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Performance Evaluation of LPG-Fueled Rotary Dryer with Forced Convection for Paddy Post-Harvest Processing

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ABSTRACT

Traditional post-harvest draying is often weather-dependent and produces low quality rice, so efficient mechanical technologies are needed for small scale farmers. This study evaluated the performance of an innovative, liquefied petroleum gas (LPG)-fueled rotary dryer engineered for post-harvest paddy processing for small-scale farmers. The system employed an indirect heating mechanism combined with forced convection at an airflow velocity of 2 m/s. Experimental trials were conducted across three drying temperatures: 45°C, 55°C, and 65°C. The results demonstrated that the LPG heating system provided high thermal stability and achieved a robust equilibrium within 30 to 40 minutes. Elevating the operating temperature significantly accelerated moisture diffusion, reducing the drying duration from 180 minutes at 45°C to 120 minutes at 65°C. Although the 65°C treatment achieved the highest initial energy efficiency, it induced severe hygroscopic stresses that dropped the head rice yield (HRY) to 60.7%. Conversely, the 55°C treatment emerged as the optimal operating condition, successfully balancing drying kinetics with grain physical integrity by yielding the highest HRY of 70.2% within 150 minutes. Further research is needed to integrate automatic temperature control systems, as well as an analysis of the economic feasibility of using LPG on a farmer scale.

INTRODUCTION

Drying is a critical post-harvest stage that plays a vital role in maintaining quality and extending the shelf life of agricultural products. This process is carried out by reducing the moisture content of the material to a safe limit, thereby inhibiting the growth of microorganisms, suppressing enzyme activity, and minimizing the risk of damage during storage (Alit et al., 2021). Among farmers, solar drying methods are still widely implemented due to their low operational costs. However, this method has several limitations, such as a heavy reliance on weather conditions, relatively long drying times, and the risk of contamination from dust or debris, which can degrade product quality. One of the widely developed artificial drying technologies is the rotary dryer. This device operates using a rotating cylinder or drum, allowing continuous mixing of the material throughout the drying process. Rotary dryers are highly suitable for drying granular or grain-based agricultural materials (Susana & Alit, 2024). For small-scale farmers, utilizing this equipment has the potential to reduce post-harvest losses that frequently occur in conventional sun-drying methods. Furthermore, an inappropriate selection of a drying system can result in high energy consumption and consequently increase production costs. Compared to several other drying methods, rotary dryers can reduce specific energy consumption by approximately 15–30% and require relatively low maintenance costs (Del Giudice et al., 2019). Granular food materials are generally dried more effectively using a rotary dryer because it can produce a more uniform

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moisture content distribution. In addition to being utilized as a drying apparatus, rotary cylinders are also widely used in the mixing, cooling, and heating processes of various granular materials (Ettahi et al., 2022). The process takes place within a closed chamber, rendering the product more hygienic as it is protected from contamination by dust, dirt, or combustion gases. The advantages of rotary dryers have also been demonstrated in various studies. Rotary drying of *Etlingera elatior* flowers at 60–90°C for four hours successfully maintained their antioxidant activity and total phenolic content. Other studies have shown that using a rice husk-fueled rotary dryer significantly accelerates the drying process compared to direct sun-drying. In drying 10 kg of coffee cherries, the required time was approximately 1,440 minutes, whereas the sun-drying method required up to 16 days. However, the use of rice husks makes the temperature of the drying room unstable, initially the temperature increases then decreases after some of the husks have turned to ash. (Susana et al., 2023).

Nevertheless, utilizing rice husk as a fuel poses several constraints, particularly during the initial stage of combustion. In this phase, the generated temperature is relatively low because a portion of the energy is consumed to evaporate the residual moisture contained within the husk, a phenomenon known as the drying zone. An alternative to overcome this constraint is utilizing liquefied petroleum gas (LPG), which is more accessible to small-scale farmers. The availability of an economical energy source is an essential factor in improving the efficiency of the post-harvest drying process. Utilizing LPG as an energy source in rotary dryers serves as an effective alternative to replace solar- and biomass-based drying. Utilizing LPG ensures a continuous drying process that remains independent of weather conditions, while simultaneously accelerating drying rates and improving final product quality (Kabeel & Abdelgaied, 2016). In contrast to sun-drying, which is highly influenced by environmental conditions, LPG can provide a more stable heat source, resulting in a more even temperature distribution during the drying process (Ezurike et al., 2022). Furthermore, LPG energy consumption is lower than that of coal, and it has a drying productivity index of approximately 0.27 dollars per quintal, which is lower than biomass that reaches 1.4 dollars per quintal (Dębowski et al., 2021). According to the Climate Technology Centre and Network (CTCN), LPG is classified as a relatively clean-burning fuel because its combustion process is nearly complete. Therefore, the utilization of LPG in developing countries can support the energy transition from biomass toward more efficient and environmentally friendly fuels. This study aims to evaluate the performance of an LPG-fueled rotary dryer for the paddy drying process. Drying is the post-harvest stage that requires the highest energy consumption compared to other stages, necessitates a more efficient system. The use of LPG as a heat source is expected to accelerate the drying process while suppressing production costs. The implemented system employs an indirect drying method, ensuring that the paddy does not come into direct contact with smoke or LPG combustion gases. In addition, the design of the apparatus compares two heat transfer mechanisms—namely natural convection without an exhaust fan and forced convection with the addition of an exhaust fan—to determine their effects on the performance of the drying process.

RESEARCH METHODS

Materials and Experimental Setup

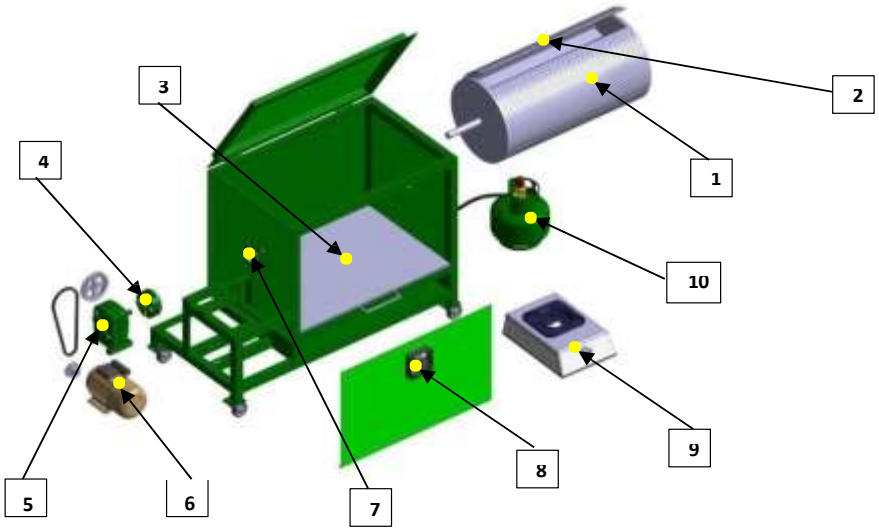
The materials utilized in this study included paddy and liquefied petroleum gas (LPG) as the energy source. The apparatus consisted of a gas stove, K-type thermocouples, a data logger, and a rotary dryer unit. The drying unit was fabricated using several materials, namely iron plates, stainless steel plates, steel shafts, and square iron tubes. Additionally, the equipment was equipped with various supporting components, including an exhaust fan, a transmission system, a gearbox, insulation rubber, trolley wheels, a drying cylinder, and an electric motor as the primary prime mover. The rotary dryer was designed to meet the requirements of small-scale farmers in the rural areas of Lombok Island; thus, it features a simple construction, economic fabrication costs, and ease of operation. The drying chamber was cylindrical with an internal diameter of 400 mm and a length of 800 mm, while the rotational speed of the cylinder was set at 10 rpm. This device was specifically engineered for drying granular agricultural materials, and in this study, it was applied

to the paddy drying process. Testing was conducted based on the apparatus design illustrated in Figure 1.

Description: 1. Rotary cylinder, 2. Cover, 3. Heating plate, 4. Connector, 5. Gearbox, 6. Electric motor 7. Bearing, 8. Exhaust fan, 9. Gas stove, 10. LPG

Figure 1. Rotary dryer schematic

Experimental procedure



Paddy was placed inside the drying cylinder and underwent movement due to the cylinder's rotation throughout the process. The cylinder rotation was generated by an electric motor connected via a gear transmission system. A cover was positioned at one end of the cylinder to serve as an inlet and outlet for the material. The cylinder wall was designed with a number of small holes to create a rougher internal surface. This surface roughness aimed to enhance airflow turbulence inside the drying chamber, thereby improving heat transfer effectiveness. Previous studies have shown that tubes with internally roughened surfaces provide superior heat transfer performance compared with conventional smooth-surfaced tubes (Boonloi & Jedsadaratanachai, 2021). The testing was performed across variations in drying temperatures, specifically 45°C, 55°C, and 65°C. The drying process was carried out until the moisture content of the paddy reached less than 14%. The airflow was circulated by an exhaust fan at an air velocity of 2 m/s. This study focused on evaluating drying characteristics, which encompassed drying heat requirements, drying rate, and energy efficiency. The moisture content, K_a (%) was determined using the initial mass of the paddy, m_t (kg) and its dry mass of paddy, m_k (kg). (Hemhirun & Bunyawanichakul, 2020). The dry mass was obtained by drying the sample using an oven at a temperature of 105–110°C until a constant mass was achieved, defined as the point when no further weight reduction occurred during the heating process.

$$K_a = \frac{m_t - m_k}{m_t} 100\% \quad (1)$$

The amount of heat used for drying Q (kJ) is shown in Equation 2.

$$Q = Q_1 + Q_2 \quad (2)$$

Q_1 is the sensible heat of the material (kJ). Q_2 is the heat to evaporate the water of the material (kJ). Q_1 is obtained based on mass, specific heat, and temperature as in Equation 3.

$$Q_1 = m_t \, C_{pb}(T_r - T_m) \quad (3)$$

$$c_{pb} = \frac{1110+44.4\,K_a}{1000} \quad (4)$$

T_rTr is the drying chamber temperature (°C), Tm is the sample temperature (°C), and c_{pb} is the specific heat of paddy (kJ/kg°C) based on Equation 4 (Bootkote et al., 2016). Q_2 is obtained based on the mass of water and the latent heat of vaporization of water as in Equation 5. h_{fg} is the latent heat of vaporization of water (kJ/kg).

$$Q_2 = m_{ah}\, h_{fg} \quad (5)$$

Energy efficiency, η (%) is based on the comparison between the amount of heat used for drying, Q (kJ) with the amount of heat used during the drying process, q (kJ)(Çengel et al., 2017).

$$\eta = \frac{Q}{q}100\% \quad (6)$$

The amount of heat used during the drying process, q (kJ) is calculated based on the mass of fuel used, m_f (kg) and the calorific value of the fuel, NK_f (kJ/kg) as in Equation 7.

$$q = m_f\, NK_f \quad (7)$$

RESULTS AND DISCUSSION

Figure 2 illustrates the temperature profiles inside the drying chamber during the paddy drying process at three temperature set points: 45°C, 55°C, and 65°C. Overall, the temperature inside the drying chamber increased progressively during the initial stage before reaching a steady-state condition. Once this equilibrium was achieved, the temperature remained relatively constant for the remainder of the drying process. This behavior demonstrates that the LPG-based heating system effectively maintained the target operating temperature throughout the drying operation.

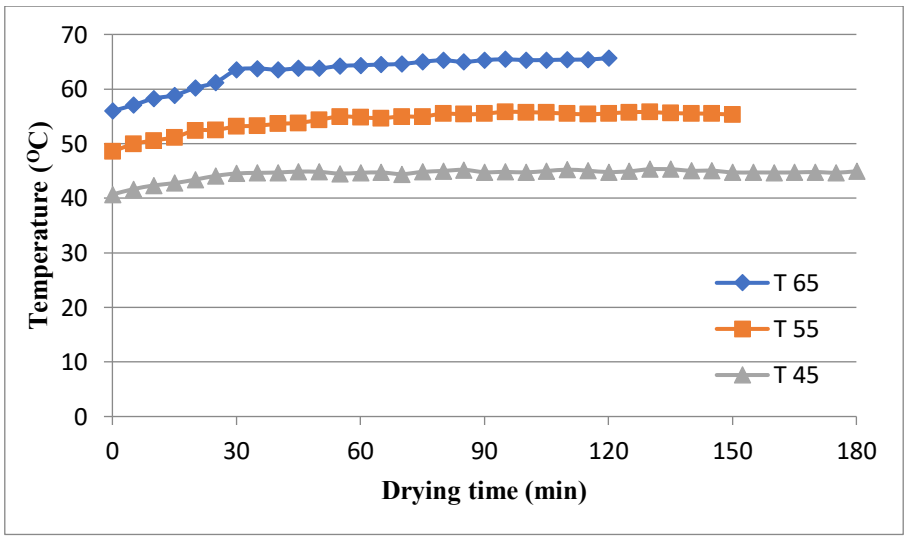


Figure 2. Temperature distribution of the drying chamber

For the 45°C treatment, the drying chamber temperature rose from approximately 40°C to 45°C within 30–40 minutes and remained relatively constant thereafter. A similar pattern was observed at 55°C and 65°C, where the actual temperatures increased progressively until reaching their respective set points. At 65°C, the time required to achieve a stable state was slightly longer due to the higher heating energy requirement. Once the steady state was reached, the temperature fluctuations were negligible, demonstrating the robust performance of the control system and good heat distribution. Temperature stability during drying is a critical factor, as it directly influences the heat and mass transfer rates from the paddy to the drying air. A constant temperature ensures

a more uniform evaporation process, allowing the moisture content of the product to be reduced in a more controlled manner. According to Pakdeekaew et.al (2024), effective temperature control in the paddy drying process can enhance energy efficiency and preserve grain quality by minimizing thermal fluctuations throughout the drying cycle.

The results of this study also reveal that the actual drying chamber temperature was slightly higher than the nominal set point during certain time intervals. This condition commonly occurs in combustion-based drying systems due to heat accumulation within the chamber and the thermal response characteristics of the apparatus. A similar phenomenon was reported by Waluyo et al., (2024), who stated that the temperature in a rotary dryer tends to experience a transient phase before achieving a stable state, driven by the interactions between the heat source, the material being dried, and the drum rotational speed. Furthermore, the stable temperature profiles observed after 60 minutes indicate that the supplied thermal energy had reached an equilibrium with the heat losses to the environment. This condition is highly advantageous as it can improve the efficiency of the drying process. A recent review by Ying & Spang, (2024) highlighted that a stable operating temperature is a primary factor in lowering the specific energy consumption (SEC) during paddy drying and enhancing the overall performance of the drying system. Consequently, the graphical data demonstrates that the LPG-fueled rotary dryer exhibits a strong capability to achieve and sustain the designated operating temperatures. This thermal stability is a key indicator that the drying process operates under well-controlled conditions, thereby promoting efficient moisture removal and ensuring high-quality paddy drying.

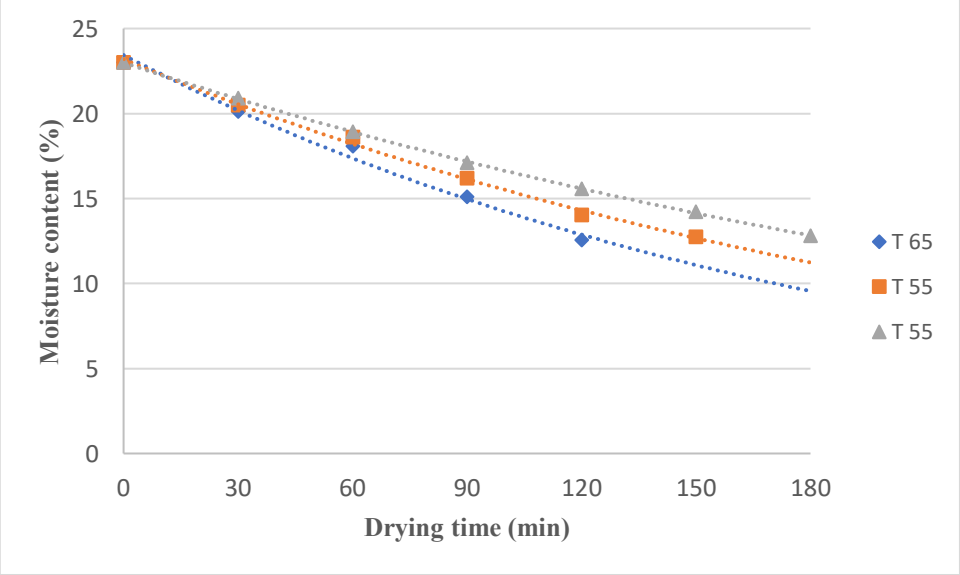


Figure 3. Paddy water content

Based on Figure 3, the moisture content of the paddy decreased over the drying time across all drying temperature variations (45°C, 55°C, and 65°C). The degradation pattern followed an exponential trend, indicating that the drying rate progressed rapidly during the initial stage and subsequently decelerated toward the end of the process. This phenomenon occurred because, at the onset of drying, the majority of the free water located on the surface and in the inter-granular spaces was easily evaporated. As the moisture content decreased, the evaporation process became dominated by the migration of bound water from the internal structure of the paddy to the surface via a diffusion mechanism, thereby reducing the drying rate. Furthermore, a higher drying air temperature generates a greater vapor pressure deficit between the paddy surface and the drying air, leading to more effective heat and mass transfer. This effect is evident in the 65°C treatment, which yielded the fastest reduction in moisture content compared to the 55°C and 45°C treatments. These results indicate that elevating the temperature can accelerate the drying process by increasing the moisture diffusion coefficient and the water evaporation rate. This result is consistent with previous studies demonstrating that higher drying temperatures enhance the rate

of moisture removal and reduce the overall drying time of cereal grains, including paddy, as long as the operating temperature remains within an acceptable range that preserves grain physical quality and seed viability. (Wang et al., 2024).

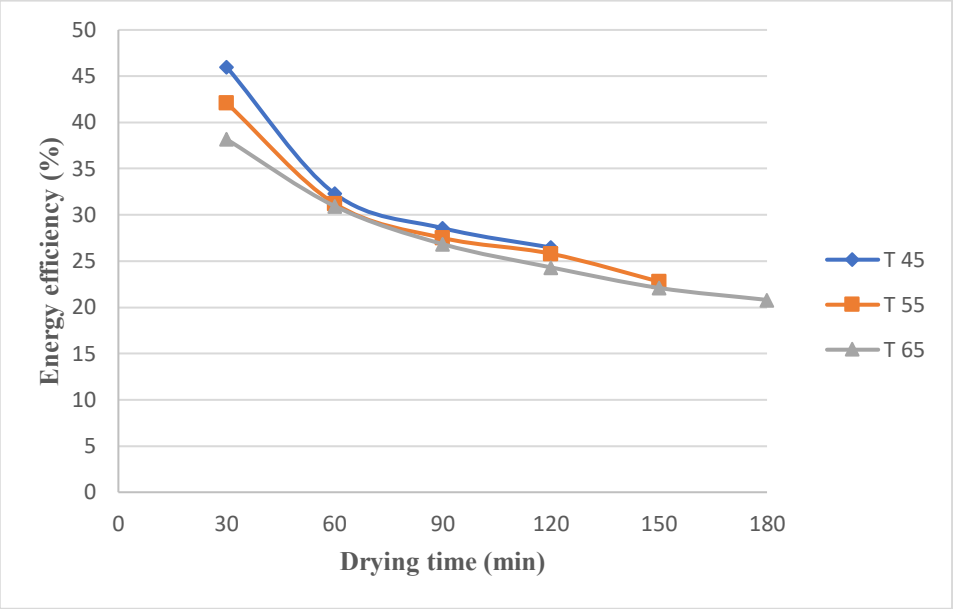


Figure 4. Energy efficiency of rotary dryer

The experimental results indicate that energy efficiency tends to decrease over the drying time across all temperature variations. At the onset of the process, energy efficiency reached its highest value, followed by a gradual decline until the completion of drying. This condition demonstrates that the thermal energy supplied during the initial stage is utilized more effectively to evaporate the free water present on the paddy surface. As the moisture content of the material depletes, the energy required to release the bound water increases, thereby reducing energy efficiency. In this graphical representation, the 45°C, 55°C, and 65°C treatments exhibited variations where the 65°C treatment yielded the highest initial energy efficiency. This observation is in agreement with the findings by A'yuni et al., (2024), who investigated paddy drying using a rotary dryer and reported that higher drying temperatures resulted in greater energy efficiency by increasing the rate of moisture evaporation, thereby reducing the overall drying time. Their study also demonstrated that increasing the temperature from 40°C to 60°C reduced total energy consumption due to the accelerated drying process (A'yuni, Kurniawan, et al., 2024).

Furthermore, a comprehensive review by Ying & Spang, (2024) indicated that the drying temperature is one of the primary factors determining specific energy consumption (SEC) in paddy drying. Higher temperatures generally enhance heat and mass transfer rates, thereby improving the efficiency of the energy utilized to evaporate each kilogram of water; however, this temperature must be carefully controlled to preserve rice quality. The narrowing gap in energy efficiency among the different temperatures toward the end of the drying process indicates that the drying mechanism becomes dominated by moisture diffusion from the internal core of the grain to its surface. Under this condition, the effect of an elevated temperature is less pronounced than in the initial drying phase, as the mass transfer rate becomes the primary limiting factor. This finding is also reported in studies on paddy drying using a staged temperature system, where the advantages of utilizing high temperatures progressively diminish as the moisture content approaches the equilibrium moisture content (EMC) of the material (Ying & Spang, 2024).

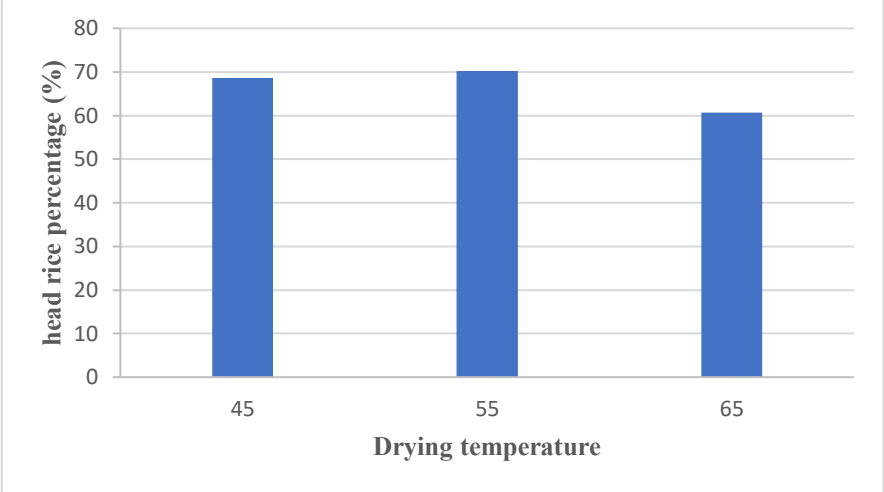


Figure 5. Quality of dried rice

Based on Figure 5, drying temperature affects head rice yield (HRY). The highest percentage of whole rice was obtained at a drying temperature of 55°C, reaching approximately 70.2% with a drying time of 150 minutes. Meanwhile, the 45°C treatment produced approximately 68.6% whole rice with a longer drying time of 180 minutes. While the lower temperature of 45°C minimizes the risk of grain damage, the longer drying period allows moisture redistribution within the grain, increasing its susceptibility to cracking during subsequent handling. Conversely, increasing the temperature to 65°C reduces the drying time to only 120 minutes, but causes the percentage of whole rice to drop to approximately 60.7%. This decrease indicates that the higher temperature accelerates the rate of water evaporation, creating a steep moisture gradient between the surface and the rice kernel. This creates internal thermal and hygroscopic stress, making the rice grains highly susceptible to cracking and breakage during the milling process. Consequently, the combination of a drying temperature of 55°C and a drying duration of 150 minutes was the optimal operating condition, as it successfully balanced the drying rate while maintaining the physical integrity of the rice grains. This finding is in line with recent research which states that drying at moderate temperatures produces higher quality milled rice compared to temperatures that are too low or too high due to minimized thermal damage and internal cracks (Zhang et al., 2025).

CONCLUSION

This study successfully demonstrated the technical feasibility and operational performance of an LPG-fueled indirect rotary dryer equipped with forced convection for rice processing. The operating temperature significantly impacted drying kinetics, thermal efficiency, and final grain physical quality. While a higher temperature of 65°C minimized drying time to 120 minutes and maximized initial energy efficiency, it produced a steep moisture gradient that caused grain cracking, significantly reducing the whole rice yield to 60.7%. In contrast, drying at 55°C for 150 minutes was the optimal process configuration. These parameters created an ideal balance by accelerating the water evaporation rate while maintaining the structural integrity of the rice, resulting in a maximum whole rice yield of 70.2%. Consequently, this affordable LPG rotary dryer offers smallholder farmers an efficient, hygienic, and weather-independent alternative to conventional solar and biomass drying methods. Further research is needed to integrate an automatic temperature control system to prevent seed cracking, as well as to conduct a long-term economic feasibility analysis at the farmer group scale

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