ISA Journal of Engineering and Technology (ISAJET)

Homepage: https://isapublisher.com/isajet/

Volume 3, Issue 3, May-Jun, 2026 ISSN: 3049-1843

Energy and Exergy Performance Evaluation of a Continuous Flow Paddy Dryer Under Varying Drying Air Temperatures

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Received: *11.04.2026* **|** ***Accepted:*** *22.04.2026* **|** ***Published:*** *01.05.2026*

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DOI: *10.5281/zenodo.19956432*

Abstract **Original Research Article**

This study presents an evaluation of the energy and exergy performance of a continuous flow paddy dryer under varying drying air temperatures (122–126 °C). The drying characteristics, energy utilization, and exergy behaviour of the system were investigated to provide an assessment of dryer performance. The drying process exhibited a predominantly diffusion-controlled mechanism with the moisture ratio decreasing from 0.935 to 0.847, indicating effective moisture removal. Energy analysis showed that the dryer operated at a moderate energy utilization efficiency of approximately 37% having limited sensitivity to temperature variation. Furthermore, the specific energy consumption decreased from 6.8 to 5.9 MJ/kg H_2O with increasing temperature indicating improved energy efficiency at higher operating conditions. Exergy analysis showed that exergy efficiency remained relatively stable at 30.6% within the temperature range of 122–125 °C but decreased to 26.1% at 126 °C. Exergy destruction remained nearly constant at approximately 6.5 suggesting that system losses are primarily governed by inherent design and operational constraints. The results show higher temperatures reduce energy consumption but degrade energy quality. Furthermore, an optimal operating range of 122–125 °C was identified where a balance between drying performance, energy utilization, and exergy efficiency is achieved. The findings provide valuable insights for the optimization and design improvement of continuous flow paddy dryers thereby contributing to enhanced energy efficiency and sustainability in agricultural drying systems.

Keywords: Energy utilization, Exergy analysis, Continuous flow dryer, Paddy rice drying, Thermodynamic modelling, Exergy Loss.

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1. INTRODUCTION

In recent times, rice has remained one of the most important staple crops globally serving as a primary food source for more than half of the world's population. In many developing nations such as Nigeria, paddy rice production contributes significantly to food security and economic sustainability (Kenmore, 2003). However, the possession of high moisture content by harvested

paddy rice makes them highly susceptible to microbial deterioration, discoloration, and quantitative losses (Shafiekhani et al., 2018). Effective drying is therefore a necessity in order to preserve grain quality and stability. Sun drying method, although widely practiced due to its low cost is limited by its dependence on weather conditions, poor control over drying parameters and non-uniform moisture removal (Inyang et al., 2017). These limitations in most cases leads to inconsistent product quality and post-harvest losses. Mechanical drying systems such as continuous flow paddy dryers have been developed and adopted in modern agricultural processing. These systems provide controlled drying conditions, improved throughput and enhanced product uniformity. However, they are associated with high energy consumption which makes energy efficiency an important concern in their designs and applications (Yu et al., 2025).

Over the years, the performance evaluation of drying systems has traditionally relied on energy analysis (that is quantifying the amount of thermal energy supplied and utilized during the drying process (EL-Mesery and El-Khawaga, 2022). This approach provides useful insights into the system efficiency but fails to account for the quality of energy present in thermal systems. Therefore, energy analysis alone may not adequately capture the true extent of inefficiencies within the drying process. Exergy analysis has been increasingly employed in the assessment of drying systems (Dincer, 2011; Panwar et al., 2012; Martynenko and Vieira., 2023). It provides a more comprehensive evaluation by quantifying the useful work potential of energy and identifying losses due to irreversibility. Furthermore, it enables the determination of exergy efficiency and exergy destruction thereby offering deeper insight into system performance and guiding optimization efforts. During drying operations, significant exergy losses are often associated with heat transfer across finite temperature differences, exhaust air discharge and internal system inefficiencies.

In recent years, there has been growing interest in integrating energy and exergy analyses with drying kinetics in order to achieve more understanding of dryer performance (Surendhar et al., 2019). Parameters such as drying air temperature, airflow rate, and moisture diffusion characteristics play a significant role in determining both the thermodynamic efficiency and the drying behaviour of paddy grains. However, limited studies have examined the combined effects of drying air temperature on system performance, energy utilization, exergy efficiency, and moisture removal characteristics in continuous flow paddy dryers. Furthermore, detailed evaluation of thermodynamic behaviour within specific sections of the drying system especially at the inlet and outlet of the drying chamber has remained insufficiently explored. Such localized analysis is essential for identifying critical zones of energy degradation and improving system design.

Therefore, this study aims to provide an assessment of a continuous flow paddy dryer by integrating system performance analysis, drying characteristics, and energy–exergy evaluation. Specifically, the study investigates the variation of inlet and outlet air temperatures with time, analyses moisture ratio evolution during drying, and evaluates the key performance indicators under varying drying air temperatures. The outcomes of this research are expected to contribute to the optimization of drying operations, reduction of energy consumption, and enhancement of overall system efficiency in paddy processing.

2. MATERIALS AND METHODS

In this study, freshly harvested paddy rice was used. The samples were sourced locally from farms within Makurdi metropolis. The samples were cleaned to remove impurities such as stones, dust and broken grains prior to drying. Initial moisture content of the paddy was determined using the oven-drying method at 105 +/- 2 ^{o}C until a constant weight was achieved. Moisture content was expressed on a wet basis.

2.1 Description of the Dryer System

A continuous flow paddy dryer comprising of a drying chamber, air heating unit, blower system and control unit was used to conduct the experiment. Ambien air was heated using an electric heater and

forced through the drying chamber by a centrifugal blower. The heated air flowed through the paddy bed enabling the removal of moisture through convective heat and mass transfer. Furthermore, the system was operated under controlled conditions with drying air temperature the primary variable parameter. Temperature sensors were fitted at the inlet and outlet of the drying chamber to monitor the thermal variations during the drying process.

2.2 Experimental Procedure

Paddy samples were fed continuously into the drying chamber and drying was performed at different drying temperatures. Key parameters that is the inlet air temperature, outlet air temperature and drying times were recorded at regular intervals. The moisture content of samples was measured periodically with the moisture ratio (MR) calculated based on the drying characteristics. The experiment was repeated until the paddy reached the desired safe moisture content for storage.

2.3 Determination of Moisture Ratio

The moisture ratio (MR) was obtained using equation 1.

$$\text{MR} = \frac{M_t - M_e}{M_i - M_e} \quad (1)$$

Where; M_t is the moisture content at time t, M_i is the initial moisture content and M_e is the equilibrium moisture content.

2.4 Energy Analysis

The energy analysis of the dryer was performed based on the first law of thermodynamics to evaluate the heat utilization within the dryer system.

The overall energy balance is expressed as;

$$Q_{in} = Q_{useful} + Q_{loss} \quad (2)$$

where Q_{in} represents the total heat supplied by the hot air generator, Q_{useful} is the energy utilized for moisture evaporation, and Q_{loss} accounts for heat losses through exhaust gases, duct walls, and other system components.

The useful heat for drying is determined from the enthalpy difference of moist air:

$$Q_{useful} = \dot{m}\boldsymbol{a}(\boldsymbol{h}in - h_{out}) \quad (3)$$

The specific enthalpy of moist air is given by:

$$h = 1.005T + W(2500 + 1.88T) \quad (4)$$

where (T) is the air temperature (°C) and (W) is the humidity ratio (kg water/kg dry air), calculated as:

$$W = 0.622\frac{P_v}{P - P_v} \quad (5)$$

The energy utilization efficiency is defined as:

$$\eta_{en} = \frac{Q_{useful}}{Q_{in}} \quad (6)$$

The specific energy consumption (SEC), which represents the energy required to remove a unit mass of water, is expressed as:

$$SEC = \frac{Q_{in}}{m_w} \quad (7)$$

where m_w is the mass of water evaporated during drying.

2.5 Exergy Analysis

Exergy analysis was conducted to evaluate the quality of energy transformations and identify irreversibility within the dryer system.

The exergy balance is expressed as:

$$Ex_{in} = Ex_{out} + Ex_{des} \quad (8)$$

The specific exergy of moist air is calculated as:

$$ex = (h - h_0) - T_0(s - s_0) \quad (9)$$

where T_0 is the ambient temperature (K), and h_0 and s_0 are properties at the reference state.

The entropy of moist air is given by:

$$s = 1.005\ln\left(\frac{T}{T_0}\right) - R\ln\left(\frac{P}{P_0}\right) + Ws_v \quad (10)$$

The exergy rate is:

$$\dot{E}x = \dot{m}_a, ex \quad (11)$$

The exergy efficiency is defined as:

$$\eta_{ex} = \frac{Ex_{useful}}{Ex_{in}} \quad (12)$$

The exergy destruction ratio is:

$$EDR = \frac{Ex_{des}}{Ex_{in}} \quad (13)$$

2.4 Drying Characteristics

Moisture content on a wet basis is calculated as:

$$M_{wb} = \frac{W_i - W_f}{W_i} \times 100 \quad (14)$$

and on a dry basis:

$$M_{db} = \frac{W_i - W_f}{W_f} \times 100 \quad (15)$$

The drying rate is expressed as:

$$R_d = \frac{M_i - M_f}{t} \quad (16)$$

The mass of water removed is:

$$m_w = W_i - W_f \quad (17)$$

3. RESULT AND DISCUSSION

3.1 Variation of Drying Air Temperature with Time

The variation of inlet and outlet air temperature with drying time is presented in Figure 1. The result showed that the inlet air temperature remained relatively stable within the range of 122 to 126 °C. This phenomenon can be attributed to the effective control of the heating system throughout the drying process.

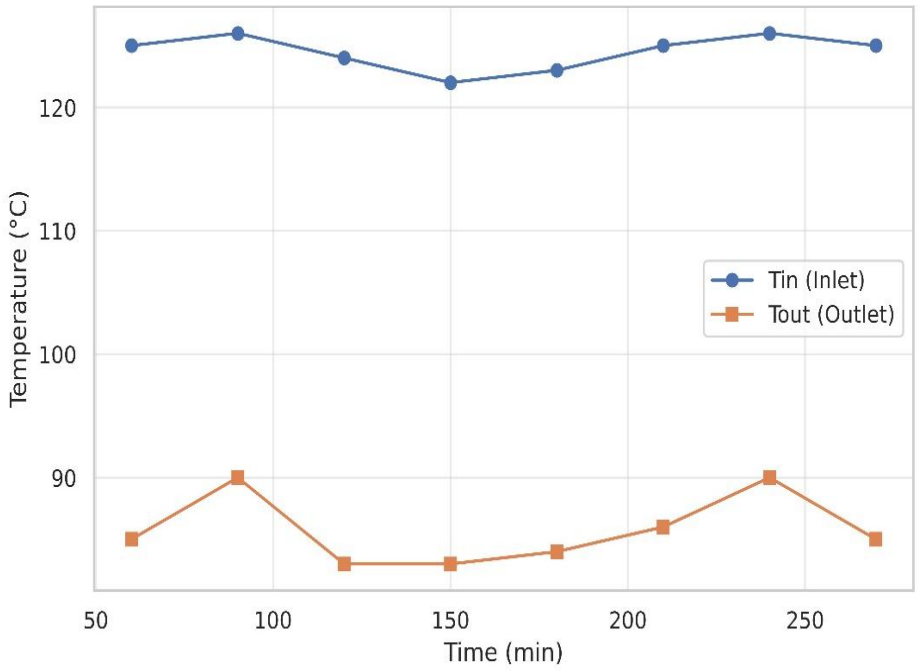

Figure 1: Plot of Inlet and outlet air temperatures vs time

The outlet air temperature exhibited lower trend compared to the inlet air temperature (between 83 °C and 90 °C). This is because of the heat transfer from the drying air paddy grains (Ref). A temperature difference ranging from 35 °C to 42 °C was observed revealing high heat utilization for moisture

evaporation. Furthermore, the initial drying stages showed the presence of high temperature values. This shows that intense heat and mass transfer occurred within the system during the initial drying stage. This is in agreement with Golpour et al., (2021) who noted that rise in temperature values are observed at the initial drying stages. However, as drying progressed, fluctuations in outlet temperature suggest variations in moisture removal rate and internal heat transfer dynamics. This behaviour is typical of convective drying systems, where the effectiveness of heat transfer decreases as the moisture content of the material reduces (Ergasheva et al., 2022).

3.2 Drying Characteristics (Moisture Ratio Analysis)

The drying behaviour of paddy was studied using the variation of moisture ratio (MR) with drying time, as presented in Fig. 2. The moisture ratio decreased overall from approximately 0.935 at 90 min to a minimum value of about 0.847 at 180 min, indicating progressive moisture removal during the drying process. Between 120 min and 180 min a more pronounced decline in MR was observed. This corresponds to an accelerated moisture migration phase usually characterized by increased temperature gradients between the drying air and the grain interior, enhanced vapor pressure differences and improved internal moisture diffusion (Jimoh et al., 2023).

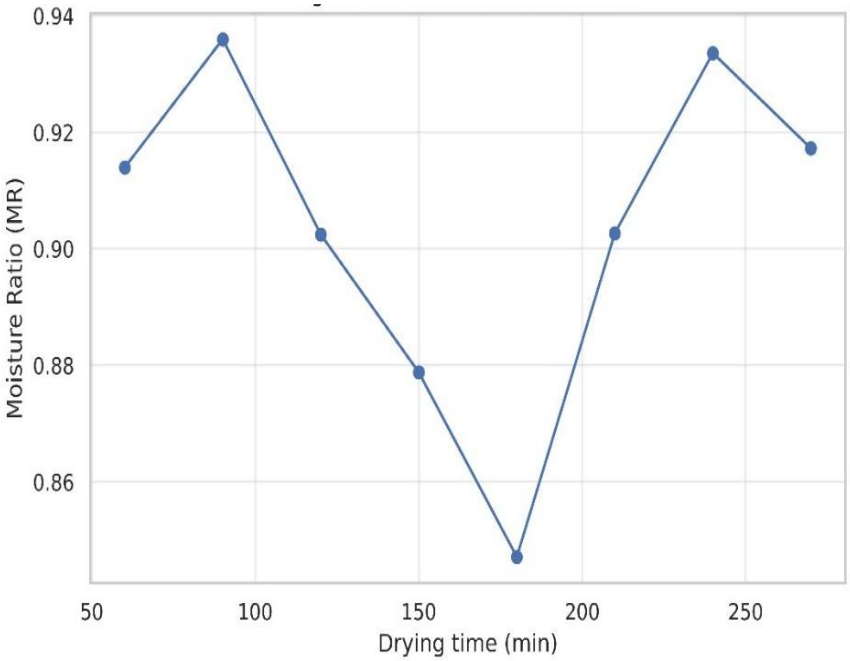

Figure 2: Plot of Moisture Ratio vs Drying Time

However, the drying curve revealed that the process predominantly occurred in the falling rate period and had no clearly defined constant rate period. This phenomenon can be described as a characteristic of most biological materials where moisture is primarily bound within the grain structure rather than existing as free surface water (Wang et al., 2024). As drying progresses toward 180 min, the moisture ratio reaches its lowest value (0.847) indicating significant moisture removal. However, a slight increase in MR is observed afterwards which deviates from the expected monotonic decay. The continuously

decreasing slope of the MR curve confirms that the drying rate declines with time (Zeng et al., 2024). This implies that extending drying time beyond a certain point yield diminishing returns in moisture removal efficiency thereby increasing energy consumption without proportional benefit.

3.3 Energy Utilization Efficiency

The variation of energy utilization efficiency (EU) with inlet air temperature is presented in Figure 3. The results showed that EU remained nearly constant at approximately 37.1% within the temperature range of 122–125 °C. This shows that the system operates under quasi-steady thermal conditions where the proportion of useful energy to total supplied energy remains largely unchanged despite variations in inlet temperature (Tulyananda et al., 2026). However, a noticeable decline to about 32.6% was observed at 126 °C. The regression analysis shows a negative linear trend with increasing inlet temperature (R^2 = 0.429, $p \approx 0.078$), indicating a weak correlation between EU and temperature. This suggests that drying air temperature alone is not the dominant parameter controlling energy utilization efficiency in the system (Ying and Spang, 2024).

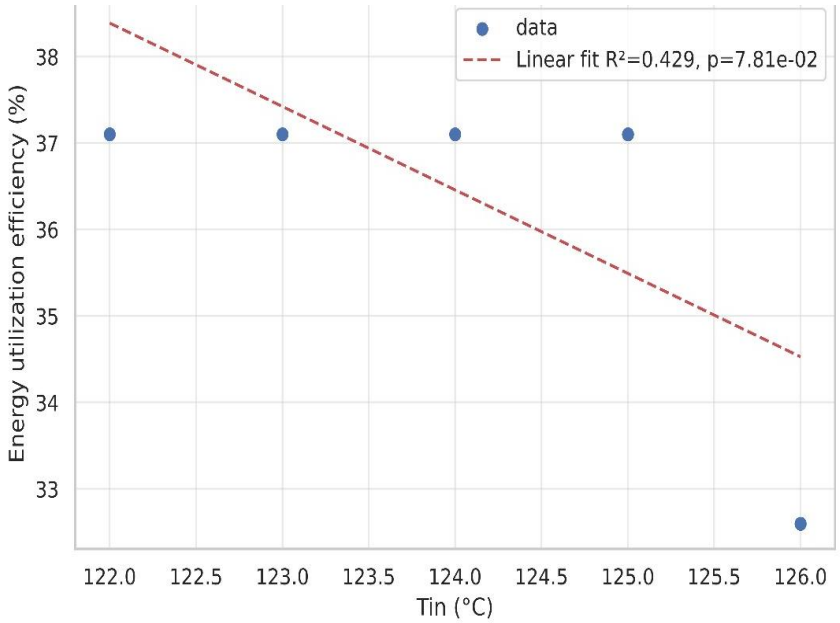

Figure 3: Plot of Energy utilization efficiency vs drying temperature

The observed EU values (~37%) indicates only about one-third of the supplied thermal energy contributes directly to moisture removal. Furthermore, the remaining energy (~63%) is lost through various other mechanisms which can be attributed to convective heat losses through exhaust air, conductive and radiative losses through dryer walls, incomplete heat transfer between drying air and paddy grains and thermal inefficiencies in airflow distribution (Duangkhamchan et al., 2024).

The balance between heat supply and moisture evaporation appears optimal between 122 ^{o}C and 125 ^{o}C resulting in stable EU values. However, the decline in EU at higher temperature (126 °C) suggests that additional heat supplied is not effectively utilized for moisture removal. Furthermore, the excess thermal energy increases heat losses to the surroundings and the moisture availability becomes limited thereby reducing the effectiveness of heat input (Lin et al., 2023). During

the falling rate period, moisture diffusion is the limiting factor which results in unproportional removal of moisture even with increase in supply of thermal efficiency. The internal resistance within the paddy grains further restricts the effective energy utilization.

3.4 Exergy Efficiency Analysis

The variation of exergy efficiency with inlet air temperature is presented in Figure 4. The results shows that exergy efficiency remained nearly constant at approximately 30.6% within the temperature range of 122–125 °C, followed by a significant decrease to about 26.1% at 126 °C. The regression analysis shows a negative trend with increasing temperature ($R^2 = 0.429$, $p \approx 0.078$). This indicates a weak but noticeable dependence of exergy efficiency on inlet air temperature. The relatively stable exergy efficiency at moderate temperatures suggests the system operates under near-equilibrium thermodynamic conditions, where the ratio of useful exergy output to exergy input remains nearly constant. However, the sharp decline at higher temperature highlights the onset of increased irreversibility within the system (Wincy and Edwin, 2023). The regression analysis shows a negative trend with increasing temperature ($R^2 = 0.429$, $p \approx 0.078$), indicating a weak but noticeable dependence of exergy efficiency on inlet air temperature. The relatively stable exergy efficiency at moderate temperatures suggests that the system operates under near-equilibrium thermodynamic conditions, where the ratio of useful exergy output to exergy input remains nearly constant (Islam et al., 2022). However, the sharp decline at higher temperature highlights the onset of increased irreversibility within the system.

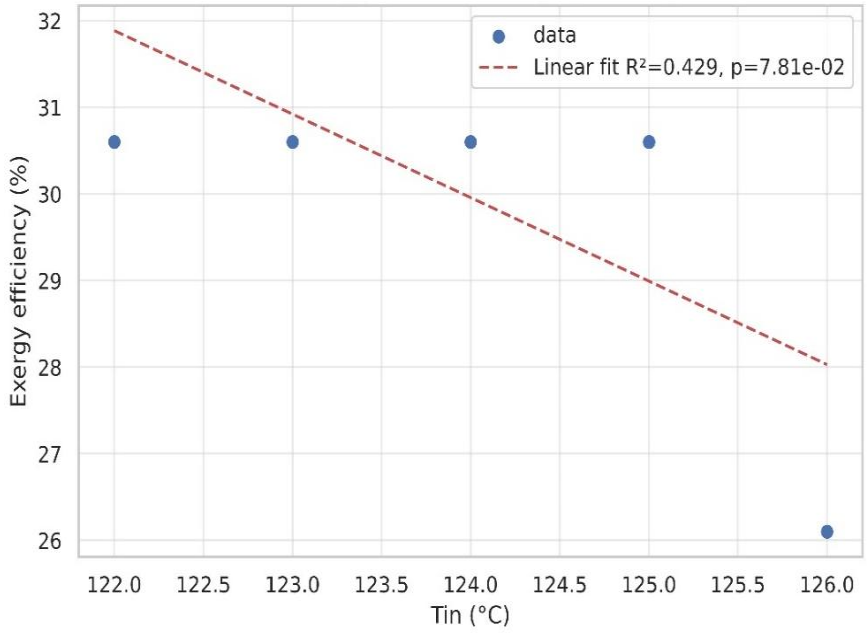

Figure 4: Plot of Exergy Efficiency vs. Drying Temperature

Exergy efficiency provides a measure of the quality of energy utilization, accounting for both energy quantity and its ability to perform useful work. The observed values (30.6%) shows that only about 30% of the supplied exergy is effectively utilized for moisture removal and approximately 70% of the

available work potential is destroyed due to irreversibility. Furthermore, the reduction in exergy efficiency at higher temperature (126 °C) can be attributed to increased irreversibility arising from large temperature gradients between drying air and ambient environment, non-equilibrium heat transfer between air and paddy grains, moisture diffusion resistance within the grain structure.

3.5 Specific Energy Consumption (SEC)

The variation of specific energy consumption with inlet air temperature is shown in Figure 5. The results reveal a strong linear decrease in SEC from approximately 6.8 MJ/kg H_2O at 122 °C to 5.9 MJ/kg H_2O at 126 °C.

The regression analysis indicates an almost perfect linear relationship (R^2 = 1.000, p ≈ 0.000), confirming that drying temperature is a dominant factor influencing energy consumption. This trend can be explained by the fact that higher temperatures the variation of specific energy consumption with inlet air temperature (see Figure 5). The observed decrease in SEC with increasing temperature can be as a result of fundamental heat and mass transfer principles. During higher temperature operation moisture diffusion is accelerated followed by a falling rate period which is shortened and the overall drying process becomes more efficient (Ying and Spang, 2024). SEC decrease causes the system to experience energy losses. This phenomenon suggests that a portion of the energy savings at higher temperatures is due to faster drying and not necessarily better heat utilization.

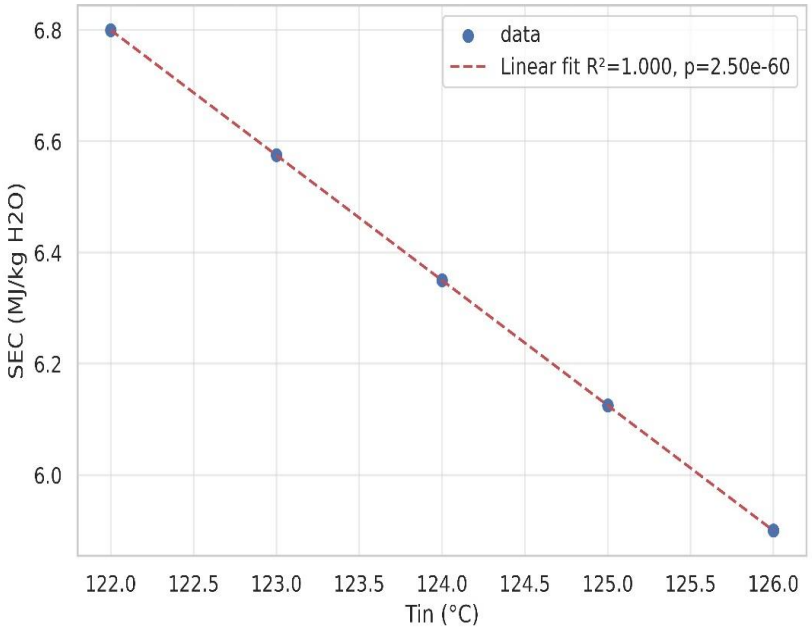

Figure 5: Plot of Specific Energy Consumption vs. Drying Air Temperature

3.6 Exergy Destruction Analysis

The variation of exergy destruction with inlet air temperature is presented in Figure 6. The results show that exergy destruction remained constant at approximately 6.5 units across all temperature values. This indicates that the irreversibility within the system is largely independent of the inlet air temperature within the investigated range. Unlike the

other explored performance indicators (EU, exergy efficiency, and SEC) exergy destruction showed no dependence on inlet air temperature within the studied range.

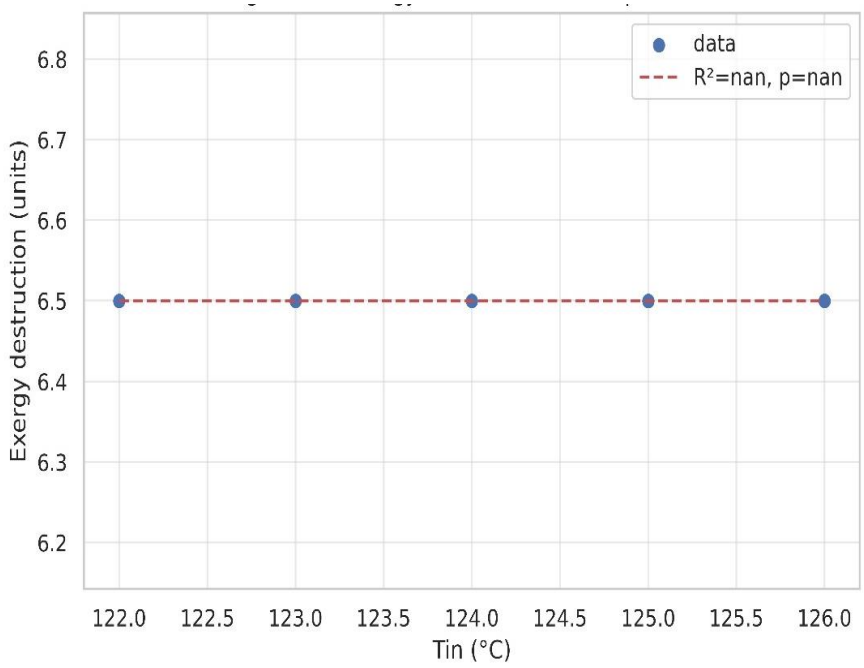

Figure 6: Plot of Exergy Destruction vs. Temperature

The constant exergy destruction suggests that system losses are dominated by structural/design factors, heat transfer inefficiencies are inherent to the dryer configuration, temperature variation alone does not significantly influence internal irreversibility. This is a very important finding, as it implies that improving system performance may require better insulation, improved airflow distribution, design modification of the drying chamber rather than simply increasing operating temperature.

4. CONCLUSION

In this study, the evaluation of a continuous flow paddy dryer was performed through analysis of drying characteristics, energy utilization, and exergy performance under varying drying air temperatures. The drying behaviour of paddy was found to be predominantly diffusion-controlled with the moisture ratio decreasing from approximately 0.935 to 0.847 over the drying period. The absence of a constant rate period showed that internal moisture migration within the grain structure covered the entire drying process. The most effective drying phase occurred between 120 min and 180 min where moisture removal was most pronounced due to favourable thermal and mass transfer gradients. The energy analysis revealed that the dryer operated at a moderate energy utilization efficiency of about 37%, indicating that a portion of the supplied thermal energy was lost to the environment or remained unutilized. The energy utilization efficiency showed minimal sensitivity to temperature variation, suggesting that system performance is constrained more by heat losses and internal resistance than by the magnitude of energy input.

The specific energy consumption (SEC) decreased with increasing drying temperature from 6.8 MJ/kg H_2O to 5.9 MJ/kg H_2O. This shows that improved

energy efficiency existed at higher temperatures. Furthermore, the exergy analysis revealed deeper insights into system inefficiencies. The exergy efficiency remained relatively stable at approximately 30.6% within the temperature range of 122–125 °C. However, a decrease to 26.1% at 126 °C was observed showing degradation in energy quality at higher temperatures. Furthermore, exergy destruction remained nearly constant at approximately 6.5 demonstrating that system irreversibilities are primarily governed by inherent design and operational constraints rather than temperature variations.

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