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Abstract

To overcome mass-transfer bottlenecks, such as case hardening, in traditional grain dehydration, this study systematically investigated the drying kinetics and thermodynamic mechanisms of Indica rice subjected to hot-air drying (HAD) and microwave drying (MD). Dehydration experiments were conducted across various operating parameters, fitted to thin-layer kinetic models, and evaluated for effective moisture diffusivity (D_{eff}) and activation energy (E_a). The results demonstrated that the Midilli *et al.*'s model best predicted the drying behavior ($R^2 > 0.99$). The volumetric heating inherent to microwave drying alleviated case-hardening-like resistance by inducing internal vapor pressure-driven moisture migration. To balance high dehydration efficiency with the prevention of thermal damage, a power level of 350 W and a loading mass of 40 g were identified as the optimal microwave drying conditions. Thermodynamically, HAD exhibited a V-shaped E_a trend (30.05, 15.18, and 37.63 kJ/mol) with increasing loading mass, driven by the competing effects of case hardening and macroscopic physical resistance.

Conversely, MD displayed a monotonic decrease in E_a (from 35.21 to 17.04 kJ/mol), reflecting a transition toward internal pressure-driven mass transfer. Notably, MD drastically reduced the equivalent activation energy to 7.95 W/g. Under the optimal conditions (350 W, 40 g), MD reduced drying time by approximately 87.5–90.0%, increased D_{eff} by about one order of magnitude, and achieved a higher drying-rate constant compared to HAD. In conclusion, dielectric heating effectively bypasses conventional thermal barriers, offering a thermodynamically superior and highly efficient pathway for quality-preserving industrial grain processing.

Key words: Drying kinetics; effective moisture diffusivity; hot-air drying; Indica rice; microwave drying.

Introduction

As one of the most consumed staple foods in the world, rice's post-harvest processing and safe storage are directly related to food security and economic benefits. At present, China's annual rice production is as high as 28.513 million tons (National Bureau of Statistics, 2025), but due to the failure to dry it in a timely manner after production, the annual grain loss exceeds 5% of the total production. Therefore, drying is not only considered the best method for preserving fruits, vegetables, and herbs, but also an effective way to reduce the risk of mold (Calín-Sánchez *et al.*, 2020; Hii *et al.*, 2021; Huang and Zhang, 2016; Sağlam and Çetin, 2022; Shewale *et al.*, 2019) and is the key to ensuring the quality of Indica rice (Duan *et al.*, 2023) processing. As a staple food for over half of the world's population, Indica rice is characterized by its long-grain structure and high starch content, which render it exclusively sensitive to thermal treatment compared to other cereal grains. The hot-air drying is mature and widely used, but its heat transfer and moisture migration occur in opposite directions, resulting in high internal mass transfer resistance (Lewicki, 2006). There are shortcomings such as long drying cycles and high energy consumption. Microwave drying relies on dielectric heating mechanism, and electromagnetic energy directly acts on polar water molecules inside the material, forming a driving force in the same direction as the water gradient, which can achieve rapid water escape. However, there is currently no systematic quantitative demonstration of the advantages and disadvantages of two drying methods for Indica rice materials in terms of macroscopic characteristics, microscopic kinetics, and energy consumption.

In the domain of traditional hot-air drying, existing studies have primarily focused on the superficial analysis of macroscopic process parameters and single-physical-field modeling. For

instance, Xia *et al.* (2023) and Li *et al.* (2021) conducted single-factor and response surface methodology optimization experiments for the hot-air drying of *Cyperus esculentus* and *Gastrodia elata*, respectively, focusing on the macroscopic effects of temperature on apparent drying rates. However, they lacked a global evaluation of various thin-layer kinetic models. Ling compared the effects of microwave and hot-air drying on moisture content and water activity of rice (Ling and Sun, 2021), but did not analyze the dynamic model and effective moisture diffusivity of hot-air drying. Although the kinetic model was established, the effect of parameter interaction on effective moisture diffusivity was not involved. Researcher (Okunola *et al.*, 2023) advanced this by conducting kinetic modeling and calculating the effective moisture diffusivity (D_{eff}) for water yam during hot-air drying. Nonetheless, these pure hot-air drying studies largely treated drying as a conventional macroscopic heat and moisture exchange process.

In recent years, microwave drying and its combination technology have attracted extensive attention due to their highly efficient dehydration characteristics. For example, already explored (Shen *et al.*, 2020; Huang *et al.*, 2020) the microwave vacuum drying characteristics of germinated brown rice and camellia oleifera seeds, but their work mainly focused on single field simulation or batch process optimization. In addition, Sharma and Prasad (2001) and An *et al.* (2024) studied the microwave hot air combined drying and confirmed its significant effect in shortening the drying time, but the mechanical difference between convective heat transfer and dielectric energy conversion is masked by the highly coupled characteristics of the physical field in the combined drying. In addition, Ling and Sun (2021) made a preliminary parallel comparison of microwave and hot-air drying of rice and observed the changes of water activity and temperature distribution, but their research lacked a thin-layer kinetic model for mathematical prediction and the calculation and analysis of effective moisture diffusivity and activation energy. Azimi-Nejadian *et al.* (2019) further measured the effective moisture diffusivity under different microwave power and thickness and calculated the specific activation energy exclusive to microwave for potato chips. Recent post-harvest engineering studies have emphasized the integrated control of energy delivery, product quality, process monitoring, and industrial applicability. These developments indicate that rice drying should be evaluated not only by dehydration efficiency but also by its underlying heat and mass transfer characteristics (Gana Yisa *et al.*, 2017; Fadeyibi, 2023; Fadeyibi *et al.*, 2025a, 2025b).

Although microwave and hot-air drying of rice have been investigated in previous studies, most available work has focused mainly on drying curves, water activity, temperature distribution, or single-process optimization. Limited attention has been paid to a combined comparison of thin-layer drying models, effective moisture diffusivity, and activation-energy characteristics under controlled loading conditions. Therefore, the novelty of this study lies in quantitatively comparing

microwave and hot-air drying of Indica rice from three linked perspectives: drying kinetics, apparent moisture diffusion, and thermodynamic sensitivity. This work clarifies how different energy-input pathways, namely surface convective heating and microwave volumetric heating, affect moisture migration and drying efficiency, and provides a theoretical basis for process optimization of Indica rice drying.

Materials and Methods

Experimental sample

The rice sample used in this study was commercially packaged Indica rice purchased from a local supermarket. The sample was selected as a representative retail rice product for drying experiments, as shown in Figure 1. Indica rice is generally characterized by a long and slender grain shape, relatively high amylose content, which may influence its moisture migration behavior and thermal response during drying.

Before the experiment, the materials were manually sorted to remove broken, immature grains and impurities. To characterize the physical dimensions of the experimental material, 30 intact grains were randomly selected and measured using a digital vernier caliper. The average grain length, width, and thickness were 6.85 ± 0.32 mm, 2.35 ± 0.14 mm, and 1.45 ± 0.09 mm, respectively. The initial moisture content of the material was determined according to the national standard GB/T 5009.3-2016 using the 105°C constant weight method at atmospheric pressure. A 10 g sample of the material was placed in an aluminum box and dried to a constant weight. The measured initial moisture content of the experimental material was 12.8%. Target moisture content was adjusted to 24% by sample wetting. Before the experiment, take out the sample and restore it to room temperature.

The amount of water required for moisture adjustment was calculated using the following equation:

$$M = \frac{m_0(x_1 - x_0)}{1 - x_1} \quad (\text{Eq. 1})$$

where M is the mass of added water (g); m_0 is the initial mass of the rice sample to be conditioned (g); x_0 is the initial moisture content of the rice sample on a wet basis; and x_1 is the target moisture content on a wet basis.

After the calculated amount of distilled water was uniformly sprayed onto the rice sample, the moistened sample was sealed in polyethylene zip-lock bags and equilibrated at 4°C for 24 h. During equilibration, the bags were manually turned every 8 h to promote uniform moisture distribution. And then sealed and stored in a constant-temperature refrigerator at 4°C for later use, in order to ensure the consistency of the initial state of the experimental samples.

Experimental equipment

As shown in Figure 2, the main experimental equipment included the Galanz G90F25YeSXLV-ADG0 microwave drying experimental station, the Mingyue MY-382 electric thermostatic drying oven used for laboratory hot-air drying, the Delixi Electric LCD electronic analytical balance, and the LDS-1G capacitive grain moisture meter.

Experimental design

To optimize drying efficiency and paddy quality, reasonable experimental parameters were determined in this study. As a heat-sensitive cereal material, paddy is prone to internal stress and grain cracking under excessive drying temperature, which seriously deteriorates rice quality, while an excessively low temperature will prolong the drying duration and reduce processing efficiency; hence, a temperature range of 45–55°C was selected to balance drying efficiency and product quality. The hot-air drying temperatures of 45, 50, and 55°C were selected as a mild temperature range for quality-oriented paddy drying. Similar mild drying temperatures have been used in rough rice or paddy drying studies when grain quality was considered; for example, Luthra *et al.* (2021) investigated rough rice drying at 40–50°C, and Xu *et al.* (2022) used 50°C as a constant-temperature hot-air drying control for paddy rice. Although higher temperatures, such as 70°C, are also used in grain drying optimization studies (Namjoo *et al.*, 2024), excessive drying temperature may increase thermal stress, fissure formation, head rice yield reduction, and undesirable changes in rice quality (Soponronnarit *et al.*, 2001; Xu *et al.*, 2022). Therefore, the present study focused on 45–55°C to compare hot-air drying with microwave drying under conservative thermal conditions. Higher-temperature hot-air drying should be further evaluated in future studies together with direct quality indicators such as fissure percentage, head rice yield, color, starch properties, and cooking quality.

The microwave powers of 200, 350, and 550 W were selected according to the stable output settings of the microwave apparatus and to represent low, medium, and high microwave energy input levels, rather than to form equal numerical intervals. Specifically, 200 W was used as the low-power baseline, 350 W as the intermediate process level, and 550 W as the high-power level for evaluating rapid dehydration and potential non-uniform heating risk. This selection was based on previous microwave drying studies on rice and paddy materials. Keshavalu *et al.* (2017) investigated parboiled paddy drying at 180, 360, 540, and 720 W, while Ling and Sun (2021) used 400 W microwave drying in a rice drying study. In addition, Silva *et al.* (2021) reported that increasing microwave power density accelerated the drying of paddy rice grains, but excessive power input could cause undesirable grain discoloration. Therefore, the selected power levels

in the present study were intended to cover a practical low-to-high power range while avoiding unnecessarily severe microwave heating.

In addition, sample loading capacity exerts distinct effects on two drying methods: it alters the microwave energy density per unit mass during microwave drying and changes the hot-air penetration resistance as well as heat and mass transfer area during hot-air drying, and thus three loading capacity gradients of 20 g, 40 g, and 60 g were adopted to further explore the comprehensive variations in heat and mass transfer, moisture migration uniformity and drying rate. In the microwave, experimental design, in order to explore the effect of initial temperature, some samples were preheated to 45°C, 50°C, 55°C in the sealed state, and then immediately dried by microwave; the experiments to explore the power and loading capacity were carried out at room temperature. The experimental flowchart is shown in Figure 3.

Figure 3 shows the schematic diagram of the experimental process. Each treatment condition was conducted once as an independent drying run; therefore, the reported results represent single-run observations under the specified drying conditions rather than replicated mean values. An intermittent weighing method was used to determine mass changes during drying. For hot-air drying, the sample mass was recorded every 10 min, whereas for microwave drying, owing to its higher dehydration intensity, the sample mass was recorded every 0.5 min. To reduce potential experimental error, all drying runs were performed using the same sample preparation procedure, vessel geometry, sample spreading method, and weighing protocol. Before each run, the hot-air oven was preheated and stabilized at the target temperature, the microwave oven was set to the target power level, and the electronic balance with an accuracy of 0.001 g was calibrated. The order of treatment runs was randomized within each experimental group to minimize possible effects of sample preparation order, ambient fluctuations, and instrument drift. During intermittent weighing, each measurement was completed within 10 s to reduce heat loss and moisture exchange with the surrounding air. The same operator and measurement procedure were used throughout the experiment to maintain procedural consistency. Based on the recorded real-time mass data, the moisture ratio (*MR*) and drying rate (*DR*) were calculated to characterize the drying kinetics. The effective moisture diffusivity was then determined by applying Fick's second law of diffusion. Furthermore, activation energy and equivalent energy barriers were quantified using Arrhenius-type equations to evaluate the thermodynamic sensitivity and energy requirement of moisture migration under different drying conditions.

Indicator measurement and calculation

During the drying process of rice grains, a time gradient is set, and samples are taken out to measure their mass at the end of each drying session. Referring to GB/T14095-2007 the direct

drying method is used to determine the moisture content of rice grains, and the dry basis moisture content at any given moment is calculated according to Eq. (1):

$$MC_{db} = \frac{m_t - m_d}{m_d} \times 100\% \quad (\text{Eq. 2})$$

$$MC_{db} = \frac{m_t - m_d}{m_d} \times 100\% \quad (\text{Eq. 3})$$

where MC_{db} is the moisture content on a dry basis at time (t); m_t is the total mass of the sample at time (t); m_d is the mass of dry matter in the sample.

The drying rate of paddy refers to the change in the dry basis moisture content of paddy per unit time. The calculation equation for the drying rate of paddy is (2):

$$DR = \frac{M_{t_1} - M_{t_2}}{t_2 - t_1} \quad (\text{Eq. 4})$$

where DR is the drying rate; M_{t_1} and M_{t_2} are the moisture content on a dry basis at times t_1 and t_2 , respectively; t_1 and t_2 are the times of adjacent sampling.

The equation for calculating the moisture ratio during microwave drying of paddy is shown in equation (Dalvand *et al.*, 2014; Benseddik *et al.*, 2019) (3):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (\text{Eq. 5})$$

Due to continuous microwave or hot air heating, M_e of Indica rice is extremely small compared to M_0 and M_t . Therefore, it can be reasonably neglected, simplifying the equation to:

$$MR = \frac{M_t}{M_0} \quad (\text{Eq. 6})$$

where MR is the moisture ratio of rice; M_t is the dry basis moisture content of rice at time t ; M_0 is the initial dry basis moisture content of rice.

Mathematical model and evaluation indicators of drying kinetics

To ensure the model's fitting accuracy and reliability for experimental data, this study conducts a comprehensive evaluation using three statistical indicators: the correlation coefficient (R^2), chi-square (χ^2), and root mean square error (RMSE). By collaboratively assessing multiple indicators, the model that best matches the microwave and hot-air drying characteristics of Indica rice is selected, capable of depicting the “dry-basis moisture content-drying rate” response features of the two drying methods. This provides a reliable kinetic basis for subsequent calculations of rate constants, effective moisture diffusivity, and activation energy and other drying process parameters. Among these, a larger correlation coefficient and smaller χ^2 and RMSE indicate higher

accuracy and stability of the drying model fitting. The equations for calculating each indicator are shown in Eqs. 7 to 9:

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2}{\sum_{i=1}^N (\overline{MR}_{\text{exp}} - MR_{\text{pre},i})^2} \quad (\text{Eq. 7})$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2}{N - n} \quad (\text{Eq. 8})$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2} \quad (\text{Eq. 9})$$

where $MR_{\text{exp},i}$ is the experimental moisture ratio MR value of the i -th data point; $MR_{\text{pre},i}$ is the predicted moisture ratio MR value of the i -th data point; $\overline{MR}_{\text{exp}}$ is the average experimental moisture ratio MR value; N is the number of experimental data points; n is the number of parameters in the mathematical model.

Results

Analysis of microwave drying characteristics

Effect of initial temperature on microwave drying

To evaluate the effect of different initial temperatures on microwave drying kinetics, the samples were pre-treated to three temperatures: 45, 50, and 55°C, and dried at a power of 200 W under different loading conditions. Calculate the moisture content and drying rate curves from equations (2) to (4), as shown in Figures 4 and 5.

The moisture ratio curves in Figure 4 generally follow an exponential decline. When the loading capacity is fixed, raising the initial temperature clearly accelerates the dehydration process. This occurs because the extra initial sensible heat shortens the preliminary heating time, allowing microwave energy to convert into latent heat much earlier. However, as the sample mass increases from 20 g to 60 g, the drying duration extends and the MR curves become noticeably flatter. The underlying reason is the drop in specific microwave power density (W g^{-1}), which weakens both the volumetric heating effect and the internal vapor pressure gradient. Yet, at heavier loads (40 g and 60 g), the MR curves for different temperatures begin to overlap. Under these thicker bed conditions, the severe energy bottleneck and the uneven distribution of electromagnetic waves completely offset the thermodynamic benefits of a higher starting temperature.

Figure 5 shows that the microwave drying process is dominated by the falling rate period. However, under high loading capacity or low power (such as 60 g, 200 W), due to the need to

absorb more sensible heat for the overall temperature rise of the material, there will be a short acceleration rate period in the initial stage. At high moisture content, the increased initial temperature generates significantly higher peak drying rates by rapidly establishing a strong internal vapor pressure gradient. However, due to the insufficient power density mentioned above, increasing the sample mass will greatly suppress this peak rate. In addition, the drying rate curve converges during the low moisture stage at the end. With the depletion of free water, the removal of bound water requires higher activation energy, and the decrease in dielectric constant of the material will weaken microwave absorption. In the end, this dominant internal mass transfer resistance completely overwhelmed any initial thermal advantage.

Effect of microwave power on microwave drying

In order to clarify the effect of microwave power on drying kinetics, experiments with different loads were carried out at 200 W, 350 W and 550 W, as shown in Figure 6 and Figure 7.

According to the curves in Figure 6, microwave power inversely affects drying time at a constant load. For a 20 g sample dried for 4 min, the *MR* reaches 0.2439 at 550 W, compared to a much higher 0.503 at 200 W (a 2.06-fold difference). Furthermore, heavier loading capacities typically reduce the overall dehydration rate at fixed power levels. This is evident in the 200 W treatments, where the 8-min *MR* increase from 0.1856 to 0.2721 and 0.3404 as the load increases from 20 g to 60 g. Yet, the 550 W treatment almost eliminates this load-induced delay. By the 4th minute, the *MR* for the 20, 40, and 60 g groups converge to 0.2439, 0.2399, and 0.2429, respectively. These closely clustered data points suggest that elevated microwave power compensates for the mass transfer resistance of thicker material beds. Among them, the 40 g group shows a slight edge in performance, implying an optimal match between material mass and microwave energy absorption.

Figure 7 indicates microwave power as a crucial determinant of the drying rate. At a fixed load, higher power input produced a taller peak rate, indicating that increased energy input enhanced the evaporative driving force. The dehydration process displays a clear two-stage behavior. In the early phase, the alternating electric field rapidly heats the abundant free water in the rice, generating a steep vapor pressure gradient that quickly drives moisture out and creates the peak rate. As free water diminishes, the matrix strongly retains the bound water, increasing mass transfer resistance and triggering a falling rate period. Under constant power, increasing the sample mass generally slows dehydration and shifts the peak later in time. At 550 W, the 20 g and 40 g batches achieved maximum rates of 0.1038 and 0.0926, respectively, during the first minute. Conversely, the thicker material layer of the 60 g batch slowed heat distribution, pushing its peak rate (0.0872) into the second minute. Although 550 W offers the fastest water removal,

it simultaneously creates violent internal vapor pressure and localized overheating. This excessive energy input not only lowers the overall energy efficiency but also risks severe structural damage like kernel fissuring.

Analysis of hot-air drying characteristics

Based on the hot-air drying characteristics of Indica rice, this paper conducted experiments with different hot air temperatures and loading capacities. The scatter plots of the variation relationships are shown in Figures 8 and 9.

As illustrated in Figure 8, as the hot air temperature rises from 45°C to 55°C, the slope of the curve steepens, leading to a substantial enhancement in dehydration efficiency. This improvement can be attributed to the intensified thermal motion of water molecules at elevated temperatures, which increases the partial pressure gradient between the interior and surface water vapor within Indica rice grains, thereby providing a stronger driving force for diffusion. Under a low loading capacity of 20 g, the 50°C treatment yielded a marginally superior final dehydration effect compared to the 55°C treatment. This kinetic lag can be ascribed to the reverse gradient inherent in conventional hot-air drying, wherein heat transfer and moisture migration occur in opposing directions. At 55°C, the faster surface moisture removal may have increased the external mass-transfer resistance during the later drying stage. This phenomenon may be associated with case-hardening-like behavior, but it was inferred only from the drying curves and drying-rate curves rather than directly confirmed by microstructural observation, hardness measurement, or internal moisture profile analysis. Therefore, the term case hardening is used here only as a possible explanation for the observed kinetic trend. A horizontal comparison reveals that an increase in loading capacity markedly decelerates the entire drying process. For instance, when dried at a conventional temperature of 45°C for 60 min, the moisture ratios of the 20 g, 40 g, and 60 g treatment groups are recorded as 0.2524, 0.2929, and 0.3646, respectively, demonstrating a characteristic mass transfer resistance effect.

As illustrated in Figure 9, the hot-air drying rate of Indica rice is influenced by both temperature and loading capacity, with the falling rate period predominating throughout the entire process. Increasing the temperature can enhance the initial drying rate. Specifically, at a loading capacity of 20 g, the maximum drying rate rises from 0.0057 to 0.0096 when the temperature is elevated from 45°C to 50°C. Nevertheless, at 55°C, the surface layer of the material hardens, leading to only a marginal increase in the rate to 0.0098 (Imaizumi *et al.*, 2015). A comparative analysis reveals that a higher loading capacity results in a thicker material layer and increased mass transfer resistance, consequently causing a progressive decline in the drying rate. At 55°C over a duration of 40 min, the drying rates for loading capacities of 20 g, 40 g, and 60 g are 0.0040,

0.0032, and 0.0029, respectively, demonstrating a clear decreasing trend. In contrast to microwave drying, the peak hot-air drying rate of 0.0098 is significantly lower than the microwave drying rate of 0.1038, confirming that the sluggish diffusion of internal moisture constitutes the primary bottleneck impeding the efficiency of hot-air drying.

Compared with hot-air drying, microwave drying produced faster moisture removal, which may be attributed to volumetric heating and the formation of an internal vapor-pressure gradient. This mechanism could reduce the dominance of surface-controlled moisture transfer under the tested conditions. However, because no direct microstructural or mechanical measurements were conducted, the mitigation of case hardening should be regarded as a possible mechanism rather than a directly verified conclusion.

Discussion

The drying behavior observed in this study should be interpreted from the difference in energy-delivery pathways between hot-air and microwave drying. In hot-air drying, heat is transferred from the grain surface to the interior by convection and conduction, whereas moisture migrates from the interior to the surface. This opposite direction of heat transfer and moisture migration increases internal mass-transfer resistance during the later drying stage. In contrast, microwave drying generates heat volumetrically through the interaction between electromagnetic energy and polar water molecules, which can enhance internal vapor-pressure-driven moisture migration. Therefore, the higher drying rate under microwave drying reflects not only faster heating but also a different moisture-transfer mechanism.

Construction and fitting of drying kinetic model

This study utilizes four thin-layer models of increasing complexity to capture different phenomenological traits during dehydration. The Newton model represents the simplest first-order exponential drying process and is suitable for describing ideal diffusion-controlled drying. The Page model introduces an empirical exponent to improve the description of non-linear moisture removal during the falling-rate period. The Logarithmic model adds a constant term to correct deviations at the later drying stage. The Midilli *et al.* model further combines a non-linear exponential term with an additional linear term, providing greater flexibility for describing drying processes involving rapid early-stage moisture removal and slower later-stage diffusion. By conducting nonlinear regression on the moisture ratio, we effectively isolated the kinetic behaviors from initial moisture variations to determine the most accurate predictive model.

To reveal the independent influence of each single variable on the drying kinetics of Indica rice, this study, based on the method of controlled variables, uniformly selected the median conditions

for the experiments: i) initial temperature of 50°C, power of 200 W, and load of 40 g; ii) power of 350 W and load of 40 g; iii) temperature of 50°C and load of 40 g.

The calculation results of the indicators are obtained through Eqs. (4), (5), and (6), as shown in Table 1.

Upon comparing all the fitting indicators of experimental data in Table 1, it was found that the R^2 values of the Midilli *et al.* model were all stable above 0.999, with the highest reaching 0.99951. Additionally, both χ^2 and $RMSE$ remained at an extremely low order of magnitude of 10^{-5} , demonstrating the best fitting degree and strong robustness. Therefore, the Midilli *et al.* model was selected as the most suitable model for describing the drying behavior of Indica rice under both microwave and hot-air drying conditions.

In the thin-layer drying kinetic model, the drying rate constant k is a core physical quantity that characterizes the rate of water migration and diffusion from the interior of the material to the outside. A larger value of k indicates a smaller mass transfer resistance and a faster drying rate. Given the overall superiority exhibited by the Midilli *et al.* model, the specific kinetic parameters a , k , n , and b extracted from it under various experiments are shown in Tables 2 and 4.

As illustrated in Table 2, in microwave drying, under the conditions of a fixed loading capacity of 40 g and a constant power of 200 W, when the initial temperature of Indica rice increases from 45°C to 55°C, the k value rises from 0.10826 to 0.15265. A higher initial temperature can shorten the preheating stage and quickly establish an internal steam pressure gradient.

The influence of microwave power should be considered together with sample loading capacity because both factors determine the microwave power density received by the grains. Increasing microwave power enhanced the drying rate by increasing the energy absorbed per unit time and strengthening the internal vapor-pressure gradient. However, excessive power input may also increase the risk of non-uniform heating and local overheating. As illustrated in Table 3, when the microwave power is increased from 200 W to 550 W with a fixed loading capacity of 40 g, the k value rises from 0.09071 to 0.26512. This is due to the enhanced volumetric heating effect of high-frequency electromagnetic fields, which significantly reduces the internal mass transfer resistance (Hao *et al.*, 2012). At 350 W, the k value shows a trend of first increasing and then decreasing with the loading capacity. This is because a very small amount of material cannot achieve optimal microwave energy absorption efficiency and energy absorption in the microwave cavity. However, when the loading capacity continues to increase to 60 g, the k value significantly decreases to 0.1695, indicating that the energy dilution effect begins to dominate.

As illustrated in Table 4, in hot-air drying, the model fitting R^2 is better than 0.997 under various operating conditions. However, the overall drying rate constant k hovers in the low range of

0.01~0.04, far lower than the microwave group. For hot-air drying, increasing air temperature enhanced the external heat supply and accelerated moisture evaporation, but the improvement was limited by the surface-to-interior heat transfer pathway and the internal diffusion resistance of rice grains. At a loading capacity of 60 g, when the temperature increased from 45°C to 55°C, the value of k steadily increased from 0.02573 to 0.04109, indicating that the expansion of gas-solid temperature difference effectively stimulated the diffusion of internal moisture.

Although 550 W produced the highest drying rate, excessive microwave power may increase the risk of non-uniform heating, local overheating, and potential grain damage. Based on the drying-rate behavior and moisture-removal efficiency, the 350 W and 40 g treatment was selected as a balanced kinetic condition under the tested microwave drying system. For the optimal microwave process, the predictive equation is established as: $MR=0.95449*\exp(-0.18391*x^{1.34164})+0.01028*x$. This result is consistent with previous microwave drying studies on rice and paddy. Keshavalu *et al.* (2017) reported that increasing microwave power shortened the drying time of parboiled paddy, while Ling and Sun (2021) also observed faster moisture removal in microwave drying than in hot-air drying of rice. Silva *et al.* (2021) further showed that increasing microwave power density accelerated paddy drying, but excessive energy input could increase the risk of non-uniform heating or discoloration.

To visually verify the predictive ability and reliability of the selected Midilli *et al.* model for the dynamic moisture changes during the drying process of Indica rice, this study conducted a graphical comparison between the experimentally measured moisture ratio and the moisture ratio predicted by the Midilli *et al.* model. The specific dynamic fitting effect is shown in Figure 10.

Calculation of the effective moisture diffusivity

In this study, rice grains were simplified as isotropic spheres to obtain an analytical solution of Fick's second law. Although indica rice grains are not perfect spheres, this assumption allows the use of an equivalent radius to represent the average diffusion path. The equivalent radius was estimated from the measured grain dimensions described in the sample characterization section. It should be noted that grain shrinkage during drying was not directly measured. Therefore, volume shrinkage was neglected in the calculation, and the obtained effective moisture diffusivity should be regarded as an apparent diffusivity. This assumption may introduce some uncertainty because shrinkage can change the internal diffusion path and moisture migration resistance. Future studies should include dynamic measurements of grain volume or microstructure to improve the accuracy of moisture diffusion analysis.

The drying process is mainly controlled by internal moisture diffusion, and the universal solution of Fick's second law can be used to describe the moisture migration behavior. Assuming that the Indica rice grains are isotropic spheres and ignoring volume shrinkage during the drying process, the analytical equation can be simplified to (8):

$$MR = \frac{6}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{r^2}\right) \quad (\text{Eq. 10})$$

Take the logarithm of both sides of the above equation and simplify to get the linear equation:

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{r^2}\right) t \quad (\text{Eq. 11})$$

where D_{eff} is the effective moisture diffusivity; r is the equivalent radius of the rice grain, the equivalent radius was calculated from the volume-equivalent diameter using the measured grain length, width, and thickness; t is the drying time.

By performing a linear regression fit of $\ln(MR)$ vs t , the D_{eff} under each operating condition can be obtained according to Eq. (10), as shown in Table 5.

$$k = -\frac{\pi^2 D_{eff}}{r^2} \quad (\text{Eq. 12})$$

Drying activation energy of Indica rice under different experimental conditions

During the hot-air drying process, the relationship between the effective moisture diffusivity D_{eff} inside Indica rice and the absolute temperature T follows the classical Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (\text{Eq. 13})$$

Taking the natural logarithm on both sides of equation (11) can be transformed into a linear relationship:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R} \left(\frac{1}{T}\right) \quad (\text{Eq. 14})$$

Where D_0 is the pre-exponential factor of the Arrhenius equation; E_a is the activation energy of hot-air drying; R is the ideal gas constant, 8.314 J (mol K)⁻¹; T is the absolute temperature of the hot air.

Unlike traditional convective heat transfer, microwave drying is a “volumetric heating” process that is not in thermodynamic equilibrium, and its energy absorption is closely related to the material mass and microwave power. Therefore, a modified Arrhenius equation is used to describe the moisture diffusion kinetics mechanism under microwave conditions:

$$D_{eff} = D_0 \exp\left(-\frac{E_a m}{P}\right) \quad (\text{Eq. 15})$$

Taking the natural logarithm on both sides of Eq. (13) and rearranging, we get:

$$\ln(D_{eff}) = \ln(D_n) - E_a \left(\frac{m}{P}\right) \quad (\text{Eq. 16})$$

where E_a is the activation energy of microwave drying; m is the initial loading capacity of the material, and P is the microwave output power.

Based on the calculated values of all experimental groups, Arrhenius fitting analysis is carried out for different load levels, temperature conditions and power parameters in this chapter. The calculation results of activation energy are shown in Table 5.

Activation energy reflects the sensitivity of effective moisture diffusivity to the drying driving force and can be interpreted as the apparent energy barrier for moisture migration. In hot-air drying, this barrier is mainly related to convective heat transfer, vapor-pressure gradient, and internal diffusion resistance. In microwave drying, the modified Arrhenius relationship uses microwave power density to describe the effect of volumetric dielectric heating, because moisture migration is strongly affected by electromagnetic energy absorption and internal vapor-pressure generation. Similar Arrhenius-type analyses have been used in hot-air and microwave drying studies of agricultural materials, including paddy and other food products (Feng *et al.*, 2012; Keshavalu *et al.*, 2017; Azimi-Nejadian and Hoseini, 2019). The results of effective moisture diffusivity and activation energy calculated by equation (8) to (14) are summarized in Table 5. The D_{eff} values ranged from $6.39 \times 10^{-11} \text{ m}^2 \text{ s}^{-1}$ and $7.62 \times 10^{-11} \text{ m}^2 \text{ s}^{-1}$, with microwave drying exhibiting values approximately one order of magnitude higher than hot-air drying. The higher effective moisture diffusivity under microwave drying indicates that volumetric heating promoted internal moisture migration more effectively than surface convective heating. Thermodynamically, hot-air drying displayed a distinct V-shaped activation energy curve across varying sample masses. The 40 g batch proved optimal, achieving the lowest E_a ($15.18 \text{ kJ mol}^{-1}$) alongside excellent Arrhenius linearity. Deviating from this optimum worsened the kinetics: lighter loads (20 g) suffered from rapid surface evaporation that quickly sealed the grain exterior, while heavier batches (60 g) presented excessive macroscopic physical resistance, driving the E_a up to $37.63 \text{ kJ mol}^{-1}$. Microwave drying behaved entirely differently. As the rice load expanded from 20 g to 60 g, its E_a steadily dropped from 35.21 down to $17.04 \text{ kJ mol}^{-1}$. Such a monotonic decline suggests that in deeper material beds, internal vapor pressure takes over as the primary driver for moisture removal, overriding the initial thermal gradient.

The effective moisture diffusivity and activation energy results further indicate the mechanistic difference between the two drying methods. The higher effective moisture diffusivity under microwave drying suggests that volumetric heating promoted internal moisture migration more effectively than surface convective heating. For hot-air drying, the variation in activation energy indicates that both rapid surface evaporation at low loading capacity and increased bed resistance at high loading capacity may raise the apparent energy barrier for moisture migration. In contrast, the decreasing activation energy observed under microwave drying suggests that a larger sample mass may improve microwave energy coupling within the tested range.

Conclusions

This study, based on the multifactor control variable method, systematically compared the thin-layer drying kinetics and internal mass transfer mechanisms of Indica rice under microwave and hot-air drying. The main conclusions are summarized in the following three points.

i) The microwave "volume heating" mechanism overcomes the mass trans-fer bottleneck of hot-air drying and determines the process parameters. Compared with the potential surface hardening limitations of traditional hot air drying processes, microwave drying greatly shortens the drying cycle. The combination of 350 W micro-wave power and 40 g loading capacity was determined as the optimal drying process for Indica rice through comprehensive optimization based on dynamic efficiency and microwave field microwave energy absorption efficiency mechanism.

ii) The Midilli *et al.* model has optimal predictive capability and can provide a mathematical basis for engineering applications. For the optimal microwave process, the predictive equation is established as: $MR=0.95449*\exp(-0.18391*x^{1.34164})+0.01028*x$.

iii) Activation energy analysis reveals a fundamental thermodynamic divergence. Hot-air drying exhibited a V-shaped E_a trend (30.05–37.63 kJ mol⁻¹), constrained by case hardening at low loads and mass transfer resistance at high loads. Conversely, microwave drying showed a monotonically decreasing E_a , reflecting a shift towards pressure-driven mass transfer. Its significantly lower equivalent E_a (7.95 W g⁻¹) confirms that dielectric heating actively bypasses conventional thermal barriers, making microwave drying thermodynamically superior for high-efficiency drying of indica rice.

A limitation of this study is that the effects of drying treatments on final grain quality and microstructural changes were not directly evaluated. Therefore, the present results should be interpreted as drying-kinetic and thermodynamic evidence rather than direct evidence that microwave drying preserved grain quality. In addition, case-hardening-related behavior was inferred only from drying kinetic curves, without direct confirmation by microstructural

observation, hardness testing, fissure analysis, or internal moisture-profile determination. Future work will systematically evaluate grain quality attributes, including fissure percentage, head rice yield, color, cooking quality, and protein content. Microstructural analysis, thermal analysis, and starch characterization will also be conducted to examine starch gelatinization, surface hardening, and internal moisture migration mechanisms. Furthermore, pilot-scale or industrial-scale validation should be performed to assess the applicability, energy efficiency, and process stability of microwave drying for indica rice processing. Future work should therefore evaluate continuous or hybrid microwave drying systems, energy efficiency, operating cost, process stability, and grain quality under commercial processing conditions.

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Figure 1. Indica rice.



Figure 2. Experimental equipment. **a)** Grain moisture meter. **b)** Halogen moisture meter. **c)** Delixi Electric LCD electronic analytical balance. **d)** Galanz G90F25YeSXLV-ADG0 microwave drying experimental station. **e)** Mingyue MY-382 electric thermostatic drying oven used for laboratory hot-air drying.

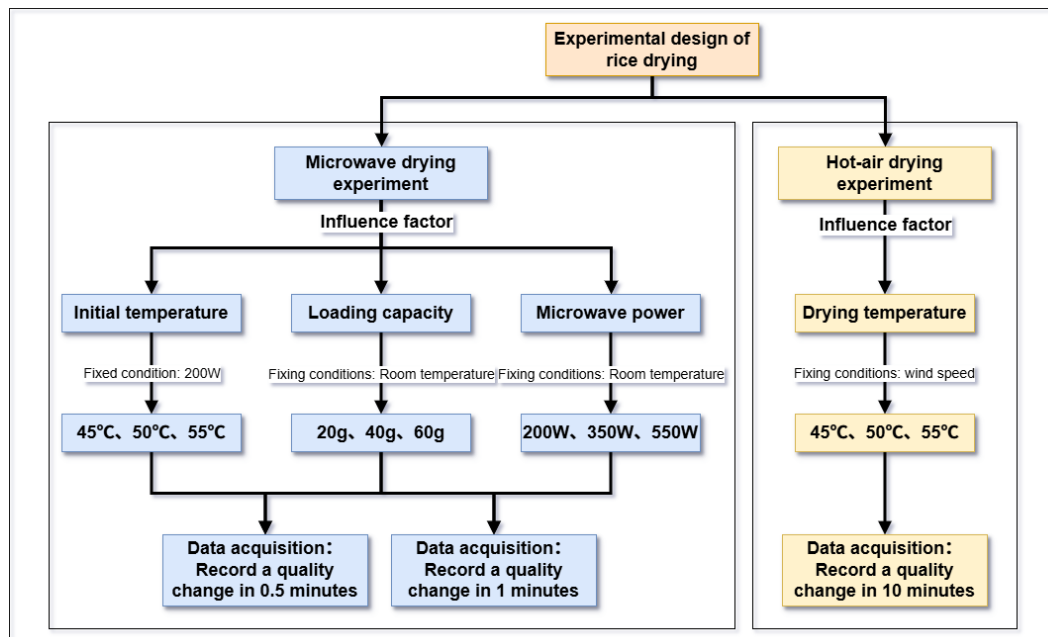


Figure 3. Schematic diagram of experimental process.

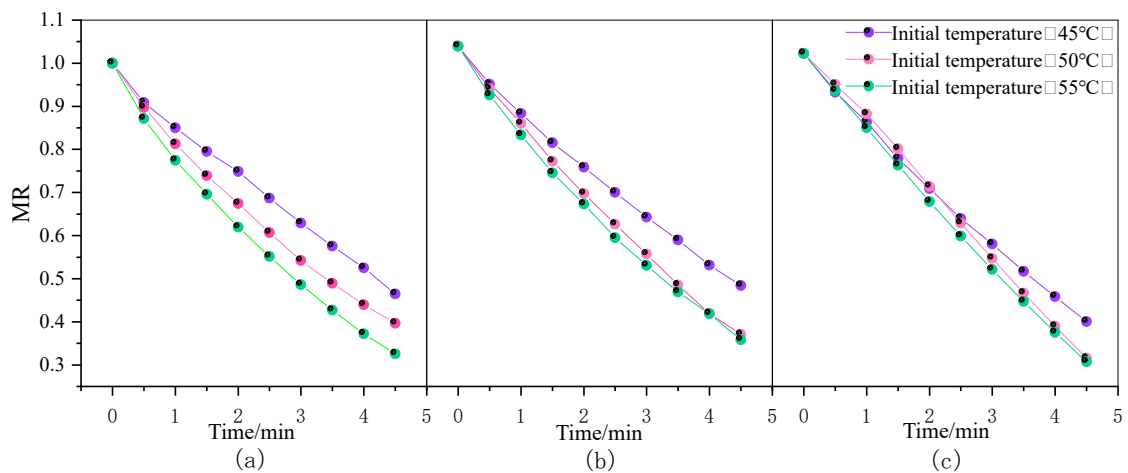


Figure 4. Effect of initial sample temperature (45, 50, and 55°C) on moisture ratio (MR) during microwave drying at 200 W under different loading capacities: **(a)** 20 g; **(b)** 40 g; **(c)** 60 g.

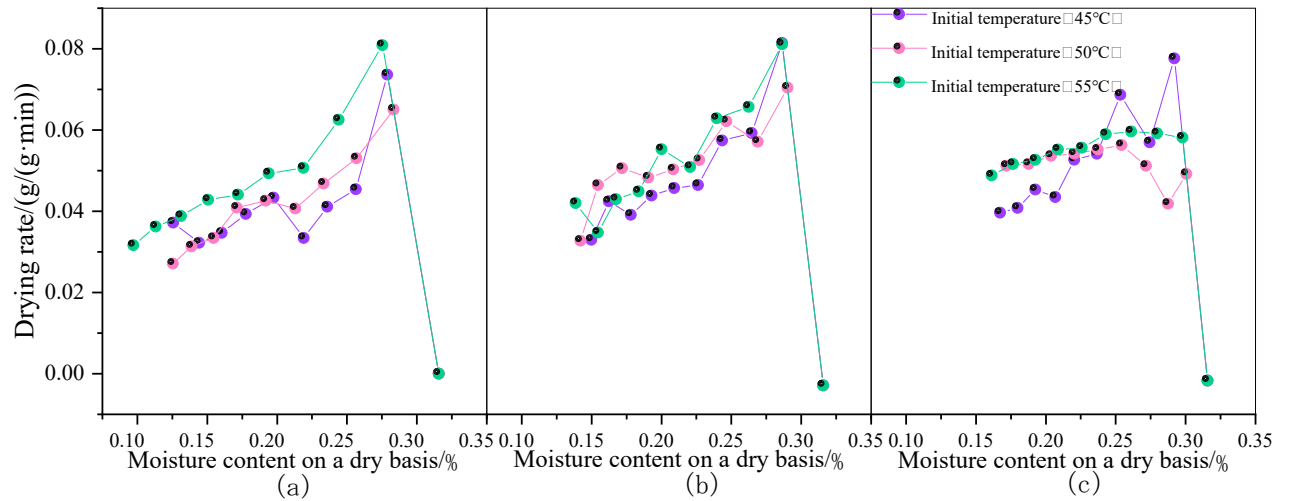


Figure 5. Effect of initial sample temperature (45, 50, and 55°C) on drying rate (DR) during microwave drying at 200 W under different loading capacities: (a) 20 g; (b) 40 g; (c) 60 g.

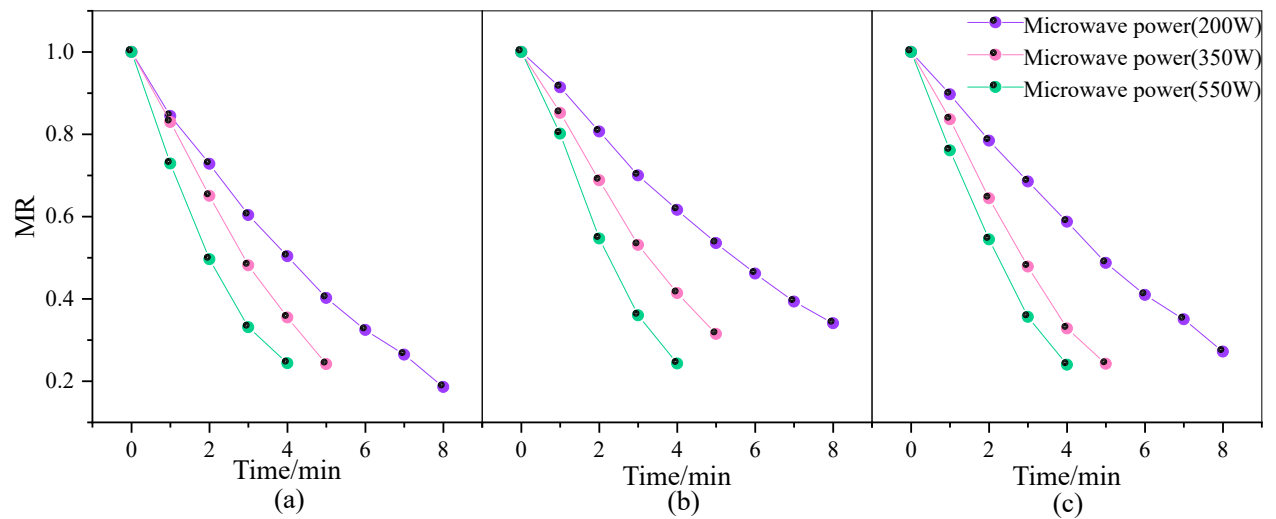


Figure 6. Effect of microwave power (200, 350, and 550 W) on moisture ratio (MR) during microwave drying under different loading capacities: (a) 20 g; (b) 40 g; (c) 60 g.

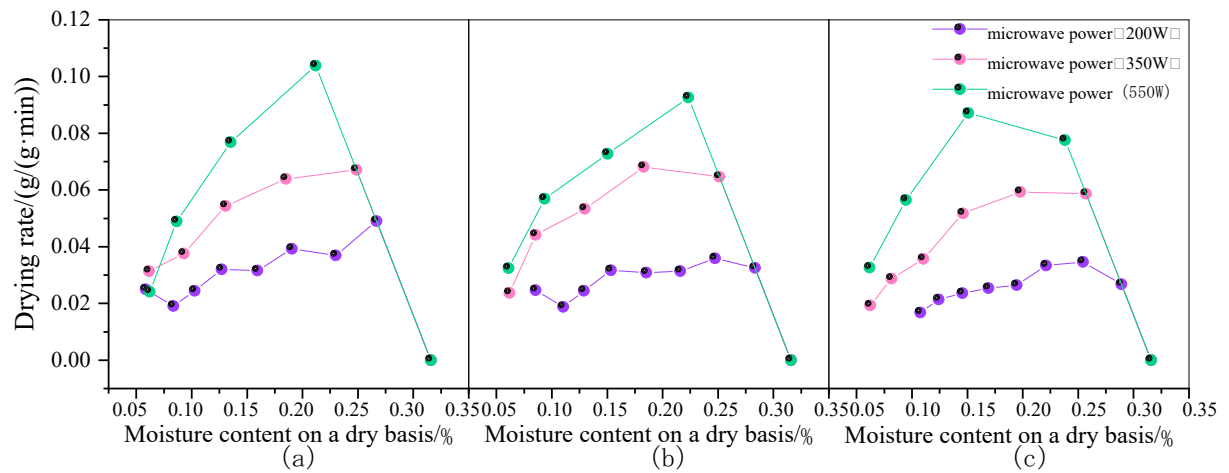


Figure 7. Effect of microwave power (200, 350, and 550 W) on drying rate (DR) during microwave drying under different loading capacities: **(a)** 20 g; **(b)** 40 g; **(c)** 60 g.

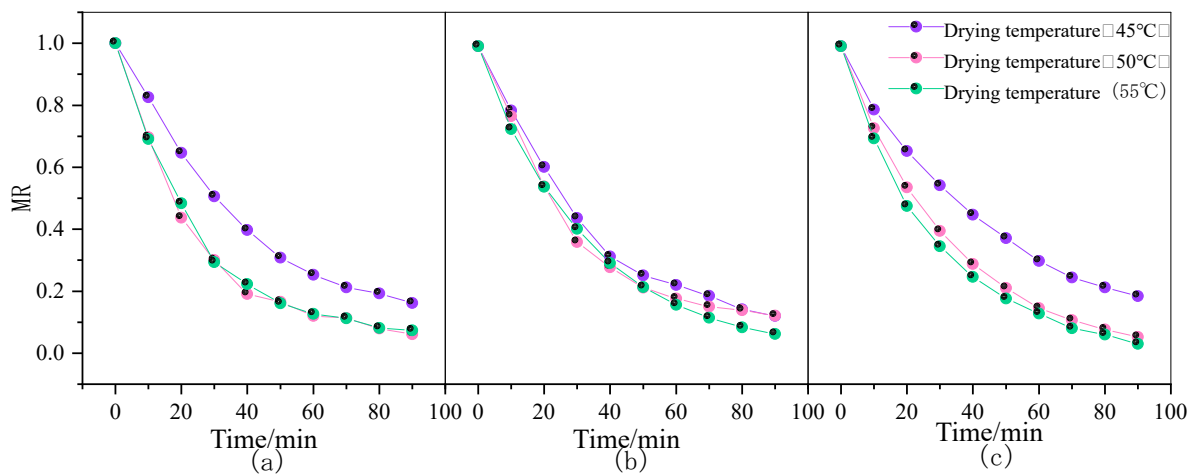


Figure 8. Effect of hot-air temperature (45, 50, and 55°C) on moisture ratio (MR) during hot-air drying under different loading capacities: **(a)** 20 g; **(b)** 40 g; **(c)** 60 g.

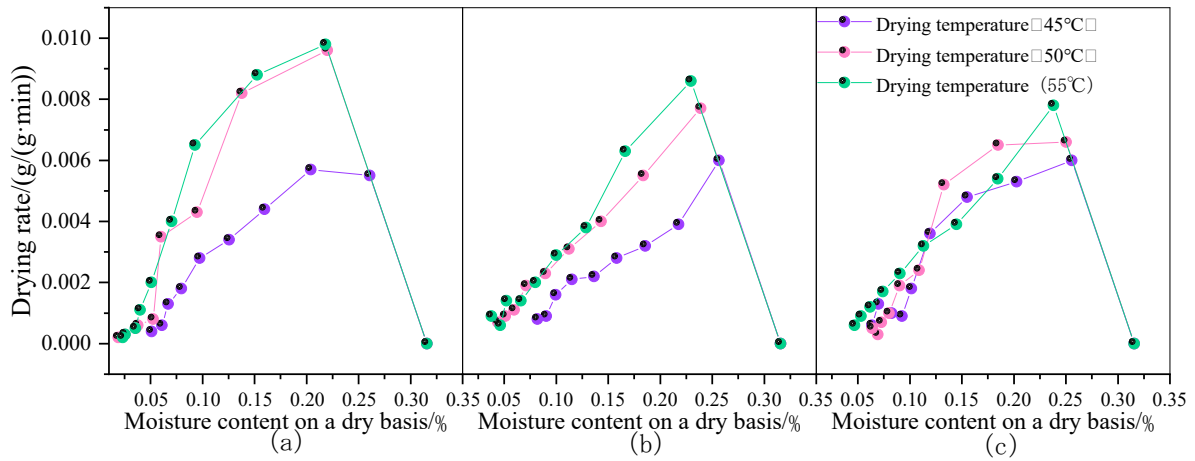


Figure 9. Effect of hot-air temperature (45, 50, and 55°C) on drying rate (DR) during hot-air drying under different loading capacities: (a) 20 g; (b) 40 g; (c) 60 g.

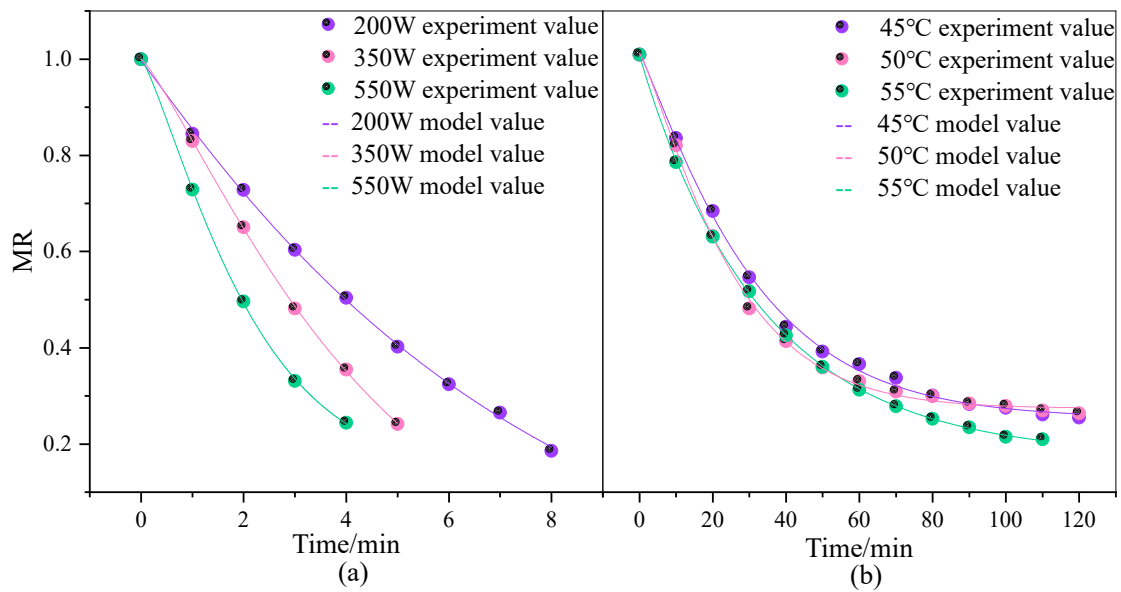


Figure 10. Comparison between experimental and Midilli *et al.* model-predicted moisture ratio (MR) values under representative microwave and hot-air drying conditions: (a) microwave drying; (b) hot-air drying.

Table 1. Mathematical model of paddy drying and its fitting results.

Model name	(Microwave 350 W, 40 g)			(Microwave 50°C, 40 g)			(Hot-air 50°C, 40 g)		
	R ²	χ^2	RMSE	R ²	χ^2	RMSE	R ²	χ^2	RMSE
Newton	0.9810	0.0016	0.0401	0.9977	0.0008	0.0087	0.9672	0.0025	0.0495
Page	0.9304	0.0060	0.0544	0.9859	0.0005	0.0143	0.9804	0.0015	0.0359
Logarithmic	0.9756	0.0021	0.0355	0.9977	0.00008	0.0079	0.9939	0.0005	0.0188
Midilli <i>et al.</i>	0.9992	0.0007	0.0054	0.9995	0.00002	0.0034	0.999	0.00008	0.0071

Table 2. Model fitting results of Midilli *et al.* model for microwave group at different initial temperatures.

Drying method	Variables	Load /g	a	k	n	b	R ²	RMSE
Microwave (effect of initial temp at 200 W)	45°C	20	1.2	0.11322	1.05492	-0.0488	0.9950	0.0099
		40	1.2	0.10826	0.97668	-0.04682	0.9992	0.0034
		60	1.2	0.09351	0.97825	-0.04612	0.9997	0.0020
	50°C	20	1.2	0.16543	0.95726	-0.04645	0.9997	0.0030
		40	1.2	0.13015	1.0297	-0.04661	0.9995	0.0034
		60	1.2	0.07832	1.20322	-0.04647	0.9998	0.0019
	55 °C	20	1.2	0.19838	0.93212	-0.04847	0.9987	0.0041
		40	1.2	0.15265	0.93823	-0.0461	0.9998	0.0022
		60	1.2	0.09743	1.06837	-0.04616	0.9999	0.0005

Table 3. Model fitting results of Midilli *et al.* model under different microwave powers in the microwave group.

Drying method	Variables	Load/g	a	k	n	b	R ²	RMSE
Microwave (effect of power)	200 W	20	1.2	0.12563	1.04546	-0.04691	0.9991	0.0066
		40	1.18449	0.09071	1.12682	-0.04251	0.9994	0.0050
		60	0.95372	0.10066	1.18401	0.01099	0.9997	0.0033
	350 W	20	1.09652	0.16768	1.20863	-0.02224	0.9997	0.0029
		40	0.95449	0.18391	1.34164	0.01028	0.9992	0.0054
		60	0.93823	0.1695	1.26951	0.01417	0.9998	0.0026
	550 W	20	0.86377	0.37393	1.24347	0.0313	0.9996	0.0031
		40	1.0134	0.26512	1.19759	-0.0032	0.9988	0.0054
		60	0.86332	0.26276	1.4964	0.03151	0.9999	0.0012

Table 4. Model fitting results of Midilli *et al.* model in the hot-air group.

Drying method	Variables	Load/ g	a	k	n	b	R ²	RMSE
Hot-air (effect of air temp)	45°C	20	0.87032	0.01402	1.20475	0.02986	0.9997	0.0038
		40	0.80957	0.01729	1.18776	0.04396	0.9977	0.0106
		60	0.91728	0.02573	0.9279	0.0098	0.9992	0.0058
	50°C	20	0.93153	0.03223	1.11093	0.01631	0.9974	0.0128
		40	0.79505	0.01724	1.25875	0.04758	0.999	0.0071
		60	0.92625	0.03093	0.98986	0.0169	0.9999	0.0019
	55°C	20	0.93115	0.03149	1.10019	0.01581	0.9983	0.0106
		40	0.9184	0.03182	0.98252	0.01863	0.9999	0.0023
		60	0.93006	0.04109	0.94282	0.01637	0.9995	0.0051

Table 5. Activation energy calculation.

Experimental conditions	Loading capacity	Change variable	$D_{\text{eff}}/(\text{m}^2 \text{ s}^{-1})$	$E_a/(\text{kJ mol}^{-1}, \text{W g}^{-1})$	R ²
Microwave drying	20 g	45-55°C	5.79×10^{-10} - 8.69×10^{-10}	35.21	0.9934
	40 g	45-55°C	4.75×10^{-10} - 6.39×10^{-10}	25.87	0.7829
	60 g	45-55°C	4.05×10^{-10} - 4.92×10^{-10}	17.04	0.79062
Microwave drying	20 g	200-550 W	6.07×10^{-10} - 1.28×10^{-9}	5.738	0.97196
	40 g	200-550 W	4.73×10^{-10} - 1.282×10^{-9}	7.952	0.98997
	60 g	200-550 W	4.39×10^{-10} - 1.29×10^{-9}	8.235	0.96173
Hot-air drying	20 g	45-55°C	7.42×10^{-11} - 1.08×10^{-10}	30.05	0.99971
	40 g	45-55°C	6.39×10^{-11} - 7.62×10^{-11}	15.18	0.99065
	60 g	45-55°C	5.36×10^{-11} - 8.25×10^{-11}	37.63	0.99767

Values in this table were obtained from single independent drying runs under each treatment condition. Therefore, ANOVA-based statistical notation or significance letters were not applied. The reported parameters are used for descriptive comparison and model-fitting evaluation only.