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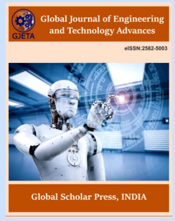

(RESEARCH ARTICLE)

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Use of diffusive and empirical models to predict drying rate of acerola seeds (Malpighia sp.)

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Abstract

The thin layer drying process of acerola seeds was analyzed using a flat plate geometry diffusion model, Page's model, and a two-part model proposed based on the diffusion equation. These models were fitted to experimental drying kinetics data of acerola seeds for an air flow speed of 1.5 m/s, at temperatures of 40, 50, 60 and 70°C, using non-linear regression by Levenberg-Marquardt method. The diffusion model was used to determine the diffusion coefficients and activation energy. The predicted and experimental results were compared using the determination coefficient (R^2) and mean square error (MSE) of the estimates as criteria. The results showed that the diffusion model is not suitable for predicting the drying rate of acerola seeds, while Page’s equation and the two-part proposed model can be safely used to predict the drying rates.

Keywords: Acerola; Drying kinetics; Thin layer drying; Page equation; Nonlinear regression

1. Introduction

Due to the nutritional health benefits of the fruit, the consumption of acerola has been increasing rapidly in several food industries. The size of the global acerola extract market is projected to reach approximately US$ 4 billion in 2024 and is expected to register a compound annual growth rate of 8.4%, as expected for the period 2019-2024 [1].

Brazil is considered the world's largest producer, consumer and exporter of acerola, produced mainly in the states of Pernambuco with 23.11% of national production; Ceará, with 14.32%; São Paulo, with 11.39%; and Bahia, with 10.48%. Acerola is also produced in the states of Rio Grande do Norte, Paraíba and Piauí [2].

In the case of agricultural products, there are still significant losses worldwide, which means a great waste of food, particularly when it comes to seasonal fruits. In Latin American countries, including Brazil, post-harvest losses of fruits and vegetables are considerably high, estimated at 30 to 45% [3, 4]. Losses of post-harvest agricultural products are inevitable, but can be minimized by improving processing techniques, especially in products that need storage in the medium and long term, such as fruits, vegetables, grains and cereals [5].

Drying has the main function of reducing the water activity in the product and, subsequently, decreasing the enzymatic activity and inhibiting the growth of microorganisms, increasing the product's useful life. In addition, other benefits of drying involve weight and volume reduction, favoring transport and storage [6, 7, 8].

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Particularly for Acerola seeds, there are few studies addressing the modeling of thin layer drying kinetics that provide alternative equations for predicting drying rates. For this reason, emphasis was given to the study of the drying kinetics of acerola seeds, which can be used, among other purposes, for the production of flour for fish feed [9] and for food supplements for humans [10, 11]. Therefore, this work aimed at modeling the drying kinetics of acerola seeds.

2. Literature review

2.1. A brief history of acerola (*Malpighia sp.*)

Acerola is a tropical fruit originally from the region that includes the Antilles, Central and South America. It belongs to the *Malpighiaceae* family, which comprises 60 genera and 1100 species [2, 12].

The consumption of Acerola has been expanding due, basically, to its high content of ascorbic acid (vitamin C) which, in some varieties, reaches up to 5,000 mg/100 g of pulp, which is up to 100 times higher than that of orange and 10 times that of guava, which are considered to have a high content of this vitamin. It is also a fruit rich in vitamin A, iron and calcium [2, 13, 14].

The significant volume of this fruit produced in Brazil has justified investments in new technology for processing and introducing new products on the market, with one of the options being the use of drying.

2.2. Drying process

The drying process aims at maximum water removal from the product, through the controlled application of heat [14]. It is a complex thermal process in which heat and mass transfer occur simultaneously with the objective of reducing the water content of the material to a level such that it can be stored for a long period, without compromising the quality of the product [6, 15, 16].

The evaluation of the drying kinetics of a product provides essential information about its behavior during the drying process, which allows, for example, to predict the time that will be spent in the process. Modeling is extremely important for the development and optimization of dryers, in addition to the standardization of drying methods [6].

Understanding the drying process requires the application of methods of analysis of transport phenomena, mainly heat and mass transfer, which involves interaction with other branches of science, such as thermodynamics, materials science and chemical kinetics [6, 8].

The drying models can be theoretical, semi-theoretical or empirical. These models are developed for a thin layer of product, dried under controlled conditions of temperature, relative humidity and air flow. These models have parameters that are determined experimentally and, in general, some empirical or semi-empirical model is fitted to these parameters, which completes the drying model. The drying equation thus determined allows to evaluate the effects of these parameters on the drying characteristics and the quality of the dry product [8, 17, 18, 19, 20].

The concept of hygroscopic equilibrium is essential for the modeling of drying kinetics, because all hygroscopic material has the property of losing or gaining moisture from the surrounding environment, tending to maintain an equilibrium relationship between the product and the ambient air. The moisture content of the product in equilibrium with the surrounding environment is called the equilibrium moisture content, which occurs when the water vapor pressure in the product is equal to that of the air in its surroundings [21, 22].

2.3. Drying theory

The physical mechanism of drying in hygroscopic-capillary-porous media, such as grains, is quite complex and generally results in equations whose solutions are complicated and often difficult to apply. Consensually, the most accepted drying mechanism is one that considers the movement of liquid (water in this case) from inside to outside the material being dried, in liquid and/or vapor form [8, 16, 23].

One of the most complete works found in the literature was developed by Luikov and collaborators, in 1966 [8, 16], who present a theory developed based on the following assumptions:

- Movement of liquid due to capillarity (capillary flow);
- Liquid movement due to the difference in moisture concentration (liquid diffusion);

- Movement of liquid due to osmotic force (diffusion on the surface);
- Movement of liquid due to the force of gravity;
- Movement of water vapor due to the difference in moisture concentration (vapor diffusion);
- Water vapor movement due to temperature difference (thermal diffusion);
- Negligible product shrinkage.

This theory is presented here, very briefly, based on the aforementioned assumptions. First, two steady-state flow equations are written:

$$\dot{m} = -\rho\left(D_m\frac{\partial M}{\partial x} + D_t\frac{\partial \theta}{\partial x}\right) \tag{1}$$

$$\dot{q} = -\left(k_t\frac{\partial \theta}{\partial x} + k_m\frac{\partial M}{\partial x}\right) \tag{2}$$

Applying the laws of mass and energy conservation to the drying of an individual particle, two differential equations are obtained in a non-steady state for the moisture content and temperature [8, 16]:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11}M + \nabla^2 K_{12}\theta \tag{3}$$

$$\frac{\partial \theta}{\partial t} = \nabla^2 K_{21}M + \nabla^2 K_{22}\theta \tag{4}$$

Discussions presented in the literature over the years by several researchers have led to the conclusion that, in the circumstances in which the drying of agricultural grains occurs, Luikov's equations can be simplified [8, 16]:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11}M \tag{5}$$

$$\frac{\partial \theta}{\partial t} = \nabla^2 K_{22}\theta \tag{6}$$

Researchers concluded that the coupled effects of temperature and moisture content can be neglected in the drying analysis, with sufficient precision in engineering involving this type of problem. In addition, the coefficient $K_{11} << K_{22}$ (that is, $D << 1/\alpha$, where α is the thermal diffusivity). Thus, Equation (6) is neglected and Equation (5) can be rewritten as:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11}M = \nabla^2 (D \cdot M) \tag{7}$$

Equation (7), the diffusion equation, is usually solved for an individual particle, but it has been used as a basis for the development of thin-layer drying models of semi-empirical hygroscopic-capillary-porous materials, such as agricultural grains, considering the diffusion coefficient, D, as a constant. Then, Equation (7) can be rewritten, in its general form, according to the shape parameter, c [24]:

$$\frac{\partial M}{\partial t} = D\left[\frac{\partial^2 M}{\partial r^2} + \frac{c}{r}\frac{\partial M}{\partial r}\right] \tag{8}$$

The solutions of Equation (8) for some regular geometries are shown in Table 1, for the boundary conditions expressed by Equation (9):

$$\begin{cases} M(r,0) = M_0 \\ M(r_0,t) = M_e \end{cases} \tag{9}$$

Table 1 Values of parameter ***c*** in the solution of the diffusion equation

Body type	Value of *c*	Solution	Equation
Flat plate	0	$M_R = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{2n+1}exp\left\{-\left[\frac{(2n+1)^2\,\pi^2}{4}\right]X^2\right\}$	(10)
Cylindrical	1	$M_R = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\left(\frac{1}{\lambda_n^2}\right)exp\left\{-\left[\frac{\lambda_n^2}{4}\right]X^2\right\}$	(11)
Spherical	2	$M_R = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}exp\left\{-\left[\frac{n^2\,\pi^2}{9}\right]X^2\right\}$	(12)

The variables in Equations (10), (11), and (12) are defined by dimensionless quantities, humidity ratio, M_R, and drying time, X, respectively:

$$M_R = \frac{\bar{M}(t) - M_e}{M_0 - M_e} \tag{13}$$

$$X = \left(\frac{A}{V}\right)(D\ t)^{1/2} \tag{14}$$

The dimensionless quantity X depends on the A/V ratio, which depends on the geometry of the body, as shown in Table 2 [24]:

Table 2 Values of the A/V ratio in the solution of diffusion equation

Body type	Variable r $[m]$	A/V ratio $[m^2/m^3]$
Flat plate	Thickness	2/r
Cylindrical	Radius	2/r
Spherical	Radius	3/r

2.4. Semi-theoretical drying models

Model derived from diffusion equation

For grain drying, the dimensionless boundary conditions are obtained by replacing the conditions defined in Equation (9) in Equation (13):

$$\begin{cases} M_R(r,0) = 1 \\ M_R(r_0,t) = 0 \end{cases} \tag{15}$$

In this work, the modeling was developed for a thin layer of acerola seeds, considering the layer as a flat plate of thickness x, and length L sufficiently large, using Equation (10). For this equation to satisfy the boundary condition of Equation (15) all terms must be used, which is impossible in practice. For this reason, it must be truncated, but in this case, it no longer satisfies the boundary condition. So, to solve this problem, three terms from Equation (10) are used, with an adjustment of the multiplying coefficient in the third term:

$$M_R = \left(\frac{8}{\pi^2}\right)\ \exp[-\varphi\ t] + \left(\frac{8}{9\,\pi^2}\right)\exp[-9\ \varphi\ t] + \left(\frac{24}{25\,\pi^2}\right)\exp[-25\ \varphi\ t] \tag{16}$$

Parameter φ depends on the diffusion coefficient, D, and the thickness of the seed layer, x. The coefficient of effective diffusion or mass diffusivity represents the ease with which matter moves through the pores of a porous medium. The greater the diffusivity of one substance in relation to the other, the faster they diffuse into each other.

In the case of grains, the empty spaces in the mass of the material layer have dimensions much larger than the diameter of the molecules of the material. In this case, the relation of the diffusion coefficient and the drying constant with the product temperature (in equilibrium with the drying fluid temperature) is, in general, defined by an Arrhenius-type equation [16].

Parameter φ in Equation (16) is experimentally determined as a function of seed layer thickness and drying temperature, and related to the diffusion coefficient by Equation (17) and Equation (18):

$$\varphi = D\left(\frac{\pi}{x}\right)^2 \tag{17}$$

$$D = D_0\, exp\left(-\frac{E_a}{\mathcal{R}\, T}\right) \tag{18}$$

where D is the effective diffusion coefficient $[m^2/s]$; D_0 is the maximum diffusion coefficient $[m^2/s]$; E_a is the activation energy $[J/mol]$; T is the temperature $[K]$, and $\mathcal{R}$ is the universal gas constant $[J/mol \cdot K]$.

Page equation

The drying equation derived from the diffusion equation, Equation (10) or (16), has been used to satisfactorily estimate the effective diffusion coefficient, D, and the activation energy, E_a. However, this equation does not fit well to moisture ratio data for agricultural products, especially grains. A reasonable alternative is to assume that the rate of moisture loss, due to the vapor pressure gradient on the surface of the material subjected to drying and the medium surrounding it, with constant temperature, is proportional to the difference between the moisture content of the material and the moisture content in equilibrium with the surrounding environment:

$$\frac{\partial \bar{M}}{\partial t} = k(\bar{M} - M_e) \tag{19}$$

The solution of Equation (19) by separating variables, within the appropriate limits, results in Equation (20):

$$\frac{\bar{M}(t) - M_e}{M_0 - M_e} = M_R = exp(-k\, t) \tag{20}$$

This equation provides reasonable results in some cases, but it is still not adequate. An equation that has been used extensively by several researchers was proposed by Page in 1949, with the inclusion in Equation (20) of a power in time, β. This equation fits well to drying kinetics data for several agri-food products, mainly grains and seeds [6, 17, 25]:

$$M_R = exp\left(-k\, t^{\beta}\right) \tag{20}$$

Parameters k and β are determined experimentally and depend mainly on the drying temperature. Empirical models are fitted to these parameters, but Arrhenius equation can also be fitted for parameter k.

3. Material and methods

3.1. Obtaining experimental data

The experiments were carried out at the Laboratory of Food Engineering by Mendes (2018), at the Federal University of Campina Grande, Brazil, and the data were kindly provided for this work. A brief description of the experimental procedures follows.

Before drying, samples of acerola seeds were prepared and properly packaged in plastic bags and kept in adequate storage conditions. Subsequently, the initial moisture content of each sample was determined by the oven standard method [26, 27] to start the drying process, in thin layer 1.0 cm thick, at temperatures of 40°C, 50°C, 60°C and 70°C and air flow of 1.5 m/s [9].

The moisture content throughout the process was obtained by weighing the trays with the seed samples at the beginning of the process and at regular intervals, but not equally spaced. In the first 30 minutes, samples were weighed every 5 minutes; between 30 and 60 minutes, weighing was carried out every 10 minutes; between 60 and 105 minutes the weighing was every 15 minutes; after 105 minutes, the samples were weighed every 60 minutes until they reached constant mass. After finishing each experiment, the samples were kept in the drying chamber, without air flow, for another 24 hours, to guarantee the stability of the final moisture content. After that time, three samples of the dry product were taken to determine the final moisture content using the standard greenhouse method [26, 27], which is equal to the dynamic equilibrium moisture content [9].

3.2 Obtaining drying kinetics curves

3.2.1. Modified diffusion equation

The model based on diffusion equation is useful to determine the effective diffusion coefficient and the diffusion activation energy. For this reason, Equation (16) was fitted to the data of drying kinetics of acerola seed, using non-linear regression by the Levenberg-Marquardt method with a maximum convergence error of 10^{-8} [28], to determine parameter φ for each drying temperature. Then, the diffusion coefficients were calculated using Equation (17), and the Arrhenius equation, Equation (18), was fitted to these data, completing the model.

3.2.2. Page's equation

Page's model expressed in Equation (20) was fitted to the data of drying kinetics of acerola seeds by the same methodology used in the previous item. Arrhenius equation was fitted to the data of parameter k, and a parabolic model was fitted to the data of parameter β, completing the Page model.

3.2.3. Proposed alternative model

Based on the diffusion equation, an alternative model was proposed, composed of a part for the drying period with constant rate, and a second part composed of three terms of diffusion equation and an exponential term, for the period with decreasing rate. The transition time from the period with constant rate to the period with decreasing rate was determined empirically.

The first part of the model was set to $0 \leq t \leq 90 \ \ min$:

$$M_R = 1{,}0 - m\ t^n \tag{21}$$

The second part of the model represents the drying period with decreasing rate, defined for $90 \leq t\ min$:

$$M_R = \frac{8}{\pi^2}\ exp(-k\ t) + \frac{1}{9\pi^2} exp(-9\ k\ t) + \frac{1}{25\pi^2} exp(-25\ k\ t) + c\ exp(-k\ t) \tag{22}$$

The parameters m, n, k and c depend on the drying temperature, and were obtained by fitting the models to the experimental moisture ratio of acerola seeds.

4. Results and discussion

The results were analyzed using the mean square error (MSE) and the coefficient of determination (R^2) as the comparison criterion. Data are presented in appropriate tables and graphics.

4.1. Modified diffusion equation

The results of the fitting of the modified diffusion equation to the moisture ratio data of acerola seeds, Equation (16), together with its statistical parameters, as well as the result of the fitting of the Arrhenius equation to the data of diffusion coefficient as a function of temperature, are shown in Table 3.

Table 3 Parameter φ, diffusion coefficient and statistical parameters of fitting of the modified diffusion equation, for drying acerola seeds in a thin layer of 1.0 cm thick, air flow of 1.5 m/s and temperature range from 40°C to 70°C.

T [°C]	$\varphi(D, x)$ $[kg/kg \cdot min]$	$D(T)$		Fitting statistics	
		$[m^2/min]$	$[m^2/s]$	MSE	R^2
40	4.3231×10^{-3}	4.3802×10^{-8}	7.3004×10^{-10}	4.8027×10^{-3}	0.9669
50	5.4447×10^{-3}	5.5166×10^{-8}	9.1944×10^{-10}	9.3855×10^{-3}	0.9345
60	7.6301×10^{-3}	7.7309×10^{-8}	12.8848×10^{-10}	7.9170×10^{-3}	0.9408
70	8.6044×10^{-3}	8.7181×10^{-8}	14.5301×10^{-10}	8.8008×10^{-3}	0.9304
Diffusion coefficient $[m^2/s]$:			$D = D_0 \, exp\left[-\frac{E_a}{\mathcal{R}\,(T + 273.15)}\right]$		
Universal gas constant $[J/mol \cdot K]$:			$\mathcal{R} = 8.3145$		
Maximum diffusion coefficient $[m^2/s]$:			$D_0 = 2.0987 \times 10^{-6}$		
Activation energy $[J/mol]$:			$E_a = 20.679.44$		
Coefficient of determination:			$R^2 = 0.9676$		
Mean squared error:			$MSE = 0.0000$		

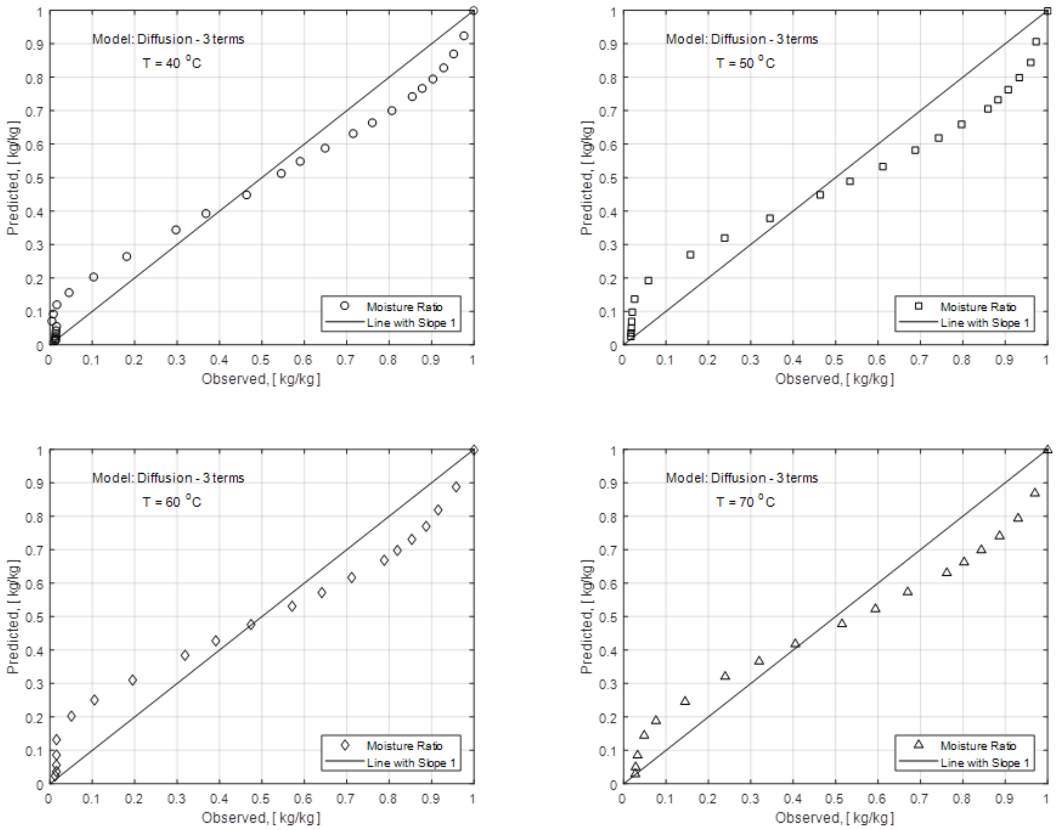

Figure 1 Comparison between predicted and experimental moisture content of acerola seeds dried in thin-layer of 1.0 cm thickness, air flow 1.5 m/s and temperature range from 40°C to 70°C, for modified diffusion equation

The modified diffusion model with three terms proved to be adequate for estimating the effective diffusion coefficient and activation energy for acerola seeds, when compared with results available in the literature for similar products [9].

However, this model is not suitable for predicting the drying kinetics of acerola seeds, because the mean square error values are the same order of magnitude as the estimated parameter, φ (Table 3), although the values of determination coefficients are high. These observations are confirmed by the graphs of correspondence between the predicted and experimental data (Figure 1) and by the drying curves (Figures 2).

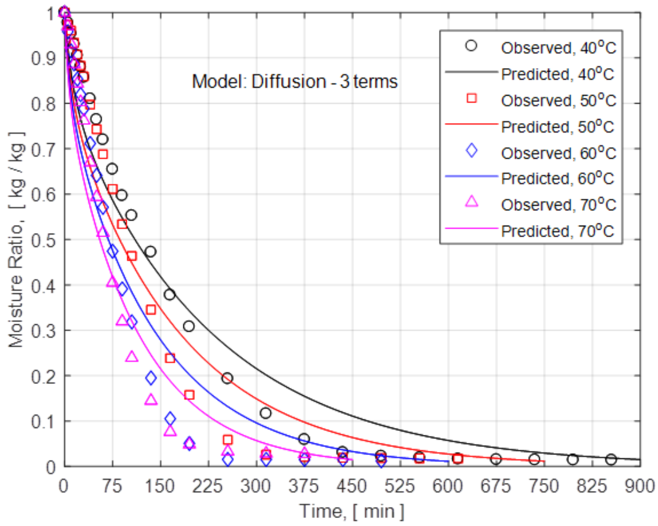

Figure 2 Drying curves of acerola seeds in thin-layer 1.0 cm thick, air flow 1.5 m/s, at temperature range from 40°C to 70°C, for the modified diffusion equation

4.2. Page's equation

Preliminary fittings to Page equation provided the first estimates for parameters k and β. The analysis of the dispersion graphs of these parameters indicated the need to refine the fittings, because despite these coefficients varied with temperature, they did not have a functional relationship defined a priori. Then, the parameters were readjusted empirically by a simultaneous inverse process, until an adequate functional relationship was obtained for the two parameters. The results are summarized in Table 4.

Table 4 Parameters $\boldsymbol{k}$ and $\boldsymbol{\beta}$ of Page equation, for predicting the drying rate of acerola seeds, dried in thin-layer 1.0 cm thick, airflow of 1.5 m/s, and temperature range of 40°C to 70°C

$\boldsymbol{T}$ [°C]	$\boldsymbol{k}$ [$\boldsymbol{1/min}$]	$\boldsymbol{\beta}$	Fitting statistics	
			$\boldsymbol{MSE}$	$\boldsymbol{R^2}$
40	2.719×10^{-3}	1.158	1.4428×10^{-4}	0.9990
50	2.991×10^{-3}	1.199	3.1637×10^{-4}	0.9978
60	3.518×10^{-3}	1.247	2.0807×10^{-4}	0.9984
70	3.806×10^{-3}	1.267	1.6644×10^{-4}	0.9987

Results of fittings of $\boldsymbol{k}$ and $\boldsymbol{\beta}$		
Fitted equations:	$k = k_0 \, exp\left(-\dfrac{A}{T + 273.15}\right)$	$\beta = b_1 T^2 + b_2 T + b_3$
Coefficient of determination:	$R^2 = 0.9904$	$R^2 = 0.9821$
Mean squared error:	$MSE = 2.5000 \times 10^{-9}$	$MSE = 1.5313 \times 10^{-5}$
Coefficients of fitting:	$k_0 = 0.1492$ $A = 1256.223$	$b_1 = -5.2500 \times 10^{-5}$ $b_2 = 9.5250 \times 10^{-3}$ $b_3 = 0.85925$

It was observed that the Page model fits very well to the moisture ratio data of acerola seeds, with mean square error, MSE, of the order of 10^{-4}, which is one order of magnitude smaller than the estimates of parameter k, indicating a good fit, corroborated by the high values of the coefficients of determination, ranging from 0.9978 to 0.9990 (Table 4). Comparisons of the predicted values with those observed for the humidity ratio through one-to-one correspondence graphs are shown in Figures 3, and the drying kinetics curves are shown in Figure 4.

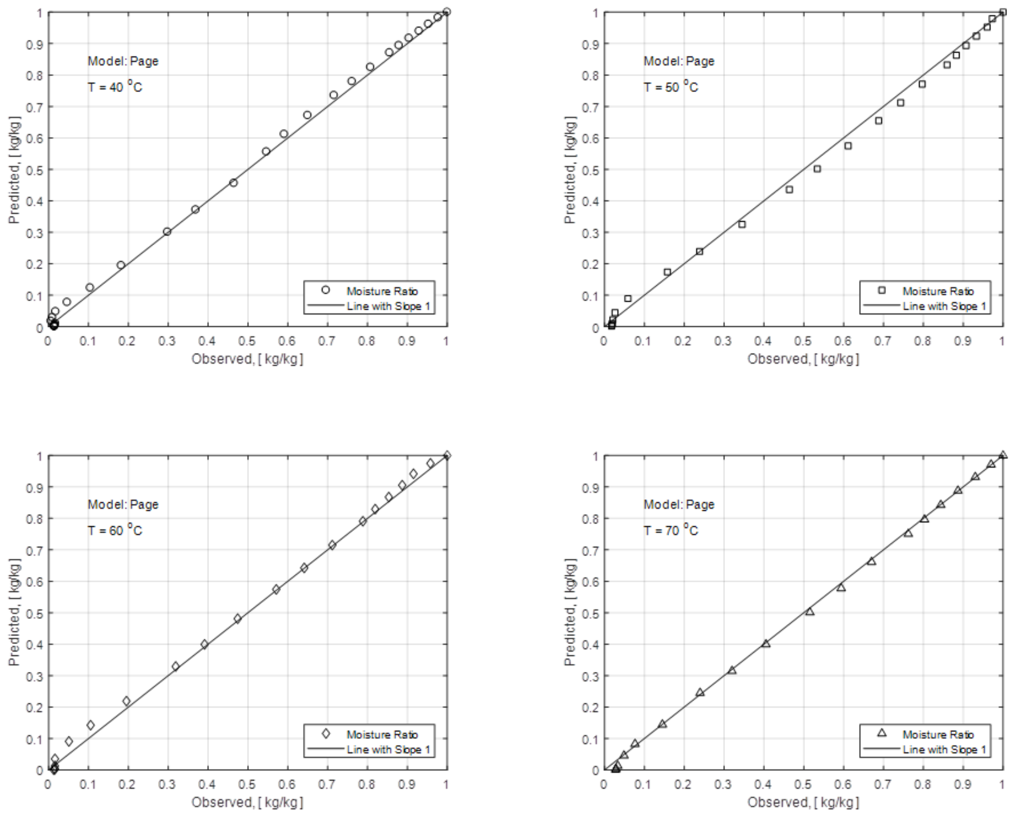

Figure 3 Comparison between predicted and experimental moisture content of acerola seeds dried in thin-layer of 1.0 cm thickness, air flow 1.5 m/s and temperature range from 40°C to 70°C, for

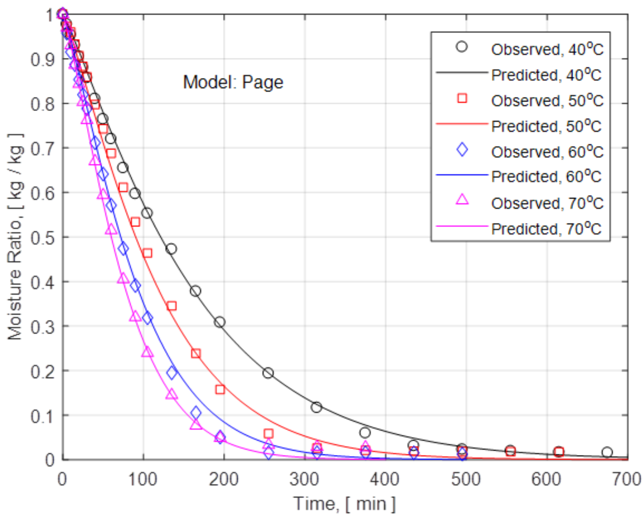

Figure 4 Drying curves of acerola seeds in thin-layer 1.0 cm thick, air flow 1.5 m/s, at temperature range from 40°C to 70°C, for Page equation

4.3. Proposed model

The results of the proposed model are summarized in Table 5 for the constant rate drying period, and in Table 6 for the falling rate drying period with.

Table 5 Estimates of parameters $\boldsymbol{m}$ and $\boldsymbol{n}$ of model proposed for thin-layer drying of acerola seeds for 1.0 cm layer thickness, air flow of 1.5 m/s, and temperature range from 40°C to 70°C, for constant rate drying period

T [°C]	m [$1/min$]	n	Fitting statistics	
			MSE	R^2
40	0.005437	0.960	2.3175×10^{-5}	0.9995
50	0.006164	0.955	3.9240×10^{-4}	0.9937
60	0.008617	0.950	8.4008×10^{-5}	0.9991
70	0.009864	0.945	3.9207×10^{-4}	0.9972
Results of fitting of m and n				
Fitted equation:	$m = m_0 \, exp\left(-\frac{A}{T + 273.15}\right)$		$n = n_1 \, T + n_2$	
Coefficient of Determination:	$R^2 = 0.9661$		$R^2 = 1.0000$	
Mean squared error:	$MSE = 1.1000 \times 10^{-7}$		$MSE = 0.0000$	
Fitting coefficients:	$m_0 = 7.878$ $A = 2288.541$		$n_1 = -5.000 \times 10^{-4}$ $n_2 = 0.980$	

Comparisons of the predicted and observed values of moisture ratio using one-to-one correspondence graphs are presented in Figure 5, and the drying curves are in Figure 6. The goodness of fit of the proposed model can also be seen in the drying kinetic curves shown in Figure 6, in which a low discrepancy between the experimental data and the predicted curves is observed. Therefore, the proposed model fits very well to the drying kinetics data of acerola seeds.

Table 6 Estimates of parameters **k** and **c** of model proposed for thin-layer drying of acerola seeds for 1.0 cm layer thickness, air flow of 1.5 m/s, and temperature range from 40°C to 70°C, for falling rate drying period.

Temperature [°C]	Coefficients		Fitting statistics	
	k	c	MSE	R^2
40	0.007073	0.3573	1.8501×10^{-4}	0.9954
50	0.011505	0.7285	1.8025×10^{-4}	0.9946
60	0.017244	1.0777	1.1439×10^{-4}	0.9936
70	0.021332	1.4759	3.0074×10^{-4}	0.9685
Equations fitted to parameters de k e c			MSE	R^2
$k = 4.8516 \times 10^{-4}\ T - 1.23952 \times 10^{-2}$			1.1750×10^{-7}	0.9960
$c = 0.03705\ T - 1.1279$			1.0858×10^{-4}	0.9994

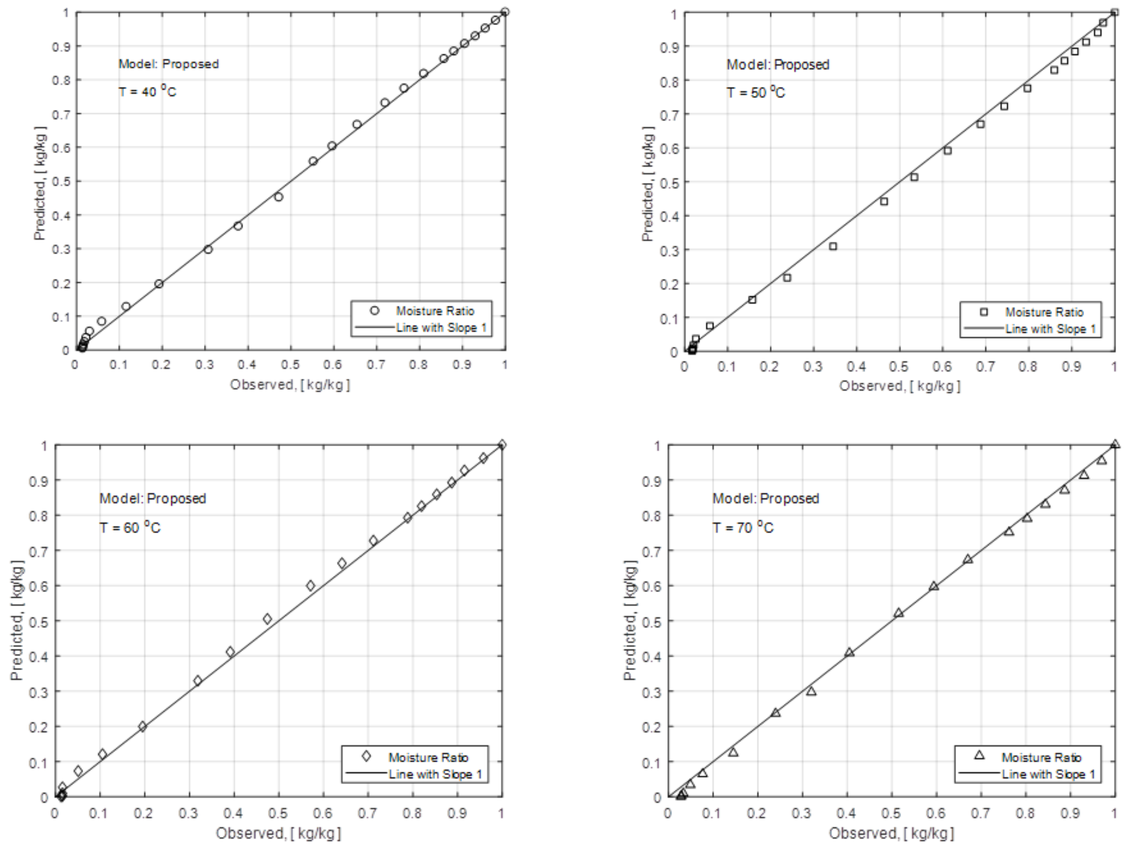

Figure 5 Comparison between predicted and experimental moisture content of acerola seeds dried in thin-layer of 1.0 cm thickness, air flow 1.5 m/s and temperature range from 40°C to 70°C, for proposed model.

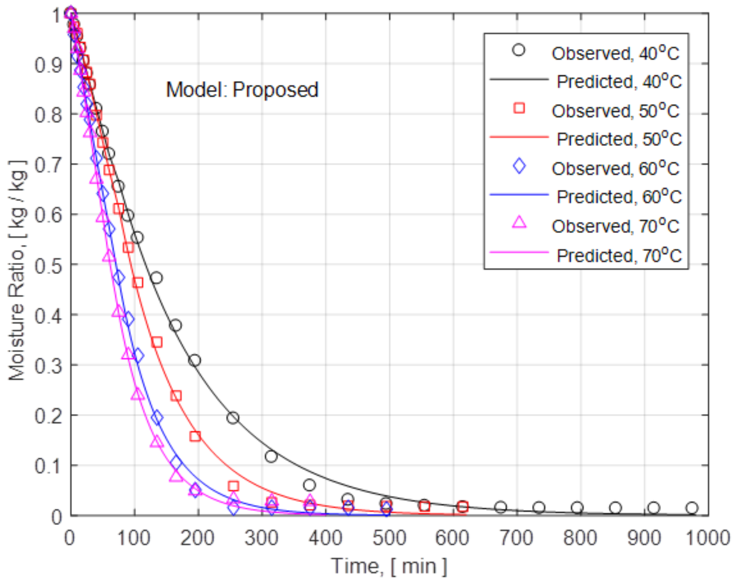

Figure 6 Drying curves of acerola seeds in thin-layer 1.0 cm thick, air flow 1.5 m/s, at temperature range from 40°C to 70°C, for the proposed model

The values of the mean squared error, MSE, varied with order of magnitude from 10^{-5} to 10^{-4}, for periods with quasi-constant drying rate. For periods with falling drying rate, the values of root mean square error remained with the order of magnitude of to 10^{-4}. In general, the model fitted very well to the data of drying kinetics of acerola seeds, with low values of mean square error and high values of coefficient of determination.

4.4. Comparison of models

According to the criterion adopted for comparing the results, Table 7 contains the values of mean square error (MSE) and coefficient of determination (R^2) of the three models. As expected, the worst model was the modified diffusion equation, with an MSE with order of magnitude of 10^{-2}. It was not possible to clearly identify differences between the Page equation and the proposed model. However, the results indicate that the proposed model looks a little better.

Table 7 Comparison of thin-layer drying models for acerola seeds dried in the temperature range from 40°C to 70°C. Layer thickness: 1.0 cm; airflow: 1.5 m/s

Model	**Temperature** [°C]	**Fitting parameters**	
		MSE	R^2
Modified diffusion equation:	40	4.8027×10^{-3}	0.9669
	50	9.3855×10^{-3}	0.9345
	60	7.9170×10^{-3}	0.9408
	70	8.8008×10^{-3}	0.9304
Page equation:	40	1.4428×10^{-4}	0.9990
	50	3.1637×10^{-4}	0.9978
	60	2.0807×10^{-4}	0.9984
	70	1.6644×10^{-4}	0.9987
Proposed model: Constant rate period	40	0.1594×10^{-5}	0.9999
	50	1.0732×10^{-5}	0.9995
	60	1.7178×10^{-5}	0.9996
	70	2.0878×10^{-5}	0.9996
Falling rate period	40	1.8501×10^{-4}	0.9954
	50	1.8025×10^{-4}	0.9946
	60	1.1439×10^{-4}	0.9936
	70	3.0074×10^{-4}	0.9685

5. Conclusion

The three-term modified diffusion equation is suitable for estimating the effective diffusion coefficient and activation energy, but it does not fit well to the acerola seed moisture ratio data.

Page's model fits well to the acerola seed moisture ratio, with mean square error estimates with order of magnitude of 10^{-4}, and coefficient of determination greater than 99.8%.

The proposed model fits very well to the drying rates of acerola seeds, with mean square error with order of magnitude ranging from 10^{-5} to 10^{-4}, and coefficient of determination greater than 99.5%

It was not possible to clearly detect differences between Page's equation and the proposed model, However, the proposed model looks slightly better than Page's equation. It should be highlighted that the Page's equation has only two parameters and the proposed model has two parts, each one with two parameters.

Therefore, it is concluded that both Page's equation and the proposed model can be equally used to predict drying rates of acerola seeds, under the conditions they were obtained. Choosing one of them depends on particular factors.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest on this article.

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