



Effect of Drying Temperature on the Drying Kinetics of Red Rice Paddy (*Oryza sativa* L.) in a Tray Dryer

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Abstract

Understanding the temperature-dependent drying kinetics and convective transport mechanism is critical for the characterization of the drying process of red rice paddy under controlled conditions. This present study evaluates the drying behavior and heat and mass transfer characteristics of red rice paddy in a laboratory-scale tray dryer over a temperature range of 30 – 80 °C, with sun drying functioning as a reference. The drying kinetics were evaluated using several thin-layer models, while convective heat and mass transfer characteristics were estimated from dimensionless-number correlations. Increasing the drying temperature enhanced moisture removal, with the average drying rate increasing from 0.0012 kg moisture/(kg dry paddy·min) during sun drying to 0.0020 kg moisture/(kg dry paddy·min) at 80 °C tray drying. Among the evaluated models, the Page model demonstrated the optimal overall fit, with an average coefficient of determination of 0.9904 and a sum of squared errors of 0.0050. The estimated convective heat transfer coefficient remained nearly constant at $68.43 \pm 0.40 \text{ W/(m}^2\cdot\text{K)}$. Conversely, the convective mass transfer coefficient exhibited an increase, rising from 0.0649 to 0.0799 m/s across the temperature range of 30 to 80 °C. The activation energy for convective mass transfer was found to be 3.70 kJ/mol. The results obtained characterize the temperature-dependent drying and convective transport behavior within the investigated drying configuration and observation period.

Keywords: Activation energy, Effective moisture diffusivity, Falling-rate period, Dimensionless number, Moisture content, Moisture ratio.

1. Introduction

Rice is a staple food for a significant proportion of the global population, particularly in Asian countries, where it is a primary source of daily caloric intake. In addition to conventional white rice, pigmented varieties such as red rice (*Oryza sativa* L.) have gained attention due to their enhanced nutritional and functional properties. Red rice has been shown to contain higher levels of protein, dietary fibre, lipids, and essential micronutrients, along with bioactive compounds such as phenolics and flavonoids, contributing to antioxidant activity [1]. Freshly harvested paddy typically exhibits a high moisture content (20–27%, wet basis), dependent on harvesting conditions [2]. Such conditions have made grains susceptible to microbial growth and biochemical deterioration, leading to quality degradation during storage [3]. Therefore, drying is viewed as a critical postharvest operation to reduce moisture content while maintaining grain quality [4].

The practice of open-air sun drying remains widely utilized due to its simplicity and cost-effectiveness. However, the efficacy of this process is highly determined by environmental conditions including solar radiation, ambient temperature, and relative humidity, which are variable and difficult to control [5]. Consequently, the drying process is frequently prolonged and non-uniform, resulting in uneven moisture distribution. In addition, exposure to open environments has been demonstrated to increase the risk of contamination from dust and insects, which has the potential to affect product quality and safety [6]. These limitations highlight the necessity for the development of more controlled drying techniques.

Mechanical drying methods, particularly hot air drying, are widely applied to overcome these limitations. By controlling parameters such as temperature, airflow, and drying time, utilizing mechanical systems, it is possible to reduce the duration of drying processes whilst simultaneously improving consistency [7]. Among these factors, temperature is a key factor in the process of moisture removal, as it has been demonstrated to enhance the vapor pressure gradient, thereby accelerating moisture diffusion and evaporation [8]. However, in the process of paddy drying, moisture transport is determined by the presence of rice husk, which may contribute to resistance to internal moisture transfer. Furthermore, excessive temperatures have been demonstrated to induce thermal stress, which can result in fissuring and quality degradation [9]. Therefore, it is deemed important to comprehend the relationship between temperature and moisture transport.

The study of drying kinetics, as stated by Zhang et al. [10], provides insight into moisture migration behavior in agricultural materials. Thin-layer drying models are frequently employed to describe alterations in moisture ratio under controlled drying conditions and to evaluate the effect of operating temperature on the observed drying behavior [11]. As indicated in the preceding research, the drying kinetics of various red rice cultivars have been the subject of investigation through the utilization of mathematical models. The findings of this research have indicated differences in the fitted parameters among the cultivars [12]. In the same study, relationships were reported between carbohydrate and amylose contents and water sorption, while ash and crude fiber were associated with specific drying periods [12]. The findings of this study indicate that both material characteristics and drying conditions can be relevant to the drying behavior described by kinetic models. However, it is important to interpret the fitted kinetic parameters obtained from different studies within their respective experimental conditions, since these parameters are determined by various factors such as drying configuration, operating conditions, material characteristics, and the moisture range investigated. Therefore, it is inappropriate to assume that kinetic parameters obtained under one drying system are directly transferable to another. Instead, characterization under a defined drying configuration provides useful information on the moisture-removal behavior under those conditions. Accordingly, the present study evaluates the drying kinetics of red rice paddy. This is achieved by subjecting the sample to analysis using a laboratory-scale tray dryer at different temperatures, with sun drying serving as a reference. Thin-layer drying models were employed to describe the moisture removal behavior observed under the present experimental conditions, while heat and mass transfer characteristics were estimated to further characterize the temperature dependence of moisture transport in the investigated drying configuration.

2. Materials and method

2.1 Raw material

Red rice paddy (*Oryza sativa* L.) utilized in this study was harvested in January 2025 from Tirtomoyo District, Wonogiri Regency, Central Java, Indonesia. The initial moisture content was measured using a G-WON GMK 303RS grain moisture meter (accuracy $\pm 0.5\%$ and resolution $\pm 0.1\%$).

2.2 Drying experimental procedure

The sun-drying process was conducted under direct sunlight, with the concrete surface covered by a tarpaulin sheet. The thickness of grain layer was maintained at 0.7 cm, with an average ambient temperature of 31 °C in Semarang, Indonesia. The sun-drying experiment was conducted for a period of 90 minutes, during which the moisture content approached the 14% wet-basis benchmark specified by SNI 6128:2020 for safe storage and milling. The drying duration of 90 minutes was applied uniformly to all tray-drying experiments, thereby ensuring an identical experimental time basis for comparison of moisture removal under the investigated drying conditions. The 90-minute period was defined as the observation timeframe for the purpose of comparing moisture removal under the experimental conditions. It should be noted that this timeframe was not intended to represent the total drying time required to achieve the target moisture content under practical drying conditions.

As illustrated in Figure 1, the experimental setup of the red rice paddy drying system is composed of different components. The drying process was conducted in a tray dryer that was equipped with a blower and heater, with a temperature accuracy of ± 1 °C. A total of 300 g of paddy was evenly distributed into four perforated containers (15 cm diameter), resulting in an average layer thickness of 0.7 cm. The dryer was developed by Universitas Diponegoro in collaboration with CV. Raja Pengeri, Surabaya, Indonesia. Air was introduced into the system via an inlet pipe (ID = 0.19 m) at an average velocity of 0.9 m/s, which was measured using an anemometer (GM8903, Shenzhen Jumaoyuan Science and Technology Co., Ltd., China). The drying chamber has a cross-sectional area of 0.275 m², corresponding to an average airflow velocity of approximately 0.1 m/s. The drying air temperature and relative humidity (RH) were monitored using a GSP-6G Digital Temperature and Humidity Data Logger (Elitech Technology, Inc., USA; temperature accuracy ± 0.5 – 1.0 °C and relative humidity accuracy $\pm 3\%$). Throughout the course of the drying experiments, relative humidity was the subject of continuous monitoring;

however, it was not subjected to independent control as an experimental variable. The measurement of moisture content was conducted utilizing a grain moisture meter at 15-minute interval throughout the 90-minute observation period for each drying condition.

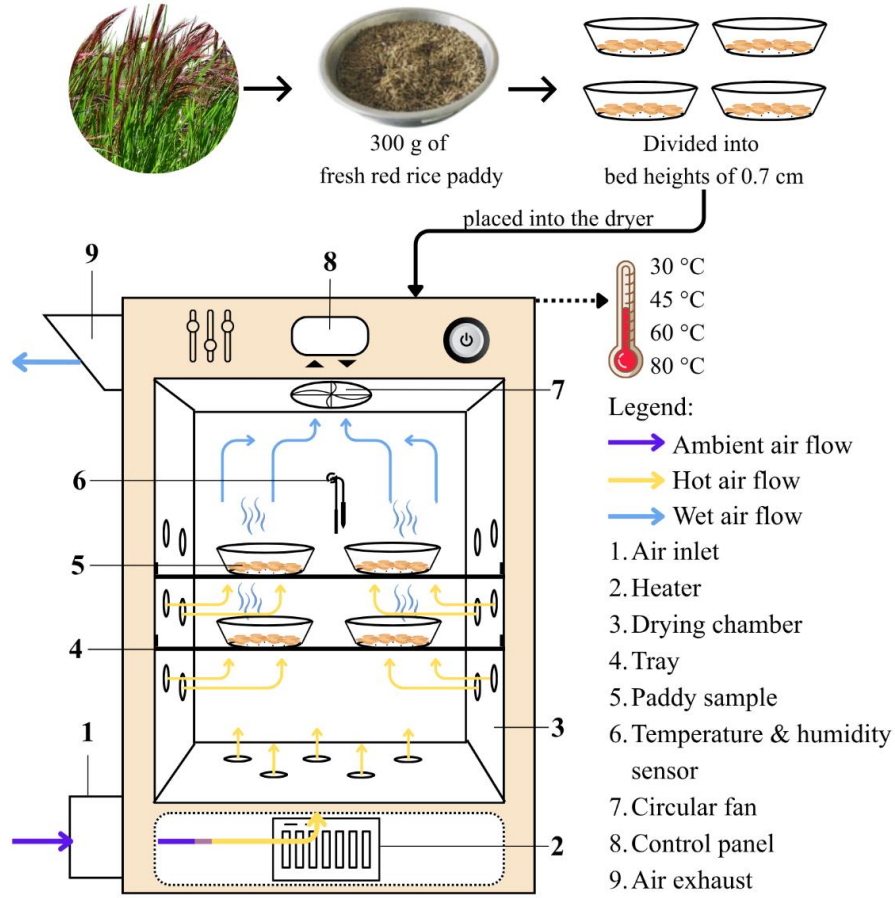


Figure 1 Schematic diagram of the experimental setup and the tray dryer used for red rice paddy drying.

2.3 Moisture content analysis and drying rate determination

Approximately 5 g of paddy was withdrawn from the drying chamber at 15-min intervals during the drying process. Subsequently, the withdrawn samples were placed in a desiccator to allow the sample temperature to stabilize prior to the measurement of moisture content. The moisture content was then measured using a G-WON GMK 303RS grain moisture meter (Seoul, South Korea), with each measurement repeated two to three times until consistent readings were obtained. Prior to the drying experiments, the moisture meter was calibrated against the conventional oven-drying method at 105 °C until a constant weight was obtained. The measured moisture content was converted from wet basis to dry basis for the purpose of subsequent calculations using Equation (1):

$$M_{db} = \frac{M_{wb}}{(100 - M_{wb})} \quad (1)$$

where M_{db} and M_{wb} are the moisture content on a dry basis (kg moisture/kg dry paddy) and wet basis (%), respectively. The drying rate (DR, kg moisture/(kg dry paddy·min)) was calculated as follows:

$$DR = \frac{(M_{db,t} - M_{db,t+\Delta t})}{\Delta t} \quad (2)$$

where $M_{db,t}$ is the moisture content at time t in dry basis (kg moisture/ kg dry paddy), $M_{db,t+\Delta t}$ is the moisture content at time $t+\Delta t$ in dry basis (kg moisture/kg dry paddy), and Δt is the time interval between measurements (min). The moisture ratio (MR) was calculated utilizing Equation (3).

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \quad (3)$$

where MR is the moisture ratio (dimensionless), M_t is the moisture content at drying time t (kg moisture/kg dry paddy), and M_0 is the initial moisture content of paddy (kg moisture/kg dry paddy), and M_e is the equilibrium moisture content (kg moisture/kg dry paddy). The equilibrium moisture content of paddy was estimated utilizing a modified Guggenheim-Anderson-de Boer (GAB) model, which relates the M_e and equilibrium relative humidity (RH). The expression adopted to calculate M_e is given in Equation (4).

$$M_e = \frac{a \cdot b \cdot a_w \cdot \left(\frac{c}{T}\right)}{(1 - b \cdot a_w) \left(1 - b \cdot a_w + \left(\frac{c}{T}\right) b \cdot a_w\right)} \quad (4)$$

The modified GAB model constants for paddy were determined as $a = 12.752$, $b = 0.507$, and $c = 220.039$. It was hypothesized that the water activity (a_w) was equivalent to the relative humidity. It has been reported that these constants exhibit a high degree of consistency across a range of different paddy varieties [13].

2.4 Paddy drying kinetics model fitting

The assumption underlying the drying kinetics analysis was that the paddy formed a thin layer with uniform temperature distribution inside the dryer. This assumption is valid for grain depths up to 20 cm [14]. A number of semi-theoretical models were utilized to analyse the experimental MR data and represent drying curves, as outlined in Table 1 [15,16]. The determination of the kinetic parameters was achieved through the utilization of nonlinear curve fitting, employing OriginPro 2024 software (OriginLab Corporation, USA). The performance of the model and the goodness of fit were evaluated using the sum of squared errors (SSE) and the coefficient of determination (R^2).

Table 1 Thin-layer drying kinetic models utilized in the present study

Model	Equation	Equation no.	Reference
Newton	$MR = \exp(-kt)$	(5)	[7]
Page	$MR = \exp(-kt^n)$	(6)	[17]
Modified-Page	$MR = \exp(-(kt)^n)$	(7)	[15]
Henderson & Pabis	$MR = a \cdot \exp(-kt)$	(8)	[4]
Logarithmic	$MR = a \cdot \exp(-kt) + b$	(9)	[7]
Wang & Singh	$MR = 1 + at + bt^2$	(10)	[16]
Aghbashlo	$MR = \exp\left(\frac{-k_1 t}{1 + k_2 t}\right)$	(11)	[18]

2.5 Evaluation of heat and mass transfer characteristics

The convective mass transfer characteristics of the paddy layer were evaluated by approximating the grain layer as a granular medium in which drying air flows around the individual grains. Hence, the mass transfer from particles to fluid was estimated using the packed-bed correlation proposed by Wakao & Funazkri [19], with the grain diameter employed as the characteristic length. The Reynolds (Re), Schmidt (Sc), and Sherwood (Sh) numbers were calculated as follows:

$$Re = \frac{\rho_a v_a d_p}{\mu_a} \quad (12)$$

$$Sc = \frac{\mu_a}{\rho_a D_a} \quad (13)$$

$$Sh = \frac{h_m d_p}{D_a} \quad (14)$$

$$Sh = 2 + 1.1 Re^{0.6} Sc^{\frac{1}{3}} \quad (15)$$

where ρ_a is air density (kg/m³), v_a is superficial air velocity (m/s) approximated by the average airflow velocity (0.1 m/s) measured across the drying chamber. This is due to the fact that the available flow area extends beyond the grain-containing sections, resulting in a flow field that is not confined to the paddy layer. μ_a is air dynamic viscosity (kg/(m.s)), d_p is the characteristic diameter of the paddy grain (0.003 m), D_a is the water vapor diffusivity

in air (m^2/s), and h_m is convective mass transfer coefficient (m/s). The correlation is applicable over a particle Reynolds number range of 3 to 10,000. To facilitate the calculation of heat transfer, the corresponding particle-to-fluid correlation for packed beds proposed by Wakao et al. [20] was applied using the Prandtl (Pr) and Nusselt (Nu) numbers.

$$Pr = \frac{\mu_a C_{p,a}}{\lambda_a} \quad (16)$$

$$Nu = \frac{h_c d_p}{\lambda_a} \quad (17)$$

$$Nu = 2 + 1.1 Re^{0.6} Pr^{\frac{1}{3}} \quad (18)$$

where $C_{p,a}$ is air specific heat capacity ($\text{J}/(\text{kg}\cdot\text{K})$), λ_a is air thermal conductivity ($\text{W}/(\text{m}\cdot\text{K})$), and h_c is convective heat transfer coefficient ($\text{W}/(\text{m}^2\cdot\text{K})$). The correlation is applicable over a particle Reynolds number range of 15 to 8,500. Subsequently, an evaluation was made of the temperature dependence on h_m . This was achieved by utilizing a linear empirical correlation and an Arrhenius-type relationship, whereby $\ln(h_m)$ was plotted against $1/T$. The Arrhenius-type relationship was expressed as follows:

$$h_m = h_0 \exp\left(-\frac{E_{a,m}}{RT}\right) \quad (19)$$

where h_0 is the pre-exponential factor, $E_{a,m}$ is the activation energy for convective mass transfer (J/mol), R is the universal gas constant ($8.314 \text{ J}/(\text{mol}\cdot\text{K})$), and T is the absolute temperature (K).

3. Results and discussion

The moisture content profile of red rice paddy under different drying conditions is presented in Figure 2(A). A continuous decrease in moisture content was observed for all methods, indicating effective moisture removal. However, it was found that both the rate and extent of reduction were influenced by drying temperature. In the preliminary stage, tray drying exhibited a more pronounced decrease in comparison to sun drying. To illustrate this, an experiment was conducted in which the moisture content was measured as a function of temperature. The results revealed that at 80°C , the moisture content decreased from 22% to 17% within 15 minutes, while sun drying only reached 21.3% over the same period. This finding suggests that higher temperatures can enhance the initial phase of moisture removal, a phenomenon that is likely attributable to an increased vapor pressure gradient between the grain surface and surrounding air [21].

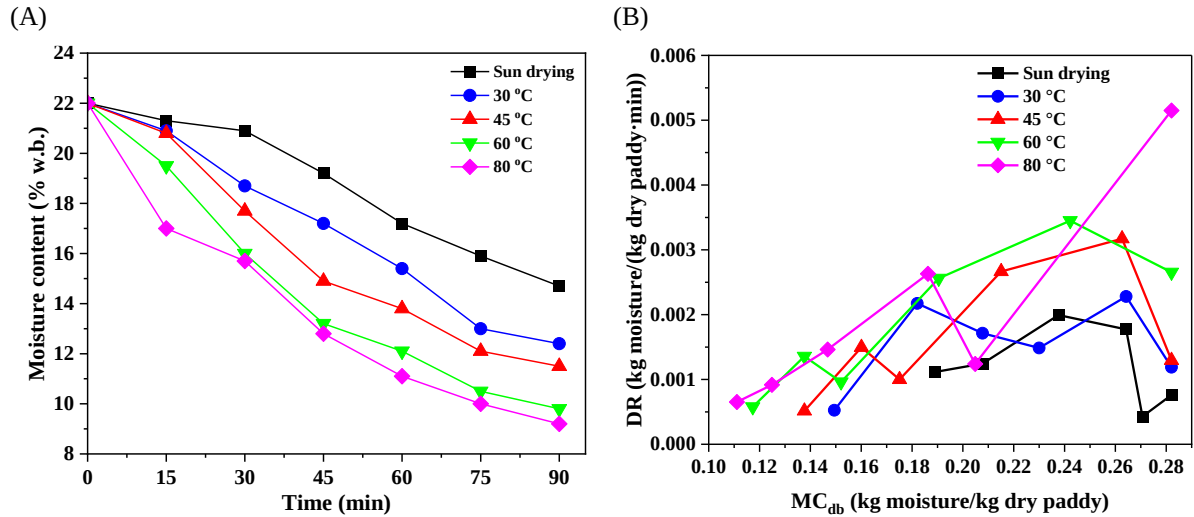


Figure 2 Drying characteristics of red rice paddy: (A) moisture content, (B) drying rate, and (C) estimated M_e from average drying-air RH and temperature.

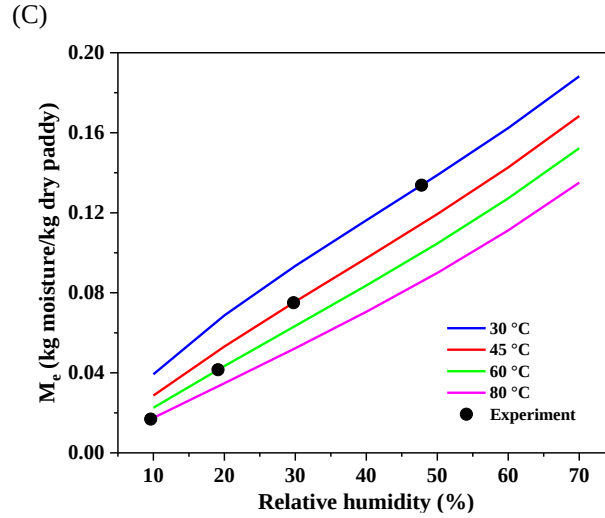


Figure 2 Drying characteristics of red rice paddy: (A) moisture content, (B) drying rate, and (C) estimated M_e from average drying-air RH and temperature. (Conf.)

A comparable temperature dependence has been documented in the context of paddy drying under controlled convective conditions [7]. During the 90-minute observation period, the moisture content continued to decrease under all drying conditions, while the drying rate generally declined with decreasing moisture content, as reflected by the drying-rate profiles shown in Figure 2(B). Despite local fluctuations being observed, as the drying rate was calculated over discrete sampling intervals, the overall drying rate decreased with decreasing moisture content. This finding suggests that the rate of moisture removal became progressively lower during the observed drying period. The decrease in drying rate with decreasing moisture content can be considered in relation to the water-interaction characteristics reported for red rice. It has been established through previous research that the levels of carbohydrate and amylose are associated with the rate of water sorption. In addition, the levels of ash and crude fiber have been shown to be related to the duration of specific drying periods in red rice [12]. These findings provide material-related context for the progressive decrease in moisture removal observed under the present drying conditions. However, due to the absence of independent analysis of the composition of the experimental red rice, these characteristics cannot be directly attributed to the observed drying behavior.

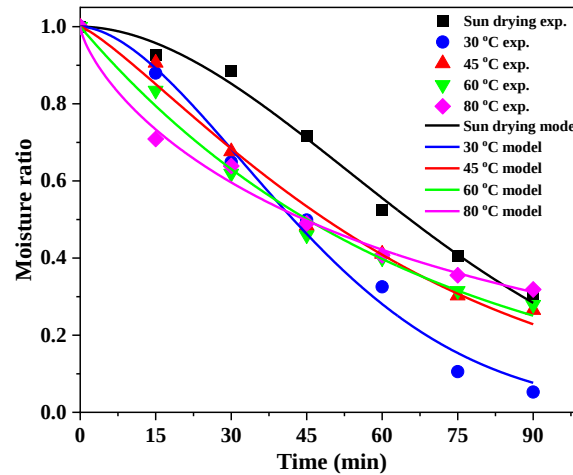


Figure 3 Page kinetics model fitting to experimental data of red rice paddy drying.

Furthermore, an increase in drying temperature was observed to result in an enhancement of the drying rate, with the rate increasing from 0.0012 kg moisture/(kg dry paddy·min) for sun drying to 0.0016, 0.0017, 0.0019, and 0.0020 kg moisture/(kg dry paddy·min) at 30, 45, 60, and 80 °C, respectively. This finding indicates that higher-temperature drying conditions facilitate a greater capacity for moisture removal. The estimated equilibrium moisture content exhibited a variation in response to the drying temperature, showing a decrease from 0.1338 kg moisture/kg dry paddy at 30 °C to 0.0169 kg moisture/kg dry paddy at 80 °C, as depicted in Figure 2(c). At the completion of the 90-minute observation period, the measured moisture contents remained above the corresponding estimated equilibrium moisture contents, indicating that equilibrium had not been reached

experimentally. Accordingly, the observed decrease in drying rate is consistent with a falling-rate drying pattern during the investigated period [22]. Such behavior has been reported for biological materials, including paddy, during the later stage of drying [23]. However, given that the experiments were conducted for a fixed 90-minute observation period and were not continued until constant moisture content was reached, the present data do not establish the complete drying period or experimental equilibrium. While higher temperatures enhance the drying rates, excessive heat has been demonstrated to induce thermal stress, thereby exerting a detrimental effect on grain quality. For instance, Utari et al. [7] reported that drying at 65.0 °C achieved high heat efficiency but reduced head rice yield due to increased kernel breakage, illustrating the trade-off between efficiency and quality. Accordingly, the use of moderate drying temperatures may provide a practical compromise between drying performance and grain quality.

The comparison between sun drying and tray drying further highlights the difference in moisture removal under the investigated conditions. As demonstrated in Figure 2(A), the process of sun drying resulted in slower and more gradual reduction in moisture, particularly during the early stage. Following a duration of 90 minutes, the sun drying process reached 14.7%, slightly above the 14% moisture-content threshold as specified by SNI 6128:2020 for safe storage and milling. Conversely, the tray-drying method led to a reduction in moisture content that fell below this benchmark within the same observation period. Consequently, within the investigated timeframe, tray drying exhibited greater moisture removal capabilities in comparison to sun drying over the observation period. This comparison reflects the moisture removal behavior observed during the experiment and does not represent the total drying time required for either method to reach the target moisture content under practical conditions. In addition, the practice of open-air drying has been demonstrated to increase exposure to dust and other contaminants that can affect product quality [6].

The findings of the thin-layer drying models for red rice paddy are summarized in Table 2, while the agreement between the experimental and predicted moisture ratios for the selected model is presented in Figure 3. All models provided reasonable fits, with R^2 values ranging from 0.8935 to 0.9951 across the investigated drying conditions. Among the evaluated models, the Page model demonstrated the highest average R^2 (0.9904) and a low average SSE (0.0050). Despite the fact that the Modified-Page model produced identical R^2 and SSE values, its fitted n values were also found to be highly close to those of the Page model. The Page model was therefore selected for its consistent fitting performance with a simpler formulation. This result is consistent with previous research on five red rice cultivars, in which the Page model also provided the best fit among the models evaluated [12]. However, it should be noted that the fitted parameters and goodness-of-fit results are specific to the respective cultivars and drying conditions. It can thus be concluded that the Page-model parameters under investigation here describe the drying behavior observed in the conditions under investigation in this study. As depicted in Figure 3, the predicted moisture ratios exhibited a high degree of correlation with the experimental data throughout the drying process.

Table 2 Drying kinetics parameters obtained from model fitting under different drying conditions

Model	Parameter	Value					Average
		Sun drying	30 °C	45 °C	60 °C	80 °C	
Newton	k	0.0101	0.0191	0.0146	0.0154	0.0148	
	R^2	0.8935	0.9210	0.9726	0.9905	0.9637	0.9483
	SSE	0.0480	0.0634	0.0139	0.0043	0.0127	0.0284
Page	k	2.68×10^{-4}	1.04×10^{-3}	0.0057	0.0153	0.0418	
	n	1.8789	1.7370	1.2355	1.0012	0.7394	
	R^2	0.9928	0.9906	0.9860	0.9905	0.9921	0.9904
	SSE	0.0033	0.0075	0.0071	0.0043	0.0028	0.0050
Modified-Page	k	0.0126	0.0191	0.0152	0.0154	0.0137	
	n	1.8736	1.7503	1.2322	0.9993	0.7396	
	R^2	0.9928	0.9906	0.9860	0.9905	0.9921	0.9904
	SSE	0.0033	0.0075	0.0071	0.0043	0.0028	0.0050
Henderson & Pabis	a	1.0833	1.0866	1.0478	1.0082	0.9518	
	k	0.0116	0.0208	0.0156	0.0155	0.0137	
	R^2	0.9191	0.9343	0.9793	0.9907	0.9733	0.9593
	SSE	0.0365	0.0528	0.0105	0.0042	0.0094	0.0226
Logarithmic	a	1.0833	1.0865	1.0478	0.9252	0.7486	
	k	0.0115	0.0208	0.0156	0.0187	0.0243	
	b	2.58×10^{-15}	7.85×10^{-17}	4.28×10^{-17}	0.0935	0.2365	
	R^2	0.9191	0.9343	0.9793	0.9923	0.9880	0.9626
	SSE	0.0365	0.0528	0.0105	0.0034	0.0042	0.0215
Wang & Singh	a	-0.0047	-0.0118	-0.0126	-0.0147	-0.0155	
	b	-3.87×10^{-5}	8.75×10^{-6}	4.63×10^{-5}	7.45×10^{-5}	9.01×10^{-5}	
	R^2	0.9810	0.9894	0.9804	0.9943	0.9791	0.9848
	SSE	0.0086	0.0085	0.0100	0.0026	0.0073	0.0074
Aghbashlo	k_1	0.0053	0.0097	0.0122	0.0161	0.0213	
	k_2	-0.0071	-0.0085	-0.0027	8.34×10^{-4}	0.0075	
	R^2	0.9801	0.9951	0.9796	0.9910	0.9891	0.9870
	SSE	0.0090	0.0039	0.0103	0.0040	0.0038	0.0062

The temperature dependence of the Page model parameters demonstrated distinct trends across the drying conditions investigated. The drying constant (k) increased progressively from 2.68×10^{-4} during sun drying to 0.0418 at 80 °C, consistent with the higher drying rates observed at elevated temperatures [7]. In contrast, the empirical exponent (n) decreased from 1.8789 under sun drying to 0.7394 at 80 °C. Despite the absence of a direct physical interpretation for n , its variation indicates that different parameter combinations were required to describe the moisture ratio profiles under the investigated drying conditions. The remaining models also provided reasonable fits but exhibited different parameter behavior. The Newton model generally produced lower R^2 values and higher SSE values in comparison to the other models, indicating that its single exponential term was less capable of representing the observed moisture ratio profiles. The Henderson and Pabis model demonstrated an enhancement over the Newton model through the introduction of a scaling coefficient (a). Contrastively, the Logarithmic model exhibited a condition-dependent contribution from its additional parameter (b). In the course of the sun-drying process conducted at temperatures of 30 °C and 45 °C, the fitted b values were found to be close to zero. Whilst, the corresponding a and k values exhibited a high degree of similarity to those obtained through the application of the Henderson and Pabis model. Accordingly, the R^2 and SSE values were found to be identical under these conditions, indicating that the fitted contribution of the b term was negligible. At temperatures of 60 and 80 °C, the fitted b values increased and the model yielded R^2 values of 0.9923 and 0.9880, respectively. These findings indicate that the contribution of the additional term exhibited variability across the range of the drying conditions investigated. The Wang & Singh model also demonstrated high fitting accuracy, particularly at 60 °C ($R^2 = 0.9943$), although its fitting performance showed greater variation among drying temperatures. Likewise, the Aghbashlo model produced satisfactory goodness-of-fit statistics, although the second parameter (k_2) remained close to zero under most drying conditions, suggesting only a minor contribution of the additional exponential term.

As summarized in Table 3, the dimensionless numbers and transport coefficients indicate a relatively consistent convective regime over 30–80 °C. This is reflected by the convective heat transfer coefficient (h_c), which remained nearly constant at 68.43 ± 0.40 W/(m²·K), indicating limited sensitivity to temperature under the present airflow conditions. This finding aligns with the observation reported by Golpour et al. [24], who reported that h_c exhibited minimal sensitivity to temperature, with a more pronounced response to air velocity. In their study, h_c demonstrated only a slight temperature dependence, although a slight decrease was observed with increasing temperature at a constant air velocity. The difference in the direction of the temperature trend observed between the two studies may be associated with differences in the operating and material conditions. However, the h_c values in this study are lower than the reported h_c range of 811–2,474 W/(m²·K), likely due to differences in flow configuration and operating conditions, particularly air velocity. Differences in moisture content, porosity, thermophysical properties, and product shape and size may also contribute to the variation in convective heat transfer coefficients between drying systems [24].

Table 3 Dimensionless numbers and heat and mass transfer coefficients at different drying temperatures of red rice paddy

T_{drying} (°C)	Reynolds number	Schmidt number	Prandtl number	Sherwood number	Nusselt number	h_m (m/s)	h_c (W/(m ² ·K))
30	20.65	0.6082	0.7029	7.733	8.016	0.0649	68.16
45	18.81	0.5966	0.7011	7.385	7.683	0.0695	68.07
60	17.50	0.5788	0.6997	7.106	7.439	0.0741	68.51
80	15.80	0.5665	0.6955	6.769	7.106	0.0799	68.95

In contrast, the convective mass transfer coefficient (h_m) demonstrated an increase from 0.0649 to 0.0799 m/s with an increase in temperature. This finding is consistent with the observation made by Zeng et al. [15] and Golpour et al. [24], who also reported an increase in mass transfer coefficients with increasing drying temperature. However, the magnitude of h_m varied considerably between the present study and the values reported by Golpour et al. [24]. In their study, the range of h_m for paddy was found to be from 5.118×10^{-8} to 4.807×10^{-6} m/s, whereas the present study yielded values between 0.0649 and 0.0799 m/s. Such differences may reflect the distinct drying configurations, airflow conditions, material characteristics, and correlations utilized to estimate the convective mass transfer coefficient. It is evident that an increase in temperature can result in enhanced molecular mobility and an increase in water vapor transport. As depicted in Figure 4(A), the relationship between h_m and temperature is expressed as a linear function ($R^2 = 0.9998$), as expressed in Equation (20).

$$h_m = 0.0003T + 0.0560 \quad (20)$$

An Arrhenius-type relationship was also observed from the $\ln(h_m)$ versus $1/T$ plot (Figure 4(B)), yielding $R^2 = 0.9999$ (Equation (21)), which can be expressed as Equation (22).

$$\ln(h_m) = -445.26 \left(\frac{1}{T} \right) - 1.2662 \quad (21)$$

$$h_m = 0.2819 \cdot \exp\left(-\frac{3701.94}{RT}\right) \quad (22)$$

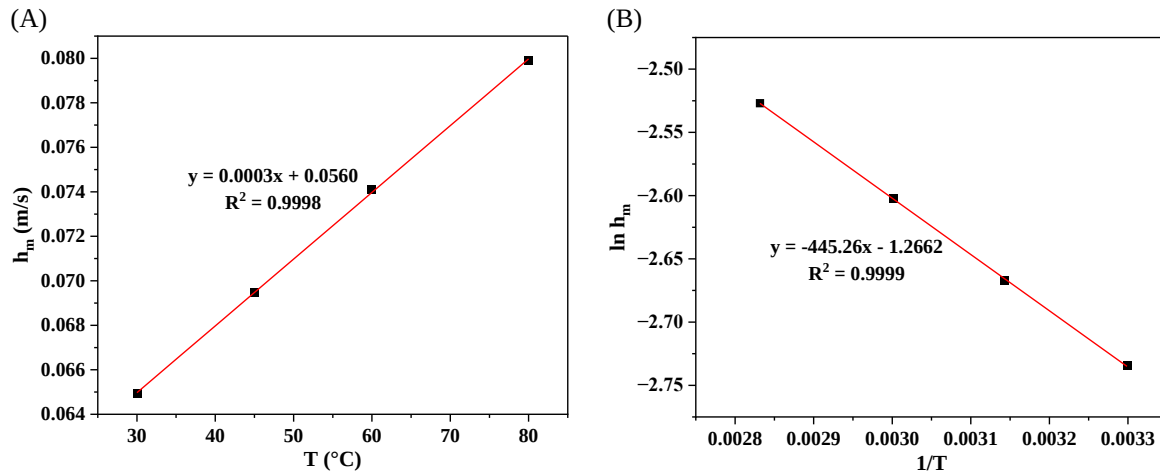


Figure 4 Temperature dependence of the convective mass transfer coefficient evaluated through (A) a linear empirical model and (B) an Arrhenius-type model.

Based on this relationship, the activation energy for convective mass transfer ($E_{a,m}$) was determined to be 3.70 kJ/mol. This value describes the temperature dependence of h_m within the range that was investigated. The observed increase in h_m with temperature is consistent with the temperature-dependent mass transfer behavior reported for thin-layer drying systems [15]. The $E_{a,m}$ obtained in the present study was substantially lower than the 72.325 – 87.386 kJ/mol reported by Golpour et al. [24] for paddy drying. Such differences in $E_{a,m}$ may arise from differences in drying conditions, material properties, airflow characteristics, and the correlations utilized to estimate the convective mass transfer coefficient. Therefore, the difference in $E_{a,m}$ between the present study and the reported values indicates that the temperature dependence of convective mass transfer can exhibit significant variation among drying systems and materials.

4. Conclusion

This study characterized the drying kinetics and heat and mass transfer behavior of red rice paddy under different drying temperatures in a laboratory-scale tray dryer. Increases in temperature have been shown to enhance moisture removal, with the average drying rate increasing from 0.0012 to 0.0020 kg moisture/(kg dry paddy·min) from sun drying to 80 °C. The Page model demonstrated the optimal overall fit, with an average R^2 of 0.9904 and SSE of 0.0050. The estimated convective heat transfer coefficient demonstrated stability, maintaining a consistent value of 68.43 ± 0.40 W/(m²·K), in contrast, the mass transfer coefficient demonstrated an increase from 0.0649 to 0.0799 m/s.

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6. Author Contributions

HH: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft; APAN: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft; DPP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft; MD: Conceptualization, Funding acquisition, Project administration; Resources; Supervision; Validation; Writing – review & editing; CLL: Validation; Writing – review & editing.

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