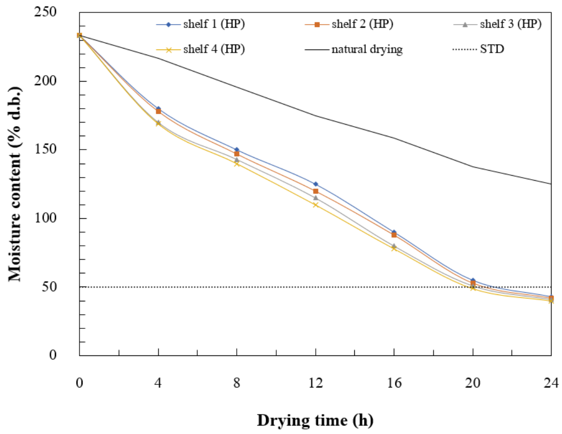

(c)

Figure 3 The moisture contents at different drying temperatures (a) 45 °C (b) 55°C and (c) 65 °C

The energy analysis focused on drying efficiency and energy consumption at different drying temperatures. The experiment revealed that controlling the drying temperature at 5 °C yielded the most favorable outcome: a drying efficiency of 2.67 kWh/kg and the lowest energy consumption of 22.13%. This is likely due to the balance between achieving sufficient drying power and minimizing energy expenditure. The surrounding environment, with a relative humidity of 70% and an average solar radiation of 550 W/m² (cloudy day), also plays a role in the dehumidification process, which requires additional energy input. Interestingly, while controlling the temperature at 45°C resulted in slightly lower drying efficiency (higher energy consumption at 2.72 kWh/kg), 55°C emerged as the optimal control temperature for this HPASD system as shown in Table 2. Compared with related works, the thermal efficiency of HPASD with heat recovery system was 22.13%, which is consistent with the result range studied in the literature and is desirable: 15-30% (Rulazi *et al.*, 2024) due to the different products and the higher Drying temperature generated by the combination of heat pump and solar collector. Moreover, HPASDs generally exhibit superior drying efficiency compared to SAHPDs (Yu *et al.*, 2024; Loemba *et al.*, 2024) due to the more stable heating process directly generated by the heat pump, which is independent of intermittent renewable energy sources.

Table 2 Drying performance at the different temperatures

Drying temperature (°C)	*SEC* (kWh/kg)	Drying efficiency (%)	Drying time (h)
45	2.72	18.92	24.0
55	2.67	22.13	22.0
65	2.85	20.09	21.0

The analysis of CIE Lab* coordinates revealed a color difference between Krajood samples dried using HPASD (55°C) and open sun methods. At the optimal temperature, HPASD resulted in a lighter (L = 45.56), less red (a = 48.45), and more yellow (b = 16.12)* sample compared to the open sun dried sample (L* = 40.66, a* = 37.75, b* = 10.15). This indicates that HPASD can potentially produce Krajood with a color that better aligns with commercial requirements for lightness, redness, and yellowness, especially when considering the desired standard moisture content (MC).

3.2 Economic analysis

The total initial capital investment for the HPASD system, including material costs for fabrication, was approximately 62,500 THB (details in Table 1). This value was used to calculate the economic feasibility of the system for drying Krajood. Southern Thailand experiences high global horizontal radiation, ranging from 400-1100 W/m^2, with sunshine hours varying throughout the year. Notably, even during the rainy season with as low as 5 sunshine hours, the HPASD can function due to its ability to operate independently of direct sunlight. For this study, we assumed 300 operating days per year, allocating the remaining days for dryer maintenance. Ten kilograms of fresh Krajood were loaded into the dryer for consecutive days, resulting in a dried product weight of approximately 5.3 kg per batch. Table 1 summarizes the key parameters used in the economic analysis. Based on these values, the estimated income stream is 18,000 THB/month, while the expense stream is 9,050 THB/month. Using these Equations 6 and 7, the Net Present Value (NPV) is estimated at 27,890 THB and the payback period is calculated to be 2.9 years, and This means it takes 3 years to recover the initial investment of 62,500 THB from the HAHPD for tomatoes and 2.9 years. Hence, this study investigated the potential profitability of utilizing Heat Pump Assisted Solar Drying (HPASD) for Krajood compared to conventional drying methods. Our findings suggest that HPASD drying offers a potentially superior economic proposition based on a comprehensive life-cycle cost assessment (Rulazi *et al*., 2024). Notably, the payback period for HPASD in Krajood drying is demonstrably shorter than the 5-year period reported by Qiu *et al*. (2016) for drying radishes, peppers, and mushrooms using a heat recovery and thermal HPASD system. In the aforementioned study by Qiu *et al*. (2016), 10 kg each of radish, pepper, and mushroom were dried using a heat recovery and thermal storage HPASD system. The payback periods reported for radish, pepper, and mushroom were 6 years, 4 years, and 2 years, respectively. In comparison, our study demonstrates a significantly shorter payback period for Krajood drying using HPASD. Since this payback period falls within the typical lifespan of a solar dryer (approximately 5 years), HPASD emerges as an economically attractive proposition for Krajood drying applications.

4. Conclusion

This study presents the design, fabrication, and performance testing of a prototype Heat Pump Assisted Solar Dryer (HPASD) specifically for drying Krajood. A comprehensive techno-economic analysis was conducted to assess the viability of this approach. The optimal drying temperature for Krajood using HPASD was established as 55°C, balancing energy efficiency with product quality. The performance of the HPASD was evaluated using Specific Energy Consumption (*SEC*) and thermal efficiency, resulting in values of 2.67 kWh/kg and 22.13%, respectively. Drying time to achieve the final moisture content in Krajood was 22 ho. Notably, open sun drying of Krajood typically requires 24 h or 3 days, highlighting the potential time savings offered by HPASD. The techno-economic analysis employed Net Present Value (*NPV*) and payback period (*PP*) calculations over a 5-year lifespan, representing the assumed operational life of the dryer before replacement. The analysis revealed significant economic benefits compared to the initial investment cost. The payback period for Krajood drying (2.9 years) aligns well with findings from previous studies. These results demonstrate the economic feasibility of HPASD for Krajood drying, suggesting its potential to reduce postharvest losses, particularly in developing countries. Further research is warranted to explore the applicability of HPASD for large-scale drying of commercial Krajood products. While Krajood was once considered a weed, its value as an export commodity has seen a remarkable transformation. Investigating the suitability of HPASD for high-volume commercial applications holds significant promise for this increasingly valuable crop.

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