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Drying kinetics and effective diffusion of buckwheat grains

Cinética de secagem e difusão efetiva de grãos de trigo mourisco

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ABSTRACT

Buckwheat has become important in the food sector as its flour does not contain gluten. Since buckwheat is a relatively new crop in the agricultural environment, there is little information available regarding its processing. Drying is one of the most important post-harvest stages of buckwheat. The aim of the present study was to describe the drying process of buckwheat grains. Buckwheat grains with a moisture content of 0.41 ± 0.01 (dry basis, d.b.) were harvested, followed by drying in an experimental dryer at the temperatures of 40, 50, 60, 70, and 80 °C, at an air speed of 0.8 m s^{-1}. The drying rate was determined, and the mathematical models generally employed to describe the drying process of several agricultural products were fitted to the experimentally obtained data. Model selection was based on the Gauss-Newton non-linear regression method and was complemented by Akaike Information Criterion and Schwarz's Bayesian Information Criterion. It was concluded that the drying rate increased with an increase in temperature and decreased with an increase in drying time. It is recommended to use the Midilli model to represent the drying kinetics of buckwheat grains at the temperatures of 40, 60, and 70 °C, while the Approximation of diffusion model is recommended for the temperatures of 50 and 80 °C. The magnitudes of effective diffusion coefficients ranged from 1.8990 × 10^{-11} m^2 s^{-1} to 17.8831 × 10^{-11} m^2 s^{-1}. The activation energy required to initiate the drying process was determined to be 49.75 kJ mol^{-1}.

Index terms: Activation energy; *Fagopyrum esculentum* Moench; mathematical models; AIC and BIC; gluten.

RESUMO

O trigo mourisco tem se destacado na cadeia alimentícia por não possuir glúten em sua farinha. Por ser uma cultura relativamente nova no meio agrícola, faltam informações referentes ao seu processamento, dentre as etapas pós-colheita a secagem é uma das mais importantes. O objetivo do presente trabalho foi descrever o processo de secagem de grãos de trigo mourisco. Os grãos foram colhidos com teor de água de 0.41 ± 0.01 (b.s.) e submetidos a secagem em secador experimental nas temperaturas de 40, 50, 60, 70 e 80 °C, e velocidade do ar de 0.8 m s^{-1}. Determinou-se a taxa de secagem e ajustou-se aos dados experimentais modelos matemáticos frequentemente utilizados para a descrição da secagem de diversos produtos agrícolas. A seleção dos modelos foi baseada no método de regressão não linear de Gauss-Newton e complementada pelo Critério de Informação de Akaike e Critério de Informação Bayesiano de Schwarz's. Conclui-se que, a taxa de redução da água foi maior para maiores temperaturas e diminuiu com o aumento do tempo de secagem; o modelo de Midilli é recomendado para representar a cinética de secagem dos grãos nas temperaturas de 40, 60 e 70 ºC; para a temperaturas de 50 e 80 ºC recomenda-se o modelo de aproximação da difusão; os coeficientes de difusão efetivo apresentaram magnitude de 1.8990 a 17. 8831 × 10^{-11} m^2 s^{-1} e; a energia de ativação requerida para iniciar o processo de secagem foi de 49.75 kJ mol^{-1}.

Termos para indexação: Energia de ativação; *Fagopyrum esculentum* Moench; modelos matemáticos; AIC e BIC; glúten.

INTRODUCTION

In the past few decades, great attention has been focused on the food product to be offered to the consumer, whether in terms of the nutritional value of the food product or the specific requirements of certain individuals. The latter includes the coeliac people, who have a permanent intolerance to gluten, a protein present mainly in wheat, rye, barley, malt, and oats. Since there is no cure currently available for gluten intolerance, the only approach to manage this disorder is to avoid its symptoms by not ingesting gluten.

In this context, buckwheat (*Fagopyrum esculentum* Moench) could serve as an excellent alternative for people with gluten intolerance who wish to consume flour-based products.

Owing to the economic potential and importance of buckwheat crop, several research works have been focused on improving its yield (Görgen et al., 2016), adaptation (Alves et al., 2016), cultivation (Vazhov; Kozil; Odintsev, 2013), and nutritional properties (Zhu, 2016). Nonetheless, studies concerning the drying process of buckwheat are scarce.

The drying process involves the simultaneous transfer of heat and mass, which may cause significant changes in food characteristics (Koç; Eren; Ertekin, 2008). The drying stage exerts a great influence on product quality as well as on the overall production costs. Therefore, this stage requires planning, and if possible, scaling in advance (Siqueira; Resende; Chaves, 2013).

These concerns could be addressed by the mathematical simulation of the drying process. Drying conditions, particularly the temperature and relative humidity, govern the rate at which water exits the grains (Koua; Koffi; Gbaha, 2019). High water removal rates during drying could alter the structure and the contents of the product (Lima et al., 2016). Such high rates could generate internal stresses within the grains that could result in mechanical injuries and reduced product quality (Agrawal; Methekar, 2017; Corrêa et al., 2017). In addition, each product exhibits unique behavior during the drying process.

Studies concerning buckwheat post-harvest processes are scarce. Therefore, understanding the behavior of buckwheat during its drying process would lay a foundation for future research in this field. In this context, the present study was conducted with the objectives of fitting mathematical models, describing the behavior of buckwheat grains during drying, and determining the parameters of effective diffusion coefficients, activation energy, and drying rate at different temperatures.

MATERIAL AND METHODS

The study was conducted at the Laboratory of Postharvest Processes of Agricultural Products, Faculty of Agrarian Sciences, Federal University of Grande Dourados.

Buckwheat grains of the cultivar IPR 91-Baili were used in the present study. The grain samples were harvested with the initial moisture content of 0.41 ± 0.01 (decimal, d.b.), which was determined through the oven method as described in the Rules for Seed Analysis (RAS), using an Ethik forced ventilation oven (model 400/D) at 105 ± 1 °C for 24 h, in three replicates (Brasil, 2009).

Thin-layer drying of the product was performed in an experimental fixed-layer dryer equipped with a system that accurately controlled the drying air flow and temperature. The different temperature and relative humidity conditions used were as follows: 40 °C, 24.42%; 50 °C, 14.61%; 60 °C, 9.05%; 70 °C, 5.78%; and 80 °C, 3.81%. Drying air speed was determined and maintained at 0.8 m s^{-1} using a digital anemometer (Instrutherm AM-100).

The grains were distributed among four trays (replicates), each with a diameter of 160 mm, fully perforated (33.97% area), and a 7.5-mm high grain layer weighing 89 g. Mass measurement during the drying process was performed using a semi-analytical scale with a resolution of 0.01 g. The drying process was interrupted, for mathematical modeling purposes, when the grain mass reached a value equivalent to 0.13 ± 0.01 (decimal, d.b.) of moisture content.

In order to assess the drying of the buckwheat grains, the drying rate (DR) of the product was determined using Equation 1.

$$DR = (Mw_0 - Mw_i) / [DM \cdot (t_i - t_0)] \quad (1)$$

Where, DR is the drying rate (kg kg^{-1} h^{-1}), Mw_0 denotes the previous total mass of water (kg), Ma_i denotes the current total mass of water (kg), DM is dry matter (kg), t_0 denotes the previous total drying time (h), and t_i denotes the current total drying time (h).

The moisture content values at the beginning, at the end, and during the drying process (calculated) were substituted in Equation 2 to calculate the moisture ratio (RX) of the buckwheat grains during drying.

$$RX = (X - X_e) / (X_i - X_e) \quad (2)$$

Where, RX is the moisture content ratio of the product (dimensionless), X_e denotes the equilibrium moisture content of the product (decimal, d.b.), X denotes the moisture content of the product (decimal, d.b.), and X_i denotes the initial moisture content of the product (decimal, d.b.).

The equilibrium moisture content of the buckwheat grains was determined experimentally by performing the drying process inside the experimental dryer under the same conditions until a constant mass was reached.

Mathematical models (Equations 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13) generally used to represent the drying process of agricultural products were fitted to the experimentally obtained data for the drying of buckwheat grains (Table 1).

Table 1: Mathematical models used for representing the drying process of agricultural products.

Model designation	Model	Equation
Page	$RX = \exp\left(-k\,t^{n}\right)$	(3)
Midilli	$RX = a\exp(-k\,t^{n}) + b\,t$	(4)
Newton	$RX = \exp(-k\,t)$	(5)
Thompson	$RX = \exp\frac{-a-(a^2+4\,b\,t)^{0.5}}{2\,b}$	(6)
Henderson and Pabis	$RX = a\exp(-k\,t)$	(7)
Verma	$RX = -a\exp(-k\,t) + (1-a)\exp(-k_1\,t)$	(8)
Logarithmic	$RX = a\exp(-k\,t) + c$	(9)
Wang & Singh	$RX = 1 + a\,t + b\,t^2$	(10)
Two-term Exponential	$RX = a\exp(-k\,t) + (1-a)\exp(-k\,a\,t)$	(11)
Two terms	$RX = a\exp(-k_0\,t) + b\exp(-k_1\,t)$	(12)
Approximation of diffusion	$RX = a\exp(-k\,t) + (1-a)\exp(-k\,b\,t)$	(13)

Where, t is drying time, h; k, $k_{o,}$ and k_1 are the drying constants, h^{-1}; a, b, c, d, and n are the coefficients of the models.

The drying kinetics experimental data were subjected to non-linear regression analysis using the Gauss-Newton method. The mathematical models were fitted to the experimental data using the program Statistica 7.0®. The selection of the drying models was based on the relative mean error (P) values, standard deviation of the estimate (SE), and the coefficient of determination (R^2). The values for relative mean error and standard deviation of the estimate were calculated using Equation 14 and 15.

$$P=100/n\sum_{i=1}^{n}\left(\left|Y-\hat{Y}\right|/Y\right) \quad (14)$$

$$SE=\sqrt{\frac{\sum_{i=1}^{n}\left(Y-\hat{Y}\right)^2}{DF}} \quad (15)$$

Where n is the number of experimental observations, Y is the experimental value, $\hat{Y}$ is the value estimated using the model, and DF denotes the degrees of freedom of the model (i.e., the difference between the number of observations and the number of parameters).

In order to further refine the selection process of the model for representing the drying process of buckwheat grains under different conditions of drying air temperature, the models presenting best fits in the Gauss-Newton method were subjected to Akaike Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC), using R 3.6.1® software in function nls. According to Wolfinger (1993), lower AIC and BIC values indicate a better fit of the selected model, thereby representing a more accurate decision making. These criteria could also be included in the selection of drying models (Gomes et al., 2018). AIC and BIC values were determined using Equation 16 and 17.

$$AIC = -2\log L + 2p \quad (16)$$

$$BIC = -2\log L + p\ln(N) \quad (17)$$

Where, p is the number of parameters of the model, N is the total number of observations, and L represents the maximum likelihood.

The effective diffusion coefficient of the buckwheat grains under different drying conditions was calculated using Equation 18, which is based on the theory of liquid diffusion and represents an analytical solution for Fick's second law, by considering the geometric form of the product to be spherical and with eight-term approximation.

$$RX = \frac{X - X_e}{X_i - X_e} = \frac{6}{\pi^2} \sum_{n_t = 1}^{\infty} \frac{1}{n_t^2} \exp\left[\frac{n_t^2 \, \pi^2 \, D_i \, t}{9} \left(\frac{3}{R_e} \right)^2 \right] \quad (18)$$

Where, D_i is the liquid diffusion coefficient ($m^2 \, s^{-1}$), R_e denotes the equivalent sphere radius and n_t is the number of terms.

The equivalent sphere radius used in the effective diffusion model was determined by randomly selecting 50 buckwheat grains and measuring the three orthogonal axes of each grain using a digital micrometer.

The volume of each grain was calculated on the basis of perpendicular diameters, using Equation 19 and 20 (Jain; Bal, 1997). The approximation of the actual volume determined through the method of displacement using a low-density fluid was considered as the basis for this calculation.

$$V_g = \frac{\pi \, D^2 \, D_1^2}{6 \, (2 \, D_1 - D)} \quad (19)$$

$$D = (D_2 \, D_3)^{1/2} \quad (20)$$

Where, V_g denotes the volume of the grain (mm^3), D_1 denotes the length of the longest axis (mm), D_2 is the length of the medium axis (mm), D_3 is the length of the shortest axis (mm), and D denotes the diameter of the spherical part (mm).

Arrhenius Equation (Equation 21) was used for evaluating the effect of temperature on the effective diffusion coefficient.

$$D_i = D_0 \exp\left(\frac{E_a}{R \, T_a} \right) \quad (21)$$

Where, D_i is the pre-exponential factor ($m^2 \, s^{-1}$), R is the universal gas constant (8.314 kJ $kmol^{-1} \, K^{-1}$), T_a denotes the absolute temperature (K), and E_a is the activation energy (kJ mol^{-1}).

RESULTS AND DISCUSSION

The buckwheat grains were dried until a moisture content of 12 ± 0.05% was reached, on a wet basis, which required drying times of 6.00, 2.25, 1.25, 0.83, and 0.50 h at the drying air temperatures of 40, 50, 60, 70, and 80 °C, respectively. These differences could be attributed to the drying conditions, physical and chemical characteristics, cultivation conditions, and the initial moisture contents of the grains (Diógenes et al., 2013). The average drying rate for the buckwheat grains throughout the drying process tended to decrease as the drying time advanced (Figure 1). This reduction could be attributed to the difficulty in removing water from the grains as the end of the process is approached, because at this time, the water is more strongly bound to the product, which increases the energy demand for water diffusion from the innermost part to the surface (Resende et al., 2009).

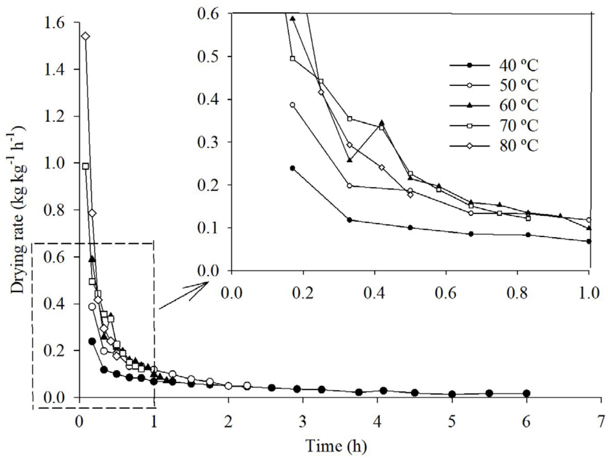

Figure 1: Moisture reduction rates for buckwheat grains at different drying air temperatures.

At higher temperatures, there is a higher partial pressure of water vapor in the product, which raises the drying rate, particularly at the beginning of the process, thereby reducing the drying time. This implies that the higher the drying air temperature, the higher is the rate at which water is removed from the product. This behavior was consistent with those of several other studies previously conducted on grain drying (Costa et al., 2011; Keneni; Hvoslef-Eide; Marchetti, 2019; Rosa et al., 2015; Siqueira; Resende; Chaves, 2012).

The relative mean error (P) indicates the level of deviation of the observed values from the estimated values. Therefore, the models with P-values lower than 10% are recommended (Table 2), while the models with P-values above 10% are excluded from the fitting (Kashaninejad et al., 2007).

Table 2: Coefficients of determination (R^2), relative mean errors (P), and the standard deviations of the estimate (SE) for the eleven models analyzed for representing the thin-layer drying of buckwheat (Fagopyrum esculentum Moench) grains under different conditions of drying air temperature.

Models	Temperature														
	40 °C			50 °C			60 °C			70 °C			80 °C		
	R^2	SE	P(%)	R^2	SE	P(%)	R^2	SE	P(%)	R^2	SE	P(%)	R^2	SE	P(%)
(3)	0.999	0.006	0.917	0.999	0.006	0.894	0.998	0.011	1.944	0.996	0.016	3.225	0.999	0.010	1.423
(4)	0.999	0.005	0.908	0.999	0.005	0.850	0.998	0.005	0.782	0.999	0.009	1.474	0.999	0.007	0.831
(5)	0.966	0.045	9.767	0.984	0.032	6.175	0.765	0.104	23.038	0.946	0.049	12.326	0.943	0.061	11.672
(6)	0.988	0.013	2.922	0.998	0.012	1.891	0.998	0.010	1.913	0.998	0.012	2.357	0.999	0.006	0.883
(7)	0.997	0.027	5.055	0.992	0.023	3.781	0.881	0.077	13.661	0.965	0.047	9.938	0.957	0.058	9.885
(8)	0.999	0.009	1.872	0.984	0.035	6.175	0.765	0.113	23.039	0.998	0.011	1.378	0.999	0.001	0.311
(9)	0.996	0.016	2.157	0.997	0.016	2.113	0.983	0.030	5.476	0.998	0.013	1.647	0.998	0.015	2.347
(10)	0.961	0.049	9.760	0.981	0.036	6.232	0.826	0.093	17.661	0.973	0.041	7.451	0.974	0.046	7.831
(11)	0.995	0.017	3.167	0.999	0.007	0.872	0.880	0.077	16.384	0.985	0.031	6.503	0.943	0.067	11.672
(12)	0.999	0.009	1.707	0.999	0.005	0.894	0.998	0.010	1.872	0.998	0.012	1.389	0.957	0.075	9.884
(13)	0.999	0.009	1.873	0.999	0.005	0.892	0.998	0.009	1.889	0.998	0.011	1.378	0.999	0.002	0.311

Finally, the following models were considered satisfactory: Page (3), Midilli (4), Thompson (6), Logarithmic (9), Two terms (12), and Approximation of diffusion (13). The other models were considered unsatisfactory because they presented P values above 10% in at least one of the conditions of drying air temperature used in the present study.

According to Kashaninejad et al. (2007), R^2 values greater than 0.95 represent a good fit for model selection. In this context, the models selected according to the P-value criterion demonstrated satisfactory performance, exhibiting R^2 values above 0.99. According to Botelho et al. (2018) and Siqueira, Resende and Chaves (2012), lower SE values indicate a better fit of mathematical models. According to this criterion, Page model (3) was suitable for the temperatures of 40 and 50 °C, while Two terms (12) and the Approximation of diffusion (13) models were suitable for the temperature of 50 °C. Midilli model (4) exhibited a satisfactory fitting for all temperatures other than 80 °C. At 80 °C, the approximation of the diffusion model demonstrated satisfactory fitting by presenting lower values of P and SE. Midilli (4) and the Approximation of diffusion (13) models have been used previously to represent the drying kinetics of grains (Khanali et al., 2012; Maia et al., 2019; Perea-Flores et al., 2012).

The values of Akaike Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC) were used as auxiliary to further refine the selection of the best model for representing the drying kinetics of buckwheat grains, considering the parameters of the models pre-selected according to Gauss-Newton criterion (Table 3). This criterion has been used previously for selecting models to represent the drying kinetics of various vegetable products, such as *Piper aduncum* L. leaves (Quequeto et al., 2019a), *Morinda citrifolia* L. grains (Quequeto et al., 2019b), and *Ipomoea batatas* L. pulp (Souza et al., 2019).

According to Wolfinger (1993), AIC and BIC criteria could assist the selection process of the models pre-selected according to the Gauss-Newton criterion. Wolfinger (1993) stated that the lower the values of AIC and BIC, the better is the fit of the model. Therefore, Midilli model (4) presented a better fit for the temperatures of 40, 60, and 70 °C, while the Approximation of diffusion (13) presented a satisfactory fitting for the temperatures of 50 and 80 °C. The drying curves (Figure 2) for buckwheat grains reflect the selected models according to the criteria adopted.

The selected models presented a good fit, describing the drying behavior of buckwheat accurately, and establishing a good correspondence between the observed and estimated values. Sousa et al. (2011) obtained a good fit with the Midilli model for forage turnip grains (*Raphanus sativus* L.) at temperatures ranging from 30 to 70 °C, while Camicia et al. (2015) obtained a good fit with the Midilli model for *Vigna unguiculata* L. Walp grains at temperatures ranging from 30 to 50 °C. Botelho et al. (2015) also obtained a good fit with the Midilli model for the drying of sorghum grains at the temperatures of 40, 50, and 60 °C, while Faria et al. (2012) obtained a better fit with the Approximation of diffusion model at temperatures ranging from 30 to 70 °C for different moisture content conditions in the drying kinetics of crambe seeds (*Crambe abyssinica* Hort).

The behavior of the fitting curves in the present study was consistent with the conditions of drying air temperature, and it was observed that longer drying times were required for lower temperatures, a situation also observed in several other studies conducted previously on the drying kinetics of various agricultural products (Keneni; Hvoslef-Eide; Marchetti, 2019; Quequeto et al., 2019a; Siqueira; Resende; Chaves, 2012; Sousa et al., 2011).

The values of the parameters of Midilli model (4) for the temperatures of 40, 60, and 70 °C revealed that the parameter "k" of the Approximation of diffusion (13) model for the temperatures of 50 and 80 °C tended to increase with the increase in the drying air temperature, while the other parameters demonstrated a random behavior (Table 4) and did not exhibit a clear tendency with the increase in temperature.

Table 3: Akaike Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC) values for the models that fitted best to the data of the drying of buckwheat (*Fagopyrum esculentum* Moench) grains at different temperatures.

Models	Temperature									
	40 °C		50 °C		60 °C		70 °C		80 °C	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
(3)	-154.842	-151.708	-83.375	-81.920	-90.188	-87.271	-74.922	-72.932	-41.367	-41.529
(4)	-157.296	-152.073	-87.389	-84.964	-92.404	-89.208	-77.047	-75.853	-45.693	-45.964
(6)	-94.091	-90.9579	-61.767	-60.312	-74.153	-72.236	-63.659	-62.465	-31.579	-31.742
(9)	-110.087	-105.909	-60.870	-58.931	-79.387	-76.830	-59.313	-57.722	-34.583	-34.799
(12)	-132.852	-127.6300	-86.479	-88.903	-86.408	-83.213	-66.422	-64.433	-59.520	-59.790
(13)	-132.957	-128.779	-90.892	-88.952	-88.298	-85.741	-68.203	-66.611	-61.501	-61.718

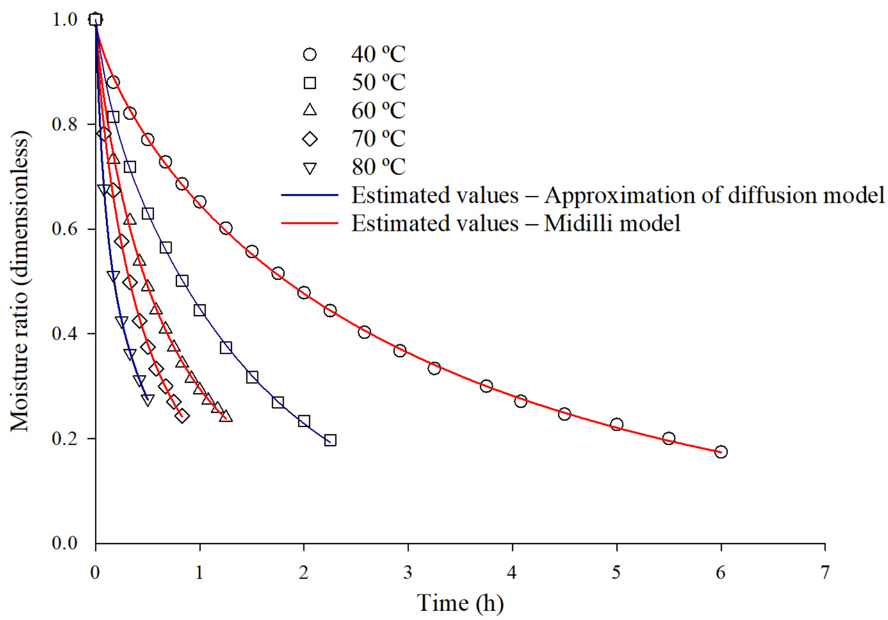

Figure 2: Moisture ratios estimated using Midilli and the Approximation of diffusion models for the drying of buckwheat (*Fagopyrum esculentum* Moench) grains at different drying air temperatures.

Similar behavior of parameter "k" was observed by Sousa et al. (2011) in the study of the drying of forage turnip (*Raphanus sativus* L.) grains, where this parameter was observed to be related to the effective diffusivity of drying in the falling-rate period and could be used to partially explain the behavior of the drying air temperature.

The effective diffusion coefficients for the buckwheat grains during drying, at temperatures ranging from 40 to 80 °C (Figure 3A), were obtained by fitting the mathematical model of liquid diffusion having eight terms for the spherical form, considering an equivalent radius of 1.97 mm, to the experimental values. The influence of this model could be described by means of the Arrhenius representation of the effective diffusion coefficient (Figure 3B).

The effective diffusion coefficient values varied from 1.8990×10^{-11} m^2 s^{-1} to 17.8831×10^{-11} m^2 s^{-1} within the temperature range of 40–80 °C (Figure 3A). As the drying air temperature increased, the diffusion coefficient also increased. According to Soares, Jorge and Montanuci (2016), lower drying air temperatures promote greater internal resistance to water transport during drying, resulting in lower values of the effective diffusion coefficient. This is contrary to what happens at higher temperatures when the water diffusion from the center to the periphery is higher.

The activation energy, considering the mechanisms of diffusion, for the studied temperature range was obtained from the slope of the Arrhenius representation of the effective diffusion coefficient plot, and was determined to be 49.75 kJ mol^{-1} (Figure 3B). This value was consistent with the corresponding values reported for various agricultural products by Zogzas, Maroulis and Marinos-Kouris (1996), i.e., 12.7–110 kJ mol^{-1}.

Activation energy is the minimum energy required by the water molecules to break the barrier as they migrate to the product surface during the drying process (Sharma; Prasad, 2004). According to Sousa et al. (2011), the higher the activation energy value, the lower is the diffusivity of water inside the product. Therefore, the activation energy obtained under the adopted drying conditions indicated a certain resistance to water diffusivity, in contrast to the findings of other studies on drying kinetics: 24.78 kJ mol^{-1} for *Raphanus sativus* L. (Sousa et al., 2011), and 33.82 kJ mol^{-1} and 35.71 kJ mol^{-1} for two sorghum cultivars (Botelho et al., 2015). However, the obtained value of activation energy was not higher than that obtained (51.03 kJ mol^{-1}) in the drying kinetics of rice grains (Corrêa et al., 2017).

In general, the values obtained were within the range reported by Zogzas, Maroulis and Marinos-Kouris (1996) for various agricultural products. The differences were closely linked to the initial moisture contents, the drying conditions adopted, and the physical and chemical characteristics of the product, with direct effects on the drying time (Diógenes et al., 2013).

Table 4: Parameters and coefficients of Midilli and the Approximation of diffusion models obtained for the buckwheat (Fagopyrum esculentum Moench) grains at different drying air temperatures.

Temperature (°C)	Mathematical models						
	Midilli				Approximation of diffusion		
	k	n	a	b	k	a	b
40	0.4274	0.7667	0.9934	-0.0016	-	-	-
50	-	-	-	-	8.373	0.117	0.081
60	0.9551	0.5947	1.0012	0.0272	-	-	-
70	1.1053	0.8498	0.9982	0.0557	-	-	-
80	-	-	-	-	11.2424	0.4224	0.1327

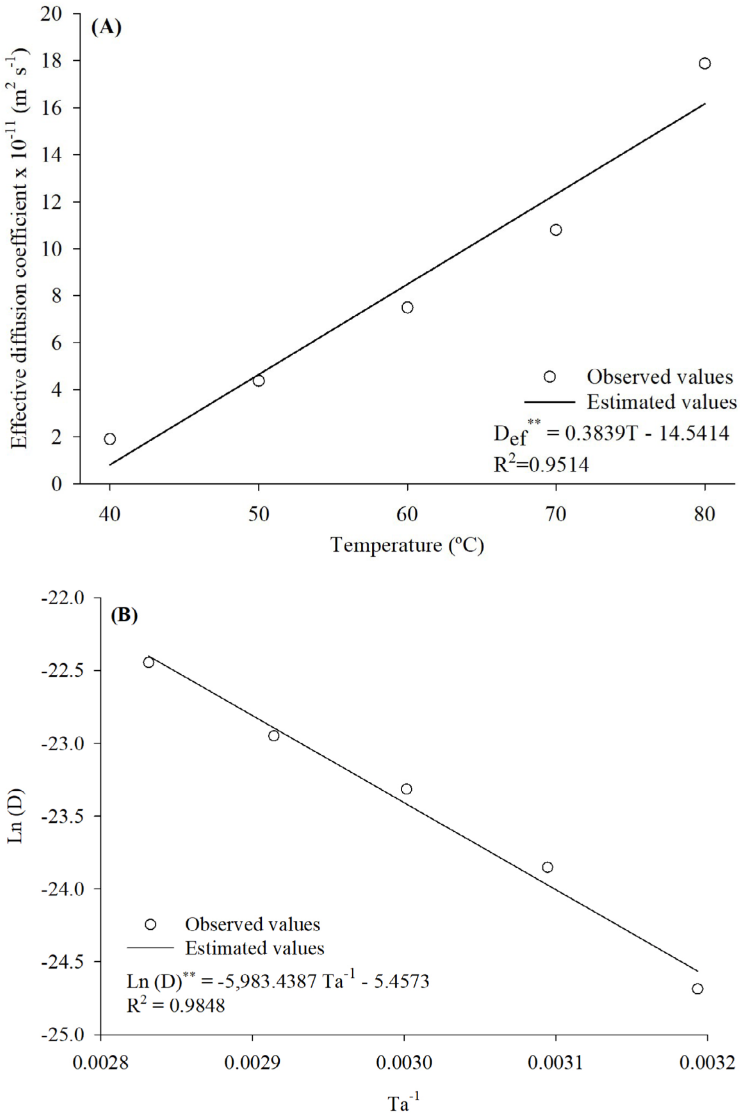

Figure 3: Average values of the effective diffusion coefficient (A) and the Arrhenius representation of the effective diffusion coefficient (B) at different drying air temperatures for buckwheat (*Fagopyrum esculentum* Moench) grains (**significant at 1%, using the t-test).

CONCLUSIONS

Midilli model presented a better fit in regard to explaining the drying kinetics of buckwheat at the temperatures of 40, 60, and 70 °C, while the Approximation of diffusion model was the most adequate for the temperatures of 50 and 80 °C. The effective diffusion coefficient tended to increase with an increase in the drying air temperature, with its values ranging from 1.8990×10^{-11} m^2 s^{-1} for the temperature of 40 °C to 17.8831×10^{-11} m^2 s^{-1} for 80 °C. The activation energy required to initiate the drying process was determined to be 49.75 kJ mol^{-1}.

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