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Energy and Exergy Performance Analysis of an Indirect LPG-Fired Batch Convective Dryer for Corn Grains Toward Sustainable Agro-Thermal Systems

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Energy and Exergy Performance Analysis of an Indirect LPG-Fired Batch Convective Dryer for Corn Grains Toward Sustainable Agro-Thermal Systems

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ABSTRACT

This study presents an energy and exergy performance analysis of an indirect LPG-fired batch convective dryer developed for corn grain drying in tropical regions. The system's thermal behavior, specific energy consumption, and exergy efficiency were experimentally evaluated at three temperature levels (50 °C, 65 °C, and 80 °C). Results showed the highest energy efficiency of 53.15% at 80 °C, while the maximum exergy efficiency of 64.54% occurred at 50 °C, indicating an inverse relationship between energy utilization and thermodynamic quality. The findings contribute to sustainable agro-thermal system design aligned with the Green Asia strategy.

Keywords: energy efficiency, exergy analysis, corn drying.

Nomenclatures

A	: Surface area of drying chamber
Cp	: Specific heat capacity of air
hfg	: Latent heat of vaporization of water
Ė	: Exergy rate (useful or input)
M	: Moisture content at time *t*
M_o	: Initial moisture content
Me	: Equilibrium moisture content
MR	: Moisture Ratio
Ms	: Mass of dry solid
mw	: Mass of evaporated water
Mw	: Mass of water
Qin	: Total input heat energy
Qloss	: Total heat loss to surroundings
R	: Drying rate
SEC	: Specific Energy Consumption
T	: Drying air temperature
T_o	: Ambient air temperature
ηen	: Energy efficiency
ηex	: Exergy efficiency
ρa	: Density of air
ṁ	: Mass flow rate of drying air
P	: Electrical power consumption
Quseful	: Useful heat energy for moisture evaporation

1. INTRODUCTION

Energy efficiency and sustainability in agricultural drying systems have become critical research topics in tropical regions, where post-harvest losses remain significant due to high humidity and inadequate drying infrastructure. Maize is one of the most widely cultivated cereal crops in Southeast Asia, but its moisture content after harvest often exceeds 25%, leading to microbial deterioration and reduced storage quality if not properly dried [1-2]. Conventional sun drying is still commonly practiced by smallholder farmers; however, this method is highly dependent on weather conditions, requires long drying times, and often produces non-uniform results [3]. To address these limitations, mechanical dryers have been increasingly developed to ensure consistent quality and improve drying efficiency [4]. Among various dryer types, convective batch dryers are widely used for grain processing because of their simple design, ease of control, and scalability for rural applications [5]. The performance of such systems strongly depends on thermal distribution, air velocity, and fuel utilization, which directly influence energy consumption and environmental impact [6]. In developing countries, most small-scale dryers rely on fossil-based fuels such as liquefied petroleum gas (LPG) due to their accessibility and stable combustion characteristics [7]. Although LPG is not a renewable fuel, optimizing its thermal utilization remains a crucial step toward energy transition and carbon reduction in agro-industrial processes [8].

To evaluate and improve the performance of grain dryers, researchers have increasingly applied energy and exergy analyses, which provide complementary insights into both the quantity and quality of energy use [9]. Energy analysis determines how effectively heat is transferred to the material, while exergy analysis quantifies the irreversibilities and losses occurring within the system, thereby indicating its thermodynamic efficiency [10]. Combining these two approaches allows engineers to identify where energy degradation occurs and how system components can be redesigned to minimize exergy destruction and improve overall sustainability [11]. This study aims to experimentally analyze the energy and exergy performance of an indirect LPG-fired batch convective dryer for corn grains, focusing on how drying temperature influences efficiency, specific energy consumption, and total heat losses. The findings are expected to contribute to the development of energy-efficient post-harvest technologies that balance productivity, energy use, and environmental responsibility in tropical agricultural systems.

2. MATERIALS AND METHOD

2.1. Experimental apparatus

The experimental setup consisted of an indirect LPG-fired batch convective dryer designed and fabricated for drying maize and other grain materials under controlled temperature conditions. The system (Figure 1-2) comprised a stainless steel drum rotating horizontally to ensure uniform heat distribution and product mixing. The drum was mounted on a mild-steel frame with an integrated control panel for temperature and timer regulation. The heating system employed a central-tube LPG burner with fins for heat distribution, supported by a centrifugal blower to circulate hot air uniformly within the drum. The system operated in open-loop mode, where hot air was discharged directly into the atmosphere without recirculation. This configuration minimized gas contamination while maintaining stable temperature distribution. A digital controller automatically maintained the drying temperature between 50 and 80 °C, while a timer and safety system prevented overheati ng and electrical faults.

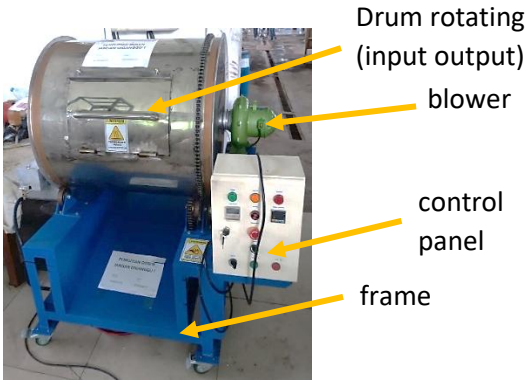


Fig. 1 Schematic layout of the LPG-fired batch convective dryer.

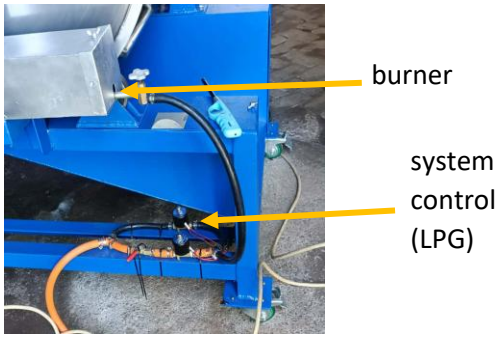


Fig. 2 LPG fuel control system.

To provide an overview of the equipment's configuration, the technical specifications are summarized in Table 1. The mechanical and thermal specifications indicate that the system is suitable for

small- to medium-scale postharvest drying applications, providing sufficient energy input and air circulation for laboratory-scale studies. The LPG burner efficiency, compact design, and temperature automation make the system ideal for studying energy and exergy performance under tropical conditions [18, 26, 36].

Table 1. Technical specifications of the batch convective grain dryer

Component/ Parameter	**Specification**
Capacity per cycle	100 kg
Overall dimension (L×W×H)	140 × 80 × 110 cm
Drum diameter	75 cm
Drum length	100 cm
Drum material	Food-grade stainless steel (SS 304)
Fin material	Heat-resistant mild steel
Main frame	Hollow mild steel 40 × 40 mm, MIG welded
Machine weight	130 kg
Drive motor	0.75 HP (~0.56 kW), 1400 RPM
Gearbox	Ratio 1:60, drum rotation ±23 RPM
Heating system	Central-tube LPG burner with finned heat distributor
Blower type	Axial/Centrifugal, 800–1500 m^3/hour airflow
Operating temperature range	45–100 °C
Control system	Digital panel with setpoint adjustment, timer, solenoid valve, and temperature sensor
Safety features	Overheat protection, circuit breaker, and emergency stop button

2.2. Material preparation

Maize (Zea mays L.) grains were selected as the test material due to their high post-harvest moisture content and importance as a staple crop in tropical regions. The raw maize was obtained from a local farmer group in Kalirejo, Probolinggo, East Java, Indonesia. Upon arrival, the grains were manually cleaned to remove impurities such as husks, dust, and broken kernels. Only intact, uniform grains (5–6 mm diameter) were used to ensure consistent heat and mass transfer during drying. The initial moisture content of the samples ranged between 46-47% (wet basis), which is typical for freshly harvested maize under tropical humidity. Before each run, approximately 5 kg of maize was weighed using a digital scale (±0.01 g accuracy) and placed evenly inside the drum. The oven-drying method (AOAC 934.01) was applied to determine the reference moisture content by drying samples at 105 °C for 24 hours, ensuring reproducibility and reliability [12, 13]. The physical properties of the grains—including shape, size, and moisture distribution—were visually examined after each run to detect any signs of heat damage or

discoloration. The results confirmed that the indirect heating configuration effectively prevented scorching and maintained grain integrity even at 80 °C.

2.3. System setup and preheating

Before each experiment, the dryer (Figure 1) was thoroughly inspected to ensure proper operation of the blower, burner, and control panel. The system was preheated for 10 minutes to reach steady-state thermal conditions at the target drying temperature (50, 65, or 80 °C). The airflow rate was adjusted to maintain a uniform distribution along the drum length. The temperature and velocity distribution within the chamber were measured at three axial positions (inlet, middle, and outlet) using Type-K thermocouples connected to a data logger. The average inlet air velocity ranged between 0.04-0.06 kg/s depending on the set temperature. Once the dryer reached the desired temperature, 5 kg of maize was loaded into the rotating drum. The drum rotated at a constant 23 RPM, driven by a 0.75 HP motor coupled to a 1:60 gearbox (Figure 3), ensuring continuous mixing of grains and minimizing localized overheating.

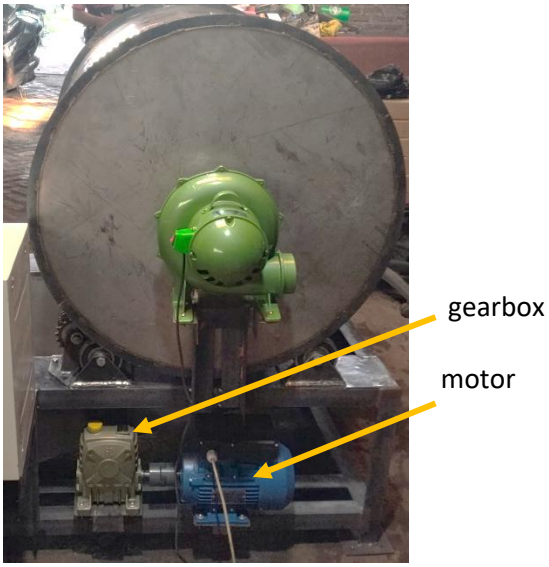


Fig. 3 Gearbox and motor used

Each experiment lasted 60 minutes, with data collected every 10 minutes for temperature, drying time, LPG consumption, and grain moisture content. Samples (100 g) were withdrawn using a stainless-steel scoop through a sampling port and quickly sealed in airtight containers to prevent moisture reabsorption before measurement. The drying temperature was maintained automatically by the digital controller through a proportional solenoid valve that regulated LPG flow. The system's operational safety

was ensured by built-in protection mechanisms—overheat cutoff, circuit breaker, and emergency stop button-allowing continuous unattended operation [17, 21].

2.4. Post-drying evaluation

At the end of each drying cycle, the maize samples were reweighed to quantify the reduction in mass and determine the final moisture content. The drying performance was then evaluated in terms of efficiency, energy consumption, and heat utilization. The specific energy consumption was obtained by comparing the total thermal energy supplied by the LPG burner with the amount of water removed during the drying process. Meanwhile, the energy efficiency reflected the proportion of the supplied heat that was effectively used to evaporate the moisture contained in the maize grains. The exergy efficiency was further assessed to evaluate the thermodynamic quality of energy use within the system. This parameter provided a more rigorous understanding of how much of the supplied energy was converted into useful work potential, considering the irreversibilities arising from temperature gradients and entropy generation in the drying air. The total heat loss of the system was determined by analyzing the difference between the total heat input and the effective latent heat absorbed by the grains for moisture evaporation. All measured data were carefully normalized to eliminate the effects of ambient variations in temperature and humidity. This ensured that any observed differences in drying performance across the three temperature levels (50, 65, and 80 °C) were solely attributed to process behavior rather than environmental fluctuations. The evaluation approach followed established methodologies in energy and exergy analysis of convective dryers as reported by Akpinar and Bicer [25], Jain et al. [27], and Karthikeyan et al. [29].

3. RESULTS AND DISCUSSION

3.1. Moisture content

The variation in moisture content during the drying process is a key parameter that determines the overall effectiveness of a drying system. As shown in Figure 4, the moisture content of maize kernels consistently decreased with time at all drying air temperatures 50 °C, 65 °C, and 80 °C. The drying curves exhibited an exponentially decreasing trend, where the most rapid reduction occurred during the early stage of drying and gradually slowed in the later period. During the first 0–20 minutes, a sharp decline in moisture content was observed, primarily due to the evaporation of free moisture located on the grain surface. Beyond this period, the remaining water was bound moisture within the internal capillary and

cellular structures of the maize kernels; hence, the evaporation rate slowed and became governed by internal diffusion mechanisms. This behavior indicates a transition from the constant-rate period to the falling-rate period, which is a well-known characteristic of convective drying processes for agricultural materials [12, 13]. Drying air temperature had a significant effect on the rate of moisture reduction. At 80 °C, the moisture content decreased from 46% to 31.5% within 60 minutes-faster than that observed at 65 °C and 50 °C, which reached 34% and 35.8%, respectively. The increase in drying temperature enhances the vapor pressure gradient between the grain surface and the surrounding air, accelerating the migration of water vapor into the drying medium. Furthermore, higher temperatures increase the moisture diffusivity inside the kernel matrix, promoting faster migration of internal water toward the surface for evaporation [14, 15]. These results agree with previous studies on convective grain drying, which demonstrated that higher air temperatures accelerate evaporation rates but may reduce energy efficiency during the final stages of drying [16].

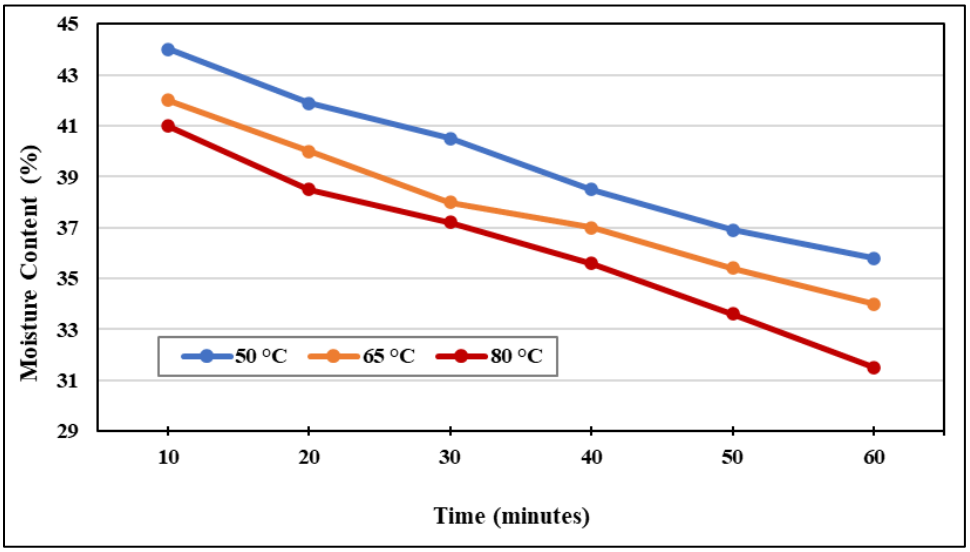


Fig 4 Moisture content of maize as a function of drying time at various air temperatures.

Although elevated temperatures shorten drying duration, they also increase the likelihood of case hardening. The outer layer of the material may dry faster than the inner core, forming a dense layer that impedes further moisture diffusion. At 80 °C, this phenomenon became evident after approximately 40 minutes, when the rate of moisture reduction slowed despite a constant air temperature. This observation is consistent with the findings of Fudholi et al. [17], who reported that uncontrolled convective drying often suffers from reduced efficiency due to vapor diffusion resistance in the surface layer of the material. Overall, the drying pattern of maize followed two distinct phases: (1) a constant-rate period, dominated by the evaporation of free surface water, and (2) a falling-rate period, controlled by the internal diffusion

of bound moisture. Drying temperatures between 65 °C and 80 °C yielded more efficient drying performance, producing final moisture contents below 35%, which is within the ideal post-harvest storage limit for maize grains. These findings corroborate the conclusions of Kumar and Tiwari [18], who emphasized that selecting an optimal drying temperature is crucial for balancing drying rate and energy efficiency while maintaining the physical and chemical quality of the dried product. Therefore, temperatures in the range of 65–80 °C are recommended as optimal operating conditions for maize drying using an indirect LPG-fired convective batch dryer under laboratory-scale conditions.

3.2. Moisture ratio

The Moisture Ratio (MR) is an essential parameter used to describe the relative change in moisture content with respect to the initial moisture during the drying process. It represents the ratio between the moisture content of the material at a given time and its initial moisture content, accounting for the equilibrium moisture content. As illustrated in Figure 5, the MR of maize kernels exhibited an exponential decline over time across all drying temperatures (50 °C, 65 °C, and 80 °C). This behavior reflects the characteristic two-phase nature of convective drying—an initial constant-rate period followed by a falling-rate period. During the early stage (0–20 minutes), MR decreased rapidly due to the evaporation of free moisture that readily diffused from the grain surface. Subsequently, the rate of decline slowed, indicating that the remaining water was bound moisture within the internal cellular structure, thus the drying process became governed by internal diffusion mechanisms [19].

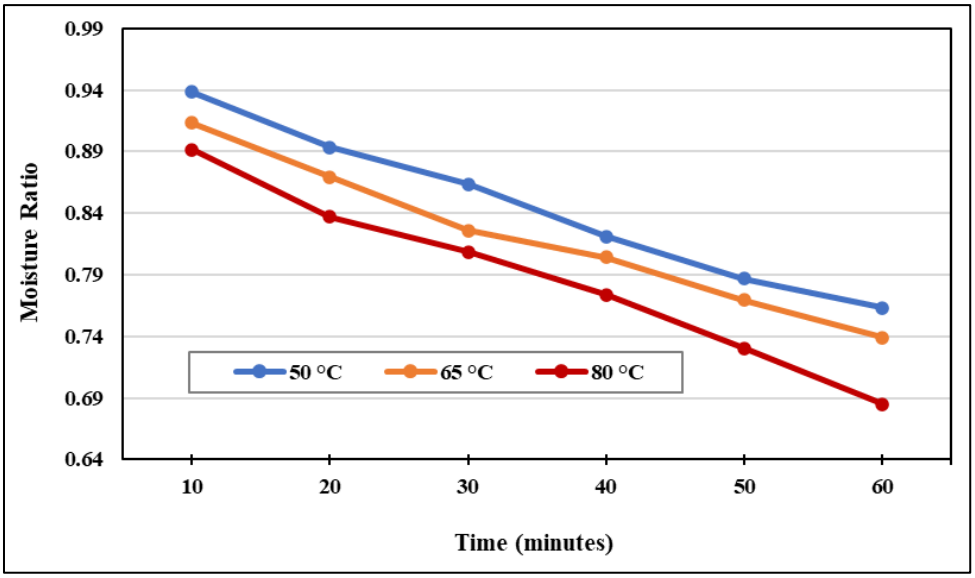


Fig 5 Variation of moisture ratio (MR) of maize grains as a function of drying time at different temperatures.

The MR values at 80 °C decreased faster than those at 65 °C and 50 °C. After 20 minutes, the MR reached 0.84 at 80 °C, while it was 0.87 and 0.89 for 65 °C and 50 °C, respectively. These results indicate that increasing the drying air temperature enhances the vapor pressure gradient between the grain surface and the surrounding air, thereby improving mass transfer and accelerating the diffusion of internal moisture. At higher temperatures, the thermal energy absorbed by the grain increases, promoting faster migration of moisture from the interior toward the surface for evaporation. This observation agrees with the findings of Phadke and Borse [19], who reported that elevated drying temperatures significantly accelerate the decrease in MR for maize kernels. The exponential reduction in MR is also consistent with widely accepted drying kinetics models used for agricultural products, such as the Page model and the Henderson–Pabis model, both of which empirically describe the relationship between MR and drying time. These models explain that MR declines rapidly at the beginning and gradually approaches equilibrium moisture content as drying progresses. According to Babalis and Belessiotis [20], this exponential behavior occurs because the moisture diffusivity within the material decreases as the moisture level drops. Similarly, Kaleemullah and Kailappan [21] observed that increasing the drying temperature from 50 °C to 80 °C could accelerate MR reduction by up to 40%, primarily due to reduced internal diffusion resistance and enhanced evaporation at the surface layer.

Overall, the observed MR trends for maize drying reveal that the mass transfer process is governed by two mechanisms: surface evaporation of free moisture during the initial stage and diffusion of bound moisture during the later stage. Lower MR values at higher temperatures indicate more efficient drying performance; however, excessive temperatures may lead to undesirable effects such as over-drying or quality degradation. Therefore, drying temperatures in the range of 65–80 °C are recommended as optimal operating conditions, as they ensure faster drying while preserving the physical characteristics of the grain. These findings are consistent with the moisture diffusion theory and previous studies on convective maize drying [19, 20, 21].

3.3. Drying rate

The drying rate is a crucial parameter that represents the rate of moisture migration from the interior of the material to the surrounding air during the drying process. It is generally expressed as the change in moisture content per unit of time (%/min). As illustrated in Figure 6, the drying rate of maize kernels at three different air temperatures 50 °C, 65 °C, and 80 °C showed a declining trend with increasing drying time. The highest drying rates occurred at the beginning of the process and gradually decreased until reaching a nearly steady condition. During the initial stage (0–20 minutes), the drying process was

rapid due to the evaporation of free moisture on the surface of the maize kernels, which was easily removed by the hot airflow. The initial drying rates reached approximately 0.50 %/min at 80 °C, 0.40 %/min at 65 °C, and 0.29 %/min at 50 °C. These differences indicate that higher drying air temperatures increase the vapor pressure gradient between the drying air and the material surface, thereby accelerating water evaporation [22]. In the subsequent stage (20–40 minutes), the drying rate began to decline as the free surface water diminished and the moisture transfer became dominated by internal diffusion of bound water from the grain interior to the surface. At this point, the drying rate decreased to approximately 0.21–0.27 %/min at higher temperatures and 0.20–0.25 %/min at lower temperatures, reflecting the shift in the controlling mechanism from surface evaporation to internal diffusion.

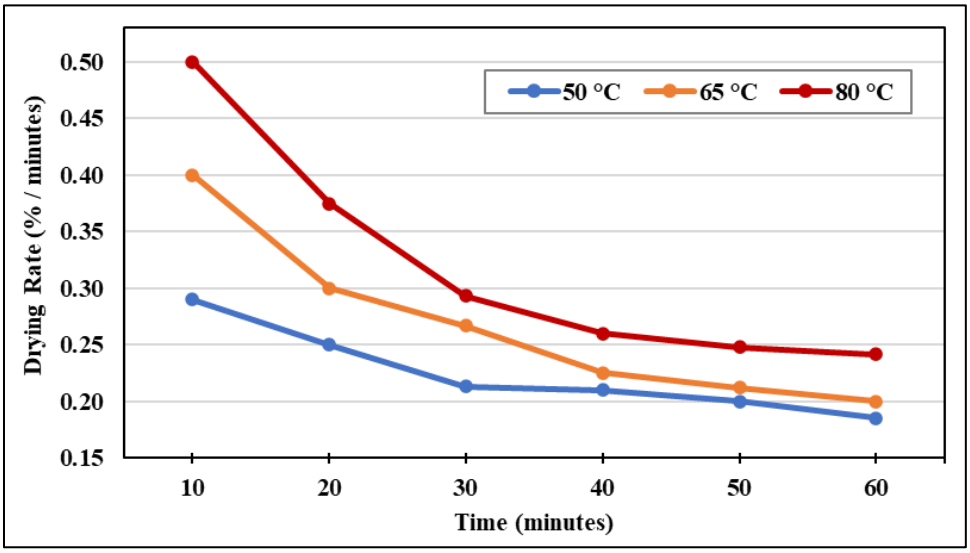


Fig 6 Variation of drying rate with drying time at different air temperatures.

Overall, the declining pattern of drying rate corresponds to the typical drying kinetics of agricultural products, which usually exhibit two major phases: the constant-rate period and the falling-rate period. The first phase is primarily governed by surface heat transfer and evaporation, while the second is controlled by internal diffusion and capillary resistance within the porous structure of the material [23]. This observation agrees with the study by Doymaz [24], who reported that most agricultural materials, including maize and soybeans, do not show a prolonged constant-rate period because the thin layer of surface water is removed quickly, and the process soon enters the diffusion-controlled stage. The present results also indicate that increasing the drying temperature from 50 °C to 80 °C enhanced the average drying rate by up to 70 %, signifying improved thermal efficiency at elevated temperatures. However, excessively rapid drying may create a steep internal moisture gradient, potentially causing microcracks or surface morphological changes due to high internal vapor pressure [25]. Therefore, drying

maize at 65–80 °C can be considered an optimal temperature range, providing a balance between faster evaporation and structural stability.

In summary, the drying rate decreased progressively with time, and higher drying air temperatures resulted in higher drying rates. The pattern followed an exponentially declining behavior typical of porous agricultural materials. This trend aligns with the findings of Babalis and Belessiotis [20], who observed that higher temperatures accelerate moisture diffusion without altering the fundamental drying mechanism. Consequently, these results can serve as a foundation for developing appropriate mathematical drying models, such as the Page or Henderson–Pabis equations, which have proven effective in describing the drying-rate decline of solid biomass materials like maize.

3.4. Electrical Power Consumption

Electrical power consumption is an important indicator for evaluating the performance of a drying system, as it directly reflects the overall energy efficiency. As presented in Figure 7, the average electrical power used by the drying unit ranged between 500 W and 970 W, with the maximum value of 965 W observed at the end of the 80 °C drying cycle. In general, the electrical power remained relatively stable throughout the process, since most of the electrical load was attributed to the operation of the air-blower, while the evaporation of moisture was primarily driven by the thermal energy supplied by the LPG burner. This behavior indicates that increasing the drying air temperature did not cause a significant surge in electrical demand; instead, a slight increase occurred near the end of the process due to higher air-flow resistance in the heated duct. Similar observations were reported by Chen et al. [26], who found that in convective dryers, the electrical load remains nearly constant because the major power requirement arises from air-circulation components rather than water evaporation.

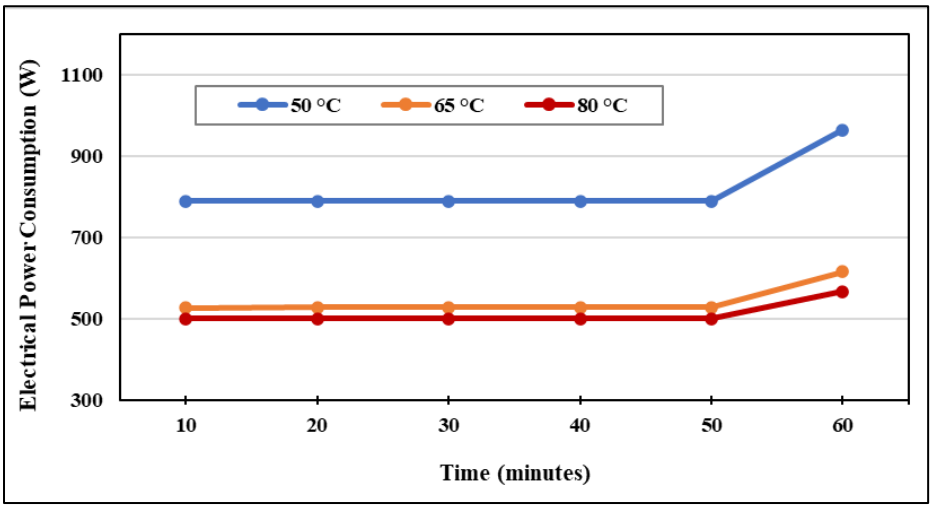


Fig 7 Variation of electrical power consumption during maize drying at different air temperatures.

Higher power consumption observed at lower drying temperatures, such as 50 °C, was mainly caused by longer operating time required to reach the same final moisture content. Conversely, higher temperatures shortened the drying duration even though instantaneous power slightly increased. Akpinar et al. [27] explained that total electrical energy consumption depends on both the drying time and heat-transfer efficiency, where increasing temperature typically reduces the total electrical energy per unit mass of evaporated water. Hence, operating at 65–80 °C provided the most energy-efficient conditions, producing high drying rates with shorter operation times. These results are in agreement with Zhang et al. [28], who reported that high-temperature drying enhances overall energy efficiency without proportionally increasing the electrical load. Overall, the tested drying system exhibited low electrical demand (<1 kW), demonstrating efficient energy utilization suitable for both laboratory-scale and semi-industrial maize drying applications.

3.5. Energy Efficiency

Energy efficiency is a key parameter for evaluating the thermal performance of a drying system, as it represents the proportion of input energy effectively utilized for the evaporation of moisture from the material. As presented in Figure 8, the energy efficiency of the maize drying system ranged between 10% and 53%, depending on the drying air temperature. The highest efficiency, 53.15%, was achieved at 80 °C during the 10th minute of drying, followed by 40.4% at 65 °C and 19.52% at 50 °C. The increase in efficiency at higher temperatures was primarily due to greater heat-transfer rates and shorter drying times, which caused a higher proportion of the supplied energy to be converted into latent heat of evaporation rather than lost to the surroundings.

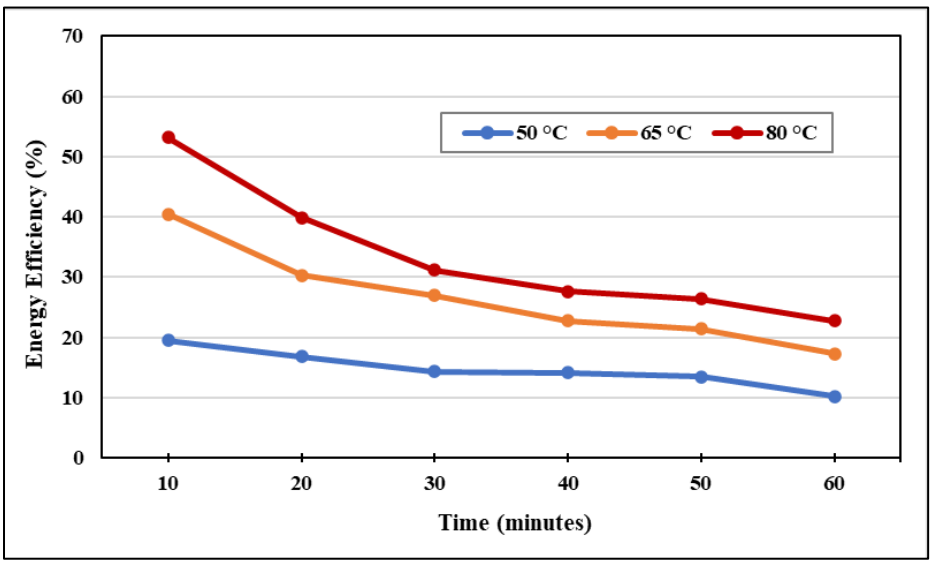


Fig 8 Variation of energy efficiency with drying time at different air temperatures.

From a thermodynamic perspective, higher energy efficiency indicates that a larger portion of the supplied heat was absorbed by the material to overcome the latent heat of vaporization. These findings are consistent with those of Jain and Pathak [30], who reported that the efficiency of convective dryers generally increases with air temperature up to a certain limit, as both the thermal conductivity of the material and the vapor pressure gradient rise simultaneously. At lower temperatures, however, efficiency decreases because a significant portion of the input energy is absorbed by the dryer walls and exhausted humid air instead of contributing to effective evaporation. Chen et al. [26] similarly noted that low energy efficiency in convective dryers is often attributed to sensible heat losses through unrecaptured exhaust air. The observed improvement in energy efficiency at higher temperatures also correlates with a decrease in Specific Energy Consumption (SEC). A lower SEC value indicates that less energy is required to evaporate each kilogram of water, thereby improving the overall energy utilization of the system. According to Sarker and Mujumdar [31], convective batch dryers without heat-recovery units typically achieve energy efficiencies between 30% and 40%, which are considered satisfactory for practical applications. In this context, the maximum efficiency of 53.15% achieved in this study demonstrates that the tested dryer design effectively transferred thermal energy to the material with minimal heat losses.

However, the efficiency did not increase linearly with temperature. Beyond 80 °C, excessive heat losses to the environment and potential product degradation due to over-drying may reduce the overall efficiency. Therefore, drying temperatures in the range of 65–80 °C can be regarded as the most thermally and practically efficient conditions for maize drying. These results align with the findings of Zhang et al. [28], who stated that maximum efficiency in convective drying systems is generally achieved within 70–85 °C for porous materials with high initial moisture content. In summary, the tested system demonstrated strong thermal performance, with a substantial proportion of input energy effectively utilized for moisture evaporation and minimal energy loss to the environment.

3.6. Noise

The measurement of noise levels was conducted as an essential part of evaluating the performance of the rotary dryer machine to ensure that its operation remains within safe limits for both operators and the working environment. The primary sources of noise in this system originate from the mechanical interaction between the rotating drum and the supporting rollers, as well as contributions from the driving motor and transmission system, which generate vibrations during operation. This phenomenon is common in rotating mechanical systems involving component contact and periodically varying dynamic forces. Based on the test results, the noise level produced remains below the permissible

threshold, indicating that the machine can be classified as safe for use. This finding is consistent with the study by Lubitz et al. [39], which states that noise in rotating machinery is predominantly influenced by mechanical interactions and system vibrations.

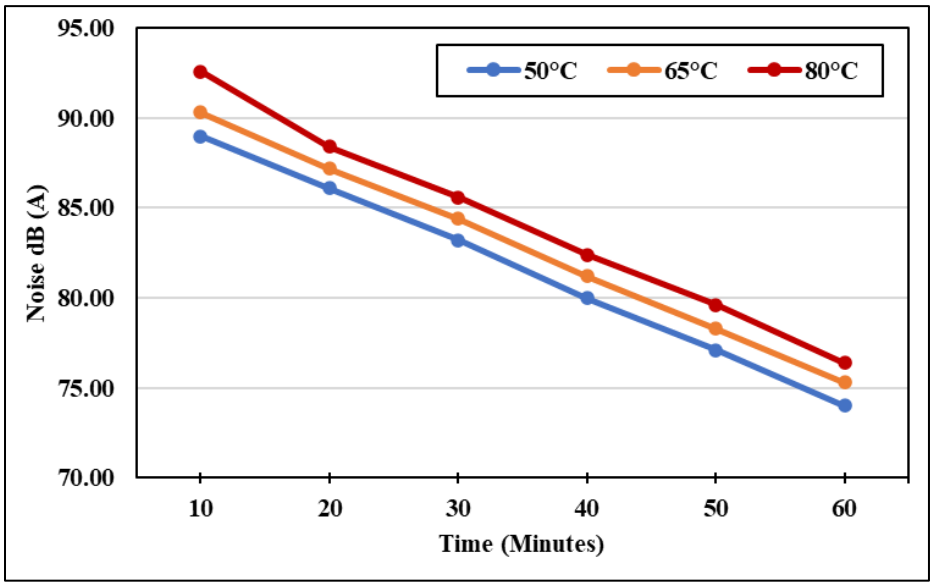


Fig 9 Measured noise levels of the rotary dryer during operation under different conditions.

The use of construction materials such as stainless steel for the drum, along with a rigid iron frame, plays a significant role in damping mechanical vibrations and reducing sound emissions caused by friction between components. In addition, placing the machine on a flat and stable surface has been proven to minimize additional vibrations that could otherwise increase noise levels during the rotation process. Structural stability and proper mechanical design contribute significantly to the overall acoustic performance of the system. These results are supported by the study of Čurović et al. [40], which demonstrates that material selection and structural stiffness affect the level of noise emission in machinery. Therefore, an appropriate structural design is a key factor in maintaining low noise levels. Although the noise level remains under control, maintenance aspects continue to play an important role in preserving the acoustic performance of the machine. Routine maintenance of components such as bearings and transmission chains is necessary to prevent increased friction that may lead to high-frequency noise. Proper lubrication is known to reduce noise levels while simultaneously extending the service life of mechanical components. Furthermore, the implementation of innovations such as installing enclosures or insulating materials on the electric motor can serve as additional solutions to reduce noise emissions. Overall, the acoustic performance of the machine indicates that the system has been well designed and properly operated, and is capable of supporting a work environment that meets occupational safety and health standards.

3.7. Vibration

Vibration analysis was conducted to evaluate the structural stability of the rotary dryer frame in supporting a 100 kg drum operating continuously. Vibrations in this system are generally caused by the imbalance in the mass distribution of materials inside the drum, as well as the dynamics of the transmission system and other rotating components. The periodic excitation arising from these conditions is a common phenomenon in rotating systems with dynamic loads. This imbalance can affect drying performance and reduce operational efficiency if not properly controlled. This is consistent with the study by Karpenko et al. [41], which states that unbalance in rotating systems is a primary source of vibration and performance degradation. Based on the observations, the use of a frame made of 4×4 cm angle iron effectively dampens vibrations, indicating that the structural design possesses sufficient stiffness. The low vibration values also suggest that the manufacturing process and shaft alignment have been carried out with high precision. This condition plays an important role in reducing dynamic deformation during the drying process. Structural stability is crucial to prevent material fatigue at welded joints and to maintain long-term system reliability. These findings are supported by the study of Xie et al. [42], which demonstrates that structural stiffness and alignment quality significantly influence vibration reduction.

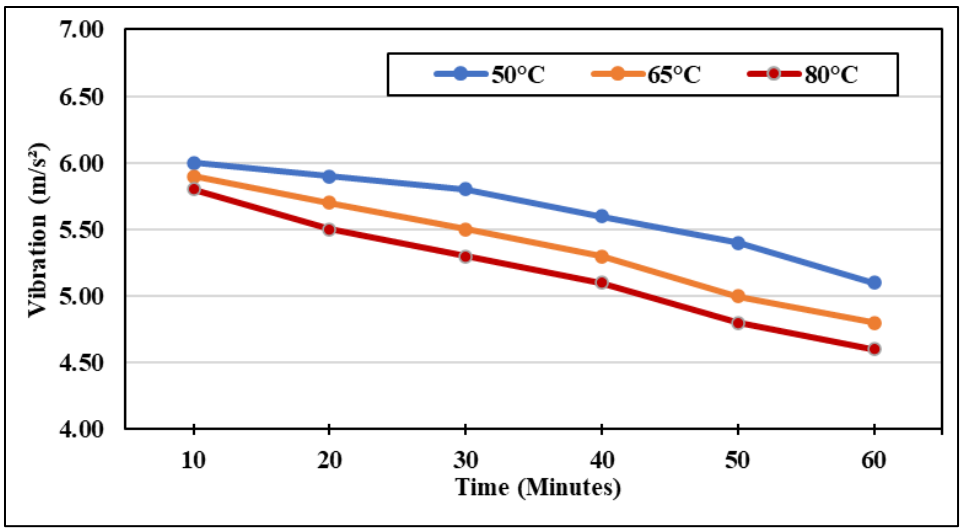


Fig 10 Variation of vibration velocity (m/s^2) with operating time for the rotary drying system.

In addition, the use of fixed supports on the frame legs has proven effective in minimizing the transmission of vibrations to the surrounding environment. Excessive vibrations can lead to decreased system performance, including the loosening of bolted joints and disturbances in measurement and control systems. Therefore, routine maintenance such as checking bolt tightness and lubricating mechanical components is highly recommended. The distribution of material inside the drum, assisted by

flights, also plays a role in maintaining rotational balance and improving the uniformity of the drying process. With minimal vibration levels, this drying machine demonstrates stable mechanical performance and has the potential for a long service life under continuous operation.

3.8. Exergy Efficiency

Exergy efficiency is an important thermodynamic parameter used to assess how effectively the input thermal energy is utilized in accordance with the Second Law of Thermodynamics, which considers both the quality of energy and process irreversibilities. It represents the ratio between the useful exergy employed for moisture evaporation and the total exergy supplied to the system. Unlike energy efficiency, which only measures the amount of energy used, exergy efficiency also accounts for the loss of work potential caused by temperature differences and entropy generation during the drying process.

As illustrated in Figure 11, the exergy efficiency of the maize drying system ranged from 10.04 % to 64.54 %, with the highest value obtained at 50 °C (64.54 %), followed by 65 °C (42.90 %) and 80 °C (36.44 %). This finding indicates that exergy efficiency does not necessarily increase with higher drying temperatures. At lower temperatures, the input energy is relatively small and more proportionally utilized for water evaporation, while heat losses to the surroundings remain limited. Consequently, thermodynamic irreversibility (entropy generation) is lower, resulting in a higher ratio of useful to total exergy. Conversely, at elevated temperatures, even though the drying rate increases, a larger portion of the supplied energy is lost through the exhaust air, which still carries considerable sensible heat. The observed behavior is directly related to the design of the LPG-fired rotary batch dryer used in this study. The stainless-steel (SS 304) drying drum rotates at a constant speed to ensure uniform temperature and moisture distribution. The system is equipped with an axial blower and an automatic control panel for regulating drying time and air temperature. Hot air generated from the burner is delivered through a closed convective channel into the drying chamber and exhausted through an outlet without a heat-recovery unit. Due to the absence of exhaust-heat utilization and limited thermal insulation on the drum walls, increasing the air temperature above 65 °C led to a noticeable rise in exergy loss through the outlet air and metal-wall conduction.

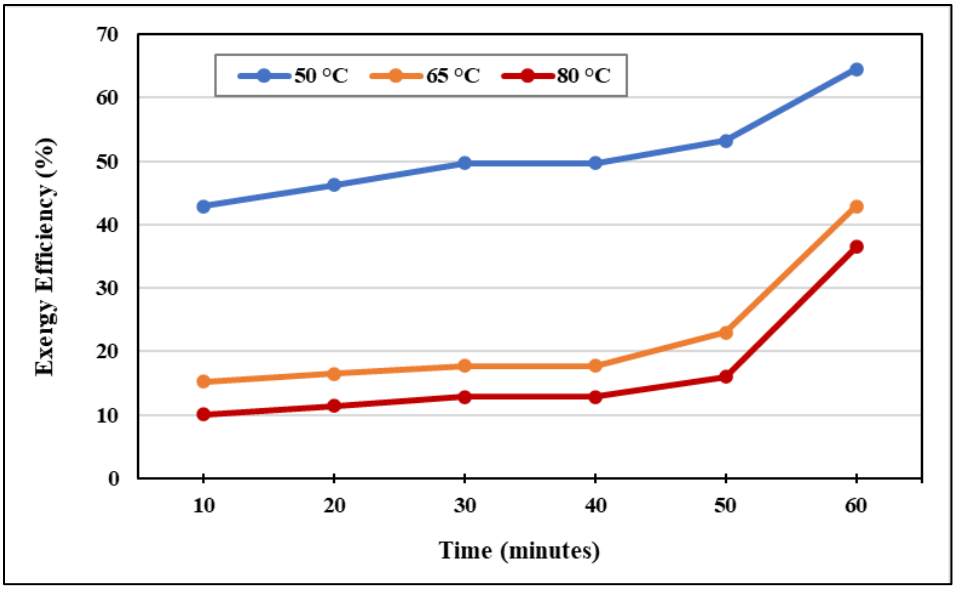


Fig 11 Exergy efficiency of the maize drying system as a function of time and temperature.

From a thermodynamic standpoint, the optimum exergy efficiency observed at 50 °C suggests that the system operated with the best balance between energy supply and utilization, resulting in minimum irreversibility. This outcome aligns with the theoretical explanation of Dincer and Rosen [33], who noted that in open convective drying systems, exergy efficiency tends to decline sharply when the ratio of drying-air temperature to ambient temperature becomes excessively high due to increased entropy generation. Similarly, Sarker and Mujumdar [31] reported that maximum exergy efficiency typically occurs at moderate temperatures (45–55 °C) for porous materials, where heat and mass transfer remain stable and exergy losses through exhaust air are still controllable. Accordingly, this study confirms that energy efficiency and exergy efficiency are not directly proportional. While energy efficiency increased at higher temperatures (80 °C), exergy efficiency decreased due to greater process irreversibility and higher heat losses. The highest exergy efficiency at 50 °C demonstrates that thermal energy was utilized more proportionally, avoiding excessive and non-productive heat input. These findings reveal that the tested horizontal-drum drying system achieved its best thermodynamic performance at low-to-moderate temperatures, and its performance could be further improved through enhanced thermal insulation or by integrating a waste-heat recovery system to minimize exergy destruction at higher operating temperatures.

4. CONCLUSION

This study evaluated the thermal and exergy performance of an LPG-fired rotary batch dryer for maize at drying air temperatures of 50 °C, 65 °C, and 80 °C. The results showed that moisture content and

moisture ratio decreased exponentially with time, following a two-stage drying behavior: an initial constant-rate period and a subsequent falling-rate period governed by internal diffusion. Higher temperatures accelerated the drying rate but increased the risk of surface hardening. The electrical power demand remained stable at 500–970 W, while the specific energy consumption decreased with higher temperatures, indicating improved thermal utilization. Energy efficiency ranged between 10–53%, reaching its peak (53.15%) at 80 °C, whereas exergy efficiency was highest (64.54%) at 50 °C due to lower thermodynamic irreversibility. In addition to thermal performance, the mechanical behavior of the system was also evaluated through noise and vibration analysis. The measured sound pressure level remained within acceptable operational limits, indicating that the interaction between the rotating drum, support rollers, and drive system did not generate excessive acoustic disturbance. Similarly, vibration levels were relatively low and stable throughout operation, confirming good mechanical balance and alignment of the rotary components. These findings suggest that the system operates smoothly without significant dynamic instability, which is essential for ensuring equipment durability, operator safety, and long-term reliability. In conclusion, the optimal drying range for maize lies between 65–80 °C, providing high energy efficiency and short drying time, while 50 °C yields the best exergy efficiency. The system demonstrated low power demand (<1 kW), stable mechanical performance, and satisfactory overall operation for laboratory- and semi-industrial-scale applications. Further improvements through heat recovery, enhanced insulation, and vibration damping are recommended to enhance overall exergy efficiency and mechanical robustness [34, 35, 36, 37, 38].

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Ethics Declaration

This study did not involve human participants, human data, or animals.

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