Determination of Short-Grain Rough Rice Drying Kinetics Under Isothermal Conditions Using an Integrated Model

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The constants of the drying kinetics models of short-grain rough rice were determined under isothermal conditions between a temperature of 40 °C and 100 °C. The initial moisture content of the rough rice was 28.2% dry basis. The results revealed that increasing the drying temperature and drying duration decreased the moisture content of the rough rice. The lowest rough rice moisture content (15.58% dry basis) was achieved at a drying temperature of 100 °C and a drying duration of 6 h. Four well-known models, *i.e.*, Page, Newton, Logarithmic, and Henderson and Pabis, were evaluated. The models were evaluated based on the highest coefficient of determination value; the lowest root means square error, and the Chi-square value. The Page and Logarithmic models fit four and three cases of the seven drying curves, respectively, among the four evaluated models. Accordingly, combining the Page and Logarithmic models in an integrated model resulted in a model that fits all the seven studied curves. Furthermore, increasing the air temperature from 40 °C to 100 °C increased the moisture diffusivity from 1.5517 × 10^{-9} m^2/s to 4.2698 × 10^{-9} m^2/s. As a result, the activation energy value reached 16.43 kJ/mol for short-grain rough rice under the studied drying conditions.

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INTRODUCTION

The grain drying process is estimated to consume 10% to 15% of the total energy requirements of all the food industries in developed countries (Klemeš *et al.* 2008). There are more than 200 types of dryers that can be used for drying agricultural products (Klemeš *et al.* 2008). The efficiency of the drying process is affected by drying features, *i.e.*, the drying temperature, air velocity, relative humidity, retention time, and pressure. Therefore, it is essential to study the drying kinetics of each particular product to analyze the drying behavior of agricultural products.

The drying conditions, type of dryer, and material characteristics influence drying kinetics. Over time, the models developed to explore the drying process using the developed dryers have been used in calculations involving the design and construction of new drying systems. Additionally, optimization of the drying process and the description of the entire drying behavior, including the combined macroscopic and microscopic medium heat and mass transfer, have been performed. Therefore, the drying kinetics models are important in deciding the ideal drying conditions, essential parameters for equipment design, process optimization, product quality improvement, energy, exergy analysis, and process automation and control (Giri and Prasad 2007; Erbay and Icier 2010).

The drying characteristics of grain and food materials are complex. It is a complicated process involving simultaneous heat and mass transfer, requiring simple illustrations to predict drying behavior and optimize the drying parameters (Yilbas *et al.* 2003). Thin-layer drying equations have been used for drying time prediction to simplify drying curves (Karathanos and Belessiotis 1999). Thin-layer drying describes the process of drying a single layer of particles. Grains are dried *via* thin-layer drying due to a faster drying process with a minimal loss of nutrients. Thin-layer drying is the basic drying laboratory examination for grains. It is primarily used to determine the drying or rewetting empirical equations (Misra and Brooker 1980). For example, Lewis and Trabelsi (2021) divided a deep bed with a 60 cm height into six 10 cm layers. Then they applied thin-layer drying models to the 10 cm layers. In addition, Chakraverty (1995) mentioned that the thin layer could be 20 cm.

Rice is an important commodity in the U.S., particularly in Arkansas. The U.S. Department of Agriculture National Agricultural Statistics Service has released its perspective planting report for 2021. Based on surveys, the USDA projects approximately 2.71 million ac of planted rice for 2021. Rice cultivars in the U.S. are classified into three categories: long-, medium-, and short-grain, according to the kernel dimensions. The length to width ratio is 3.0 to 3.6 (dimensionless) for long, 2.1 to 2.3 (dimensionless) for medium- and 1.7 to 2.0 (dimensionless) for short-grain rough rice. Long-grain rice is typically dry and fluffy when cooked. Medium-grain rice is moister, tender, and generally stickier than long-grain rice. Short-grain rice is almost round and regularly sticky with a soft texture, essential to the Japanese preference for food (USDA 2019). Short grain rice only accounts for 1% to 2% of U.S. rice production. In other words, the projected acreage of short-grain rice is expected to be 54,000 acres.

Short-grain rice is also used for alcohol production. Koshihikari is known for its excellent eating qualities, flavor, texture, and brewing sake, a Japanese alcoholic beverage. Koshihikari from Japan has been recognized as a premium quality, short-grain cultivar. The current short-grain rice cultivars in the United States are Koshihikari crosses, *i.e.*, RU9601099 from Arkansas and CH-202 from California (Norman and Johnson 1999; Andaya and McKenzie 2014). Arkansas and California are the two-leading rice-producing states in the U.S. California primarily produces medium- and short-grain rice. However, the demand for short-grain rice is rising because of the increasing popularity of sushi and sake. Due to its premium price and different applications, short-grain rice may open up new opportunities for rice farmers in Arkansas. Accordingly, there is a need to determine the drying kinetics of short-grain rough rice.

Grain drying methods can be classified into the following approaches: field drying, natural air drying, low temp drying, high-temperature drying, and combination or dryeration. Permitting the grain to dry in the field is the most widely used method in developing countries. Natural air or low-temperature rice drying is best designated as filling or partially filling bins with freshly harvested rough rice, then running fans to purge air through the bins until the desired moisture content is attained. High-temperature drying is either directed in the grain bin or inside a pass dryer. Heated air is purged through the grain until the grain dries. Combination and dryeration are done by partially drying grain with high-temperature dryers, and then the residue of the drying process is done with low-temperature air and fans (Sadaka *et al.* 2017; Atungulu and Sadaka 2019).

Grain drying models use mathematical equations as tools to explain the drying phenomenon. Thus, the development of these models aims to find mathematical equations for characterizing the system of interest (Gunhan *et al.* 2005). The three categories of thin-layer drying models illustrate the drying phenomenon. They include theoretical models, semi-theoretical models, and empirical models. Theoretical models contemplate only the internal resistance to moisture transfer between the product and the air (Midili *et al.* 2002; Pancharia *et al.* 2002). In contrast, the semi-theoretical and empirical models consider only the external resistance.

The theoretical models need assumptions about the product's geometry, mass diffusivity, and conductivity (Ece and Cihan 1993; Demirtas *et al.* 1998). However, the empirical models neglect the basics of the drying progression and present a direct relationship between the average moisture and drying time using regression analysis (Wang and Singh 1978; Ozdemir and Devres 1999). Thus, the semi-theoretical models compromise the theoretical and empirical ones. They are derived from the simplification of Fick's second law of diffusion.

Researchers developed numerous drying kinetics models that best fit the specific drying conditions for their experiments. These models include Henderson and Pabis, Lewis, Logarithmic, Modified Henderson and Pabis, Page, Modified Page, Two-term exponential, Two-term, Verma, and Midilli models (Kumar *et al.* 2012). For example, the Page model, which was developed more than 70 years ago, represented the best fit for several drying cases. However, Byler *et al.* (1987) reported that this commonly used drying model for thin-layer was inadequate for modeling parboiled rice.

Bualuang *et al.* (2011) developed a mathematical model to describe the drying kinetics of medium and long-grain parboiled rice. They found that the Guggenheim-Anderson-de Boer (GAB) model best fit the experimental data. Golmohammadi *et al.* (2016) investigated the intermittent drying characteristics of paddy rice for various temperatures and tempering times. They found that the Midilli model was the most appropriate for the first drying stage. However, the Two-Term model was most suitable for the second drying stage. Manikantan *et al.* (2014) investigated the drying characteristics of paddies in an integrated dryer with various heating sources (single and combined) at different temperatures. They reported that the Wang and Singh model best described the drying behavior of the paddy for solar, biomass, and a combination of solar and electrical heating sources, while the Page model also adequately described the drying characteristics for an electrical heating source. Beigi *et al.* (2017) studied the deep bed drying of rough rice at various thin layers, drying air temperatures, and flow rates. They also compared mathematical models and artificial neural networks (ANN) to predict the drying curves. They found that the Midilli model best described the drying curves, and that the ANN modeling had a better prediction of the drying curves. Finally, Harchegani *et al.* (2012) evaluated a non-equilibrium model that predicted the drying characteristics of rough rice in a deep-bed dryer. Their model was able to predict the drying behavior of rough rice accurately.

Moreover, a complete understanding of the drying kinetics of short-grain rice is essential for the optimum design of short-grain rice dryers. Thus, this manuscript will fill the research gap in the knowledge of short-grain rice drying kinetics. Thus, the objective of this paper includes the following: (a) evaluating four thin layer models, *i.e.*, Page, Newton, Logarithmic, and Henderson and Pabis, for the drying kinetics of short-grain rough rice under isothermal conditions, and (b) finding a simple mathematical solution for the multi best fit models of the drying curves.

EXPERIMENTAL

Short-grain Rice Collection, Characterization, and Drying

Short-grain rough rice was procured from the Rice Research and Extension Center (Stuttgart, AR) and stored at 4 °C. Approximately 50 kg of the rice sample was visually examined to remove any damaged kernels. The sample was divided into seven subsamples and stored in polyethylene bags. These subsamples were again held in the refrigerator at 4 °C. The physical parameters of the short-grain rough rice, *i.e.*, the moisture content (%), bulk density (kg/m^3), geometric mean diameter (mm), and 1000 kernel mass (g), were investigated. The initial moisture content of the short-grain rough rice was determined using ASAE standard S352.2 (1988). Five samples were collected to assess their average moisture content. The short-grain rough rice bulk density was determined by dividing the mass of the short-grain rough rice by the volume it occupied. The bulk density of the short-grain rough rice was replicated five times to determine the average bulk density value. The short-grain rough rice's length, width, and thickness were measured for 100 kernels using a digital caliper (General Ultratech, Series – 147, Secaucus, NJ) with a 0.02 mm accuracy. The geometric mean diameter was then calculated.

The rough rice samples were dried using a setup-point digital forced air convection oven (Across International FO19040.110, China), as shown in Fig. 1. The oven had a precise temperature control capability that quickly achieved isothermal drying conditions. A scale (Mettler Toledo - PL1502E - Precision Balance, Greifensee, Switzerland) was placed on the top of the furnace to determine the rough rice sample weight. The scale has a capacity of 1520 g with a 0.01 g readability. A metal wire was hung from the top opening through the center of the heating chamber to transfer the sample weight to the scale. The other end carried the sample in a perforated metal container. The rice drying container was cylindrical with an 8.5 cm diameter and a 9.5 cm height.

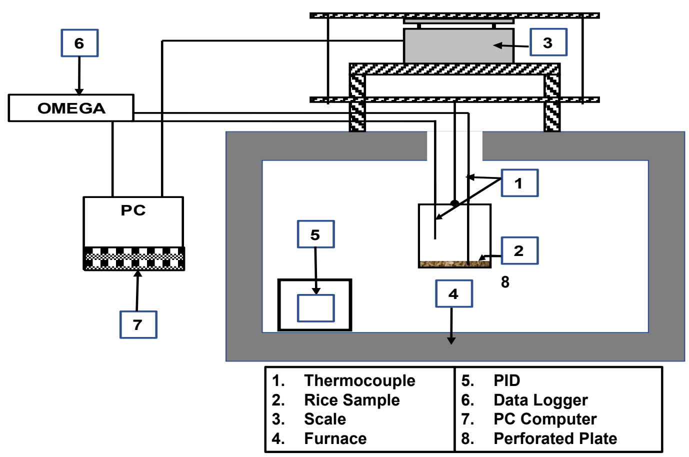

Fig. 1. A schematic drawing of the furnace drying system

The container wall was perforated while the bottom was solid. The height of the rice sample was 2.5 cm. First, the scale was connected to a computer *via* an RS232 for continuous weight recording. Next, a thermocouple (type J) was placed in the center of the rice sample. Then it was connected to a datalogger (TC-08 OMEGA, Akron, OH). Finally, the data logger was used to automate recording the temperature measurements every 30 sec. The data logger was connected to a computer. It should be mentioned that the relative humidity in the lab stayed at 54.0% ± 1.5%. There was no adjustment to the air's relative humidity entering the oven. The initial moisture content of the rough rice was 28.2% db.

The isothermal kinetics of the rough rice drying process were studied at different temperatures, including 40, 50, 60, 70, 80, 90, and 100 °C for 6 h. Approximately 250 g of rough rice was placed in the container, heated to the desired temperature level, and then it was maintained under isothermal conditions for 6 h. The container was cleaned and inspected before each run to avoid the influence of any remaining residuals.

Isothermal Kinetics Analysis of Grain Drying

The moisture ratio (MR) of grain is the proportion of the removed moisture at any time to the overall removed moisture during the drying process. The MR values were determined under isothermal conditions according to Eq. 1,

$$MR = \frac{M-M_e}{M_0-M_e} \quad (1)$$

where *MR* is the moisture ratio (dimensionless), *M* is the moisture content of grain at any time (%, dry basis), M_o is the initial moisture content (%, dry basis), and *I* is the equilibrium moisture content (%, dry basis).

The equilibrium moisture content was calculated using the equation reported by Khanali *et al.* (2016), as shown in Eq. 2,

$$M_e = \left(\frac{ln(1-RH)}{-4.726\times10^{-6}\times(1.8*T+491.7)}\right)^{1/2.386} \quad (2)$$

where *T* is the air temperature (°C), and RH is the relative humidity in decimals.

The drying curves obtained from the developed system for short-grain rice under isothermal conditions were fitted with four well-known drying models, *i.e.*, the Page, Newton, Logarithmic, and Henderson and Pabis models. Various authors gave the thin-layer drying models as follows: The Page model is shown in Eq. 3 (Page 1949; Zhang and Litchfield 1991):

$$MR = \exp(-k_P t^{n_p}) \quad (3)$$

The Newton model is shown in Eq. 4 (Liu and Bakker-Arkema 1997):

$$MR = \exp(-k_N t) \quad (4)$$

The Logarithmic model is shown in Eq. 5 (Akpinar *et al.* 2003):

$$MR = a_L + b_L \exp(-k_L t) \quad (5)$$

The Henderson and Pabis model is shown in Eq. 6 (Henderson and Pabis 1961):

$$MR = c_H\, exp(-k_H t) \quad (6)$$

In these equations, K_p is the Page model constant (dimensionless), n_p is the Page reaction order, *t* is the time (min), K_N is the Newton model constant (dimensionless), K_L is the Logarithmic model constant (dimensionless), a_L and b_L are the Logarithmic model constants (dimensionless), K_H is the Henderson, and Pabis model constant (dimensionless), and c_H is the Henderson and Pabis model constant (dimensionless).

Model Fitting to the Experimental Data

The experimental data fit into the four models for short-grain rough rice. The nonlinear regression was performed using the Solver feature of MS-Excel (Microsoft, version 2013, Chula Vista, CA). The preliminary guesses of the model factors were incorporated based on values published in the literature. The minimization technique was used to reduce the square difference between the experimental moisture ratio values and those attained by fitting the data to the models. The values of the coefficient of determination (R^2), root mean square error (*RMSE*), and chi-square (X^2) were presented along with the kinetics factors to determine the best-fit state. The model with the highest R^2 and lowest *RMSE* and X^2 was chosen as the best model to fit the experimental data. Numerous researchers used the evaluation criteria of the highest R^2 and the lowest *RMSE* and X^2 (Kingsly and Singh 2007; Roberts *et al.* 2008; Phanphanich and Mani 2010; Erbay and Icier 2010; Yun *et al.* 2013; Manikantan *et al.* 2014; Sundaram *et al.* 2016; Sadaka and Atungulu 2018; Owusu-Sekyere *et al.* 2021; Sitorus *et al.* 2021). The *RMSE* and X^2 were calculated according to Eqs. 7 and 8, respectively,

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \quad (7)$$

$$X^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-z} \quad (8)$$

where *RMSE* is root mean square error, *N* is the experimental data points number, $MR_{\text{exp,i}}$ is the experimental moisture ratio, $MR_{\text{pre,i}}$ is the predicted moisture ratio, X^2 is the chi-square value, and *z* is the number of parameters.

Fick's second law was used to determine the effective moisture diffusivity (D_{eff}) and activation energy (E_{a}), as shown in Eq. 9,

$$\frac{\partial MR}{\partial t} = \nabla\left[D_{eff}\ (\nabla MR)\right] \quad (9)$$

where D_{eff} is the effective moisture diffusivity (m^2/s).

The mathematical solution of Eq. 9 is shown in Eq. 10,

$$MR = \frac{6}{\pi^2}\sum_{n=0}^{\infty}\exp\left(-\frac{\pi^2 D_{eff}}{r^2}.t\right) \quad (10)$$

where *r* is the geometric mean radius of the rice kernel (m) (Ashraf *et al.* 2012).

Equation 10 could be further simplified into a straight-line equation, as shown in Eq. 11 (Dadali *et al.* 2007).

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

A straight line is obtained from Eq. 11 by plotting ln(*MR*) *versus* the drying duration, and the D_{eff} for each temperature can be calculated from the slope, as calculated by Eq. 12,

$$Slope = \frac{\pi^2\ D_{eff}}{r^2} \quad (12)$$

An Arrhenius relationship usually expresses the temperature dependence of D_{eff}, as shown in Eq.13,

$$D_{eff} = D_o \exp\left(-\frac{E_a}{R\ (T+273.15)}\right) \quad (13)$$

where D_0 is the pre-exponential factor (m^2/s), E_{a} is the activation energy (kJ/mol), *T* is the drying temperature (°C), and *R* is the ideal gas constant (8.314 J/K.mol) (Cai and Chen 2008).

The activation energy can be calculated by simplifying Eq. 13 into a straight-line equation, as shown by Eq. 14,

$$\ln(D_{eff}) = \ln(D_o) - \frac{E_a}{R}\left(\frac{1}{(T+273.15)}\right) \quad (14)$$

The activation energy could be determined from the slope of the straight line formed from plotting ln(D_{eff}) *versus* [1 / (T + 273.15)].

RESULTS AND DISCUSSION

Physical Properties of Short-grain Rough Rice

The physical properties of the short-grain rough rice were obtained. The results showed that the moisture content, the bulk density, the geometric mean diameter, and the mass of 1000 kernels reached 22.0% ± 0.3% wet basis, 567.60 kg/m^3 ± 7.01 kg/m^3, 3.65 mm ± 0.15 mm, and 22.5 g ± 0.30 g, respectively, for short-grain rough rice.

Effects of the Drying Temperature and Drying Duration on the Rough Rice Temperature, Moisture Content, Moisture Ratio, and Drying Rate

Figure 2 shows the effects of the drying temperature and drying duration on the rice temperature. First, it is clear that increasing the drying temperature and the drying duration increased the rice temperature measured at the center of the sample. It should be mentioned that the sensor was embedded in the middle of the grain layer (approximately 3.25 cm from any sample surface). Additionally, the rice temperature did not reach the setup temperature due to the required energy to evaporate the moisture from the grain. For instance, at the setup temperatures of 100 and 40 °C, the rough rice temperature reached 76.9 and 36.6 °C, respectively, after 6 h. This could be due to the relatively short duration (6 h). Therefore, increasing the time to greater than 6 h could increase the rice temperature.

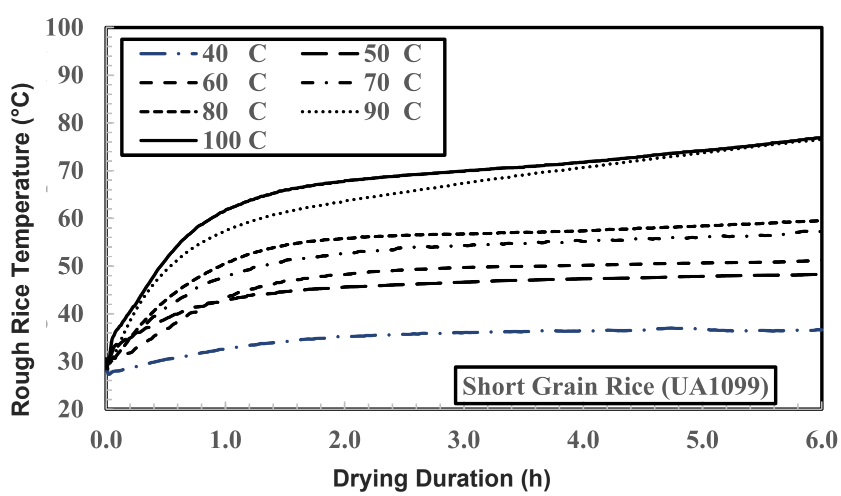

Fig. 2. Effects of the drying temperature and drying duration on the short-grain (UA1099) rough rice temperature measured at the center of the sample (sample thickness was 7.5 cm)

The effects of the drying temperature and drying duration on the moisture content of short-grain rough rice are shown in Fig. 3. The moisture content (dry basis) was obtained from the continuous measurements of the weight readings. It was assumed that the only source of loss was moisture loss, and there was no dry matter loss included under the studied temperature levels. The results showed that increasing the drying temperature and the drying duration decreased the rough rice moisture content. For example, at a drying temperature of 100 °C and a 6 h drying time, the moisture content decreased to 15.58% (dry basis). There was a sharp decrease in the moisture content during the first 3 h of the experimental runs. However, the following decrease in moisture content after 3 h was minor. However, at a drying temperature of 40 °C and a 6 h drying time, the moisture content decreased to 22.00% (dry basis). With the lower temperatures, *i.e.*, 40 °C and 50 °C, the reduction in the moisture content was nearly linear. Consequently, increasing the drying duration at these lower temperatures may result in a plateau shape in the moisture ratio curve.

Normally, drying occurs at a falling rate in most cases. However, this case took place under a temperature higher than 50 °C. The results showed a high moisture removal rate at temperature levels of 60 °C and higher. O'Brien and Siebenmorgen (2006) also indicated that all rough-rice drying curves exhibited a typical exponential drying relationship.

The drying curves were near-linear under the lower temperature levels of 40 and 50 °C. The primary reason for the near-liner shape under the drying temperatures of 40 and 50 °C was the low energy supply to the sample corresponding to these two temperature levels. It should be mentioned that the temperature levels were considerably lower than the set temperature. Other researchers reported similar observations. Ondier *et al.* (2010) reported a near-linear moisture removal rate during the first 10 h of drying rough rice at a drying temperature of 26 °C and a relative humidity of 42%. They also reported that the drying duration required to reach a 12.5% moisture content for Wells rice samples, which had an initial moisture content of 19.6%, required 10.0 h at a temperature of 34.5 °C.

Nadhari *et al.* (2017) investigated the drying characteristics of oil palm trunks under isothermal conditions. The isothermal temperature conditions selected for their study were 25, 30, 35, and 40 °C. The drying characteristics showed that the moisture content decreased almost linearly with time at a temperature range of 25 to 40 °C. Hosain *et al.* (2016) studied the effect of the temperature and loading density on the drying kinetics of wheat. The study was conducted at drying temperatures of 40, 45, and 50 °C. They reported that the moisture ratio continuously decreased throughout the drying progress. In addition, their results revealed that the required drying time to a specific moisture ratio decreased as the drying temperature of wheat was increased.

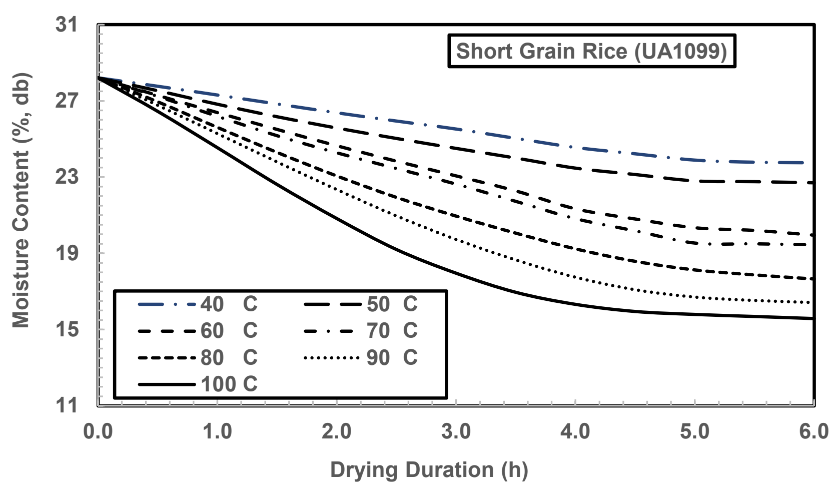

Fig. 3. Effects of the drying temperature and drying duration on the moisture content of short-grain rough rice (UA1099)

Figure 4 shows the effects of the drying temperature and drying duration on the moisture ratio of short-grain rough rice. Since the moisture ratio values were determined from the moisture content of the grain, the correlations followed a similar trend, as shown in Fig. 3. Increasing the drying temperature decreased the equilibrium moisture content, which lowered the final moisture ratio. At drying temperatures of 40 and 100 °C, the final moisture ratios reached 0.744 (dimensionless) and 0.343 (dimensionless), respectively. A sharp decrease in the moisture ratio values was observed at higher drying temperatures and during the first 3 h of the drying process. The lower temperature levels showed a nearly linear relationship between the moisture ratio values and the drying duration. These cases may represent lower energy supplied to the grain to evaporate moisture. The last few hours of the drying process showed less moisture loss, as evident by the near plateau level of the moisture content. The moisture loss variation was directly affected by the binding forces between the moisture and grain. Chen *et al.* (2012) reported that water in any material could be separated into bound water and free water. The bound water is dispersed inside the material and bound by strong forces, which require additional energy for removal. The free water is usually present on a surface with weak bonding forces with the material. It evaporates early at a moderately low drying temperature (below 60 °C). The evaporated water is typically considered the free moisture inadequately bound to the grain.

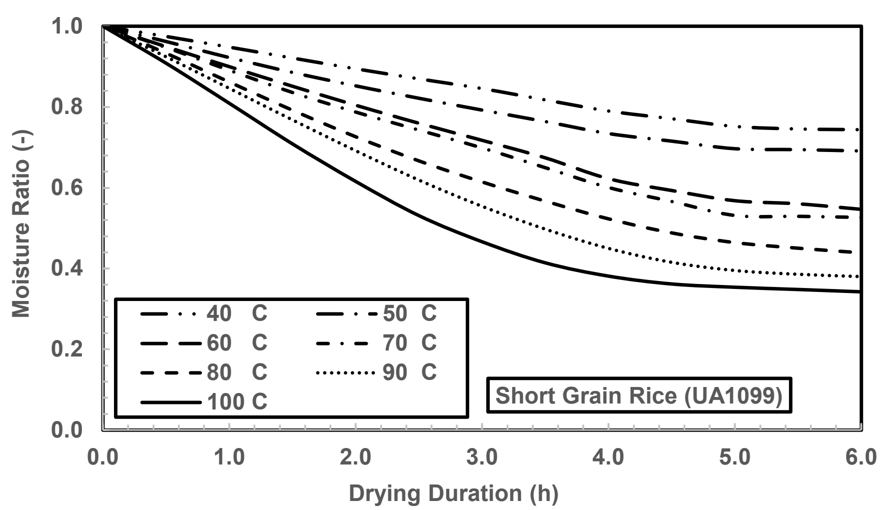

Fig. 4. Effects of the drying temperature and drying duration on the moisture ratio of short-grain rough rice (UA1099)

The drying temperature and drying duration effects on the drying rate were calculated and presented in Fig. 5. The drying temperature increased the drying rate during the first 3 h. For example, increasing the drying temperature from 40 to 100 °C increased the drying rate from 0.90 %/h to 3.67 %/h during the first hour of drying. The maximum drying rate of 3.715 %/h was obtained at a temperature of 100 °C and during the second hour of the drying process. However, during the last 3 h of the drying process, the drying rate decreased compared to the first 3 h. This observation might be due to the lower availability of moisture to be removed during the longer drying duration, predominantly under higher temperatures.

Effects of the Drying Temperature on the Short-Grain Rough Rice Drying Kinetics Constants for the Page, Newton, Logarithmic, and Henderson and Pabis Models

The moisture ratio data *versus* the drying time was statistically analyzed to determine the values of the coefficient of determination (R^2), the root means square error (RMSE), and the chi-square (X^2). Table 1 shows the drying constants of the Page model, Newton model, Logarithmic model, and Henderson and Pabis model. Essentially, the Page model represents the best fit model for 57.1% of the studied cases, as evident by the R^2 values ranging between 0.9968 and 0.9841. In addition, the Logarithmic model represents the best fit model for 42.9% of the studied cases, with an R^2 in the range 0.9968 to 0.9895.

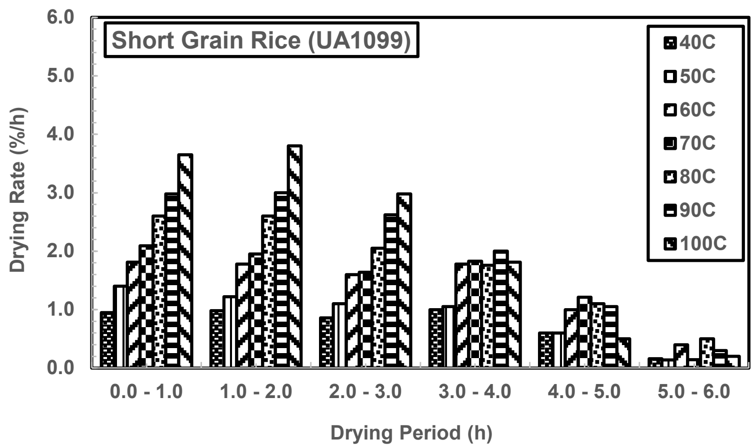

Fig. 5. Effects of the drying temperature and drying duration on the drying rate of rough rice

Determination of the Drying Kinetic Parameters Using an Integrated Model

The previous results yielding two best fit models represent a challenge in selecting the best fit model to run a comprehensive conclusion. Therefore, it was essential to overcome the challenge mathematically. Thus, the Page and Logarithmic models were mathematically integrated into one model to overcome this challenge. The integrated model is shown in Eq. 15,

$$MR = k_I\ [(\exp(-k_P t^n)) + (a_L + b_L \exp(-k_L t))] \tag{15}$$

where K_I is the integrated model constant (dimensionless).

The results showed that the integrated model was the best fit, fitting 100% of the studied cases with adjusted R^2 values ranging between 0.9994 and 0.9984 (not shown in Table 2). The values of the RMSE and X^2 ranged between 0.1210 and 0.0020 and 0.0002 and 0.0000, respectively. The reason for this is the fact that it is a mathematical combination of the two models.

Calculations of the Effective Moisture Diffusivity and Activation Energy

The effective moisture diffusivity (D_{eff}) values were calculated for drying short-grain rough rice based on Eq. 12 and are shown in Table 3. By increasing the drying temperature from 40 °C to 100 °C, the moisture diffusivity increased from 1.5517×10^{-9} m^2/s to 4.2698×10^{-9} m^2/s. More moisture was evaporated at a high drying temperature because the temperature is the leading driving force of moisture evaporation.

Table 1. Effects of the Drying Temperature on the Kinetics Constants for the Studied Models Under Isothermal Conditions for Short-Grain Rough Rice

Model	Temp	Drying Constants								Statistical Parameters		
	°C	K_p	$K_{.N.}$	$K_{.L.}$	K_H	n_p	a_L	b_L	C_H	R^2	RMSE	X^2
Page	40	0.0430				1.2732				0.9955	0.0079	0.0001
Newton	40		0.0640							0.9831	0.0171	0.0003
Logarithmic	40			0.0687			0.0000	1.0183		0.9823	0.0146	0.0003
Henderson&Pabis	40				0.0687				1.0183	0.9823	0.0146	0.0003
Page	50	0.0735				1.0698				0.9968	0.0065	0.0000
Newton	50		0.0813							0.9952	0.0082	0.0001
Logarithmic	50			0.0826			0.0000	1.0052		0.9950	0.0078	0.0001
Henderson&Pabis	50				0.0826				1.0052	0.9950	0.0078	0.0001
Page	60	0.2263				1.4181				0.9841	0.0033	0.0001
Newton	60		0.3563							0.9567	0.0032	0.0001
Logarithmic	60			0.3830			0.0000	1.1013		0.9491	0.0032	0.0001
Henderson&Pabis	60				0.3831				1.1013	0.9491	0.0032	0.0001
Page	70	0.1193				1.0188				0.9961	0.0088	0.0001
Newton	70		0.1224							0.9963	0.0090	0.0001
Logarithmic	70			0.1349			0.0582	0.9494		0.9967	0.0085	0.0001
Henderson&Pabis	70				0.1238				1.0051	0.9964	0.0087	0.0001
Page	80	0.1675				0.9380				0.9924	0.0146	0.0003
Newton	80		0.1541							0.9896	0.0165	0.0003
Logarithmic	80			0.2353			0.2289	0.7862		0.9968	0.0102	0.0001
Henderson&Pabis	80				0.1526				0.9946	0.9894	0.0163	0.0003
Page	90	0.2263				1.4181				0.9940	0.2116	0.0529
Newton	90		0.1855							0.9853	0.0214	0.0005
Logarithmic	90			0.2591			0.1699	0.8528		0.9926	0.0171	0.0003
Henderson&Pabis	90				0.1865	1.2732				0.9854	0.0213	0.0005
Page	100	0.2584								0.9732	0.0255	0.0007
Newton	100		0.2240				0.0000	1.0183		0.9634	0.0368	0.0016
Logarithmic	100									0.9895	0.0219	0.0006
Henderson&Pabis	100									0.9623	0.0364	0.0016

Table 2. Effects of the Drying Temperature on the Kinetics Constants for the Integrated Model Under Isothermal Conditions for Short-Grain Rough Rice

Temp (°C)	Drying Constants						Statistical Parameters		
	K_l	K_p	$K_{L.}$	n_p	a_L	b_L	R^2	RMSE	X^2
40	0.7061	0.0409	0.0210	1.4552	0.2477	0.2827	0.9955	0.0073	0.0001
50	0.3348	0.0001	0.1227	4.3582	0.0000	1.9860	0.9997	0.0020	0.0000
60	0.6378	0.1291	0.0203	1.3151	0.1886	0.3617	0.9976	0.0082	0.0001
70	0.5374	0.1650	0.0153	1.4228	0.4987	0.3356	0.9974	0.0085	0.0001
80	0.4175	0.1096	0.8237	1.8308	0.9884	0.4094	0.9999	0.0023	0.0000
90	0.6373	0.2392	0.0156	1.4216	0.2870	0.2679	0.9987	0.0075	0.0001
100	0.6711	0.2786	0.0162	1.5447	0.4059	0.761	0.9984	0.0121	0.0002

Table 3. Effects of Drying Temperature on the Moisture Diffusivity and Activation Energy for Short-Grain Rough Rice

Temperature (°C)	Moisture Diffusivity (m^2/s)	Activation Energy (kJ/mol)
40	1.5517×10^{-9}	16.43
50	1.8362×10^{-9}	
60	2.6941×10^{-9}	
70	2.7007×10^{-9}	
80	3.2062×10^{-9}	
90	3.8847×10^{-9}	
100	4.2698×10^{-9}	

Therefore, the practical moisture diffusivity value increased as the drying temperature increased. This phenomenon may occur due to more energy being provided at higher drying temperatures, which increases the activity of water molecules and increases the drying rate. As the temperature increased, the bound moisture became distributed inside the grain with moderately strong bonding began to evaporate in the drying process.

Additionally, the primary constituent of rice (starch) is a polymer of glucose. Its thermal and material properties vary depending on the processing temperature and moisture content (Slade and Levine 1995). Thus, as it goes through a glass transition, the change of state of starch plays an important role in rice drying. Perdon *et al.* (1999) reported that this state transition occurs in the rice drying temperature range.

The values of the D_{eff} attained from the current study were comparable to those stated in the literature. Correa *et al.* (2011), Chen *et al.* (2012), and Sandeep *et al.* (2013) assessed the effective diffusivity coefficient at various temperature levels. They all also decided that the D_{eff} values increased as the drying temperature increased. Doymaz (2004) studied the effects of the air temperature, airflow rate, and sample thickness on the drying kinetics of carrot cubes. The calculated values for the moisture diffusivity ranged from 0.776×10^{-9} m^2/s to 9.335×10^{-9} m^2/s. In addition, Erbay and Icier (2009) dried olive leaves in a tray drier at various temperatures and air velocities. The moisture diffusivity ranged from 1.0544×10^{-9} m^2/s to 4.9735×10^{-9} m^2/s.

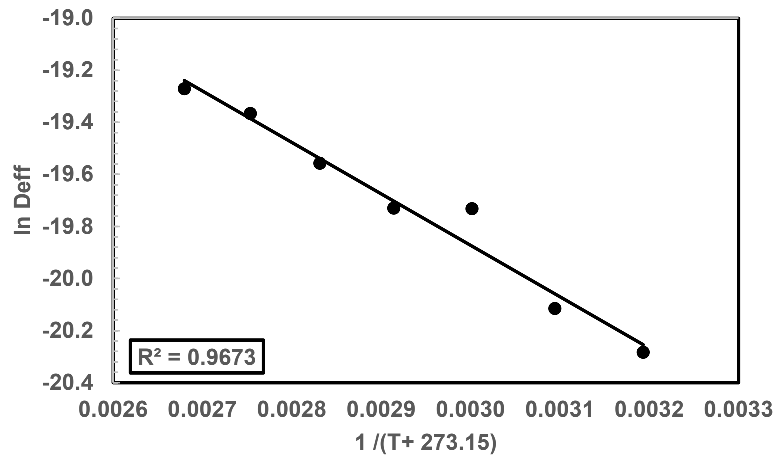

Fig. 6. Relationship between the ln(D_{eff}) and the reverse of the absolute temperature for short-grain rough rice

The activation energy value was calculated according to Eq. 14. A linear correlation between $ln(D_{eff})$ and $[1 / (T + 273.15)]$ is shown in Fig. 6 as an Arrhenius type dependence. The quantity of the activation energy was calculated from the slope of the line. It reached 16.43 kJ/mol for short-grain rough rice under constant drying conditions. The activation energy value was lower than the value reported by Golmohammadi *et al.* (2016). They studied the drying characteristics of rice at various temperatures and tempering times and found the activation energy to be 22.99 kJ/mol. Yogendrasasidhar and Setty (2019) experimented with thin-layer drying of pearl millet using a multistage fluidized bed dryer. The activation energy was 17.56 kJ/mol for the single-stage fluidized bed dryer.

CONCLUSIONS

- The drying kinetics of short-grain rough rice under isothermal drying conditions were explored.
- The moisture reduction values were profoundly higher than the residual drying duration during the first 3 h.
- Increasing the drying temperature and the drying duration decreased the moisture ratio values.
- The Page and Logarithmic models fit four and three of the seven studied drying curves during the thin layer drying of short-grain rough rice, respectively.
- Integrating the Page and Logarithmic models in one equation resulted in the best fit of all studied cases.
- Increasing the air temperature from 40 to 100 °C increased the moisture diffusivity from 1.5517×10^{-9} m^2/s to 4.2698×10^{-9} m^2/s.
- The quantity of the activation energy was calculated from the slope of the line. It reached 16.43 kJ/mol for short-grain rough rice under constant drying conditions.

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