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Relationship between thermal driving force and moisture removal characteristics during corn drying in an LPG fired single cylinder rotary dryer

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ABSTRACT

Drying is an essential post-harvest process to reduce the moisture content of shelled corn to a safe storage level while maintaining product quality. This study investigated the thermal and mass transfer characteristics of shelled corn drying in an LPG-fired single-cylinder rotary dryer operating at a constant air velocity of 7.9 m/s. The drying performance was evaluated based on temperature distribution, thermal driving force, moisture removal, drying rate, moisture ratio, and the relationship between thermal driving force and drying rate. Temperature measurements included inlet air, outlet air, ambient air, and material temperatures. The results showed that the inlet air temperature remained relatively stable at 70.5–72.5°C, while the material temperature gradually increased from 61.4 to 66.7°C during drying, indicating stable heat transfer conditions. Moisture removal and drying rate continuously decreased with drying time due to the reduction of free moisture and the increasing resistance to internal moisture migration. Regression analysis demonstrated a positive relationship between thermal driving force and drying rate. The temperature difference between the material and outlet air produced a stronger correlation with drying rate than the temperature difference between inlet air and material. These findings indicate that temperature deference two is a more representative thermal driving force parameter for describing heat and mass transfer during convective drying of shelled corn. The study provides useful information for evaluating and optimizing the thermal performance of rotary drying systems.

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1. INTRODUCTION

Corn (Zea mays L.) is a food commodity that plays a vital role in supporting food security and the livestock feed industry. After harvesting, shelled corn typically retains a relatively high moisture content, making it susceptible to microbial growth, quality deterioration, and spoilage during storage. Drying is one of the most

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effective methods for reducing moisture content to a safe level, thereby maintaining storage stability and product quality. This process involves simultaneous heat and mass transfer (Baidhe et al., 2025; Ge et al., 2024; Bhattacharjee et al., 2024).

Convection drying is the most widely applied method for drying agricultural products because it effectively reduces moisture content through a relatively simple operating system, offers high drying capacity, and is easily implemented across various production scales. One widely used technology is the rotary dryer, which operates via direct contact between hot air and the material; this facilitates heat transfer from the air to the material's surface, followed by mass transfer specifically the migration of moisture from the material's interior to the surface where it subsequently evaporates into the airflow. In a rotary dryer system, the rotation of the cylinder continuously mixes the material, thereby enhancing contact between the hot air and the material, improving temperature distribution uniformity, and increasing heat and mass transfer efficiency during the drying process, which ultimately improves the efficiency of the drying operation (Yan et al., 2026; Ramachandran et al., 2024; Kilic, 2024; Susana et al., 2023). Recent studies indicate that the drying of agricultural materials is a coupled process involving simultaneous heat and mass transfer. Heat transfer provides the energy required for water evaporation, while mass transfer governs the migration of moisture from the material's interior to the surface.

The performance of the convection drying process is determined not only by the type of dryer and operating conditions but also by the magnitude of the thermal driving force generally defined as the temperature difference between the drying air and the material's surface. This temperature difference serves as the primary energy source governing the rate of convective heat transfer to the material. A greater thermal driving force results in more thermal energy being transferred to the material, thereby intensifying the heating and water evaporation processes. The absorbed thermal energy is subsequently utilized to raise the material's temperature while simultaneously providing the latent heat required to convert water into vapor. Concurrently, moisture within the material migrates toward the surface via mechanisms of liquid diffusion, vapor diffusion, and capillary flow before finally being released into the drying air. The performance of the convection drying process is determined not only by the type of dryer and operating conditions but also by the magnitude of the thermal driving force generally defined as the temperature difference between the drying air and the material's surface. This temperature difference serves as the primary energy source governing the rate of convective heat transfer to the material. A greater thermal driving force results in more thermal energy being transferred to the material, thereby intensifying the heating and water evaporation processes. The absorbed thermal energy is subsequently utilized to raise the material's temperature while simultaneously providing the latent heat required to convert water into vapor. Concurrently, moisture within the material migrates toward the surface via mechanisms of liquid diffusion, vapor diffusion, and capillary flow before finally being released into the drying air. The process of water release is known as moisture removal a process involving the reduction of water content in a material due to mass transfer during drying. The extent of moisture removal is typically evaluated using the Drying Rate parameter, which indicates the rate of water release per unit of time, and the Moisture Ratio, which describes the change in water content relative to initial conditions throughout the drying process. Consequently, examining the relationship between the thermal driving force (an indicator of heat transfer) and moisture removal (an indicator of mass transfer) is crucial for understanding the heat and mass transfer characteristics during convective drying (Bergman et al., 2017; Cengel & Ghajar, 2020; Defraeye, 2014; Yan et al., 2026).

Numerous studies on the drying of corn and agricultural products have reported on drying kinetics, temperature distribution, effective moisture diffusivity, energy requirements, and heat and mass transfer modeling across various types of dryers. Most of these studies have focused on the effects of air temperature, air velocity, or material characteristics on the rate of moisture reduction and product quality; however, evaluations of the quantitative relationship between the thermal driving force (for heat transfer) and moisture removal (as an indicator of mass transfer) remain relatively limited, particularly for LPG-fired single-cylinder rotary dryer systems operated at constant air velocity. However, understanding the relationship between these two parameters is crucial for explaining the interplay of heat and mass transfer mechanisms during drying and for providing a more robust basis for evaluating and optimizing dryer performance. Therefore, this study evaluates the relationship between the thermal driving force and both the drying rate and moisture ratio using simple linear regression analysis, thereby establishing a quantitative link between heat and mass transfer mechanisms during the drying of shelled corn.

Based on the foregoing, this study aims to evaluate the relationship between the thermal driving force and moisture removal during the drying of shelled corn using an LPG-fired single-cylinder rotary dryer at a constant air velocity of 7.9 m/s. Moisture removal characteristics were evaluated using the Drying Rate and Moisture Ratio parameters, while the relationship between the thermal driving force and these two parameters was analyzed using simple linear regression to determine the regression equation and the coefficient of determination (R^2). The results of this study are expected to provide a more comprehensive understanding of the relationship

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between heat and mass transfer mechanisms in convective drying and to serve as a basis for evaluating and developing LPG-fueled rotary dryer systems.

2. RESEARCH METHODS

This study employs a single-cylinder rotary dryer designed for continuous drying using a forced-convection system. Heat is generated by burning Liquefied Petroleum Gas (LPG) in a burner to produce hot air. A blower directs this hot air into the drying cylinder, while an electric motor rotates the cylinder, ensuring the shelled corn is continuously agitated during the drying process. The combination of hot airflow and cylinder rotation results in more uniform heat distribution and enhances contact between the drying air and the corn surfaces, thereby accelerating heat transfer and moisture removal. The material used was shelled corn with an initial mass of 5,000 g for each test. Air temperatures were measured using K-type thermocouples placed at the air inlet, the drying chamber, and the air outlet. Mass measurements were performed using a digital scale, while air velocity was measured using an anemometer. Figure 1 shows the single-cylinder rotary dryer configuration used in this study.

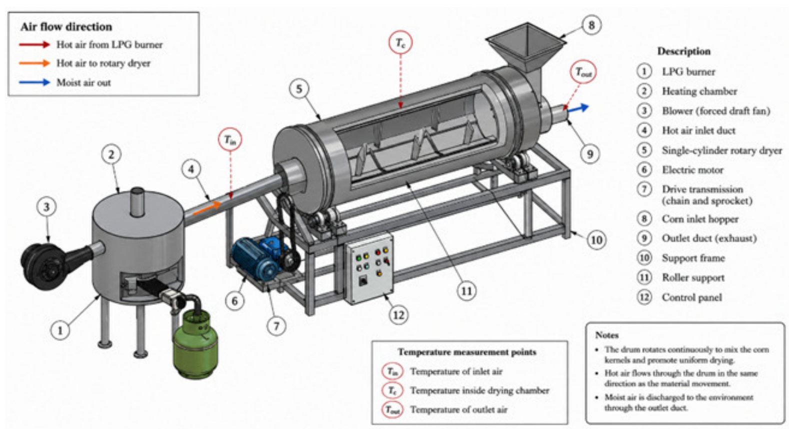

Figure 1. Schematic of the experimental setup for corn drying in an LPG-fired single-cylinder rotary dryer

Ambient air is drawn in by a blower and directed into a heating chamber equipped with an LPG burner. The combustion of LPG generates hot air, which then enters the drying drum through the air inlet. Inside the drum, the shelled corn is agitated by the rotation of the cylinder, ensuring that the entire surface area of the material comes into more uniform contact with the hot air. During this process, heat is transferred via convection from the hot air to the surface of the corn. The thermal energy absorbed by the material is used to evaporate the moisture within the corn kernels. Water vapor is then carried by the airflow toward the outlet. Air temperatures were measured at three locations: the inlet air temperature (T_{in}), the drying chamber temperature (T_c), and the outlet air temperature (T_{out}). The mass of the corn was measured periodically to determine moisture release characteristics during the drying process. This study analyzed the relationship between the thermal driving force represented by the air temperature difference and moisture removal, as indicated by mass reduction, drying rate, and moisture ratio. The research was conducted under steady operating conditions; thus, only a single test condition was analyzed. The measured variables included drying time (minutes), inlet air temperature (Tin), drying chamber temperature (T_c), outlet air temperature (T_{out}), thermal driving force (ΔT), corn mass, mass loss, drying rate, and moisture ratio. The initial mass of the corn (shelled corn) was 5,000 g, the air velocity was constant at 7.9 m/s, a single-cylinder rotary dryer was used, LPG served as the energy source, and the drum rotation speed was fixed at 12 rpm.

Heat transfer characteristics were analyzed using thermal driving forces (ΔT_1 and ΔT_2), specifically, the temperature differences between the inlet air (T_{in}) and the drying chamber (T_c), and between the drying chamber (T_c) and the outlet air (T_{out}), as presented in equation (1) (Bergman et al., 2017; Cengel and Ghajar, 2020).

$$\Delta T_1 = T_{in} - T_c \tag{1}$$

$$\Delta T_2 = T_c - T_{out} \tag{2}$$

Mass loss is used as the primary indicator to evaluate moisture removal during the drying process. Mass loss, Δm (g), is calculated based on the difference between the initial mass of the corn before drying, m_o (g), and the mass of the corn at the time of observation, m_t (g), as presented in equation (2) (Mujumdar, 2014).

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$$\Delta m = m_o - m_t \tag{3}$$

The drying rate is calculated based on the change in the mass of shelled corn at each observation time interval. This parameter establishes the relationship between the thermal driving force and moisture removal. The drying rate is calculated using equation (4) (Mujumdar, 2014; Brooker et al., 1992).

$$DR = \frac{\Delta m}{\Delta t} \tag{4}$$

DR is the drying rate (g/hour), Δm is the decrease in corn mass, and Δt is the observation time interval (hours).

The corn moisture content obtained from testing is expressed on a wet basis. For the analysis of drying characteristics, this moisture content is converted to a dry basis, assuming the mass of the dry matter remains constant during the drying process. The conversion is performed using equation (5) (Mujumdar, 2014; Brooker et al., 1992; Singh and Heldman, 2014).

$$M_{db} = \frac{M_{wb}}{100 - M_{wb}} \tag{5}$$

M_{db} represents the dry-basis moisture content (kg water/kg dry matter), and M_{wb} is the wet-basis moisture content (%). The dry-basis moisture content from Equation 5 is used to calculate the moisture ratio. Dry-basis moisture content and Moisture Ratio (MR) serve as standard parameters in the analysis of drying characteristics and kinetics (Bhattacharjee et al., 2024). Moisture Ratio (MR) expresses the relative change in moisture content during the drying process and is commonly used to analyze the drying characteristics and kinetics of agricultural materials (Doymaz, 2004; Midilli et al., 2002). The MR value is calculated based on the dry-basis moisture content. In this study, the equilibrium moisture content (M_e) was not measured. Therefore, consistent with common practice in drying characteristic studies, the Me value is considered negligible compared to the initial moisture content (M_o) and the moisture content at a given time (M_t), and can thus be disregarded. Consequently, the Moisture Ratio is calculated using the simplified equation shown in equation (6) (Doymaz, 2004; He et al., 2024; Mihret et al., 2024; Celik et al., 2026).

$$MR = \frac{M_t}{M_o} \tag{6}$$

The measurement data were analyzed to evaluate the heat and mass transfer characteristics during the drying process of shelled corn. The relationship between the thermal driving force (independent variable) and the drying rate and moisture ratio (dependent variables) was analyzed using simple linear regression. Microsoft Excel was used to determine the regression equations and coefficients of determination (R^2), which served to evaluate the strength of the relationship and the trend of the thermal driving force's influence on moisture removal (Montgomery et al., 2021).

3. RESULTS AND DISCUSSION

Temperature characteristics are a key parameter in evaluating the heat transfer process during convective drying. Changes in the drying air and material temperatures reflect the amount of thermal energy transferred from the air to the material, which is subsequently utilized to raise the material's temperature and evaporate moisture during the drying process. Therefore, analyzing temperature distribution is essential for understanding the heat transfer mechanisms involved and their relationship with mass transfer processes during the drying of shelled corn in an LPG-fired single-cylinder rotary dryer. Figure 2 illustrates the variations in ambient air temperature (T_a), dryer inlet air temperature (T_{in}), drying chamber temperature (T_c), and dryer outlet air temperature (T_{out}) during the drying process using an LPG-fired single-cylinder rotary dryer at a constant air velocity of 7.9 m/s. Figure 2 shows the average ambient air temperature (T_a), inlet temperature (T_{in}), drying chamber temperature (T_c), and outlet temperature (T_{out}) across three test runs. The average inlet temperature (T_{in}) remained relatively stable within the 70.5-72.5°C range, with a mean of 71.35°C throughout the drying process. Temperature data from the three test runs are presented in table 1. This indicates that the LPG combustion system was capable of providing a relatively constant heat supply, thereby allowing the dryer's operating conditions to be maintained throughout the process. Maintaining a stable inlet air temperature is crucial, as it determines the amount of thermal energy available for transfer to the material via convection. According to Cengel and Ghajar (2020), the drying air temperature is a key parameter governing the rate of heat transfer to the material's surface during convective drying. A stable drying air temperature is essential for providing a continuous supply of thermal energy for convective heat transfer to the material surface. This condition contributes to a stable drying rate and enhances the uniformity of heat distribution within the drying chamber.

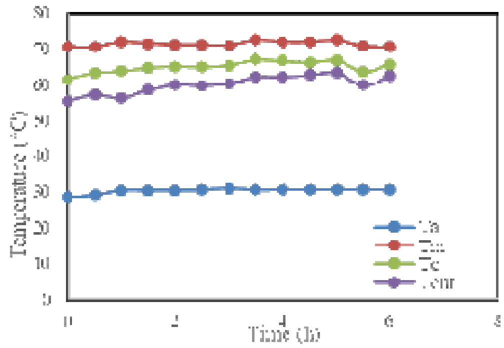

Figure 2. Temperature profiles of drying air and corn during the drying process in an LPG-fired single-cylinder rotary dryer at an air velocity of 7.9 m/s

Table 1. Temperature data from three experiments

Experiment	Time (hour)	T_a (°C)				T_{in} (°C)				T_c (°C)				T_{out} (°C)			
		1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
1	0	28.6	28.5	28.4	28.5	70.7	70.6	70.5	70.6	61.5	61.4	61.3	61.4	55.4	55.3	55.2	55.3
2	0.5	29.1	29	28.9	29	70.6	70.5	70.4	70.5	63.3	63.2	63.1	63.2	57.3	57.2	57.1	57.2
3	1	30.3	30.2	30.4	30.3	71.8	71.9	72	71.9	63.6	63.7	63.8	63.7	56.2	56.3	56.4	56.3
4	1.5	30.4	30.2	30.3	30.3	71.6	71.5	71.4	71.5	64.7	64.6	64.5	64.6	58.5	58.4	58.3	58.4
5	2	30.3	30.2	30.4	30.3	71.1	71	71.2	71.1	65	64.9	65.1	65	59.8	59.8	60.1	59.9
6	2.5	30.3	30.2	30.4	30.3	71.1	70.9	71.3	71.1	64.9	64.7	64.8	64.8	59.6	59.7	59.8	59.7
7	3	30.9	30.8	30.7	30.8	71.2	70.9	70.6	70.9	65.4	65.3	65.2	65.3	60.3	60.4	60.2	60.3
8	3.5	30.4	30.3	30.5	30.4	72.5	72.4	72.6	72.5	66.9	66.8	67	66.9	62.2	61.9	62.2	62.1
9	4	30.4	30.5	30.6	30.5	71.8	71.9	72	71.9	66.4	66.5	66.6	66.5	62.2	61.8	62.3	62.1
10	4.5	30.5	30.6	30.4	30.5	71.9	71.9	71.9	71.9	66.2	66	66.1	66.1	62.8	62.8	62.5	62.7
11	5	30.4	30.5	30.6	30.5	72.3	72.4	72.5	72.4	66.6	66.7	66.8	66.7	63.4	63.1	63.4	63.3
12	5.5	30.5	30.6	30.4	30.5	70.7	70.8	70.6	70.7	63.6	63.7	63.5	63.6	59.8	59.9	59.7	59.8
13	6	30.3	30.4	30.5	30.4	70.4	70.5	70.6	70.5	65.5	65.6	65.7	65.6	62.2	62.4	62.6	62.4
Mean		30.18	30.15	30.19	30.18	71.36	71.32	71.35	71.35	64.89	64.85	64.88	64.88	59.98	59.92	59.98	59.96
SD		0.622	0.659	0.701		0.674	0.705	0.784		1.554	1.565	1.650		2.572	2.524	2.617	

Uniform airflow distribution within the drying chamber, along with control of temperature and air velocity, is critical for maintaining stable heat and mass transfer during the drying process. Uneven air distribution can lead to temperature gradients within the material, thereby lowering the local thermal driving force, reducing the rate of moisture removal, and resulting in inconsistent product quality (Asrate and Ali, 2025). The temperature used to dry the shelled corn (T_c) increased gradually from an average of 61.3°C to approximately 67°C, yet remained lower than the inlet air temperature. This indicates that heat from the drying air was continuously transferred to the material, raising the corn's temperature while simultaneously supplying the latent heat required for the water evaporation process (Bergman et al., 2017; Defraeye, 2014). The average outlet air temperature (T_{out}) increased from 55.3°C to 63.3°C, while the ambient temperature (T_a) remained relatively constant, averaging between 28.5°C and 30.8°C. The rise in outlet air temperature indicates that the air still carried thermal energy after passing through the corn layer, whereas the stability of the ambient temperature suggests that temperature changes during drying were primarily influenced by the dryer's operating conditions. Overall, the temperature profile indicates that the drying process proceeds under stable thermal conditions, allowing for continuous heat and mass transfer throughout the process. The drying air temperature is the dominant factor influencing the thermal driving force. Increasing the temperature raises the thermal energy transferred to the material, thereby accelerating moisture diffusion, enhancing mass transfer, and speeding up the reduction of the moisture ratio during the drying process (Keshavarziyan et al., 2025).

The thermal driving force is calculated based on the temperature difference between the drying air and the shelled corn, as well as the temperature difference between the shelled corn and the exhaust air. Changes in these two parameters are used to evaluate heat transfer characteristics during the drying process. Based on the calculation results shown in figure 3, the value of ΔT_1 decreased from 9.2°C at the start of drying to 4.9°C at the end of drying.

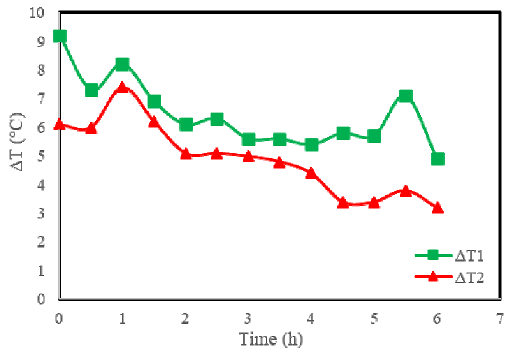

Figure 3. Variation of thermal driving force (ΔT_1 and ΔT_2) during corn drying in an LPG-fired single-cylinder rotary dryer at an air velocity of 7.9 m/s

This decrease indicates that the corn temperature is approaching the drying air temperature, thereby reducing the driving force for convective heat transfer. This condition suggests that the thermal energy transferred to the material tends to decrease as the corn's moisture content drops during the drying process. Meanwhile, the ΔT_2 value also decreased from 6.1°C to 3.2°C, indicating that the outlet air temperature is approaching the material temperature. This indicates that the temperature gradient within the drying chamber decreases and the heat transfer process proceeds with diminishing intensity. The reduction in ΔT_1 and ΔT_2 suggests that the heat transfer mechanism becomes less dominant during the final stage of drying; consequently, the rate of moisture removal is expected to slow down. Therefore, the relationship between changes in the thermal driving force and parameters such as the drying rate and moisture ratio, which serve as indicators of moisture removal, is further analyzed. The results shown in figure 3 indicate that the thermal driving force parameter can serve as a simple indicator to characterize changes in heat transfer during the drying of shelled corn and provide a basis for evaluating the relationship between heat transfer mechanisms and moisture removal. The moisture removal conditions are presented in figure 4.

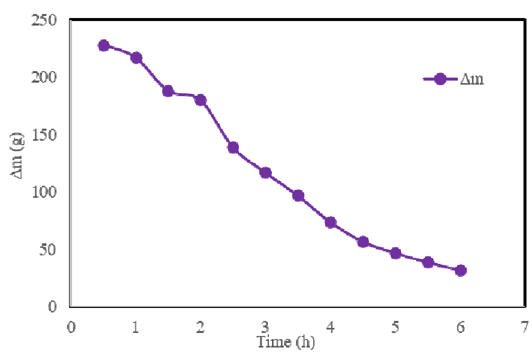

Figure 4. Mass loss as an indicator of moisture removal (Δm) during corn drying in an LPG-fired single-cylinder rotary dryer at an air velocity of 7.9 m/s

Figure 4 shows the average mass loss of shelled corn at each interval during the drying process. The average mass loss decreased gradually from 228 g at the start of drying to 32 g at the end of the process. This is also presented in table 2, which includes data from three experimental runs regarding the initial and final masses of the shelled corn. This trend indicates that moisture removal was most intense during the initial drying stage, when the free water content was high and thus more easily evaporated. As the moisture content decreased, the remaining moisture consisted predominantly of bound water, which requires more energy to diffuse to the surface, resulting in a progressively smaller amount of water being evaporated at each interval. The reduction in moisture removal aligns with the analysis of the thermal driving force; a smaller temperature difference between the drying air and the corn results in less thermal energy being available for evaporation. This condition diminishes the material's ability to release water during drying, causing the mass transfer process to slow down as drying progresses. The decrease in mass at each interval indicates a reduced moisture removal rate during convective drying.

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Table 2. Data on the mass and mass change of corn from three experiments

Experiment	Time (hour)	m_o (g)				m_t (g)				Δm (g)			
		1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
1	0	5000	5000	5000	5000	5000	5000	5000	5000	0	0	0	0
2	0.5	5000	5000	5000	5000	4773	4772	4771	4772	227	228	229	228
3	1	4773	4772	4771	4772	4555	4554	4556	4555	218	218	215	217
4	1.5	4555	4554	4556	4555	4368	4366	4367	4367	187	188	189	188
5	2	4368	4366	4367	4367	4187	4186	4188	4187	181	180	179	180
6	2.5	4187	4186	4188	4187	4048	4047	4049	4048	139	139	139	139
7	3	4048	4047	4049	4048	3932	3931	3930	3931	116	116	119	117
8	3.5	3932	3931	3930	3931	3834	3833	3835	3834	98	98	95	97
9	4	3834	3833	3835	3834	3759	3760	3761	3760	75	73	74	74
10	4.5	3759	3760	3761	3760	3703	3704	3702	3703	56	56	59	57
11	5	3703	3704	3702	3703	3655	3656	3657	3656	48	48	45	47
12	5.5	3655	3656	3657	3656	3617	3618	3616	3617	38	38	41	39
13	6	3617	3618	3616	3617	3584	3585	3586	3585	33	33	30	32
Mean		4,187.00	4,186.69	4,187.08	4,186.92	4,078.08	4,077.85	4,078.31	4,078.08	108.92	108.85	108.77	108.85
SD		505.622	505.197	505.321		466.926	466.300	466.444		75.568	75.784	75.663	

Figure 5 shows that the drying rate (DR) decreased gradually during the drying process, from an average of 456 g/h at the start of drying to 64 g/h at the end of the process. This decline indicates that moisture removal occurred most rapidly during the initial stage, when the free water content was high and thus easier to evaporate. As the moisture content decreased, the remaining moisture consisted predominantly of bound water, which required more time to diffuse to the surface, causing the drying rate to continue to fall.

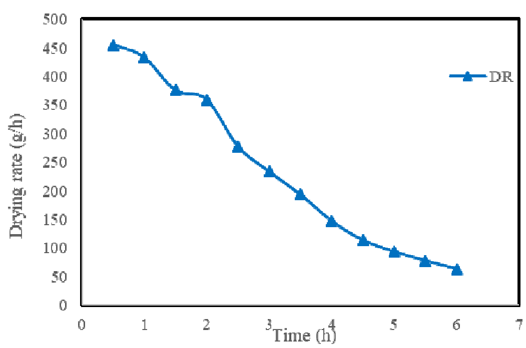


Figure 5. Variation of drying rate (DR) during corn drying in an LPG-fired single-cylinder rotary dryer at an air velocity of 7.9 m/s

The decrease in the drying rate corresponds to the reduction in the thermal driving force during the drying process. The smaller the temperature difference between the drying air and the material, the less thermal energy is available for evaporation, resulting in a reduced rate of moisture removal. This condition demonstrates that moisture release is influenced not only by the drying air temperature but also by moisture migration from the interior to the surface. These results indicate that heat and mass transfer occur simultaneously in determining the drying characteristics of shelled corn, consistent with Chen et al. (2026), who stated that the drying process is governed by the interaction between heat transfer, mass transfer, and moisture redistribution within porous materials.

Figure 6 presents the changes in the Moisture Ratio (MR) value during the drying process. The drying rate trend observed in figure 5 is also reflected in the changes in the Moisture Ratio (MR), which decreases gradually throughout the drying process. The decline in the MR value indicates that the moisture content relative to the initial state continues to decrease as a result of continuous moisture removal. A lower MR value signifies a reduction in the amount of water remaining within the shelled corn, meaning that mass transfer becomes increasingly governed by moisture diffusion from the interior to the surface. Thus, the change in Moisture Ratio confirms that the reduction in thermal driving force and drying rate during drying contributes to the material's diminishing ability to release water as the process nears completion. Figure 6 shows that the Moisture Ratio (MR) decreases gradually from 1.00 at the start of drying to 0.398 at the end of the process.

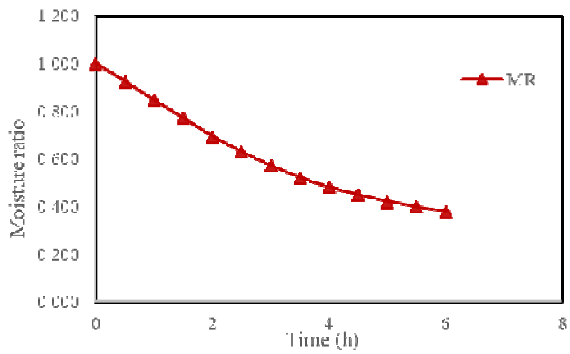


Figure 6. Changes in moisture ratio during corn drying in an LPG-fired single-cylinder rotary dryer

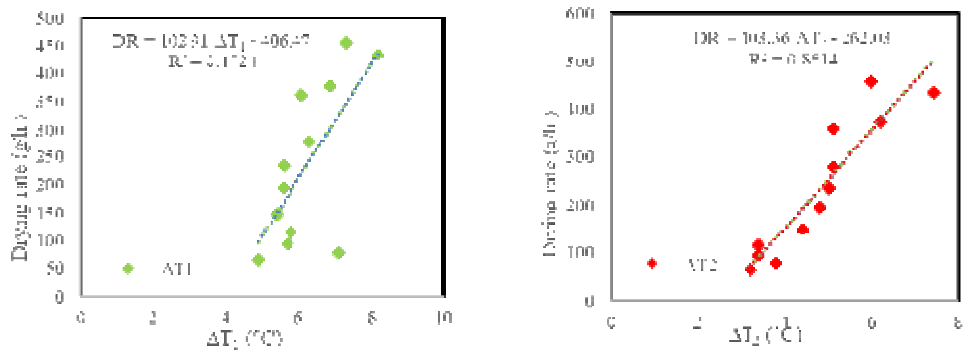
The decrease in MR indicates that the moisture content relative to the initial state continues to decline during drying, reflecting a continuous moisture removal process. The decline in MR is relatively rapid during the initial stage because the evaporation of free water dominates the drying process. Subsequently, the MR value decreases more slowly due to increasing resistance to moisture diffusion from the interior of the seed to the surface. This condition indicates a shift in the mass transfer mechanism from surface evaporation dominance to internal moisture diffusion, a characteristic common to the drying of porous materials. The decrease in MR is also consistent with the analysis of the thermal driving force and drying rate; the reduced temperature difference between the drying air and the material results in less energy available for evaporation, thereby causing the moisture removal rate to decline, as presented in table 3, which contains data for each of the three replicates. This relationship demonstrates that heat and mass transfer occur simultaneously in determining the drying characteristics of shelled corn.

Table 3. Data on thermal driving force, drying rate, and moisture ratio for three replicates

Experiment	Time (hour)	Drying Rate, DR (g/h)				ΔT1 (°C)				ΔT2 (°C)				Moisture Ratio, MR			
		1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
1	0	0	0	0	0	9.2	9.2	9.2	9.2	6.1	6.1	6.1	6.1	1.000	1.000	1.000	1.000
2	0.5	0.454	0.456	0.458	0.456	7.3	7.3	7.3	7.3	6	6	6	6	1.000	1.000	1.000	1.000
3	1	0.436	0.436	0.43	0.434	8.2	8.2	8.2	8.2	7.4	7.4	7.4	7.4	0.925	0.925	0.924	0.925
4	1.5	0.374	0.376	0.378	0.376	6.9	6.9	6.9	6.9	6.2	6.2	6.2	6.2	0.846	0.846	0.847	0.846
5	2	0.362	0.36	0.358	0.36	6.1	6.1	6.1	6.1	5.2	5.1	5	5.1	0.772	0.771	0.772	0.772
6	2.5	0.278	0.278	0.278	0.278	6.2	6.2	6.5	6.3	5.3	5	5	5.1	0.694	0.694	0.695	0.694
7	3	0.232	0.232	0.238	0.234	5.8	5.6	5.4	5.6	5.1	4.9	5	5	0.630	0.630	0.630	0.630
8	3.5	0.196	0.196	0.19	0.194	5.6	5.6	5.6	5.6	4.7	4.9	4.8	4.8	0.573	0.572	0.572	0.572
9	4	0.15	0.146	0.148	0.148	5.4	5.4	5.4	5.4	4.2	4.7	4.3	4.4	0.522	0.521	0.522	0.522
10	4.5	0.112	0.112	0.118	0.114	5.7	5.9	5.8	5.8	3.4	3.2	3.6	3.4	0.481	0.481	0.482	0.481
11	5	0.096	0.096	0.09	0.094	5.7	5.7	5.7	5.7	3.2	3.6	3.4	3.4	0.449	0.450	0.448	0.449
12	5.5	0.076	0.076	0.082	0.078	7.1	7.1	7.1	7.1	3.8	3.8	3.8	3.8	0.421	0.422	0.422	0.422
13	6	0.066	0.066	0.06	0.064	4.9	4.9	4.9	4.9	3.3	3.2	3.1	3.2	0.398	0.399	0.398	0.398
Mean		0.22	0.22	0.22	0.22	6.47	6.47	6.47	6.47	4.92	4.93	4.90	4.92	0.67	0.67	0.67	0.67
SD		0.151	0.152	0.151		1.222	1.224	1.239		1.301	1.270	1.271		0.220	0.219	0.219	

After analyzing the changes in thermal driving force, drying rate, and moisture ratio during the drying process, the relationship between thermal driving force and moisture removal characteristics was evaluated using simple linear regression. The analysis was conducted on three sets of experimental data, which were then averaged for each drying time point. Thermal driving force was expressed as ΔT_1 and ΔT_2, while the drying rate (DR) served as the dependent variable. Regression parameters were calculated using Microsoft Excel based on the general equation DR = a + bΔT, where DR is the drying rate (g/h), ΔT is the thermal driving force (°C), a is the intercept (constant), and b is the regression coefficient (slope); the results are presented in Figure 7. Based on figure 7(a), the regression equation is DR = 102.91 ΔT_1 - 406.47, with a coefficient of determination (R^2) of 0.4724. This value indicates a relatively weak linear relationship between ΔT_1 and DR, implying that changes in

ΔT_1 do not account for the majority of the variation in the drying rate. Nevertheless, the positive regression coefficient suggests a trend where an increase in the thermal driving force is accompanied by an increase in DR. Physically, this condition is associated with the increased thermal energy available for water evaporation at the material surface. This trend is consistent with the studies of Nowacka et al. (2024), Poós and Varju (2024), and Arpaci et al. (2025), which highlight the significance of temperature difference regarding heat and mass transfer intensity during convective drying.



(a) (b)

Figure 7. The relationship between thermal driving force and drying rate, (a) the temperature difference between the incoming air and the drying room against the drying rate (ΔT_1) and (b) the temperature difference between the drying room and the outgoing air against the drying rate (ΔT_2)

Figure 7(b) illustrates the relationship between the drying rate and the temperature difference between the material and the dryer's exhaust air (ΔT_2). The resulting regression equation is DR = 103.36ΔT_2 - 262.03, with a coefficient of determination (R^2) of 0.8614. The higher R^2 value indicates that ΔT_2 has a stronger linear relationship with the drying rate compared to ΔT_1. Thus, under the experimental conditions employed, ΔT_2 is more representative of changes in the drying rate. However, this R^2 value does not imply that the entire drying mechanism is governed solely by ΔT_2, as the moisture removal process is also influenced by internal moisture migration, airflow distribution, and material characteristics. This aligns with the concept of coupled heat and mass transfer in porous materials (Defraeye, 2014; Chen et al., 2026). Residual analysis was conducted by averaging data from the three experimental sets at each time interval to determine the mean drying rate. Subsequently, linear regression and residual analysis were performed using ΔT_1 and ΔT_2 as the thermal driving forces. The relationship between the drying rate and ΔT_1 was relatively weak ($R^2 = 0.4724$) and exhibited several significant residuals. In contrast, ΔT_2 demonstrated a stronger relationship with the mean drying rate ($R^2 = 0.8614$) and a lower Root Mean Square Error (RMSE) 50.80 g/h versus 99.11 g/h for ΔT_1. Residuals for the ΔT_2 based model were generally closer to zero; therefore, simple linear regression using ΔT_2 is considered more adequate for representing the experimental drying rate data. To verify the adequacy of the linear models, a residual analysis was performed on three averaged datasets. Residuals were calculated as the difference between the experimental drying rate (DR) and the DR predicted by the regression. The results showed that the ΔT_1 model had an RMSE of 99.11 g/h, whereas the ΔT_2 model yielded a lower RMSE of 50.80 g/h. Furthermore, the residuals for the ΔT_2 model were generally closer to zero than those for the ΔT_1 model. These results indicate that the linear regression based on ΔT_2 provides a better representation of the experimental drying rate data. Consequently, ΔT_2 was selected as the more representative thermal driving force for analyzing the linear relationship with the DR under the conditions of this study.

Overall, the results indicate a positive relationship between the thermal driving force and the drying rate, with ΔT_2 offering greater explanatory power than ΔT_1. However, the decline in the drying rate during the process is not solely determined by changes in the thermal driving force; it is also linked to reduced moisture content and increased internal mass transfer resistance. Therefore, the interplay between heat and mass transfer must be considered simultaneously to explain the drying characteristics of shelled corn in an LPG-fired single-cylinder rotary dryer. These findings align with those of Baidhe et al. (2025) and Yan et al. (2026) regarding the interrelationship among heat supply, internal moisture migration, and evaporation during the drying of agricultural products.

4. CONCLUSION

Based on the research results, it can be concluded that drying shelled corn using a single-cylinder rotary dryer fueled by LPG occurs under stable thermal conditions, with an inlet air temperature ranging from 70.5-

72.5°C. These conditions produce a thermal driving force that maintains heat and mass transfer processes during drying. As drying time increases, moisture removal, drying rate, moisture ratio, and dry base water content decrease gradually as a result of decreasing free water content and increasing resistance to moisture diffusion within the material. Regression analysis shows that thermal driving force has a positive relationship with drying rate. The relationship between ΔT_1 and the drying rate yielded the equation DR = 102.91ΔT_1 – 406.47 (R^2 = 0.4724), whereas the relationship between ΔT_2 and the drying rate yielded the equation DR = 103.36ΔT_2 – 262.03 (R^2 = 0.8614). The higher coefficient of determination for ΔT_2 indicates that the temperature difference between the material and the exhaust air serves as a more representative thermal driving force parameter for explaining heat and mass transfer characteristics during the drying of shelled corn. These results demonstrate that evaluating the thermal driving force specifically ΔT_2 can serve as an effective indicator for assessing drying characteristics and provide a basis for optimizing rotary dryer performance in the shelled corn drying proces.

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REFERENCES

Arpaci, E., Atayılmaz, S.O., Gemici, Z., Exploring mathematical modeling and CFD in convective drying of fruits and vegetables: A review, Food and Bioprocess Technology, 18, 3195-3222, 2025.

Asrate, D.A., Ali, A.N., Review on the recent trends of food dryer technologies and optimization methods of drying parameters, Applied Food Research, 5(1), 100927, 2025.

Baidhe, E., Clementson, C.L., Hellevang, K., Zhulu, L., Comprehensive analysis of drying kinetics, heat and mass transfer, and thermodynamic properties in high-temperature drying of high-moisture corn, Journal of Food Process Engineering, 48, e70159, 2025.

Bergman, T.L., Lavine, A.S., Incropera, F.P., DeWitt, D.P., Fundamentals of Heat and Mass Transfer, 8th ed., John Wiley & Sons, New York, 2017.

Bhattacharjee, S., Mohanty, P., Sahu, J.K., Sahu, J.N., A critical review on drying of food materials: Recent progress and key challenges, International Communications in Heat and Mass Transfer, 158, 107863, 2024.

Brooker, D.B., Bakker-Arkema, F.W. Hall, C.W., Drying and Storage of Grain and Oilseeds, 4th ed., Van Nostrad, 1992.

Celik, E., Parlak, N., Meral, Z.K., Cay, Y., Experimental investigation of convective drying behavior of in-shell hazelnuts: moisture diffusivity, transport phenomena, and pressure drop, Heat Mass Transfer, 62, 99, 2026.

Cengel, Y.A., Ghajar, A.J., Heat and mass transfer: Fundamentals and Applications, 6th ed., McGraw-Hill, New York, 2020.

Chen, S., Qin, Z., Wang, T., Zhang, J., Zhang, R., Zou, Y., Shi, J., Modeling and simulation of mass transfer in food processing: recent advances in governing equations, workflow, and applications, Foods, 15(12),2084, 2026.

Defraeye, T., Advanced computational modelling for drying processes - A review, Applied Energy, 131, 323–344, 2014.

Doymaz, I., Convective air drying characteristics of thin layer carrots, Journal of Food Engineering, 61(3), 359-364, 2004.

Ge, M., Chen, G., Liu, W, Liu, C., Study of heat and mass transfer during drying process of maize grain pile based on computed tomography, Biosystems Engineering, 248, 82-96, 2024.

He, J., Song, W., Li, J., Ding, T., Guan, J., Wu, J., Wang, J., Study on a moisture ratio curve model for refractance window drying based on a d-optimal mixture design, Journal of Food Quality, 1, 8604374, 2024.

Keshavarziyan, F., Mirzaei, H., Firouz, M.S., Mahonak, A.S., Khanali, M., Shamsabadi, H.A.T., Optimization and analysis of heat and mass transfer parameters during hot air frying of chicken fillet, Applied Food Research, 5(1), 100818, 2025.

Kilic, M., Sahin, M., Hassan, A., Ullah, A., Preservation of fruits through drying—A comprehensive review of experiments and modeling approaches, Journal of Food Process Engineering, 47(3), e14568, 2024.

Midilli, A., Kucuk, H., Yapar, Z., A new model for single-layer drying, Drying Technology, 20(7), 1503-1513, 2002.

Mihret, Y.K., Hailemesikel, S.T., Alemu, A.G., Delele, M.A., Modeling the drying kinetics, performance evaluation, and economic analysis of rice drying using a rice husk-fueled mixed-flow dryer, Energy Conversion and Management: X, 24, 100774, 2024.

Montgomery, D.C., Peck, E.A., Vining, G.G., Introduction to linear regression analysis, 6th ed., John Wiley & Sons, 2021.

Mujumdar, A.S., Handbook of industrial drying, 4th ed., CRC Press, Taylor & Francis Group, New York, 2014.

Nowacka, M., Matys, A., Witrowa-Rajchert, D., Innovative technologies for improving the sustainability of the food drying industry, Current Food Science and Technology Reports, 2, 231-239, 2024.

Poos, T., Varju, E., Review for convection based evaporation of open liquid surface and equations of evaporation rate, International Communications in Heat and Mass Transfer, 157, 107755, 2024.

Ramachandran, R.P., Nadimi, M., Cenkowski, S., Paliwal, J., Advancement and innovations in drying of biopharmaceuticals, nutraceuticals, and functional foods, Food Engineering Reviews, 16, 540–566, 2024.

Singh, R.P., Heldman, D.R., Introduction to Food Engineering, 5th ed., Academic Press, 2014.

Susana, I G.B., Alit, I.B., Okariawan, I D.K., Rice husk energy rotary dryer experiment for improved solar drying thermal performance on cherry coffee, Case Studies in Thermal Engineering, 41, 102616, 2023.

Yan, Y., Ding, T., Wang, J., Chen, X., Xu, J., Research progress regarding heat and mass transfer characteristics of agricultural products under different drying methods, and associated applications: A review, Foods, 15(14), 2530, 2026.

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