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Adjustment of mathematical models in the drying of cagaita pulp in foam-layer

Maisa Dias CAVALCANTE[1], Celso Martins BELISÁRIO[2*], Daniel Emanuel Cabral de OLIVEIRA[3], Geisa Priscilla Araújo Gomes MAIA[2], Weder Nunes FERREIRA JÚNIOR[2], Osvaldo RESENDE[2]

Abstract

The cagaita is a native fruit from Brazilian Cerrado region. Among conservation techniques and to increase shelf life of the fruit, foam bed drying becomes ideal. This study adjusted mathematic models of foam drying of the cagaita pulp at different temperatures to determine the net diffusion coefficient and the activation energy of this process. As the foam layer drying has a shorter drying time due to the greater exposure of the surface area to the air, it allows the application of lower dehydration temperatures, so it used 40, 50, 60 and 70 °C, the data observed were better fitted to the Midilli model. The net diffusion coefficient increased with temperature and the activation energy was 25.368 kJ mol^{-1}.

Keywords: *Eugenia dysenterica*; activation energy; liquid diffusion.

Practical Application: The cagaita is an indigenous of the Brazilian Cerrado fruit, which can be consumed fresh or processed (as jellies, ice creams, liqueurs, and juices). Because it is very perishable, it needs to be preserved by various techniques to increase its shelf life. One technique that preserves food products is foam-layer drying. Liquid or semi-liquid foods are transformed into powder by agitation and incorporation of a foaming agent, followed by dehydration. In addition, a mathematical modeling in the drying process is able to predict moisture removal behavior, estimate drying time, energy expenditure and equipment sizing.

1 Introduction

The Brazilian Cerrado covers almost two million square kilometers of Brazil, and includes the states of Goias, Tocantins, Mato Grosso do Sul, Minas Gerais, Bahia, Mato Grosso, Maranhão, and Piauí. It contains a rich variety in fruits, some of which have medicinal properties, high nutritional potential, and unique flavors not found in other fruits (Klink & Machado, 2005).

The cagaita is an indigenous of the Brazilian Cerrado fruit, which can be consumed fresh or processed (as jellies, ice creams, liqueurs, and juices). Because it is very perishable, it needs to be preserved by various techniques to increase its shelf life (Costa et al., 2017).

One technique that preserves food products is foam-layer drying. Liquid or semi-liquid foods are transformed into powder by agitation and incorporation of a foaming agent, followed by dehydration (Ng & Sulaiman, 2018).

This drying process is recommended for products that are sensitive to heat or contain sugars, mainly because they require a shorter exposure time and lower temperatures than used in other techniques (Fernandes et al., 2014).

To simulate and obtain data on product behavior during water removal, different mathematical models are used, which are based on external variables such as temperature and relative humidity of the air during the drying process (Resende et al., 2008).

A mathematical modeling in the drying process is able to predict moisture removal behavior, estimate drying time, energy expenditure and equipment sizing (Keneni et al., 2019).

Diffusion of water during drying is a complex process that involves different mechanisms, such as molecular diffusion, capillary diffusion, surface diffusion, hydrodynamic flow, vapor diffusion, and diffusion activation energy (Goneli et al., 2009).

The objective of this work was to propose and adjust mathematical models of the foam-layer drying process of cagaita at different temperatures, and to determine the effective diffusion coefficient and activation energy for this process.

2 Material

Cagaita fruits were collected in the region of Montes Claros, Goiás, Brazil (16°06'20 "S and 51°17'11" W), packed in 30 × 40 cm polyethylene bags, placed in thermal boxes and transported to the Laboratory of Phytochemistry of IF Goiano–Campus Rio Verde. The albumina was purchased in powder by the Naturovos trademark (Salvador do Sul, RS, Brazil) at a store specializing in raw materials for the Food Industry in Rio Verde Goiás, Brazil.

3 Methods

The Cagaita were then selected for size, absence of mechanical injury, and maturation stage and the chosen fruits were then sanitized in chlorinated water for 15 min and dried on paper towels.

The fruits were homogenized in a Toturgan® electric pulper, and the pulp was packed in 25 × 35 cm polyethylene bags

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[1]*Universidade Estadual Paulista – UNESP, São José do Rio Preto, SP, Brasil*
[2]*Instituto Federal Goiano – IF Goiano, Campus Rio Verde, Rio Verde, GO, Brasil*
[3]*Instituto Federal Goiano – IF Goiano, Campus Iporá, Iporá, GO, Brasil*
[*]Corresponding author: celso.belisario@ifgoiano.edu.br

and stored in a freezer at -18 °C until analysis. For foaming, commercial, unflavored albumin (8% w/w) was added to the pulp, and the mixture was then shaken with a domestic shaker brand Arno, model SX 15 for 15 min.

Approximately 100 g of the formed foam was added onto unperforated aluminum trays and dried in an oven, using forced air circulation at 40, 50, 60, and 70 °C, to determine drying kinetics.

To determine drying curves and to adjust the models, the pulp was dried to a constant mass. The water contents of the product were determined in a greenhouse at 105 ± 3 °C, in three replicates, until constant mass was reached.

The experimental data obtained from the drying of the cagaita pulp with an emulsifier were used to adjust the mathematical models frequently used to describe drying processes of vegetable products, as presented in Table 1.

For the adjustment of the mathematical models, non-linear regression analysis (Equation 13) was performed by the Gauss Newton method.

$$RX=\frac{X^*-X_e^*}{X_i^*-X_e^*} \quad (13)$$

Where:

RX – moisture ratio, non-dimensional;

X^* – moisture content, dry basis;

X^*_e – moisture content equilibrium, dry basis;

X^*_i – initial moisture content, dry basis.

The models were selected based on the magnitude of the coefficient of determination (R^2), the chi-squared test (χ^2), the mean relative error (P), and the estimated standard deviation (SE). Additionally, an average relative error below 5% was considered one of the criteria for the selection of models, as per (Mohapatra & Srinivasa Rao, 2005).

To evaluate net diffusion, we used the model of the flat plate geometry with an approximation of eight terms (Equation 14), which was adjusted to the experimental data of foam-layer drying of the cagaita pulp, and we considered the surface area and volume.

$$RX=\frac{X^*-X_e^*}{X_i^*-X_e^*}=\frac{8}{\pi^2}\sum_{n_t=0}^{\infty}\frac{1}{(2_{nt}+1)^2}\exp\left[\frac{-(2_{nt}+1)^2*\pi^2*D*T}{4}\left(\frac{S}{V}\right)^2\right] \quad (14)$$

Where:

RX – moisture ratio, non-dimensional;

X^* – moisture content, dry basis;

X^*_e – moisture content equilibrium, dry basis;

X^*_i – initial moisture content, dry basis;

nt – number of terms;

S – surface area, m^2;

V – volume, m^3.

Table 1. Mathematical models (Equation 1 to 12) applied to drying kinetics data.

Equation	Model	
$RX=1+at+bt^2$	Wang and Sing	(1)
$RX=a.\exp(-kt)+(1-a)\exp(-k_1t)$	Verma	(2)
$RX=\exp\left(\frac{(-a-\left(\sqrt{a^2-4.b.t}\right)}{2.b}\right)$	Thompson	(3)
$RX=\exp(-k.t^n)$	Page	(4)
$RX=\exp(-k.t)$	Newton	(5)
$RX=a.\exp(-k.t^n)+b.t$	Midilli	(6)
$RX=a.\exp(-k.t)+c$	Logarithmic	(7)
$RX=a.\exp(-k.t)$	Henderson and Pabis	(8)
$RX=a.\exp(-k.t)+b.\exp(-k_0.t)+c.\exp(-k_1.t)$	Henderson and Pabis, modified	(9)
$RX=a.\exp(-k.t)+(1-a)\exp(-k.a.t)$	Two-term Exponential	(10)
$RX=a.\exp(-k_0.t)+b.\exp(-k_1.t)$	Two-term	(11)
$RX=a.\exp(-k.t)+(1-a)\exp(-k.b.t)$	Diffusion Approximation	(12)

t – time (h); k, k_o, k_1 – constant of the equation (h^{-1}); a, b, c, n – parameters of the equations; RX – moisture ratio, non-dimensional.

The dimensions of length, width, and thickness were measured with a digital caliper.

The relationship between the diffusion coefficient and the drying air temperature is described by Equation 15.

$$D=D_0.\exp\left(\frac{-E_a}{R.T_{abs}}\right) \tag{15}$$

Where:

D_0 – Pre-exponential factor;

E_a – Activation energy, kJ mol $^{-1}$;

R – Universal Gas Constant, 8.134 kJ kmol^{-1} K $^{-1}$;

T_{abs} – Absolute temperature, K.

The Arrhenius expression coefficients were log-linearized according to Equation 16.

$$\ln D = \ln D_o - \frac{E_a}{R}.\frac{1}{T_{abs}} \tag{16}$$

In addition to the previous parameters, the Akaike information criterion (AIC) and the Bayesian Schwarz information criterion (BIC) were used. The AIC allows us to use the principle of parsimony in choosing the best model, that is, according to this criterion, the most parameterized model is not always the best (Burnham & Anderson, 2004).

AIC is used to compare non-nested models or to compare three or more models. Lower AIC values reflect a better fit (Akaike, 1973). BIC also considers the degree of parameterization of the model, and therefore, the smaller the BIC value is Schwarz (1978), the better the model adjustment is.

3 Results and discussion

Drying curves of cagaita foam at 40, 50, 60, and 70 °C. The values were estimated from Midilli model are shown in Figure 1.

It was observed that the drying time decreases with the increase in the temperature. Ferreira et al. (2012) previously explained that due to the increase in the drying rate, the heat transfer potential between the air and the layer of the product is increased, resulting in greater water reduction in a shorter period compared with lower drying rates.

The curves have a steeper slope due to the increase in the amount of heat transferred from the air to the dried material. Similar behaviors were reported by Baptestini et al. (2015) in a study of foam drying of graviola.

As seen in Table 2, the Page model fitted better at 50, 60, and 70 °C than the other models; the Two-term Exponential fitted better at 50 °C and 70 °C than the others ; and the Two-term fitted better at 70 °C than the others. In order to adjust the mathematical models, P must be less than 10% (Mohapatra & Srinivasa Rao, 2005), R^2 must be next to the unit, and SE must be close to zero (Resende et al., 2006).

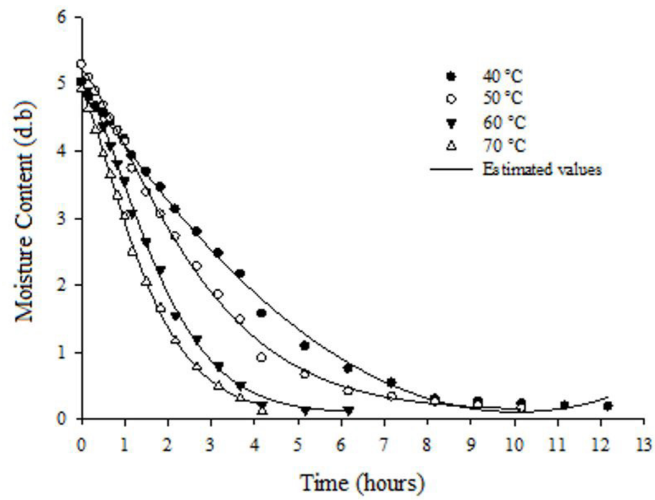

Figure 1. Foam-layer drying curves of cagaita pulp (*Eugenia dysenterica* DC) at different temperatures.

The Diffusion Approximation model and the Henderson and Pabis Modified model were adapted to the experimental data obtained at drying at 70 °C. The Midilli model, followed by the Wang and Sing model, was the best model to represent the drying kinetics of powdered cagaita pulp at all temperatures.

The models for the same mathematical models in foam-layer drying were found by Silva et al. (2008) in the dehydration of the tamarind pulp, with temperatures between 50 and 80 ° C, where the best models that represent the behavior of the dehydration curves were of Midilli and Kucuk. Alves & Rodovalho (2016) with avocado pulp, with temperatures of 50 to 80 ° C, and the best model of Wang and Sing. In Table 3, the AIC and BIC confirmed that the fit of the Wang and Sing model was better at 40 and 50 °C, whereas the Midilli model was better adjusted at 60 and 70 °C.

When analyzing the drying kinetics of the crushed jambu mass, evaluating the AIC and BIC parameters, it found the best Midilli model for temperatures of 60 and 70 ° C (Gomes et al., 2018). The Midilli model is probably associated with the rapid loss of water at the beginning of the process steps, generating a drying curve that best characterizes mathematically by this model (Goneli et al., 2009).

The values of the net diffusion obtained for the different drying temperatures are shown in Figure 2. The curve shows a linear, increasing behavior in which the values of the diffusion coefficient increased with the increase in the temperature.

According to Baptestini et al. (2015), this behavior is predictable, because the temperature is inversely correlated to the viscosity, which facilitates the diffusion of water molecules in the capillaries of the product. The same behavior was observed by Alves & Rodovalho (2016), in their study of foam-layer drying kinetics of avocado pulp. The variation in the effective diffusion coefficient as a function of drying temperature is described by the ratio of Arrhenius (Figure 3).

Table 2. Coefficient of determination (R^2), mean relative error (P), and estimated standard deviation (SE) of models analyzed during the foam-layer drying of cagaita pulp.

Model	40 °C				50 °C			
	SE	χ^2	P	R^2	SE	χ^2	P	R^2
Wang and Sing	0.0013	0.9988	6.56	0.9975	0.0012	0.9989	8.6330	0.9978
Verma	0.0026	0.9974	14.26	0.9949	0.0034	0.9967	18.6592	0.9934
Thompson	0.0121	0.9881	38.88	0.9764	0.0089	0.9913	28.9043	0.9827
Page	0.0020	0.9981	10.51	0.9961	0.0011	0.9989	5.7286	0.9979
Newton	0.0121	0.9881	38.87	0.9764	0.0089	0.9913	28.8968	0.9827
Midilli	0.0011	0.9989	6.95	0.9978	0.0010	0.9990	6.9005	0.9981
Logarithmic	0.0025	0.9976	13.51	0.9952	0.0028	0.9973	16.8926	0.9945
Henderson and Pabis	0.0088	0.9914	32.38	0.9828	0.0057	0.9944	22.1547	0.9889
Two-term Exponential	0.0023	0.9978	14.52	0.9956	0.0012	0.9988	6.5252	0.9977
Two-term	0.0022	0.9978	12.35	0.9957	0.0024	0.9953	15.3219	0.9953
Diffusion Approximation	0.0026	0.9974	14.26	0.9949	0.0034	0.9967	18.6591	0.9934
Henderson and Pabis, modified	0.0022	0.9978	12.37	0.9957	0.0024	0.9977	15.3223	0.9953
	60 °C				70 °C			
	SE	χ^2	P	R^2	SE	χ^2	P	R^2
Wang and Sing	0.0031	0.9965	9.46	0.9930	0.0014	0.9982	4.9067	0.9964
Verma	0.0038	0.9957	13.93	0.9914	0.0025	0.9969	9.7008	0.9938
Thompson	0.0180	0.9792	47.07	0.9588	0.0098	0.9876	23.4831	0.9754
Page	0.0010	0.9989	9.83	0.9978	0.0005	0.9994	2.8481	0.9988
Newton	0.0180	0.9792	47.07	0.9588	0.0098	0.9876	23.4804	0.9754
Midilli	0.0007	0.9992	4.98	0.9984	0.0004	0.9994	1.7747	0.9989
Logarithmic	0.0027	0.9969	10.97	0.9939	0.0019	0.9976	8.1507	0.9953
Henderson and Pabis	0.0025	0.9971	10.06	0.9942	0.0062	0.9922	18.0108	0.9844
Two-term Exponential	0.0016	0.9982	15.72	0.9964	0.0006	0.9992	5.0435	0.9985
Two-term	0.0025	0.9971	10.06	0.9942	0.0005	0.9994	3.5532	0.9988
Diffusion Approximation	0.0038	0.9957	13.93	0.9914	0.0025	0.9969	9.7008	0.9938
Henderson and Pabis, modified	0.0025	0.9971	10.06	0.9942	0.0017	0.9979	7.4712	0.9957

Table 3. Akaike information criterion (AIC) and Bayesian Schwarz information criterion (BIC) selection criteria of the models with best adjustments of the cagaita pulp drying kinetics at different temperatures.

Temperature (°C)	Wang and Sing		Midilli	
	AIC	BIC	AIC	BIC
40	-101.57	-98.583	-100.08	-95.105
50	-97.819	-94.981	-96.744	-92.022
60	-59.796	-57.672	-78.389	-74.858
70	-65.79	-63.872	-78.883	-65.79

The activation energy for drying the foam of the powdered cassava pulp was 25.368 kJ mol^{-1} at a temperature range of 40 to 70 °C. Similar values were found for bananas dried by the same method (Thuwapanichayanan et al., 2008), which had an activation energy of 25.19 kJ mol^{-1} at a temperature range of 60, 70 and 80 °C.

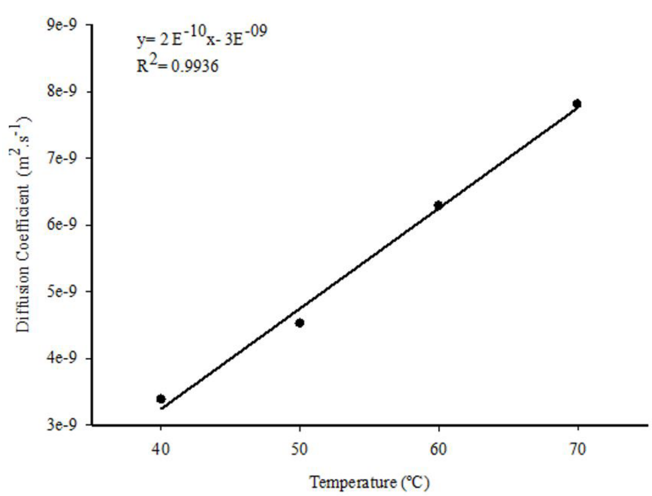

Figure 2. Diffusion Coefficient vs. temperature obtained by foam-layer drying of cagaita pulp (*Eugenia dysenterica* DC).

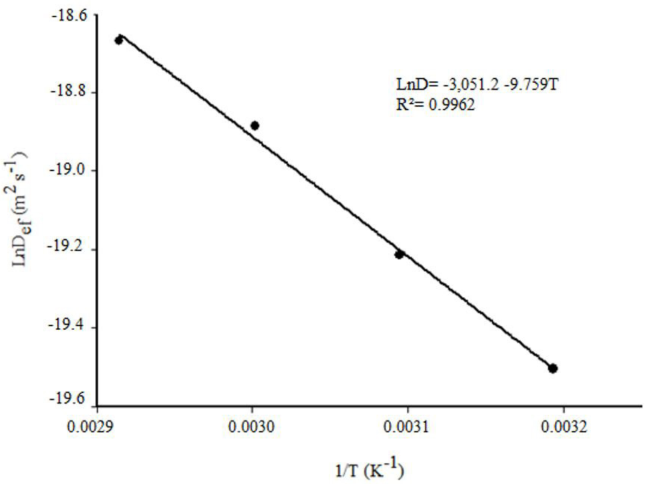

Figure 3. Arrhenius plot of cagaita foam drying at a temperature range of 40, 50, 60 and 70 °C, including regression equation and its coefficient of determination.

The lower the activation energy is, the greater the water diffusivity in the product is. Our reported values are within the energy activation range reported by Zogzas et al. (1996), i.e., between 12 and 110 kJ mol^{-1}.

4 Conclusion

The Wang and Sing models at 40 and 50 °C and the Midilli model at 60 and 70 °C were the ones that best fit the experimental data of the drying curves of the foam-layer drying of cagaita using AIC and BIC parameters. With increasing air temperature, a reduction in the drying time of the cagaita pulp foam occurred. The net effective diffusion coefficient increases with increasing drying temperature. The value of the activation energy is within the established parameters.

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