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Original research article

Energy-Efficient Paddy Rice Dehumidification using a Thermosyphon System

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ABSTRACT

Efficient post-harvest drying is vital to maintain paddy rice quality, prevent spoilage, and extend storage life. This study presents a thermosyphon-based dehumidification system, tested with hot air and hot water heating at 60, 70, and 80 °C. The system includes a cylindrical drying chamber with automated controls for higher efficiency. Performance was evaluated using drying time, energy efficiency, and specific energy consumption (SEC). Results showed the system reduced paddy rice moisture from 26.65% to the target 14% (d.b.). Drying times with hot air were 128, 76, and 50 hours, while hot water required 104, 62, and 42 hours at 60, 70, and 80 °C, respectively. Hot water at 80 °C achieved the fastest drying, completing the process in 42 hours. Energy performance analysis revealed the lowest SEC of 89.05 kWh/kg$_{water}$ for hot water at 80 °C, whereas hot air at 60 °C recorded the highest SEC of 1,204 kWh/kg$_{water}$. Overall, the thermosyphon system demonstrated strong potential for balancing drying speed and energy use. The study supports thermosyphon-based drying as a scalable, energy-efficient solution for post-harvest rice management, with hot water offering both rapid drying and efficiency.

Keywords: Energy efficiency; Hot air drying; Hot water drying; Paddy rice drying; Thermosyphon systems

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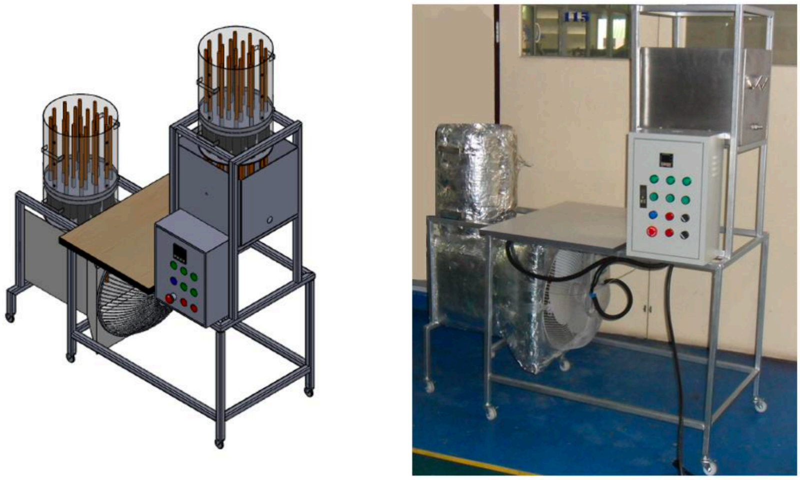
1. Introduction

Paddy rice is a staple food crop worldwide, with Thailand being one of the largest exporters in the global market [1]. Effective post-harvest management is critical to preserving grain quality, preventing microbial spoilage, and ensuring long-term storage stability [2-4]. Freshly harvested paddy typically contains high moisture levels that encourage spoilage, germination, and grain deterioration [5, 6]. To maintain its quality and market value, the moisture content of paddy rice must be reduced to a safe level, ideally around 14% (wet basis) [7]. However, conventional drying methods, such as sun drying and hot-air drying, often result in uneven moisture reduction, excessive energy consumption, and environmental concerns, which highlights the need for more innovative and energy-efficient drying solutions [8].

Thermosyphon-based dehumidification systems have emerged as a promising alternative to traditional drying methods [9]. These systems utilize natural convection for heat transfer, relying on the phase change of working fluids to move heat efficiently. This passive mechanism makes thermosyphons energy-efficient, cost-effective, and environ-mentally friendly, making them ideal for sustainable agricultural practices [10, 11]. Their application has been explored in various fields, including space heating and crop drying, where reducing energy consumption while maintaining performance is essential.

This study aims to develop and evaluate a thermosyphon-based drying system specifically designed for paddy rice using R134a as a working fluid [12]. The system incorporates a cylindrical drying chamber with automated controls to ensure precise moisture reduction and efficient operation. Two heat transfer methods, hot air and hot water, were tested under varying temperature conditions (60°C, 70°C, and 80°C) to evaluate drying performance, energy efficiency, and consistency under distinct heating mechanisms. Key performance indicators, including drying time, energy efficiency, and specific energy consumption (SEC), were analyzed to determine the system's effectiveness [13].

The experimental results demonstrated the potential of the thermosyphon-based system to achieve uniform and consistent moisture reduction while minimizing energy usage [14]. Higher energy source temperatures accelerated moisture removal, and hot water consistently showed better energy efficiency than hot air across all tested conditions. The system effectively reduced the initial moisture content of paddy rice from 26.65% to the target level of 14% (dry basis), addressing the limitations of conventional drying methods in terms of inconsistency and energy demands. These findings underscore the potential of thermosyphon-based systems to enhance agricultural sustainability by offering an energy-efficient and scalable solution for post-harvest drying. This research contributes to advancing energy-efficient technologies in agricultural drying, offering valuable insights into optimizing thermosyphon-based systems for post-harvest use. Furthermore, it establishes a foundation for integrating renewable energy sources, such as solar and geothermal energy, into future drying technologies [15]. These innovations align with global efforts to promote sustainability and energy efficiency in agricultural practices, supporting the broader adoption of environmentally responsible drying technologies [16]. Additionally, the principles of thermosyphon-based heat transfer can be applied to polymer processing, offering potential energy



(a) CAD design (b) Fabricated prototype

Fig. 1. Dehumidification device for paddy rice using a thermosyphon.

savings and improved heat distribution in manufacturing processes [17-19].

2. Methodology

This study aimed to evaluate the performance of a thermosyphon-based dehumidification system for drying paddy rice. The system was designed and constructed to utilize hot air and hot water as heat transfer media and was tested under three temperature conditions: 60°C, 70°C, and 80°C. In this study, both hot air and hot water were produced using electrically heated elements to ensure consistent temperature control. Nonetheless, the system is modular and adaptable for renewable sources such as solar thermal collectors or biomass boilers, particularly for the hot water pathway, enhancing its sustainability and reducing dependency on grid electricity. The experimental setup, procedures, and performance evaluation methods are detailed below. All experiments were conducted in triplicate to ensure repeatability. The uncertainty in specific energy consumption (SEC) was estimated at ±2.5%, primarily due to variations in power input and moisture content measurements.

2.1 Design and construction of the device

Thermosyphon-based dehumidification device was designed to meet the drying requirements of paddy rice. The device design was guided by CAD modeling to optimize component arrangement. A prototype was fabricated and insulated to enhance thermal efficiency (Fig. 1.). Key components of the system included:

2.1.1 Drying chamber

A cylindrical chamber for paddy rice storage, with a diameter of 310 mm and a height of 275.23 mm, constructed from 1 mm thick stainless steel. The chamber accommodated 12 kg of paddy rice for testing, distributed for even exposure to heat.

2.1.2 Thermosyphon heat exchanger

Constructed from 21 copper tubes, each with a diameter of 12.7 mm and a length of 490 mm. The thermosyphon was divided into three sections (evaporator, adiabatic, and condenser sections) using R134a, with a density of 1,220 kg/m³ at the saturated liquid phase, as a working refrigerant.

2.1.3 Automated control unit

Provided precise temperature regulation and process monitoring. It monitored and maintained the set temperatures (60°C, 70°C, and 80°C) for each test run.

2.1.4 Structural components

Lightweight materials were used for ease of construction and operation.

2.2 Initial moisture content of paddy rice

The initial moisture content of the paddy rice at any time (t) was determined using:

$$M_d = \frac{m_i - m_d}{m_d} \times 100\%, \tag{2.1}$$

where M_d, m_i and m_d are moisture content (% dry basis, d.b.), initial mass of the sample (g) and final (dry) mass of the sample (g), respectively. Freshly harvested paddy rice was prepared and tested. After testing 9 samples of paddy rice, the average value of initial and final mass of the samples were $m_i = 29.062$ g and $m_d = 22.946$ g, which can be substituted in Eq. (2.1) to get:

$$M_d = \frac{29.062\ g - 22.946\ g}{22.946\ g} \times 100\% = 26.65\%. \tag{2.2}$$

This calculation confirms that the average initial moisture content of the paddy rice was 26.65% on a dry basis.

2.3 Experimental setup and procedures

The experiments were conducted to evaluate the device's performance using two heat transfer methods: hot air and hot water. Tests were performed at three temperature levels (60°C, 70°C, and 80°C) to reduce the initial moisture content of 26.65% (d.b.) to the target moisture content of 14% (d.b.). The performance metric is to get the time taken to achieve the target moisture level. The average ambient RH during the drying trials was approximately 65% ± 4%, monitored using a calibrated digital hygrometer.

2.3.1 Sample preparation

Paddy rice (variety: Chai Nat 1) was soaked in water for 10 minutes, drained, and air-dried for 10 minutes to ensure a uniform and controlled initial moisture content across all samples. It was then stored in a sealed container and refrigerated at 10°C for 24 hours. This method was selected instead of using naturally harvested paddy, which typically exhibits variable moisture content due to uneven maturation and environmental conditions, potentially introducing inconsistencies into the analysis. Afterward, the initial moisture content was determined using the gravimetric method and found to be 26.65% ± 0.34% (d.b.), confirming the uniformity of the sample set.

2.3.2 Drying process

The heat transfer unit is responsible for delivering thermal energy to the paddy rice using either hot air or hot water. In the hot air experiments, the heated air was circulated through the drying chamber using a tunnel setup (320 mm × 360 mm × 400 mm). Heat was supplied by two 2.8 kW heaters and distributed by a fan (Hatari HA-I18M1, 18", 1317 rpm). The air velocity was maintained at 2.62 m/s. Similarly, in the hot water experiments, the thermal energy was delivered using a 42.41 L water tank heated by two 3 kW immersion heaters. Water circulation was ensured by a Grundfos pump at a flow rate of 7.83×10^{-5} m^3/s.

2.3.3 Monitoring and measurements

Monitoring and measurements included several performance metrics to evaluate the system's efficiency. Temperature profiles were monitored over an 8-hour period to assess thermal performance and stabilization efficiency. Moisture content was measured every 30 minutes using gravimetric methods. Specific energy consumption (SEC) was calculated as the energy required to remove one kilogram of water for each test condition, providing a measure of energy efficiency. The SEC can be determined using the equation:

$$SEC = \frac{\sum E}{m_{water}}, \qquad (2.3)$$

where SEC, E and m_{water} are the specific energy consumption (kWh/kg$_{water}$), total energy consumption (kWh) and total mass of water removed (kg). Performance metrics also included the determination of stabilization time for the drying chamber at set conditions, with lower SEC values indicating higher energy efficiency.

Fig. 2 presents the schematic of the thermosyphon-based drying system, showing both hot air (Fig. 2a) and hot water (Fig. 2b) configurations. In the hot air setup, ambient air is heated by an electric heater and circulated by a fan through the thermosyphon tubes to dry the paddy rice. The hot water setup uses a pump to circulate water through a closed loop, heated by an electric heater, transferring heat via convection and conduction.

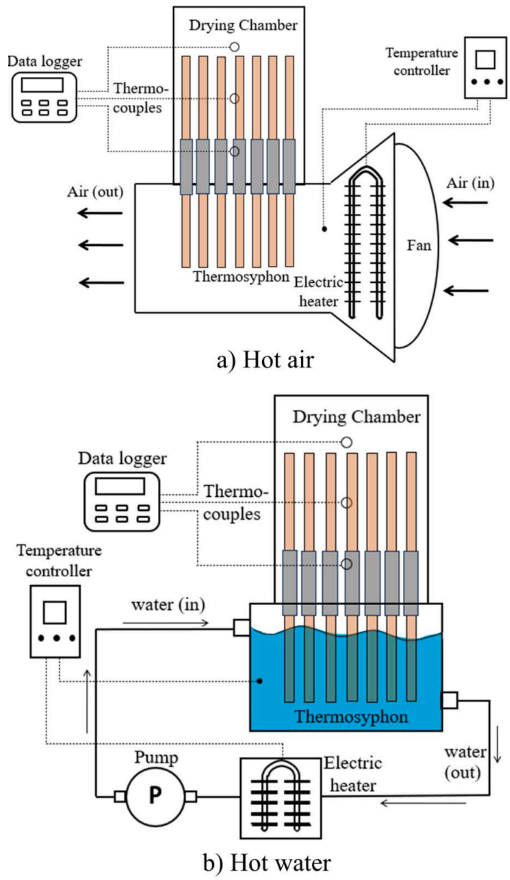


Fig. 2. Schematic of the thermosyphon-based drying system.

3. Results and Discussion

The results of this study demonstrate the performance of a thermosyphon-based dehumidification system for paddy rice drying, focusing on two heat transfer methods, hot air and hot water, tested at three temperature levels (60°C, 70°C, and 80°C). The system effectively reduced the initial moisture content from 26.65% to 14% (d.b.), with notable differences in drying behavior, energy consumption, and duration between the two methods.

3.1 Temperature profiles

The temperature profiles (Figs. 2-3) revealed that both hot air and hot water systems stabilized the temperature of paddy rice effectively, with higher inlet temperatures leading to quicker stabilization. Hot water demonstrated superior heat distribution due to its conductive heat transfer mechanism, resulting in faster and more uniform heating compared to the convective transfer of hot air. This rapid heating significantly contributed to the shorter drying times observed for hot water. Fig. 3 illustrates the temperature profiles of paddy rice using hot water at three temperatures over an 8-hour period. The conductive heat transfer in hot water enabled quicker stabilization as the temperature increased. Similarly, Fig. 4 presents the temperature profiles for hot air, which showed slower stabilization and less uniform heating due to the convective heat transfer mechanism.

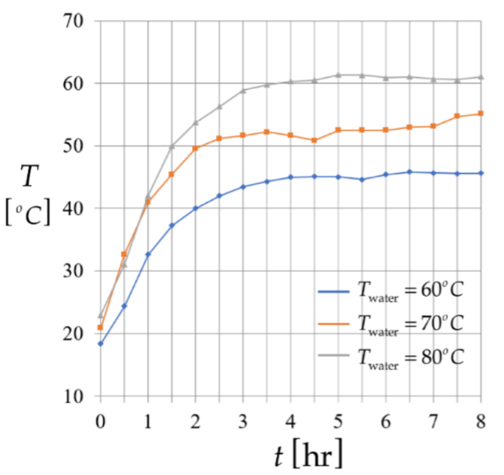


Fig. 3. Paddy rice temperarture (T) versus time (t) with 60°C (blue curve), 70°C (orange curve) and 80°C (grey curve) water temperature (T_{water}).

3.2 Moisture reduction rates

The moisture content of paddy rice decreased significantly with increasing temperatures, as shown in Figs. 4-5. Moisture reduction trends (Figs. 6–8) further confirmed the influence of temperature and heat transfer mechanisms. At 80°C, the hot air method achieved the shortest drying time of 42 hours, compared to 50 hours for hot water, indicating the hot air system's potential in time-sensitive scenarios despite its higher energy demand. Moisture distribution measurements at different vertical layers (top, middle, bottom) of the drying bed indicated a maximum deviation of ±0.4% d.b., confirming that the conductive heating via the hot water loop facilitated more uniform drying compared to hot air. This supports the claim of enhanced drying uniformity.

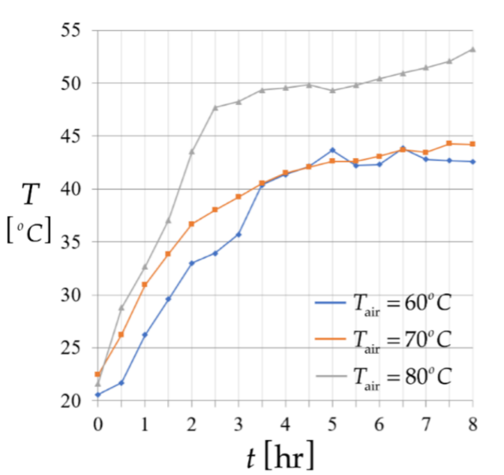


Fig. 4. Paddy rice temperature (T) versus time (t) with 60°C (blue curve), 70°C (orange curve) and 80°C (grey curve) hot air temperature (T_{air}).

Figs. 7-9 compare the drying behaviors of hot air and hot water at each temperature level. Hot water consistently achieved faster drying rates than hot air, attributed to the superior efficiency of conductive heat transfer. Although hot air was slower, its consistent performance makes it suitable for operations where energy efficiency is secondary to time flexibility.

3.3 Energy efficiency

Energy analysis (Fig. 10) highlighted the energy efficiency of the hot water sys-

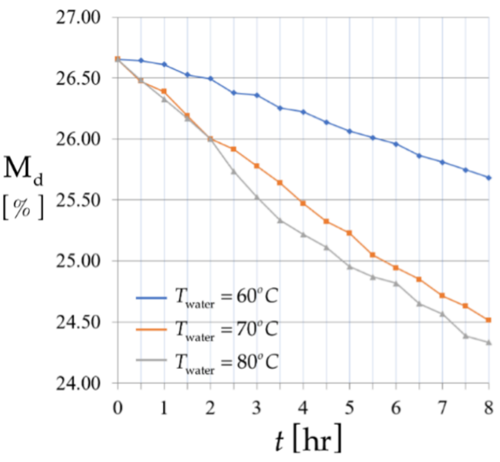


Fig. 5. Paddy rice moisture ($M_{d,water}$) versus time (t) with 60°C (blue curve), 70°C (orange curve) and 80°C (grey curve) water temperature (T_{water}).

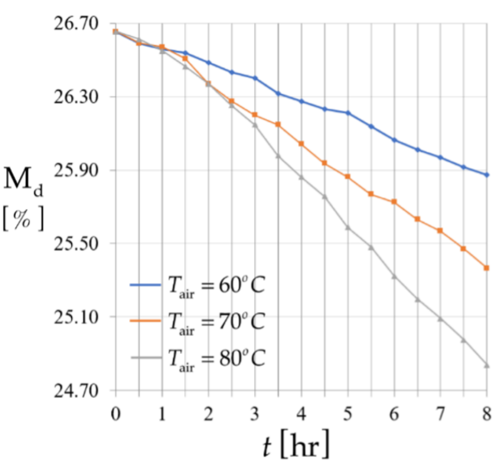


Fig. 6. Paddy rice moisture for hot air (M_d) versus time (t) with 60°C (blue curve), 70°C (orange curve) and 80°C (grey curve) hot air temperature (T_{air}).

tem, which consistently required less energy than hot air across all temperature levels. The lowest specific energy consumption (SEC) was observed for hot water at 80°C, with an SEC of 89.05 kWh/kg$_{water}$, compared to the highest SEC of 1,204 kWh/kg$_{water}$ for hot air at 60°C. This com-

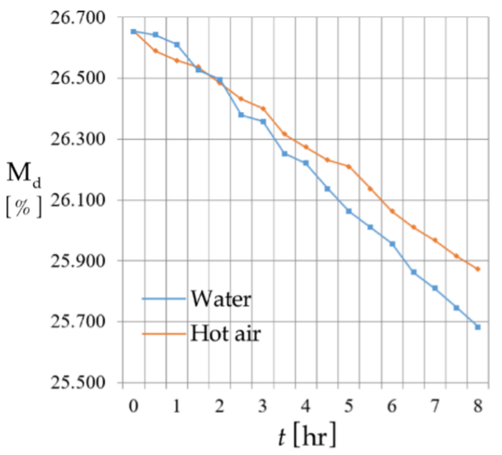


Fig. 7. Paddy rice moisture ($M_{d,air}$) versus time (t) for hot water (blue curve) and hot air (orange curve) at 60°C.

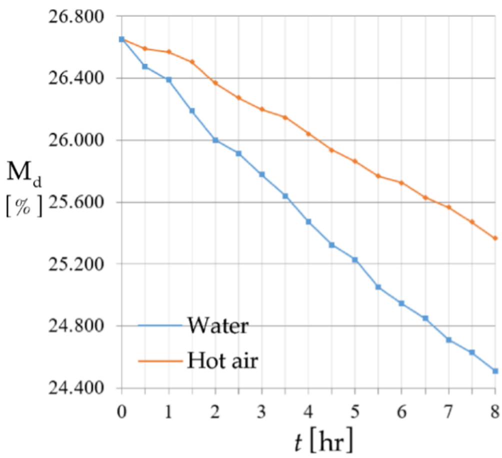


Fig. 8. Paddy rice moisture (M_d) versus time (t) for hot water (blue curve) and hot air (orange curve) at 70°C.

parison highlights the energy-saving potential of the proposed method. These results reinforce hot water's suitability for energy-conscious operations aiming to minimize operational costs. Fig. 9 illustrates the SEC trends for both methods. SEC decreased with increasing temperatures for both hot air and hot water, but the latter demonstrated superior energy efficiency, particularly at higher temperatures. Thus, hot

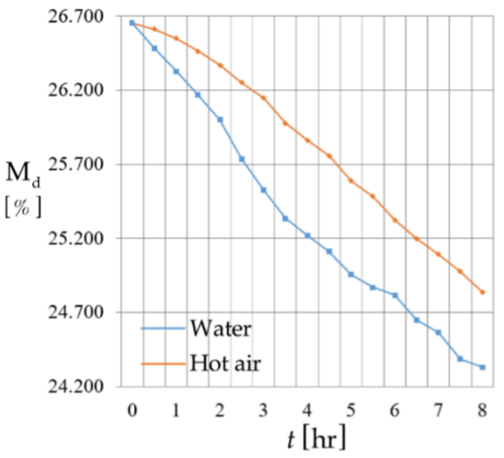


Fig. 9. Paddy rice moisture (M_d) versus time (t) for hot water (blue curve) and hot air (orange curve) at 80°C.

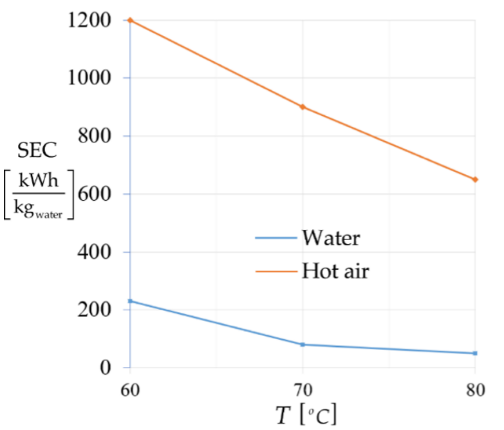


Fig. 10. Specific energy consumption (SEC) for hot water (blue curve) and hot air (orange curve) at three temperature levels (60°C, 70°C and 80°C)

water presents a viable option for energy-efficient drying where longer processing times are acceptable.

3.4 Moisture reduction rates

Hot water provided rapid drying across all tested temperatures, making it ideal for scenarios where drying speed is a priority. Moreover, hot water offered significant energy savings, aligning with sustainable agricultural practices. The thermosyphon system demons-trated versatility by catering to both time-sen-sitive and energy-conscious needs, validating its potential as a reliable post-harvest drying technology. It effectively balanced energy efficiency and drying performance. Hot water excelled in reducing moisture content faster than hot air, particularly at higher tempe-ratures, highlighting its advantages for scala-ble and sustainable applications. These find-ings underscore the system's adaptability and contribution to improving post-harvest paddy rice management.

4. Conclusion

This study evaluated a thermosyphon-based dehumidification system for paddy rice drying, comparing hot air and hot water as heat transfer methods at 60°C, 70°C, and 80°C. The system effectively reduced the moisture content of paddy rice from 26.65% to 14% (d.b.), showcasing its efficiency in post-harvest drying. To reach the final moisture contents, 14% (d.b.), drying durations varied, with hot air requiring 128, 76, and 50 hours, and hot water completing the process in 104, 62, and 42 hours, respectively. The fastest moisture reduction occurred with hot water at 80°C, completing the process in just 42 hours.

Energy efficiency analysis showed the hot water method was significantly more efficient, particularly at 80°C, with a specific energy consumption (SEC) of 89.05 kWh/kg$_{water}$, compared to 1,204 kWh/kg$_{water}$ for hot air at 60°C. Short-term tests over 8 hours reinforced these findings, as hot water at 80°C reduced moisture content by 2.32%, while hot air at 60°C achieved only a 0.97% reduction. These results confirm the energy-saving advantages of the hot water method.

Temperature profiles revealed both systems effectively stabilized the paddy rice temperature, with higher inlet temperatures accelerating stabilization. The hot water system's superior performance is attributed to its enhanced convective heat transfer and more uniform thermal distribution within the drying chamber, ensuring consistent drying across the paddy layers. However, despite its longer drying duration, the hot air method demonstrated stable performance across all trials, making it suitable for applications where drying speed is less critical and where consistent operation over extended periods is acceptable. These findings highlight the thermosyphon-based system's potential as an efficient alternative for paddy rice drying in both small and large-scale operations. The hot water method reduces drying time and energy consumption, offering a cost-effective solution, particularly in regions with thermal energy sources. Its ability to maintain stable temperatures helps preserve rice quality during drying.

From an economic standpoint, the system's reliance on passive circulation and potential for integration with low-cost thermal energy (e.g., solar collectors or biomass waste heat) makes it a financially viable solution. The reduced energy consumption also translates to lower operational costs, especially in rural or off-grid agricultural communities. This study provides a foundation for optimizing energy-saving and scalable drying solutions in agricultural post-harvest management. Future research should focus on integrating renewable energy sources and hybrid systems to enhance the sustainability and performance of thermosyphon-based drying solutions for large-scale applications [20-22]. Overall, the system demonstrates strong potential to improve rice drying efficiency, reduce energy consumption, and enhance operational effectiveness.

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