Open Journal of Applied Sciences, 2022, 12, 822-844
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Determination of the Drying Kinetics Modeling and Activation Energy of Medium-Grain and Long-Grain Rough Rice under Isothermal Conditions

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How to cite this paper: Sadaka, S. and Kalyankar, V. (2022) Determination of the Drying Kinetics Modeling and Activation Energy of Medium-Grain and Long-Grain Rough Rice under Isothermal Conditions. *Open Journal of Applied Sciences*, **12**, 822-844.
https://doi.org/10.4236/ojapps.2022.125056

Received: April 1, 2022
Accepted: May 28, 2022
Published: May 31, 2022

Abstract

The available literature revealed a gap in reporting the rough rice drying kinetics parameters under isothermal conditions, particularly for Arkansas medium- and long-grain varieties. Therefore, medium-grain (RO170112 and Titan) and the long-grain (Diamond and Wells) rough rice varieties were dried under isothermal conditions. The drying process occurred under 40˚C, 50˚C, 60˚C, 70˚C, 80˚C, 90˚C, and 100˚C in a system emulating the thermogravimetric analyzer. Drying kinetics models were studied for four well-known models: Page, Newton, Logarithmic, and Henderson & Pabis. The drying kinetics constants were determined for the four studied models. The initial moisture content of rough rice was 28.2% db. Profound moisture reduction was observed during the first three hours of drying, followed by less moisture content reduction. The results showed that at the drying temperature of 100˚C and after 6 hours of the drying process, the lowest moisture content reached 13.9% (db) for Titan rough rice. The drying rate of rough rice ranged between 7.41 and 2.01%/h during the first hour of drying under the studied temperature range of 40˚C to 100˚C. The drying rate was higher with the higher temperature levels during the first three hours. Among all the studied models, the Page, Newton, and Logarithmic models best fit 25%, 25%, and 50% of the twenty-eight studied cases. The challenge that arose from these results led to evolving a mathematical solution by joining the three models in one equation. The combined model showed the best fit for all the studied cases, with R^2 ranging between 0.9999 and 0.9954 for the medium- and long-grain rice varieties. Increasing the drying temperature increased the effective moisture diffusivity values. The highest effective moisture diffusivity of 18.104×10^{-9} m^2/s was obtained at the drying temperature of 100˚C for medium-grain rice, Titan. The activation energy values ranged between 17.77 and 24.48 kJ/mol for the four rough rice varieties.

Keywords

Drying Kinetics, Effective Moisture Diffusivity, Long-Grain Rice, Medium-Grain Rice, Activation Energy

1. Introduction

The USDA projected about 1,096,698.1 hectares of planted rice for 2021 [1]. According to kernels dimensions, rice cultivars in the U.S. are classified into three categories: long-, medium-, and short-grain. Long-grain rice is typically dry and fluffy when cooked. Medium-grain rice is moister and tender than long-grain rice. Short-grain rice is almost round and regularly sticky with a soft texture [2]. Arkansas and California are the two leading rice-producing states in the U.S. Typically, the moisture content of harvested rough rice is 20% - 22% wet basis (wb). Therefore, the rice should be dried to a safe moisture content of 13% to avoid spoilage during storage. The grain drying process is estimated to utilize 10% to 15% of the total energy requirements of all the food industries in developed countries [3] [4] [5]. During the drying processes, the primary factor of all the stated techniques is the mass transfer of water from grain tissues to their surroundings and vice versa. This transfer occurs through several mechanisms such as capillary flow, diffusion of water due to concentration differences, surface diffusion, and vapor diffusion in the pores due to pressure gradient. The efficiency of the drying process is affected by drying features, *i.e.*, drying temperature, air velocity, relative humidity, product retention time, and pressure. These factors vary according to the agricultural products and technique of drying. So, it is essential to study the drying kinetics of each product to analyze the drying behavior of agricultural products.

Several thin-layer drying equations were used for drying prediction to simplify drying curves [6]. Aguerre *et al.* [7] studied the drying kinetics of rough grain rice. They calculated diffusion coefficients using nonlinear regression analysis by comparing actual and predicted values of the grain moisture content. They did not find differences between the diffusion coefficients for rewetted materials and harvested ones. The activation energy was calculated to be 41.4 kJ/mol. Golmohammadi *et al.* [8] studied 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. They also found that the Two-Term model was most appropriate for the second drying stage. The activation energy was calculated to be 22.987 kJ/mol. The effective moisture diffusivity values ranged from 3.89 and 6.58×10^{-9} m^2/s over their temperature range. The authors concluded that the drying rate is significantly improved by adding a tempering period between the drying stages and increasing the drying temperature. Tezcan *et al.* [9] observed the SEC values of 3.77 - 4.45 kJ/kg during the thin-layer drying of dill leaves in a continuous type IR dryer.

Paddy drying characteristics were investigated in an integrated dryer with various heating sources (single and combined). Wang and Singh's model best described the drying behavior of the paddy for solar, biomass, and a combination of solar and electrical heating sources. The Page model adequately described the drying characteristics for an electrical heating source, as reported by Manikantan *et al.* [10]. Beigi *et al.* [11] studied the deep bed drying of rough rice kernels at various thin layers, drying air temperatures, and flow rates. They compared mathematical models and artificial neural networks to predict the drying curves. The Midilli model best described the drying curves out of all the mathematical models.

On the other hand, the ANN modeling has better predictions of drying curves. Bualuang *et al.* [12] studied the thermo-physical properties. They developed a mathematical model to explore the drying kinetics of medium and long-grain parboiled rice. They found that the GAB model fit the experimental data the best. The authors also found that the thermophysical properties of the rice varieties depend on the moisture content of the samples. Harchegani *et al.* [13] evaluated a non-equilibrium model that predicted the drying characteristics of rough rice in a deep-bed dryer. They studied the effects of temperature, air velocity, and relative humidity in the drying process. The authors found that the drying air temperature had the most significant impact on the drying process. Therefore, they concluded that their model accurately predicted the rough rice drying behavior. Jindal and Siebenmorgen [14] studied the effects of oven drying temperature and drying time on the determination of the whole kernel, long-grain rough rice at different moisture content levels ranging from 9% to 22% (w.b.). They developed an equation that relates the standard and apparent moisture contents used to quantify the effects of oven drying temperatures and times. They reported that the simplified oven method could be used for rapid moisture measurement with accuracy similar to that of a standard Association of Official Analytical Chemists (AOAC) method. Experiments were performed on thin-layer wheat drying to develop a kinetic model based on internal control for water transfer and the absence of temperature gradients inside the kernel [15]. The authors found the activation energy to be 39.0 kJ/mol. Using these parameters in their kinetic model, they found that drying times could be decreased by about four times when raising the air temperature from 40˚C to 70˚C. The bed height did not make a difference.

Two major challenges are facing the development of kinetic models. First, the periodic sampling or, in other words, the intermittent sampling of agricultural products to determine the drying kinetics could present a challenge as the drying conditions could vary. Additionally, the lack of data related to kinetic Arkansas parameters of Arkansas medium- and long-grain rough rice drying needs to be investigated. Therefore, the objectives of this study were: 1) to determine the drying kinetics parameters of medium-grain rice (RO170112 and Titan) and long-grain rice (Diamond and wells) using four well-known models, and 2) to quantify the effective moisture diffusivity and the activation energy for drying the studied rough rice varieties.

2. Materials and Methods

2.1. Medium- and Long-Grain Rice Collection, Characterization, and Drying

Arkansas medium-grain rough rice (RO170112, Titan) and long-grain rough rice (Diamond, Wells) were procured from the Rice Research and Extension Center, Stuttgart, AR, USA, and then stored at 4˚C. First, approximately 50 kg of each rice variety was visually examined to remove any damaged kernels. Next, each sample was divided into seven subsamples and stored in polyethylene bags. These subsamples were again stored in the refrigerator at 4˚C. Subsequently, the physical parameters of rough rice samples, such as moisture content (%), bulk density (kg/m^3), length, width, thickness, and 1000 kernel mass (g), were determined. The initial moisture contents of rough rice samples were determined using ASAE S352.2 [16]. The rough rice samples' bulk densities were determined by dividing the mass of rough rice by the volume it occupies. Kernel dimensions are primary quality factors in processing, drying, handling equipment, breeding, marketing, and grading, as Adair *et al.* [17] reported. Thus, the dimensions of the rough rice, *i.e.*, length, width, and thickness, were measured using a digital caliper (General Ultratech, Series—147, Secaucus, NJ, USA). The caliper has an accuracy of 0.02 mm. The geometric mean diameter was then calculated by taking the cube root of the product of the three basic dimensions.

Rough rice samples were dried using a set-point digital forced air convection oven, as shown in **Figure 1**. The furnace 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

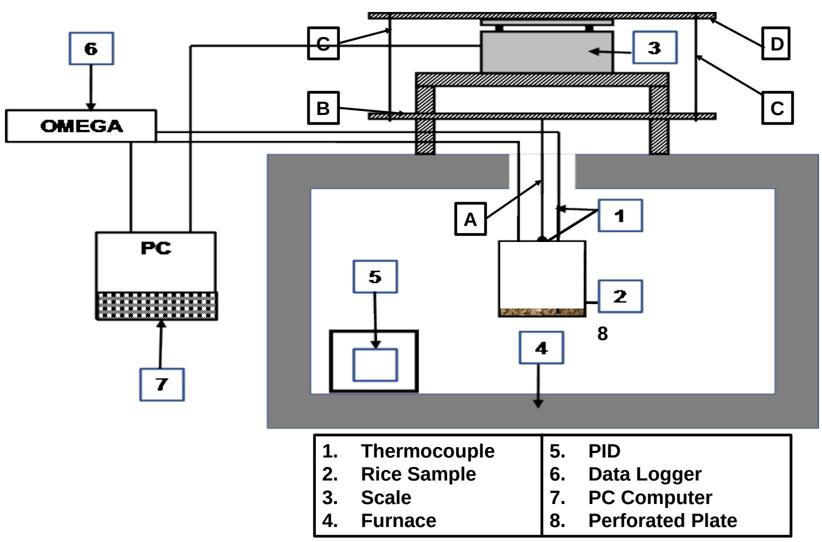

Figure 1. A schematic drawing of the furnace drying system.

top of the furnace to determine the rough rice sample weight. The scale has a capacity of 1520 g with 0.01 g readability. The scale was connected to a P.C. via an RS232 for continuous weight recording. It was adjusted to send the sample weight every 10 seconds to a spreadsheet.

About 90 g of rough rice was placed in the sample container, and then the container was placed in the furnace. The container wall is perforated while the bottom is solid. It is cylindrical with an 8.5 cm diameter and 9.5 cm height. The height of the rice sample was 2.5 cm. Therefore, the rice sample resembles a thin layer. Lewis and Trabelsi [18] divided a deep bed of 60 cm in height into six 10-cm layers. Then they applied thin-layer drying models on layers of 10 cm in height. Also, Chakraverty [19] mentioned that the thin layer could be 20 cm. A metal wire was hung from the oven top opening through the center of the heating chamber to transfer the sample weight to the scale. The sample weight was transferred vertically through the verticle rod (A) connected to a horizontal rod (B). The horizontal rod transferred the sample weight to the scale via other vertical and horizontal rods (C and D) (**Figure 1**). The other end carried the sample in a perforated metal container.

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, Ohio). Finally, the data logger was used to automate recording the temperature measurements every 30 seconds. The data logger was connected to a P.C. It should be mentioned that the relative humidity in the lab stayed at 54.0% ± 1.5%. The initial moisture content of rough rice was 28.2% d.b. Next, the furnace was heated to the desired temperature. It was attached to the suspended wire and then maintained under isothermal conditions. For six hours, the isothermal kinetics of the rough rice drying was studied at different temperature levels, *i.e.*, 40˚C, 50˚C, 60˚C, 70˚C, 80˚C, 90˚C, and 100˚C. Then, the container was then cleaned and inspected before each run to avoid the influence of any remaining residuals.

2.2. Isothermal Kinetic Analysis of Grain Drying and Model Fitting to the Experimental Data

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. On the other hand, equilibrium moisture content (M_e) is the state of equilibrium moisture content of grain that will be eventually achieved with the environment for a given air temperature and RH. The *MR* and M_e values were determined under isothermal conditions by the following equations Equation (1) and Equation (2) [20]:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

$$M_e = \left(\frac{\ln(1 - RH)}{-4.726 \times 10^{-6} \times (1.8 * T + 491.7)} \right)^{1/2.386} \tag{2}$$

where

MR = Moisture ratio (dimensionless),

M = Moisture content at any time > 0 (%, dry basis),

M_0 = Initial moisture content (%, dry basis), and

M_e = Equilibrium moisture content (%, dry basis).

T = Air temperature in ˚C, and

RH = Air relative humidity in decimals.

The drying curves obtained from the developed system for medium-grain rice and long-grain rice under the isothermal conditions were fitted with four well-known drying models: the Page [21] [22], Newton [23], Logarithmic [24], and Henderson & Pabis models [25] as shown in Equations (3)-(6), respectively.

$$MR = \exp\left(-k_P t^{n_P}\right) \tag{3}$$

$$MR = \exp\left(-k_N t\right) \tag{4}$$

$$MR = a + b\exp\left(-k_L t\right) \tag{5}$$

$$MR = c\exp\left(-k_H t\right) \tag{6}$$

where

K_p = Page model costant (dimensionless),

n_p = Page reaction order, (dimensionless),

t = Time (min),

K_N = Newton model costant (dimensionless),

K_L = Logarithmic model constant (dimensionless),

a, b = Logarithmic model constants (dimensionless),

K_H = Henderson and Pabis model constant (dimensionless),

c = Henderson and Pabis model constant (dimensionless).

2.3. Model Fitting to the Experimental Data

The experimental data were fitted into the models above for the studied cases. The nonlinear regression was performed using the Solver feature of MS-Excel (Microsoft, version 2013, Chula Vista, CA, USA). 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) and Root Mean Square Error ($RMSE$) were calculated to determine the best-fit state. The model with the highest R^2 and least $RMSE$ was chosen as the best model fitting the experimental data. It should be mentioned that numerous researchers used the evaluation criteria of the highest R^2 and lowest $RMSE$ [26].

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

where

$RMSE$ = Root mean square error,

N = Experimental data points number,

$MR_{exp,i}$ = Experimental moisture ratio,

$MR_{pre,i}$ = Predicted moisture ratio.

2.4. Determination of the Effective Moisture Diffusivity and Activation Energy

To determine the effective moisture diffusivity (D_{eff}) and activation energy (E_a), Fick's second law, shown in Equation (8), was used as follows.

$$\frac{\partial MR}{\partial t} = \nabla\left[D_{eff}\left(\nabla MR\right)\right] \tag{8}$$

where

D_{eff} = Effective moisture diffusivity (m^2/s).

The mathematical solution of Equation (8) is shown in Equation (9) [27].

$$MR = \frac{6}{\pi^2}\sum_{n=0}^{\infty}\exp\left(-\frac{\pi^2 D_{eff}}{r^2}\cdot t\right) \tag{9}$$

where

r = Geometric mean radius of the rice kernel (m).

Equation (9) could be further simplified into a straight-line equation, as shown in Equation (10) [28].

$$\ln MR = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{r^2}\cdot t\right) \tag{10}$$

A straight line is obtained from Equation (10) by plotting ln(MR) versus drying duration, and the D_{eff} for each temperature can be calculated from the slope:

$$\text{Slope} = \frac{\pi^2 D_{eff}}{r^2} \tag{11}$$

An Arrhenius relationship typically shows the temperature dependence of D_{eff} as in Equation (12) [29] [30].

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R\left(T + 273.15\right)}\right) \tag{12}$$

where

D_0 = Pre-exponential factor (m^2/s),

E_a = Ativation energy (kJ/mol),

T = Drying temperature (˚C), and

R = Ideal gas constant (8.314, J/K·mol).

The activation energy can be determined by simplifying Equation (12) into a straight line, as shown in Equation (13).

$$\ln\left(D_{eff}\right) = \ln\left(D_0\right) - \frac{E_a}{R}\left(\frac{1}{T + 273.15}\right) \tag{13}$$

The activation energy could be determined from the slope of the straight line formed from plotting ln(D_{eff}) versus [l/(T + 273.15)] [31].

3. Results and Discussion

3.1. Physical Properties of Medium-Grain and Long-Grain Rough Rice

Rice is produced and sold based on grain size and shape. Therefore, rice's physical properties, *i.e.*, moisture content, bulk density, dimensions, and weight, are of prime importance. The physical properties of medium-grain (RO170112 and Titan) and long-grain (Diamond and Wells) rough rice were obtained, as shown in Table 1. The results showed that the moisture content of rice samples ranged between 21.86% and 22.31% w.b. The bulk density of medium- and long-grain rice ranged between 540.23 and 607.85 kg/m^3. The length of medium-grain rice for RO170112 and Titan were 8.38 and 8.54 mm, respectively.

On the other hand, the length of long-grain rice (Diamond and Wells) was 9.05 and 9.48 mm, respectively. Therefore, as the name implies, the long-grain rice was lengthier than the medium-grain rice. Test weight measure of quality is a useful relative indicator of total milled rice yields. Test weight measures the amount of unfilled, shriveled, and immature grain based on the size standards established for the three-grain types [32]. The mass of 1000 medium- and long-grain rice kernels ranged between 24.5 and 26.0 g.

3.2. Effects of Drying Temperature and Drying Duration on Medium- and Long-Grain Rice Temperature, Moisture Content, Moisture Ratio, and Drying Rate

Figure 2 shows drying temperatures and durations effects on the two medium rough rice grains (RO170112 and Titan) and two long-grain rough rice (Diamond and Wells) temperatures. Increasing the drying temperature and the drying duration increased the rice temperature measured at the center of the container. The rice temperatures increased exponentially in the first two hours until they reached almost a plateau in the remaining four hours, except in the cases of higher temperatures. The rice temperature was usually less than the desired temperature, with the highest temperature of 82.4˚C. It was achieved at the drying temperature of 100˚C and after 6 hours for long-grain rice (Diamond). At

Table 1. Medium and long-grain rough rice properties.

Rough Rice Variety	Properties and Units						
	*Moisture content (%, w.b.)	*Bulk density (kg/m^3)	**Grain Length (mm)	**Grain Width (mm)	**Grain Thickness (mm)	**Grain Geometric Mean Diameter (mm)	*Mass of 1000 kernels (g)
Medium-grain (RO170112)	22.11 ± 0.32	540.23 ± 9.48	8.38 ± 0.34	3.09 ± 0.23	2.08 ± 0.18	3.77 ± 0.21	25.2 ± 0.8
Medium-grain (Titan)	21.86 ± 0.33	592.67 ± 0.67	8.54 ± 0.35	2.90 ± 0.20	1.99 ± 0.16	3.66 ± 0.17	26.0 ± 1.0
Long-grain (Diamond)	22.31 ± 0.34	607.85 ± 3.98	9.05 ± 0.40	2.42 ± 0.18	1.90 ± 0.08	3.47 ± 0.14	24.5 ± 0.2
Long-grain (Wells)	21.92 ± 0.35	566.52 ± 1.16	9.48 ± 0.54	2.32 ± 0.17	1.90 ± 0.12	3.47 ± 0.15	24.5 ± 1.2

*Average of 5 samples; **Average of 50 samples.

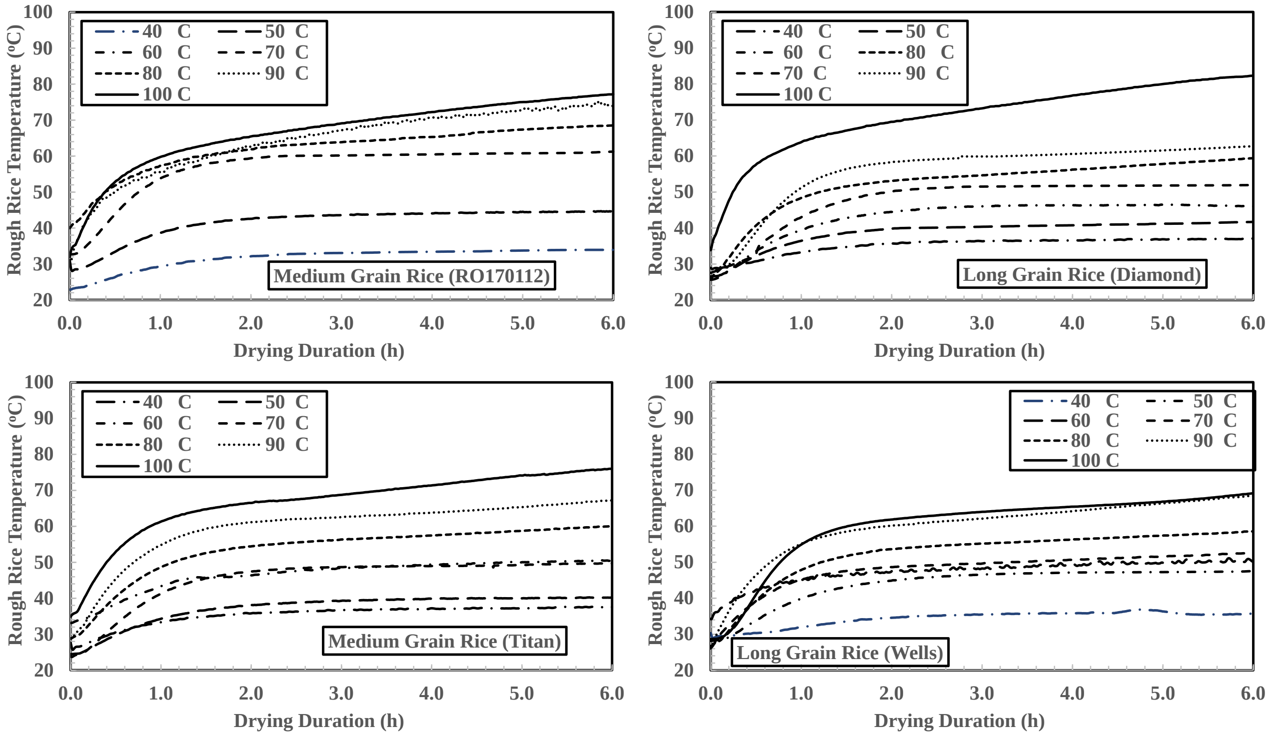

Figure 2. Effects of drying temperature and drying duration of rough rice temperature for medium- and long-grain rough rice.

the lower desired temperatures, *i.e.* 40˚C and 50˚C, the rice temperatures were very close to the desired temperatures after 6 hours. The rice temperature did not reach the drying temperature due to the required energy to evaporate the moisture from the grain. It should be mentioned that the rice sample is being considered thin-layer. Chakraverty [16] mentioned that the thin layer could be 20 cm. Therefore, increasing the drying duration beyond 6 hours could help increase the rice temperature.

The effects of drying temperature and drying duration on the moisture content of medium- (RO170112 and Titan) and long-grain (Diamond and Wells) rough rice are shown in **Figure 3**. First, it should be mentioned that the initial moisture contents of the four rice varieties were obtained using the oven method. Next, 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. There is no dry matter loss included under the studied levels of temperature. The results showed that increasing the drying temperature and the drying duration decreased the rough rice moisture content for both the medium- and long-grain rice. For instance, at the drying temperature of 100˚C and after 6 hours of the drying process, the moisture content decreased to 15.0, 13.9, 14.4, and 14.0% (db) for RO170112, Titan, Diamond, and Wells rough rice, respectively. Jindal and Siebenmorgen [11] [33] also reported that increasing the oven temperature would decrease the rough rice moisture content. Charmongkolpradit *et al.* [34] studied the effect of drying temperature on moisture contents of purple waxy corn kernel using a tunnel dryer. Their experimental results

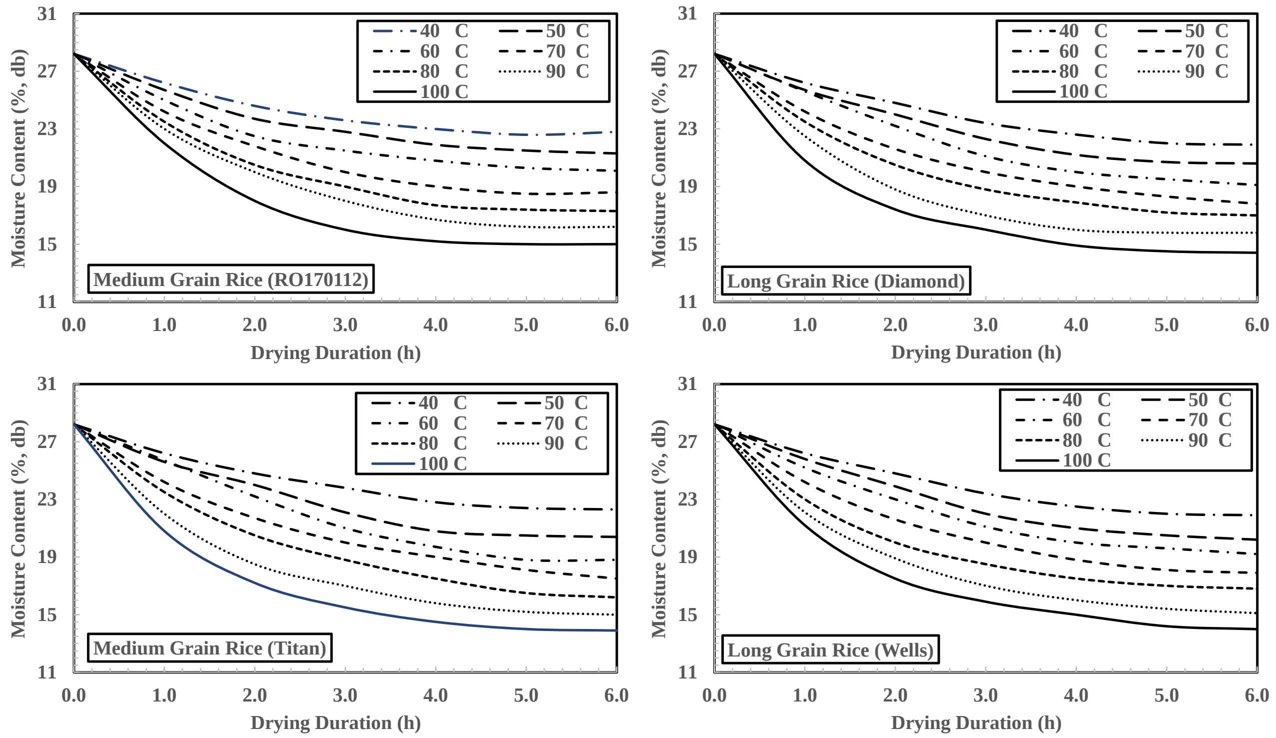

Figure 3. Effects of drying temperature and drying duration on rough rice moisture content for medium- and long-grain rough rice.

revealed that the moisture content in purple waxy corn kernel decreased with the drying temperature, which agrees with the present study.

At the drying temperature of 40˚C and after 6 hours of the drying process, the moisture content decreased to 22.8, 22.3, 21.9, and 21.9% (db) for RO170112, Titan, Diamond, and Wells rough rice, respectively. It was observed that with the highest temperature levels, *i.e.* 100˚C and 90˚C, there was a sharper decrease in the moisture content during the first 3 hours of the run compared with the last 3 hours. On the other hand, at the lower temperatures, *i.e.*, 40˚C and 50˚C, the reduction of moisture content was nearly linear. As mentioned above, the linear moisture reduction would support the slight increase in the rice temperature. Similar results were reported by Kaveh and Szumny [35]. It should be mentioned that increasing the drying duration beyond 6 hours may lead to a plateau in the drying curves at lower temperature levels. The moisture content data showed that more than 12.2 moisture points were lost from the four rice varieties after three hours of drying and at 100˚C drying temperature. Conversely, only 4.8 moisture points or less were lost from the four rice varieties after three hours and 40˚C drying temperature. The lower moisture reduction corresponding to the lower temperature levels resulted from lower energy quantities supplied to the rice samples.

The moisture ratio values versus drying duration curves for the medium- and long-grain rough rice drying treatments are shown in **Figure 4**. In general, the curves show a decreasing trend as drying progresses. A sharp decrease in the

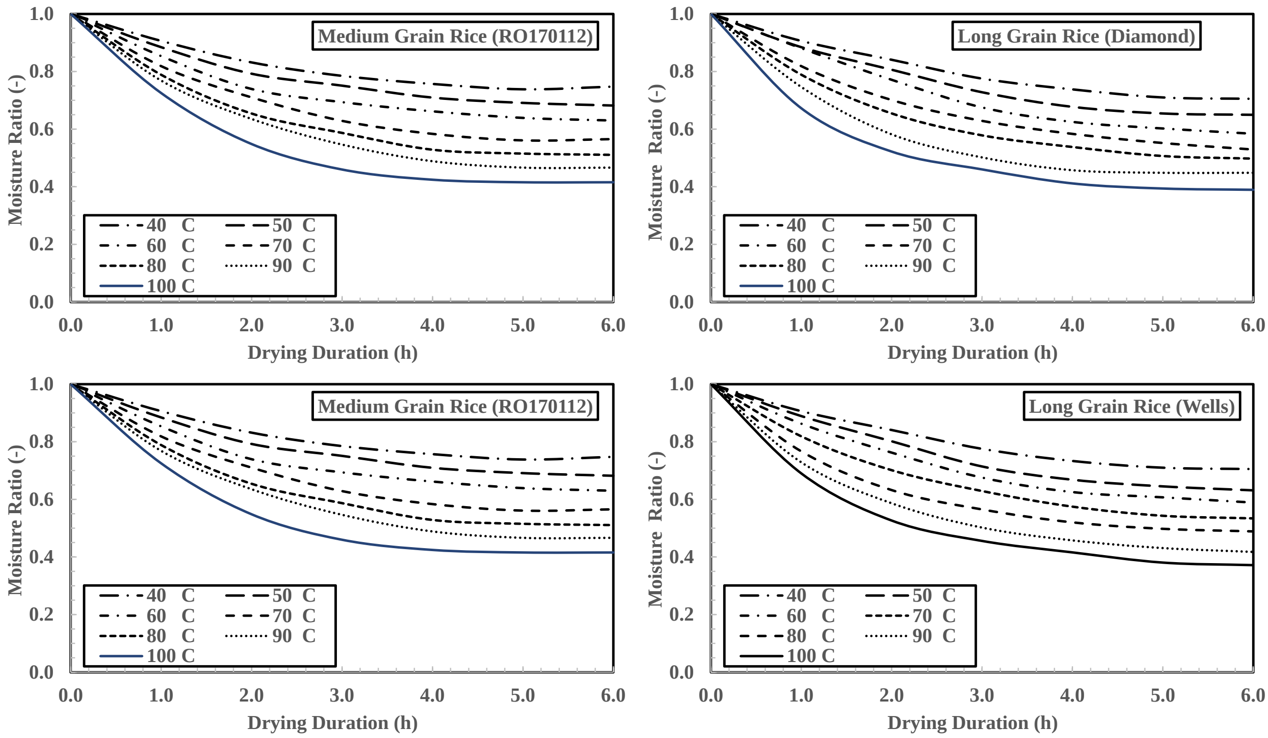

Figure 4. Effects of drying temperature and drying duration on rough rice moisture ratio for medium- and long-grain rough rice.

moisture ratio was observed with higher drying temperatures than with lower temperatures. For example, at the drying temperature of 100˚C and after 6 hours of the drying process, the moisture ratio of RO170112, Titan, Diamond, and Wells varieties reached 0.416, 0.367, 0.389, and 0.372, respectively. Almost double the moisture ratio values were observed at the drying temperature of 40˚C and after 6 hours. Because the moisture ratio values were determined from the moisture content of the grain, the correlations followed a similar trend, as shown with the moisture content data. A sharp decrease in the moisture ratio values was observed under higher drying temperatures and during the first three hours of the drying process. The lower temperature levels showed a nearly linear relationship between moisture ratio values and 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 curves. The moisture loss alteration was directly affected by the binding forces between moisture and grain. Chen *et al.* [36] reported that water in any material could be separated into bound water and free water. The bound water is dispersed inside the material and bounded by strong forces, which require more energy for removal. The free water is usually present on a surface with weak forces with the material. Free water leaves early by evaporation at a moderately low drying temperature (below 60˚C). The evaporated moisture is typically considered the free moisture inadequately bound to the grain.

The effects of drying temperature and drying duration on the drying rate were calculated and presented in **Figure 5** [37]. Increasing the drying temperature increased the drying rate for the four studied rice varieties (RO170112, Titan, Diamond, and Wells) under the first three hours of drying durations. Therefore, it can be postulated that the higher the drying temperature, the higher the energy supplied to evaporate moisture from the rice. These results agree with Berruti *et al.* [38]. Additionally, Coradi *et al.* [39] and Prasetyo *et al.* [40] stated that the increase in drying temperature accelerated the reduction in grain moisture content. The maximum drying rate of 7.41%/h was achieved under the drying temperature of 100˚C and during the first hour of drying long-grain rice, Diamond.

Similarly, Charmongkolpradit *et al.* [30] stated that their results showed that the drying rate increased with increasing temperature. The highest rate was obtained at 80˚C. The drying rate decreased to 2.0, 1.7, 1.4, and 1.6%/h for rice varieties of RO170112, Titan, Diamond, and Well, respectively, under the drying temperature of 100˚C and after three hours. The results revealed that, generally, increasing the drying duration decreased the average drying rate. It is due to reducing the available moisture during the last few hours of the drying under the highest temperature.

3.3. Effects of Drying Temperature on the Medium- and Long-Grain Rough Rice Drying Kinetic Constants for Page, Newton, Logarithmic, and Henderson & Babis Models

The moisture ratio data versus drying duration were analyzed statistically to determine the correlation coefficient (R^2) values, and the root means square error

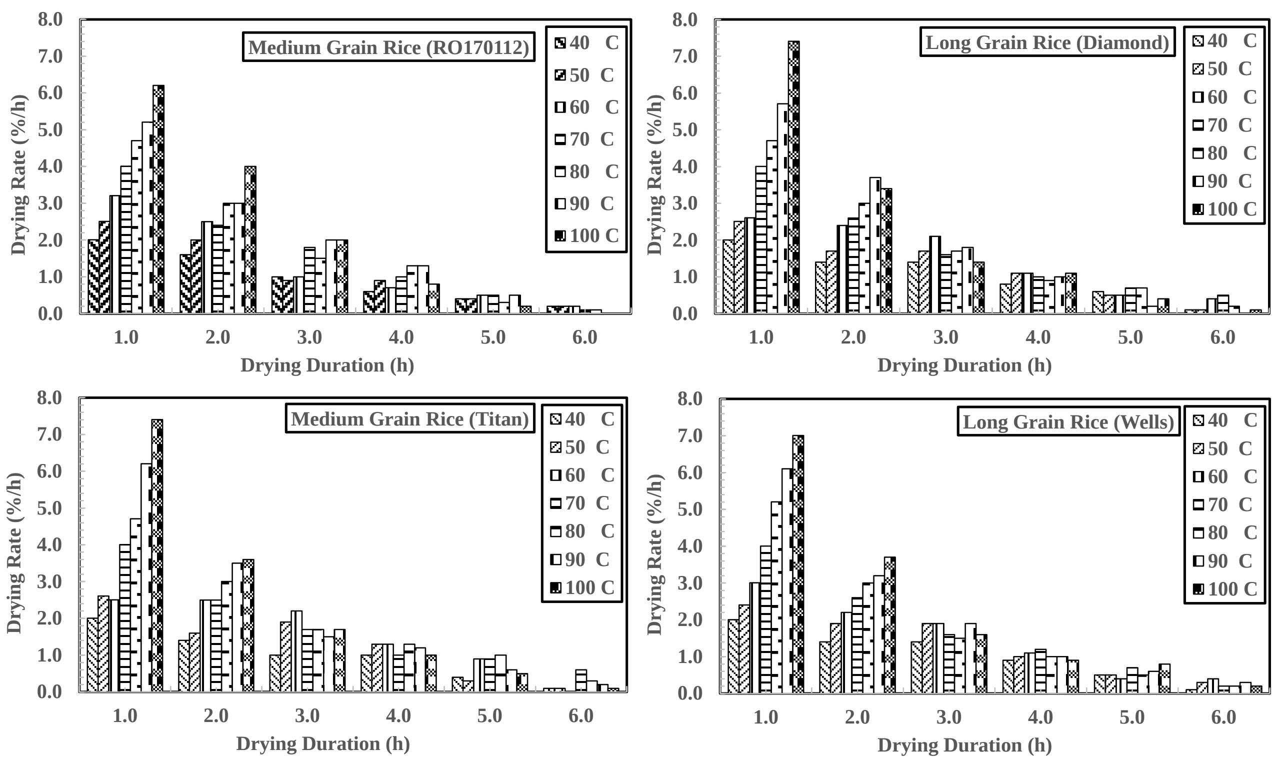

Figure 5. Effects of drying temperature and drying duration on rough rice drying rate for medium- and long-grain rough rice.

(*RMSE*). These values were obtained for the Page, Newton, Logarithmic, and Henderson models. The drying data described the drying kinetics of medium- and long-grain rough rice. The moisture ratio of the four models followed the parabolic model. The estimated parameters and statistical analysis of the models examined for the different drying conditions are illustrated in Tables 2-5 for RO170112, Titan, Diamond, and Wells rough rice. The Page, Newton, and Logarithmic models fit 25%, 25%, and 50% of the studied cases. The results arose a challenge in selecting the best fit model to run a comprehensive conclusion.

Table 2. Effects of drying temperature on the kinetic constants isothermal conditions for medium-grain rough rice (RO170112).

Model	Temp ˚C	Drying Constants								Statistical Parameters	
		K_p	K_N	K_L	K_H	n_p	a_L	b_L	C_H	R^2	*RMSE*
Page	40	0.0556				0.9917				0.9979	0.0037
Newton	40		0.0549							0.9977	1.1541
Logarithmic	**40**			**0.1121**			**0.4339**	**0.5738**		**0.9988**	**0.0039**
Henderson & Pabis	40				0.0552				1.0009	0.9977	0.0037
Page	50	0.0784				1.0296				0.9969	0.0060
Newton	50		0.0818							0.9972	0.0064
Logarithmic	**50**			**0.0907**			**0.0669**	**0.9394**		**0.9974**	**0.0059**
Henderson & Pabis	50				0.3925				1.1402	0.9547	0.3933
Page	**60**	**0.1038**				**1.0986**				**0.9980**	**0.0064**
Newton	60		0.1191							0.9975	0.0115
Logarithmic	60			0.1233			0.0000	1.0152		0.9974	0.0091
Henderson & Pabis	60				0.1233				1.0152	0.9974	0.0091
Page	70	0.1129				1.0883				0.9881	0.0163
Newton	70		0.1275							0.9888	0.0187
Logarithmic	**70**			**0.1322**			**0.0000**	**1.0169**		**0.9889**	**0.0170**
Henderson & Pabis	70				0.1322				1.0169	0.9889	0.0170
Page	80	0.1771				0.9429				0.9862	0.0203
Newton	80		0.1641							0.9829	0.0216
Logarithmic	**80**			**0.2589**			**0.2342**	**0.7880**		**0.9937**	**0.0150**
Henderson & Pabis	80				0.1634				0.9977	0.9828	0.0215
Page	90	0.2028				0.9645				0.9874	0.0209
Newton	90		0.1937							0.9857	0.0214
Logarithmic	**90**			**0.2742**			**0.1732**	**0.8503**		**0.9941**	**0.0161**
Henderson & Pabis	90				0.1943				1.0018	0.9858	0.0214
Page	100	0.2092				1.5337				0.9697	0.1807
Newton	100		0.2204							0.9666	0.0347
Logarithmic	**100**			**0.3452**			**0.2008**	**0.8357**		**0.9865**	**0.0255**
Henderson & Pabis	100				0.2209				1.0016	0.9667	0.0346

Table 3. Effects of drying temperature on the kinetic constants isothermal conditions for medium-grain rough rice (Titan).

Model	Temp °C	Drying Constants								Statistical Parameters	
		K_p	K_N	K_L	K_H	n_p	a_L	b_L	C_H	R^2	*RMSE*
Page	**40**	**0.0179**				**1.4980**				**0.9942**	**0.0042**
Newton	40		0.0377							0.9843	1.2775
Logarithmic	40			0.1121			0.4339	0.5738		0.9689	0.0533
Henderson & Pabis	40				0.0439				1.0253	0.9833	0.0125
Page	50	0.0490				1.1350				0.9906	0.0083
Newton	50		0.0596							0.9952	0.0114
Logarithmic	**50**			**0.0638**			**0.0000**	**1.0162**		**0.9954**	**0.0082**
Henderson & Pabis	50				0.0638				1.0162	0.9954	0.0082
Page	60	0.0804				1.2048				0.9929	0.0108
Newton	**60**		**0.1073**							**0.9952**	**0.0212**
Logarithmic	60			0.1158			0.0000	1.0320		0.9951	0.0151
Henderson & Pabis	60				0.1158				1.0320	0.9951	0.0151
Page	70	0.0959				1.1615				0.9945	0.0102
Newton	**70**		**0.1202**							**0.9951**	**0.0186**
Logarithmic	70			0.1273			0.0000	1.0261		0.9949	0.0143
Henderson & Pabis	70				0.1273				1.0261	0.9949	0.0143
Page	80	0.1716				0.9652				0.9847	0.0215
Newton	80		0.1638							0.9825	0.0219
Logarithmic	**80**			**0.2527**			**0.2215**	**0.8048**		**0.9933**	**0.0164**
Henderson & Pabis	80				0.1649				1.0036	0.9827	0.0219
Page	90	0.1911				0.9936				0.9856	0.0221
Newton	90		0.1896							0.9853	0.0222
Logarithmic	**90**			**0.2604**			**0.1571**	**0.8706**		**0.9929**	**0.0181**
Henderson & Pabis	90				0.1924				1.0093	0.9857	0.0218
Page	100	0.2393				0.9557				0.9713	0.0339
Newton	100		0.2264							0.9680	0.0345
Logarithmic	**100**			**0.3435**			**0.1851**	**0.8530**		**0.9863**	**0.0263**
Henderson & Pabis	100				0.2282				1.0055	0.9684	0.0344

Table 4. Effects of drying temperature on the kinetic constants isothermal conditions for long-grain rough rice (Diamond).

Model	Temp °C	Drying Constants								Statistical Parameters	
		K_p	K_N	K_L	K_H	n_p	a_L	b_L	C_H	R^2	*RMSE*
Page	**40**	**0.0291**				**1.3451**				**0.9982**	**#NUM!**
Newton	40		0.0484							0.9929	0.0158
Logarithmic	40			0.0542			0.0000	1.0232		0.9922	0.0107
Henderson & Pabis	40				0.0542				1.0232	0.9922	0.0107

Continued

Page	**50**	**0.0604**				**1.1942**				**0.9965**	**0.0060**
Newton	50		0.0799							0.9951	0.0149
Logarithmic	50			0.0853			0.0000	1.0208		0.9947	0.0111
Henderson & Pabis	50				0.0853				1.0208	0.9947	0.0111
Page	60	0.0723				1.1642				0.9951	0.0079
Newton	**60**		**0.0914**							**0.9963**	**0.0153**
Logarithmic	60			0.0973			0.0000	1.0225		0.9962	0.0110
Henderson & Pabis	60				0.0973				1.0225	0.9962	0.0110
Page	70	0.0835				1.1194				0.9958	0.0076
Newton	**70**		**0.0989**							**0.9973**	**0.0127**
Logarithmic	70			0.1038			0.0000	1.0184		0.9973	0.0093
Henderson & Pabis	70				0.1038				1.0185	0.9973	0.0093
Page	**80**	**0.1087**				**1.1580**				**0.9968**	**0.0083**
Newton	80		0.1351							0.9961	0.0183
Logarithmic	80			0.1423			0.0000	1.0258		0.9958	0.0141
Henderson & Pabis	80				0.1423				1.0259	0.9958	0.0141
Page	90	0.1970				0.9199				0.9832	0.0241
Newton	90		0.1774							0.9763	0.0264
Logarithmic	**90**			**0.3026**			**0.2562**	**0.7733**		**0.9949**	**0.0160**
Henderson & Pabis	90				0.1761				0.9960	0.9761	0.0264
Page	100	0.2968				0.7612				0.9722	0.0328
Newton	100		0.2204							0.9437	0.0500
Logarithmic	**100**			**0.4694**			**0.3059**	**0.7174**		**0.9927**	**0.0165**
Henderson & Pabis	100				0.2041				0.9518	0.9381	0.0459

Table 5. Effects of drying temperature on the kinetic constants isothermal conditions for long-grain rough rice (Wells).

Model	Temp °C	Drying Constants								Statistical Parameters	
		K_p	K_N	K_L	K_H	n_p	a_L	b_L	C_H	R^2	*RMSE*
Page	**40**	**0.0341**				**1.2856**				**0.9970**	**0.0113**
Newton	40		0.0519							0.9821	0.0179
Logarithmic	40			0.0575			0.0000	1.0225		0.9816	0.0140
Henderson & Pabis	40				0.0552				1.0009	0.9818	0.0195
Page	50	0.0506				1.1225				0.9854	0.0106
Newton	**50**		**0.0604**							**0.9867**	**0.0127**
Logarithmic	50			0.0636			0.0000	1.0123		0.9866	0.0112
Henderson & Pabis	50				0.0636				1.0123	0.9866	0.0112

Continued

Page	60	0.0677				1.1328				0.9947	0.0078
Newton	**60**		**0.0819**							**0.9952**	**0.0125**
Logarithmic	60			0.0861			0.0000	1.0162		0.9950	0.0098
Henderson & Pabis	60				0.0861				1.0162	0.9950	0.0098
Page	**70**	**0.0885**				**1.0923**				**0.9992**	**0.0034**
Newton	70		0.1008							0.9987	0.0087
Logarithmic	70			0.1041			0.0001	1.0121		0.9986	0.0065
Henderson & Pabis	70				0.1041				1.0123	0.9986	0.0065
Page	80	0.1254				1.0192				0.9968	0.0083
Newton	**80**		**0.1288**							**0.9973**	**0.0085**
Logarithmic	80			0.1521			0.0977	0.9146		0.9984	0.0073
Henderson & Pabis	80				0.1308				1.0074	0.9974	0.0079
Page	90	0.1746				0.9749				0.9860	0.0205
Newton	90		0.1689							0.9849	0.0207
Logarithmic	**90**			**0.2413**			**0.1868**	**0.8350**		**0.9920**	**0.0169**
Henderson & Pabis	90				0.1698				1.0032	0.9850	0.0207
Page	100	0.2887				0.7732				0.9806	0.0285
Newton	100		0.2173							0.9551	0.0455
Logarithmic	**100**			**0.4480**			**0.2998**	**0.7212**		**0.9963**	**0.0127**
Henderson & Pabis	100				0.2021				0.9547	0.9504	0.0415

3.4. Present Study

An equation combining Page, Newton, and Logarithmic models was established, as shown in Equation (14). The newly developed model combines the previously mentioned three models in a mathematical formula to obtain one equation that fits all cases.

$$MR = k_I \left[\exp\left(-k_P t^n\right) + \exp\left(-k_N t\right) + \left(a + b\exp\left(-k_L t\right)\right)\right] \quad (14)$$

where

K_I = Integrated model constant (dimensionless).

Table 6 shows the drying constants resulting from the developed equation and the statistical values of R^2 and *RMSE*. The results showed that the developed equation provided the highest R^2 for all the 28 studied cases for medium and long-grain rice. The coefficient of determination (R^2) ranged between 0.9913 and 1.0000. Similarly, the values of *RMSE* were the lowest compared with the three individual models, Page, Newton, and Logarithmic. Therefore, adding the model to the comparison led to its superiority among the studied models. The developed model could be introduced to overcome the multiplicity of the best fit models for agricultural products. The reason is that the recently developed model (Equation (14)) is derived from combining the well-known models in one

Table 6. Effects of drying temperature on the kinetic constants isothermal conditions for different varieties of rough using the integrated model.

Rough Rice Variety	Temp ˚C	*Drying constants*							Statistical Parameters	
		K_I	K_p	K_N	K_L	n_p	a_L	b_L	R^2	*RMSE*
Medium Grain Rough Rice (RO170112)	40	0.2737	0.1279	0.0669	0.0000	1.2158	0.7730	0.8822	0.9992	0.0025
	50	0.4024	0.0163	0.1983	0.0159	1.6303	0.2455	0.2532	0.9977	0.0059
	60	0.3813	0.0628	0.2112	0.0165	1.5331	0.3434	0.2792	0.9989	0.0056
	70	0.2659	0.0205	0.3064	0.0138	2.9500	1.0147	0.6514	0.9954	0.0125
	80	0.3003	0.1025	0.4781	0.0139	2.0553	1.2751	0.0660	0.9998	0.0024
	90	0.3785	0.1046	0.5280	0.0141	1.5580	0.3435	0.3491	0.9958	0.0139
	100	0.3345	0.1335	0.4680	0.0142	2.2707	0.4599	0.5258	0.9999	0.0025
Medium Grain Rough Rice (Titan)	40	0.4016	0.0249	0.0206	0.0264	1.7257	0.2214	0.2785	0.9966	0.0044
	50	0.3707	0.1043	0.0236	0.0154	1.3314	0.3604	0.3531	0.9964	0.0061
	60	0.3582	0.0590	0.1923	0.0146	1.6869	0.4861	0.3377	0.9971	0.0087
	70	0.3268	0.0182	0.3471	0.0148	2.4288	0.6140	0.4706	0.9961	0.0108
	80	0.3027	0.1019	0.4670	0.0139	2.0812	1.2650	0.0631	0.9998	0.0028
	90	0.3397	0.1391	0.3425	0.0131	1.8068	0.4709	0.4635	0.9989	0.0092
	100	0.3466	0.1265	0.4810	0.0000	2.2846	0.8217	0.0653	0.9999	0.0020
Long Grain Rough Rice (Diamond)	40	0.3959	0.0345	0.0404	0.0250	1.5833	0.2422	0.2910	0.9989	0.0031
	50	0.4322	0.0206	0.1274	0.0319	1.7130	0.0348	0.2865	0.9979	0.0059
	60	0.3218	0.0244	0.2432	0.0129	2.0170	0.7029	0.4306	0.9969	0.0079
	70	0.3073	0.0287	0.2859	0.0160	2.0122	0.7290	0.5498	0.9978	0.0070
	80	0.3107	0.0220	0.3797	0.0139	2.6644	1.2179	0.0001	0.9995	0.0042
	90	0.3659	0.2852	0.1564	0.0196	1.6438	0.3121	0.4219	0.9997	0.0034
	100	0.2963	0.1991	0.7748	0.0280	2.0100	0.3501	1.0240	0.9998	0.0039
Long Grain Rough Rice (Wells)	40	0.1678	0.0000	0.0001	0.0813	8.2687	0.0015	4.0450	0.9975	0.0087
	50	0.4889	0.0957	0.0001	0.0150	1.2975	0.0000	0.0445	0.9872	0.0114
	60	0.4160	0.0153	0.1698	0.0190	1.8034	0.1955	0.2231	0.9962	0.0079
	70	0.4157	0.0421	0.1709	0.0228	1.4513	0.0293	0.3779	0.9994	0.0035
	80	0.3234	0.0791	0.3263	0.0139	1.6530	1.0061	0.0976	0.9993	0.0044
	90	0.3749	0.0912	0.4248	0.0141	1.5038	0.3460	0.3531	0.9939	0.0156
	100	0.3248	0.4061	0.5744	0.0165	1.3146	0.4832	0.6550	0.9982	0.0087

equation. It was observed that the model constant (K_I) has no relationship with drying temperature. The only downside of the developed equation is increasing the number of drying constants.

3.5. Calculations of the Effective Moisture Diffusivity and Activation Energy

The effective moisture diffusivity was calculated by using the method of slopes.

The natural logarithm of moisture ratio values was plotted against drying duration according to the experimental data obtained at various drying temperatures for each rice variety. The slopes of the determined lines were determined and used to calculate the effective moisture diffusivity under the temperature level and for each rice variety. It should be mentioned that the values of the coefficients of determination (R^2) of these lines were more than 0.8746. The Effective Moisture Diffusivity (D_{eff}) values for drying medium- and long-grain rough rice are shown in **Table 7**. By increasing drying temperature from 40˚C to 100˚C, effective moisture diffusivity increased from 4.807 ×10^{-9} m^2/s to 17.491 × 10^{-9} m^2/s for RO170112, from 3.931 × 10^{-9} m^2/s to 18.104 × 10^{-9} m^2/s, for Titan, from 4.832 × 10^{-9} m^2/s to 15.232 × 10^{-9} m^2/s, for Diamond, and from 5.139 × 10^{-9} m^2/s to 15.320 × 10^{-9} m^2/s for Wells. Sandeepa *et al.* [41], Correa *et al.* [39], and Chen *et al.* [31] assessed the effective diffusivity coefficient at various temperature levels. They all also agreed that the D_{eff} values increased with the increase in the drying temperature.

More moisture is evaporated with a high drying temperature as the temperature is the leading driving force of moisture evaporation. Therefore, the moisture diffusivity value increased with the increase in the drying temperature. It can be postulated to more energy being provided at higher drying temperatures, which improves the activity of water molecules and amplifies the drying rate. As the temperature increased, the bound moisture distributed inside the grain with moderately strong bonding began to evaporate in the drying process. The values of the D_{eff} attained from the current study were comparable to those stated in the literature. Onwude *et al.* [42] performed modeling of the thin-layer drying characteristics of various agricultural products. They reported that effective moisture diffusivity values were 10^{-6} and 10^{-12} m^2/s. Also, Golmohammadi *et al.* [6] studied the intermittent drying characteristics of paddy rice for various temperatures

Table 7. Effects of drying temperature on the moisture diffusivity and activation energy for short-grain rough rice.

Temp	Moisture Diffusivity (m^2/s)			
	Medium-grain Rice (RO170112)	Medium-grain Rice (Titan)	Long-grain Rice (Diamond)	Long-grain Rice (Wells)
40	4.807 × 10^{-09}	3.931× 10^{-09}	4.832 × 10^{-09}	5.139 × 10^{-09}
50	7.257 × 10^{-09}	5.594 × 10^{-09}	7.634 × 10^{-09}	5.620 × 10^{-09}
60	10.908 × 10^{-09}	10.304 × 10^{-09}	8.740 × 10^{-09}	7.642 × 10^{-09}
70	11.564 × 10^{-09}	11.328 × 10^{-09}	9.157 × 10^{-09}	9.236 × 10^{-09}
80	13.578 × 10^{-09}	13.628 × 10^{-09}	12.737 × 10^{-09}	11.337 × 10^{-09}
90	16.081 × 10^{-09}	16.029 × 10^{-09}	14.339 × 10^{-09}	14.225 × 10^{-09}
100	17.491 × 10^{-09}	18.104 × 10^{-09}	15.232 × 10^{-09}	15.320 × 10^{-09}
	Activation Energy (kJ/mol)			
	19.98	24.48	17.77	19.26

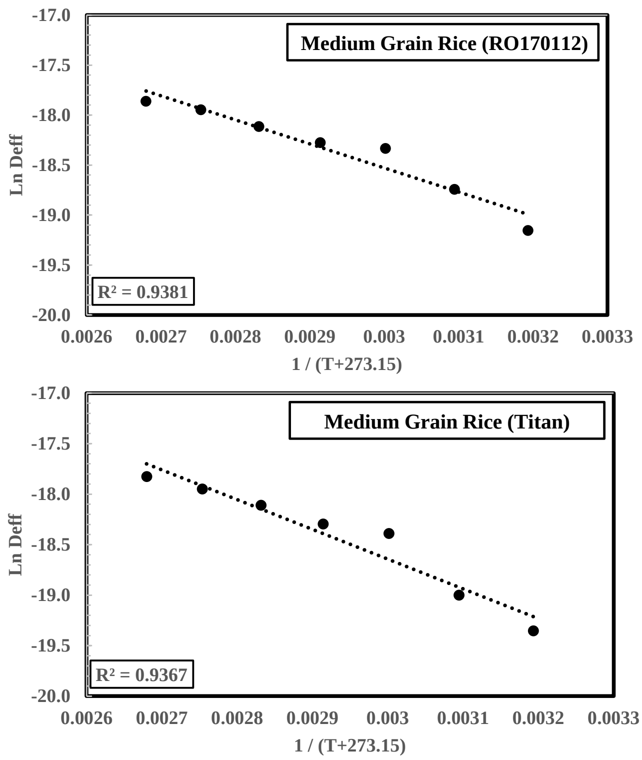

Figure 6. Effects of reverse absolute drying temperature on the natural logarithm of moisture diffusivity for medium- and long-grain rough rice.

and tempering times. The effective moisture diffusivity values ranged from 3.89 × 10^{-9} and 6.58 × 10^{-9} m^2/s over their temperature range.

Activation energy values were also calculated by using the method of slopes. The natural logarithm of effective moisture diffusivity values for each rice variety was plotted against [1/(T + 273.15)]. Figure 6 shows these linear correlations for RO170112, Titan, Diamond, and Wells rice varieties. The activation energy was calculated from the slope of the line. It was found to be 19.98, 24.24, 17.77, and 19.26 kJ/mol for RO170112, Titan, Diamond, and Wells. Onwude *et al.* [37] cited that the activation energies for various agricultural products were 14.42 and 43.26 kJ/mol. They concluded that air temperature and thickness are the most relevant factors for drying. Golmohammadi *et al.* [6] found that the activation energy was 22.99 kJ/mol. Resende *et al.* [43] dried sorghum grains at different air velocities and drying temperatures to determine this drying process's drying kinetics and thermodynamic properties. They concluded that the activation energies were 27.12 and 45.02 kJ/mol for their two air velocities of 0.5 and 1.0 m/s, respectively. Sadaka *et al.* [44] reported that the activation energy for the wheat drying increased from 14.76 kJ/mol, at a heating rate of 2˚C/min, to 28.17 kJ/mol, at a heating rate of 10˚C/min.

4. Conclusions

The drying kinetics of Arkansas medium-grain (RO170112 and Titan) and long-grain (Diamond and Wells) rough rice were determined under isothermal conditions. A system that matches the thermogravimetric analyzer was used. The isothermal conditions took place at 40˚C, 50˚C, 60˚C, 70˚C, 80˚C, 90˚C, and 100˚C. Several significant conclusions could be drawn from the investigational work described in this manuscript.

- The moisture content reached 15.0%, 13.9%, 14.4%, and 14.0% (db) for RO170112, Titan, Diamond, and Wells rough rice, respectively, at the drying temperature of 100˚C and after 6 hours of the drying process.
- Page, Newton, and Logarithmic models were the best fit for 25%, 25%, and 50% of the twenty-eight studied cases.
- Combining Page, Newton, and Logarithmic models in a combined model resulted in the best fit model that fits 100% of the studied cases.
- By increasing the drying temperature from 40˚C to 100˚C, effective moisture diffusivity increased for all studied rice varieties.
- Effective moisture diffusivity reached 17.491×10^{-9} m^2/s, 18.104×10^{-9} m^2/s, 15.232×10^{-9} m^2/s, and 15.320×10^{-9} m^2/s for RO170112, Titan, Diamond, and Wells rice varieties, respectively at the drying temperature of 100˚C.
- The activation energy was 19.98, 24.48, 17.77, and 19.26 kJ/mol for RO170112, Titan, Diamond, and Wells rice varieties.

Acknowledgements

The authors would like to thank the Department of Biological and Agricultural Engineering, University of Arkansas, and the Division of Agriculture, University of Arkansas System, for financial support. In addition, the authors appreciate the staff members of the Rice Research and Extension Center, Stuttgart, Arkansas, for their continuous support. Finally, the authors would like to thank Mr. Holand Oscar Morton, Undergraduate Research Assistant, Department of Biological and Agricultural Engineering, University of Arkansas.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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