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Drying kinetics and thermodynamic properties of peanut seeds (*Arachis hypogaea* L.)

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Abstract

The aim of this study was to evaluate the drying process and determine the activation energy, effective diffusion coefficient, and thermodynamic properties of peanut seeds. The peanut seeds (variety "Amena 018"), harvested with an initial moisture content of 0.36 ± 0.003 kg kg^{-1} db, were dried in a forced circulation oven at temperatures of 40, 45, 50, 55, and 60°C until they reached a final moisture content of 0.11 ± 0.001 kg kg^{-1} db. The mathematical models were adjusted by nonlinear regression using the Gauss-Newton method, Akaike's information criterion (AIC), and Schwarz's Bayesian information criterion (BIC). The two-term model showed the best fit for the temperatures of 40, 45, 50, and 55°C, and the two-term exponential for 60°C; the drying rate increased with increasing temperature and decreased with increasing drying time, the effective diffusion coefficient varied from 7.5097×10^{-11} to 11.5741×10^{-11} m^2 s^{-1} for the 40-60°C range, and the activation energy was 18.54 kJ mol^{-1}. The enthalpy, entropy, and Gibbs free energy values ranged from 15.931 to 15.765 kJ mol^{-1}, -0.110401 to -0.110916 kJ mol^{-1} K^{-1}, and 50.504-52.718 kJ mol^{-1}, respectively, for temperatures from 40 to 60°C.

Keywords: drying rate; mathematical modeling; activation energy; enthalpy.

Practical Application: Understanding the peanut seed drying process is important to preserve physiological quality.

1 INTRODUCTION

The peanut (*Arachis hypogaea* L.) is a native plant of South America, specifically to the region between 10° and 30° South latitude. It is one of the main oilseeds in Mozambique and is cultivated by smallholder farmers (Coelho et al., 2017). The peanut crop adapts to dry climates and can enrich the soil through nitrogen fixation, a special feature of leguminous plants. Peanut seeds are high in vitamins, provide a high yield of easily digestible oil, and can be used for human consumption, canning, and medicinal products (Settaluri et al., 2012).

Worldwide production was estimated at 54.24 million tons in 2022, in an area of 30.54 million hectares, corresponding to an average yield of 1776.20 kg ha^{-1}. The Asian continent leads the group of largest growers with 31.70 million tons, followed by the African continent with 17.36 million tons (FAOSTAT, 2024). In Mozambique, peanut production is concentrated in the northern and southern parts of the country. According to data from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT, 2024), for the year 2022, Mozambique produced approximately 114.16 thousand tons of peanuts, with an average yield of 500 kg ha^{-1}, which is much lower than the global average yield for the same period, making the scenario very much worried if losses associated with postharvest processes are taken into account.

Seeds of high physiological quality are essential for ensuring good germination and vigor, thus providing greater production volumes, yields, and physiological quality (Silva et al., 2015). However, when the seeds reach the point of greatest dry matter accumulation and the highest physiological quality, they have a high moisture content, usually above 40% wb, which makes the harvesting process difficult (Queiroz et al., 2011). Seeds remaining in this state can induce high levels of metabolic activity and, consequently, reduce their physiological quality (Marcos-Filho, 2015). Therefore, it is important that the seeds are subjected to a drying process as close as possible to physiological maturity, as long as it is possible to harvest them without significant damage.

The drying process is important in terms of both energy consumption and the influence of this operation on the final quality of the product. According to Resende et al. (2010), the simulation of a mathematical model of the drying process is crucial for the development and improvement of equipment used for drying grains in general.

The mathematical models commonly used to describe the drying kinetics of various agricultural products in thin layers are grouped into theoretical models, which consider only the internal resistance, the transfer of heat and water between the product and the hot air, and semitheoretical models and

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empirical models, which consider only the internal resistance, the temperature and the relative humidity of the drying air (Midilli et al., 2002).

Numerous models have been proposed to describe the thin-layer drying kinetics of agricultural products. However, mathematical models are specific to each product and drying condition (Moura et al., 2021). The movement of water, characterized by the drying rate, can cause physical and structural damage that affects not only the proximal composition but also, more importantly, the physiological potential of the seeds (Ullmann et al., 2015).

The use of techniques such as adjusting mathematical models can help in preserving the quality and use energy efficiently during the drying process, thus reducing losses (Isquierdo et al., 2013). With this information, it is possible to estimate the drying time and, consequently, the energy expenditure that will determine the cost of the process (Siqueira et al., 2020). In this context, the aim of this study was to adjust mathematical models of drying kinetics and determine the effective diffusion coefficients, activation energy, and thermodynamic properties of peanut seeds.

2 MATERIALS AND METHODS

Peanut seeds of the local variety "Amena 018" were harvested manually from a farmer's field in the district of Sussundenga, Manica Province, Mozambique (19°41'27.0"S, 33°16'17.5"E), with an initial moisture content of 0.36 ± 0.003 kg kg^{-1} db. The initial moisture content was determined using the standard oven method with three 15-g samples at a temperature of 105 ± 1°C for 24 h. After harvesting, the seeds were threshed and then subjected to a drying process in an INDERLAB forced circulation oven at temperatures of 40, 45, 50, 55, and 60°C and relative humidities of 31.20, 24.01, 19.93, 14.86, and 12.04%, respectively.

Drying was carried out in metallic trays with fully perforated bottoms containing 150 ± 0.09 g of seeds. Drying was monitored by means of weighing at regular intervals and proportionally varied for each drying condition using a semianalytical balance (KERN) with a resolution of 0.01 g until a final moisture content of 0.11 ± 0.001 kg kg^{-1} db was reached. After drying, the data obtained were used to determine the drying rate using Equation 1:

$$DR=\frac{(X_0-X_i)}{(t_i-t_0)} \tag{1}$$

Where:

DR: the drying rate (kg kg^{-1} h^{-1});

X_0: the previous moisture content (decimal, db);

X_i: the current moisture content (decimal, db);

t_0: the total previous drying time (h);

t_i: the total current drying time (h).

2.1 Moisture content rate

The moisture content ratio values (Equation 2) were calculated from the experimental data on the initial and final moisture contents and over the course of drying:

$$RX=\frac{X-X_e}{X_i-X_e} \tag{2}$$

Where:

RX: the moisture content ratio (dimensionless);

X: the current moisture content (decimal, db);

X_e: the equilibrium moisture content (decimal, db);

X_i: the initial moisture content (decimal, db).

The equilibrium moisture content of peanut seeds under the conditions of temperature and relative humidity of the drying air evaluated in this study was obtained from the modified Henderson equation (Equation 3), which describes the hygroscopic equilibrium of peanut seeds (Corrêa et al., 2007):

$$X_e=\left[\frac{\ln(1\text{-}RH)}{-a\times(T+b)}\right]^{1/c} \tag{3}$$

Where:

HR: the relative humidity (decimal);

T: the drying temperature (°C);

a: 0.0002;

b: 38.4115;

c: 1.5619.

2.2 Mathematical models

Using the experimental moisture content ratio data, the mathematical models for drying peanut seeds were adjusted using models commonly used to represent the drying kinetics of agricultural products, as shown in Table 1 (Silva et al., 2018; Siqueira et al., 2020).

2.3 Effective diffusion coefficient

The effective diffusion coefficient was calculated for the different drying air temperature conditions by fitting the mathematical model of liquid diffusion (Equation 16) to the experimental data for drying peanut seeds. This equation is the analytical solution of Fick's second rule, without taking into account the volumetric contraction of the product, based on a spherical geometric shape with an eight-term approximation and the boundary condition of the known moisture content on the surface of the product (Brooker et al., 1992):

$$RX = \frac{X - X_e}{X_i - X_e} = \frac{6}{\pi^2} \sum_{n_t=1}^{\infty} \frac{1}{{n_t}^2} \exp\left[\frac{{n_t}^2 \pi^2 D_{ef}\, t}{9}\left(\frac{3}{r_e}\right)^2\right] \tag{16}$$

Where:

t: the drying time (s);

D_{ef}: the liquid diffusion coefficient ($m^2\ s^{-1}$);

r_e: the equivalent ratio (m);

n_t: the number of terms.

The equivalent radius (Equation 17) was determined by measuring the orthogonal axes of 50 peanut seeds using a digital micrometer with a resolution of 0.01 mm. The equivalent volume of seeds (Equation 18) was determined, considering the geometric shape of a triaxial sphere (Mohsenin, 1986):

$$r_e = \sqrt[3]{\frac{3V_s}{4\pi}} \tag{17}$$

$$V_s = \frac{\pi L_s W_s T_s}{6} \tag{18}$$

Where:

r_e: the equivalent radius (m);

V_s: the equivalent seed volume (m^3).

To evaluate the influence of the drying air temperature on the effective diffusion coefficient (D), the Arrhenius equation was used (Equation 19):

$$D = D_0 \exp\left(\frac{-E_a}{RT}\right) \tag{19}$$

Table 1. Thin-layer models have been employed in mathematical modeling of the drying kinetics of peanut seeds.

Model	Equation	
Page	$RX = \exp(-k\, t^n)$	(4)
Midilli	$RX = a \exp(-k\, t^n) + b\, t$	(5)
Newton	$RX = \exp(-k\, t)$	(6)
Thompson	$RX = \exp\{[-a - (a^2 + 4\, b\, t)^{0.5}]/(2\, b)\}$	(7)
Henderson & Pabis	$RX = a \exp(-k\, t)$	(8)
Verma	$RX = -a \exp(-k\, t) + (1 - a) \exp(-k_1\, t)$	(9)
Logarithmic	$RX = a \exp(-k\, t)$	(10)
Wang & Singh	$RX = 1 + a\, t + b\, t^2$	(11)
Two-term exponential	$RX = a \exp(-k\, t) + (1 - a) \exp(-k\, a\, t)$	(12)
Two terms	$RX = a \exp(-k_0\, t) + b \exp(-k_1\, t)$	(13)
Approximation of diffusion	$RX = a \exp(-k\, t) + (1-a) \exp(-k\, b\, t)$	(14)
Valcam	$RX = a + b + c\, t^{1.5}\, d\, t^2$	(15)

t: the drying time; k, k_0, and k_1: drying constants; a, b, c, d, g, and n: model coefficients. Source: Silva et al. (2018); Siqueira et al. (2020).

Where:

D_0: the preexponential factor;

R: the universal gas constant (8.314 kJ $kmol^{-1}\ K^{-1}$);

T: the temperature (K);

E_a: the activation energy (kJ mol^{-1}).

The relationship between Ln D_{ef} and the inverse of the temperature (T^{-1}) provides a linear line whose angular coefficient allows the value of the activation energy to be estimated using Equation 20:

$$\mathrm{Ln}D_{ef} = \mathrm{Ln}D_0 - \left(\frac{E_a}{R}\right) T^{-1} \tag{20}$$

2.4 Thermodynamic properties

The thermodynamic properties of dry peanut seeds (*Arachis hypogaea* L.) were determined using the method described by Jideani and Mpotokwana (2009), which is widely used to describe the thermodynamic properties of various agricultural products (Equations 21-23):

$$\Delta H = E_a - RT \tag{21}$$

$$\Delta S = R\left(\ln D_0 - \ln\frac{k_B}{h_p} - \ln T\right) \tag{22}$$

$$\Delta G = \Delta H - T\Delta S \tag{23}$$

Where:

ΔH: the enthalpy (J mol^{-1});

ΔS: the entropy (J $mol^{-1}\ K^{-1}$);

k_B: Boltzmann's constant (1.38×10^{-23} J K^{-1});

k_p: Planck's constant (6.626×10^{-34} J s^{-1});

ΔG: the Gibbs free energy (J mol^{-1}).

2.5 Statistical analysis

The data were analyzed using the Statistica 7.0® and R 4.4.0® software. The models with the best fit were selected using the nonlinear regression analysis via the Gauss-Newton method and complemented by the Akaike information criterion (AIC) and Bayesian information criterion (BIC). The analysis considered the magnitude of the coefficient of determination adjusted by the model (R^2), the relative mean error (P, Equation 24), and the estimated mean error (SE, Equation 25) (Silva et al., 2018; Siqueira et al., 2012):

$$P = \frac{100}{n} \sum_{i=1}^{n} \left(\frac{|Y - \hat{Y}|}{Y}\right) \tag{24}$$

$$SE=\sqrt{\frac{\sum_{i=1}^{n}(Y-\hat{Y})^{2}}{DF}} \qquad (25)$$

Where:

Y: the experimentally observed value;

$\hat{Y}$: the value estimated by the model;

n: the number of experimental observations;

DF: the degree of freedom of the model (the difference between the number of observations and the number of model parameters).

The AIC and the BIC were used to further select the best-fitting models. According to this criterion, higher absolute values of the AIC (Equation 26) and BIC (Equation 27) indicate a better fit of the model preselected by the Gauss-Newton method. This criterion has been used with good accuracy to choose models with the best fit for the drying kinetics of various agricultural products (Ferreira et al., 2021; Siqueira et al., 2020):

$$AIC=-2\log L+2p \qquad (26)$$

$$BIC=-2\log L+p\,Ln(n) \qquad (27)$$

Where:

p: the number of model parameters;

n: the number of model observations;

L: the maximum likelihood, considering the estimates of the parameters.

3 RESULTS AND DISCUSSION

Seeds subjected to higher drying temperatures showed higher drying rates (Figure 1), especially at the beginning of the process, as a result of greater water availability at this stage. As the drying time increased, the curves overlapped, and there was a decreasing trend in the drying rate, regardless of the drying air temperature. According to Siqueira et al. (2020), as drying continues, water tends to come out with greater difficulty because it is bound stronger, which has also been observed in various studies related to the drying kinetics of agricultural products (Keneni et al., 2019; Siqueira et al., 2012).

The drying times were 12.83, 10.83, 8.33, 6.83, and 5.50 h at 40, 45, 50, 55, and 60°C, respectively. Therefore, increasing the drying air temperature reduced the time needed for the product to reach the desired moisture content, which is due to the higher drying rate observed at higher temperatures. According to Goneli et al. (2009), increasing the temperature increases the level of vibration of the water molecules, thus contributing to faster water diffusion.

Tables 2A and 2B show the estimated mean error (SE), relative mean error (P), coefficient of determination (R^2), Akaike information criterion (AIC), and Schwarz's Bayesian information criterion (BIC) that are used to describe the drying kinetics of peanut seeds at different temperatures. The mean relative error (P) describes the deviation of the observed values from the estimated curve of the model. For the selected model to be considered adequate, this error must be less than 10% (Kashaninejad et al., 2007). In relation to the P values, with the exception of the Verma model (9), the other models exhibited P values under 10% for all temperatures and are therefore considered acceptable for describing the drying kinetics of peanut seeds (Mohapatra & Rao, 2005).

The estimated mean error (SE) and coefficient of determination (R^2) were used to select the best model for representing the drying kinetics of various agricultural products. Lower SE values indicate a better fit of the mathematical model (Siqueira et al., 2012). Therefore, the mathematical models Midilli (5), Thompson (7), two-term exponential (12), two-term (13), approximation of diffusion (14), and Valcam (15) were the ones that fit best, as they had lower SE values at least one of the temperatures, and at 60°C, all the selected models fit.

The Newton (6), Henderson & Pabis (8), and Wang & Singh (11) models had higher values at all drying air temperatures, so they did not satisfactorily describe the drying of peanut seeds under the described conditions. According to Aguerre et al. (1989), models with coefficients of determination (R^2) greater than 0.95 are good fits. Therefore, almost all the models have good accuracy in representing the drying kinetics of peanut seeds, with the models that cumulatively provided a satisfactory fit for the P and SE parameters standing out. The ability of a model to adequately represent a given physical process is inversely proportional to the value of the estimated mean error.

AIC and BIC have been used satisfactorily as additional criteria for selecting drying kinetics models for various agricultural products (Ferreira et al., 2021; Gomes et al., 2018; Gomes et al., 2022; Mabasso et al., 2024; Siqueira et al., 2020). These values make it possible to select the best model among those

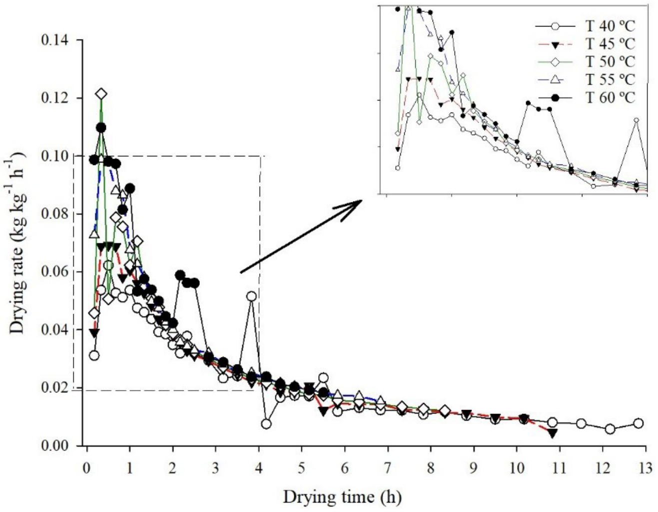


Figure 1. Drying rate of peanut seeds at different drying air temperatures.

preselected by the Gauss–Newton method due to its level of accuracy. Higher absolute AIC and BIC values indicate a better model fit (Wolfinger, 1993).

Thus, the two-term model showed the highest absolute AIC and BIC values for temperatures of 40, 45, 50, and 55°C, while the two-term exponential model showed the highest absolute values at 60°C (Table 2). The selected models showed good fitting accuracy, according to the proximity between the estimated and expected values (Figure 2). The two-term model has been recommended by other researchers for various agricultural products, especially *Arachis hypogea* L. (Araujo et al., 2017) and *Tamarindus indica* L. (Ferreira et al., 2021).

The selected curves showed a satisfactory fit between the observed experimental data and the data estimated by the two-term and two-term exponential models, as the statistical indices used were effective in selecting the models.

Increasing the temperature increases the drying potential of the air and heat transfer in the product, increasing the rate of replacement of water vapor on the surface of the product through diffusion. In this way, the drying speed decreases continuously over time, according to the proximity of the moisture content to its equilibrium moisture content, at which point the adsorption and desorption processes cease. Table 3A shows the mean values of the effective diffusion coefficient obtained during the drying of peanut seeds for different drying air temperatures (40, 45, 50, 55, and 60°C).

For the two-term model, the "a" and "g" coefficients had decreasing trends. The "b" coefficient increased as the drying air temperature increased. The magnitude of the drying constant "k" for the two-term model increases as the drying air temperature increases. This parameter is an estimate that represents the effects of temperature and is correlated with the effective diffusivity during the drying process in the decreasing period and is used as an explanatory factor for drying behavior (Madamba et al., 1996). Similar phenomena have been observed in various research reports on the drying kinetics of products such as grains of *Zea mays* L. (Coradi et al., 2015), leaves of *Serjania marginata* Casar (Martins et al., 2015), fruits of *Arachis hypogaea* L. (Araujo et al., 2017), and seeds of *Cucumis melo* L. (Silva et al., 2018).

Figure 3 shows the values of the effective diffusion coefficients (Figure 3A) and the Arrhenius representation (Figure 3B)

Table 2A. Coefficient of determination (R^2), relative mean error (P), estimated mean error (SE), Akaike information criterion (AIC), and Schwarz's Bayesian information criterion (BIC) of peanut seeds (*Arachis hypogaea* L.) subjected to different air drying conditions.

Model	Temperature (°C)	SE	P (%)	R^2	AIC	BIC
Page	40	0.010	1.683	0.999		
	45	0.011	1.574	0.999		
	50	0.011	1.487	0.999		
	55	0.011	1.294	0.999		
	60	0.008	1.307	0.999		
Midilli	40	0.008	1.544	0.999	-253.318	-245.130
	45	0.009	1.520	0.999	-217.935	-210.304
	50	0.009	1.485	0.999	-195.478	-188.308
	55	0.009	1.346	0.999	-107.011	-104.347
	60	0.006	0.934	0.999	-176.593	-170.499
Newton	40	0.019	5.094	0.998		
	45	0.029	6.428	0.993		
	50	0.032	6.870	0.991		
	55	0.034	6.716	0.988		
	60	0.025	5.053	0.994		
Thompson	40	0.008	1.602	0.999	-210.649	-205.737
	45	0.008	1.541	0.999	-160.958	-156.379
	50	0.008	1.413	0.999	-142.179	-137.877
	55	0.008	1.310	0.999	-125.822	-121.825
	60	0.006	0.791	0.999	-129.459	-125.802
Henderson & Pabis	40	0.017	4.127	0.998		
	45	0.024	4.698	0.996		
	50	0.025	4.795	0.994		
	55	0.026	4.572	0.993		
	60	0.020	3.719	0.996		
Verma	40	0.168	46.527	0.795		
	45	0.190	44.263	0.663		
	50	0.225	50.953	0.395		
	55	0.035	6.716	0.988		
	60	0.026	5.053	0.994		

Table 2B. Coefficient of determination (R^2), relative mean error (P), estimated mean error (SE), Akaike information criterion (AIC), and Schwarz's Bayesian information criterion (BIC) of peanut seeds (*Arachis hypogaea* L.) subjected to different air-drying conditions.

Model	Temperature (°C)	SE	P (%)	R^2	AIC	BIC
Logarithmic	40	0.010	2.529	0.999		
	45	0.013	2.701	0.999		
	50	0.012	2.143	0.999		
	55	0.013	2.358	0.998		
	60	0.007	1.192	0.999		
Wang & Singh	40	0.034	8.823	0.992		
	45	0.035	7.390	0.990		
	50	0.032	5.951	0.990		
	55	0.032	5.968	0.990		
	60	0.022	3.828	0.996		
Two-term exponential	40	0.007	1.536	0.999	-259.973	-255.060
	45	0.007	1.104	0.999	-234.514	-229.935
	50	0.008	1.065	0.999	-209.925	-205.623
	55	0.008	1.289	0.999	-186.757	-182.760
	60	0.006	0.831	0.999	-183.239	-179.583
Two terms	40	0.006	1.187	0.999	-269.989	-261.801
	45	0.006	0.904	0.999	-251.220	-243.589
	50	0.006	0.848	0.999	-222.935	-215.765
	55	0.005	0.716	0.999	-207.648	-200.987
	60	0.006	0.756	0.999	-181.024	-174.930
Approximation of diffusion	40	0.008	1.403	0.999	-258.542	-251.991
	45	0.007	1.148	0.999	-233.088	-226.983
	50	0.007	1.009	0.999	-212.784	-207.048
	55	0.006	0.857	0.999	-198.076	-192.747
	60	0.006	0.753	0.999	-182.296	-177.421
Valcam	40	0.007	0.859	0.999	-264.844	-256.656
	45	0.006	0.689	0.999	-246.544	-238.913
	50	0.006	0.694	0.999	-219.105	-211.935
	55	0.006	0.686	0.999	-202.852	-196.191
	60	0.006	0.815	0.999	-179.374	-173.280

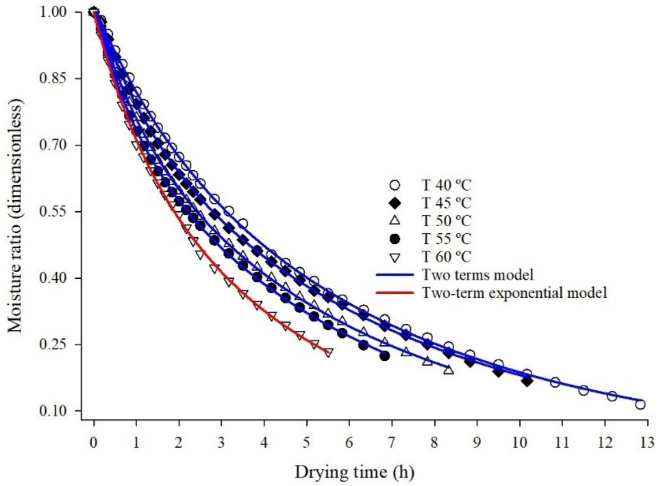


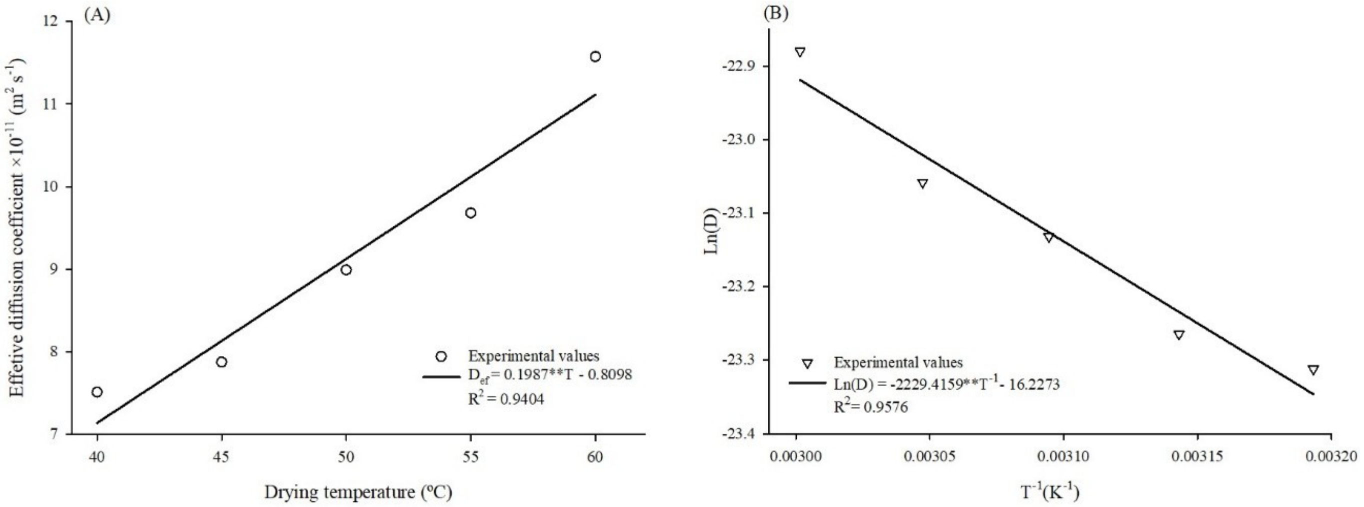
Figure 2. Moisture content ratio values estimated by the two-term and two-term exponential models for drying peanut seeds at different temperatures.

for peanut seeds for the different drying conditions investigated. The experimental drying values were adjusted based on Fick's rule and the geometric shape of a triaxial spheroid with an equivalent radius of 5.51 mm.

The effective diffusion coefficients ranged from 7.5097×10^{-11} to 11.5741×10^{-11} for the temperature range between 40 and 60°C (Figure 3A). According to Madamba et al. (1996), the effective diffusion coefficient for drying agricultural products ranges from 10^{-11} to 10^{-9} m^2 s^{-1}. The dependence of the effective diffusion coefficient on the temperature of the drying air has been satisfactorily described by the Arrhenius equation (Corrêa et al., 2007; Kashaninejad et al., 2007). The diffusion coefficient increases as the temperature increases, and the viscosity of the water decreases at higher temperatures, which is the factor involved in promoting the diffusion of water through the capillaries of the seed, allowing this fluid to move inside the product (Goneli et al., 2009).

As the activation energy indicates the ease with which the water molecules overcome the energy barrier during diffusion inside the product, the lower the activation energy is, the greater the diffusivity of the water in the product (Corrêa et al., 2007). The lower the activation energy is, the faster the water will be removed from the product, indicating that products with higher moisture contents will have lower activation energy (Siqueira et al., 2012).

The activation energy for the peanut seed drying phenomenon was 18.54 kJ mol^{-1}, which is within the range described for drying agricultural products, which varies from 12.7 to 110 kJ



**Significant at p<0.01 according to the t-test.

Figure 3. (A) Mean values of the effective diffusion coefficients and (B) Arrhenius representation for drying peanut seeds at temperatures of 40, 45, 50, 55, and 60°C.

Table 3. Coefficients for the two-term (40, 45, 50, and 55°C) and two-term exponential (60°C) models (A) and enthalpy (ΔH), entropy (ΔS), and Gibbs free energy (ΔG) values for the different drying conditions of peanut seeds (*Arachis hypogaea* L.) (B).

Mathematical models (A)

Temperature (°C)	**Two-term**				**Two-term exponential**	
	a	**k**	**b**	**g**	**a**	**k**
40	0.7825*	0.1439*	0.2321*	0.4938*	-	-
45	0.7764*	0.1456*	0.2415*	0.7108*	-	-
50	0.2476*	0.8440*	0.7677*	0.1626*	-	-
55	0.2304*	1.0725*	0.7837*	0.1790*	-	-
60	-	-	-	-	0.2526*	0.8471*

Thermodynamic properties (B)

Temperature (°C)	**ΔH (kJ mol^{-1})**	**ΔS (kJ mol^{-1} K^{-1})**	**ΔG (kJ mol^{-1})**
40	15.931	-0.110401	50.504
45	15.890	-0.110533	51.057
50	15.848	-0.110662	51.610
55	15.807	-0.110790	52.163

*Significant at $p < 0.05$ by the t-test.

mol^{-1} (Zogzas et al., 1996). This value is lower than that found in other studies for peanut seeds, which was 35.24 kJ mol^{-1} (Araujo et al., 2017). These differences may be related to the drying conditions, such as the shape and size of the seed, initial moisture content, and chemical composition of the product.

Table 3B shows the thermodynamic properties of peanut seeds (*Arachis hypogaea* L.) dried at 40, 45, 50, 55, and 60°C. Enthalpy values for drying peanut seeds (*Arachis hypogaea* L.) decreased with increasing drying air temperature, indicating a lower energy demand to promote drying at higher temperatures (Table 3B). The same trend was observed for the absolute entropy values, with higher absolute values occurring at higher temperatures.

For Corrêa et al. (2010), negative entropy values and trends reflect greater excitation of water molecules at higher temperatures and chemical adsorption or structural changes in the adsorbent (Moreira et al., 2008). According to the same approach, the Gibbs free energy increased as the temperature of the drying air increased. In this context, it can be concluded that the drying process did not occur spontaneously but rather as a result of the increase in the difference in partial pressure of the water vapor caused by the heating of the air, especially at higher temperatures, thus forcing the water out of the seed through the simultaneous exchange of heat and mass between the drying air and the product (Brooker et al., 1992).

4 CONCLUSION

The drying rate of the peanut seeds increased with increasing drying air temperature and decreased with increasing drying time. The two-term exponential model was the best fit for a temperature of 60°C, while for temperatures of 40, 45, 50, and 55°C, the two-term model was more suitable for describing the drying kinetics of peanut seeds in a thin layer. The effective diffusion coefficient varied from 7.5097×10^{-11} to 11.5741×10^{-11} m^2 s^{-1} for the drying air temperature range of 40-60°C, and the activation energy was 18.54 kJ mol^{-1}. The enthalpy, entropy, and Gibbs free energy values ranged from 15.931 to 15.765 kJ mol^{-1}, -0.110401 to -0.110916 kJ mol^{-1} K^{-1}, and 50.504 to 52.718 kJ mol^{-1}, respectively, for temperatures from 40 to 60°C.

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