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DRYING KINETICS OF THE SLICED PULP OF BIOFORTIFIED SWEET POTATO (*Ipomoea batatas* L.)

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KEYWORDS

liquid diffusion,
activation energy,
Wang and Singh.

ABSTRACT

Biofortified sweet potato (*Ipomoea batatas*) is one of the foods with the highest contributions of carotenoids in the diet, especially provitamin A carotenoids. Thus, this study aimed to analyze the drying kinetics of the biofortified sweet potato pulp using the Akaike (AIC) and Schwarz's Bayesian (BIC) information criteria for model selection, as well as determine the effective diffusion coefficient and activation energy under different drying conditions. The biofortified sweet potatoes were sliced into chips and submitted to drying in an air circulation oven at 1.0 m s^{-1} at temperatures of 45, 55, 65, and 75 °C until constant mass. The mathematical models Wang and Singh, Verma, Thompson, Page, Newton, Midilli et al., logarithmic, Henderson and Pabis, two-term exponential, two-term, diffusion approach, frequently used to predict the drying of vegetal products, were adjusted to the data. The Wang and Singh model was selected to represent the drying of the biofortified sweet potato pulp by exhibiting the best adjustment for most conditions. The AIC and BIC criteria were suitable for selecting the Wang and Singh model. The effective diffusion coefficient increased as drying air temperature increase and the activation energy for liquid diffusion was 29.18 kJ mol^{-1}.

INTRODUCTION

Sweet potato (*Ipomoea batatas* Lam.) has a prominent role, as it is one of the most important food crops in the world (Kim et al., 2012). It also has a significant β-carotene content, whose regular intake can prevent and combat blindness and infant mortality caused by vitamin A deficiency, especially in poorer populations that do not have access to other vitamin A sources (Nascimento et al., 2013).

Drying is a process used to preserve food quality by reducing the availability of water to deterioration reactions, increasing food stability, and reducing the volume and mass of the product (Casarin et al., 2016). Reducing the amount of water in agricultural products provides longer shelf life and avoids the degradation of benign substances to the consumer (Tontul & Topuz, 2017). Drying is also the commercial process most used to preserve food and, when compared to other long-term preservative methods, it has a low cost and simpler operation (Alexandre et al., 2013).

The application of reliable mathematical models allows predicting the behavior of the various phenomena that occur during the drying process, which implies the reduction of the operational cost (Dionello et al., 2009). Several criteria can be used to verify the adjustment of mathematical models of drying in plant products. However, some parameters have limitations and it is necessary to adopt additional criteria to reinforce and endorse decision-making, such as the Akaike (AIC) and Schwarz's Bayesian (BIC) information criteria (Gomes et al. 2018).

Chemical composition and physical structure differ from one product to another, making water outlet specific to each material. In drying studies involving water diffusion there are variations in the values of the effective diffusivity coefficient due to the complexity of plant products, such as different prediction methods, type of material, moisture content, drying process, as well as the methodology used to obtain it (Goneli et al., 2007).

Thus, the aim of this study was to analyze the drying kinetics of the biofortified sweet potato pulp using the AIC and BIC criteria for model selection, as well as determine the effective diffusion coefficient and activation energy for the process.

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MATERIAL AND METHODS

The experiment was carried out at the Laboratory of Post-Harvest of Plant Products of the Federal Institute of Education, Science, and Technology of Goiás, campus of Rio Verde. An amount of 3 kg of CNPH1210 biofortified sweet potatoes, with the initial moisture content of 3.796±0.018 (decimal dry basis), were manually peeled using metal knives. Subsequently, the pulp was sliced into chips of approximately 4.6 x 4.0 x 0.2 cm (length, width, and thickness), adapted according to Borges et al. (2008), with a domestic grater. The slices of potato pulps were dried in an air circulation oven at 1.0 m s^{-1} and temperatures of 45, 55, 65, and 75 °C. Samples of 150 g were uniformly distributed in a 0.54 cm layer in rectangular aluminum trays (25 x 10 cm) without drilling, with four replications for each drying temperature.

The reduction of moisture content during the drying was performed by the gravimetric method (loss of mass). The initial moisture content of the product is known and the drying process occurs until reaching a constant mass. The mass reduction was monitored with a 0.01 g resolution scale.

To determine the equilibrium moisture content, samples of biofortified sweet potato were weighed every 24 hours until reaching three weighing measures until constant mass. The moisture contents of the material were determined in an oven regulated at 105 °C for 24 hours.

For determining the moisture content ratios of biofortified sweet potato during drying, [eq. (1)] was used.

$$RX = \frac{X - X_e}{X_i - X_e} \quad (1)$$

Where,

RX is the moisture content ratio of the product (dimensionless);

X is the moisture content of the product (db);

Xi is the initial moisture content of the product (db), and

Xe is the equilibrium moisture content of the product (db).

Mathematical models frequently used to represent the drying of plant products (Table 1) were adjusted to the experimental data of biofortified sweet potato drying.

TABLE 1. Mathematical models used to predict the drying of plant products.

Model designation	Model	
$RX = 1 + a\,t + b\,t^2$	Wang and Singh	(2)
$RX = a \cdot \exp(-k \cdot t) + (1-a)\exp(-k_1 \cdot t)$	Verma	(3)
$RX = \exp\left(\left(-a - \left(a^2 + 4 \cdot b \cdot t\right)^{0.5}\right) / 2 \cdot b\right)$	Thompson	(4)
$RX = \exp\left(-k \cdot t^n\right)$	Page	(5)
$RX = \exp(-k \cdot t)$	Newton	(6)
$RX = a \cdot \exp(-k \cdot t^n) + b \cdot t$	Midilli et al.	(7)
$RX = a \cdot \exp(-k \cdot t) + c$	Logarithmic	(8)
$RX = a \cdot \exp(-k \cdot t)$	Henderson e Pabis	(9)
$RX = a \cdot \exp(-k \cdot t) + (1-a)\exp(-k \cdot a \cdot t)$	Two-term exponential	(10)
$RX = a \cdot \exp(-k_0 \cdot t) + b \cdot \exp(-k_1 \cdot t)$	Two-term	(11)
$RX = a \cdot \exp(-k \cdot t) + (1-a) \cdot \exp(-k \cdot b \cdot t)$	Diffusion approach	(12)

t: drying time, h; **k**, **k_o**, **k_1**: drying constants, h^{-1}; and **a**, **b**, **c**, **n**: parameters of the models.

Mathematical models were adjusted from non-linear regression analysis by the Gauss-Newton method. The significance of model parameters was evaluated by the t-test adopting a 5% significance level. The degree of adjustment of each model was verified according to the magnitudes of the coefficient of determination (R^2), relative mean error (P), and estimated mean error (SE). The relative and estimated mean errors were calculated according to eqs (13) and (14), respectively.

$$P = \frac{100}{n} \sum \frac{|Y - \hat{Y}|}{Y} \quad (13)$$

$$SE = \sqrt{\frac{\sum (Y - \hat{Y})^2}{DF}} \quad (14)$$

Where,

n is the number of experimental observations;

Y is the value of the moisture content ratio experimentally observed;

$\hat{Y}$ is the value of the moisture content ratio estimated by model, and

DF is the degree of freedom of the model (difference between the number of observations and the number of model parameters). $\hat{Y}$

To select a single model for describing the drying process at each condition, the models with the best adjustments were submitted to the Akaike (AIC) and Schwarz's Bayesian (BIC) information criteria.

The AIC and BIC criteria were used as a counterpart in choosing the best mathematical model to predict the phenomenon. AIC allows using the principle of parsimony in choosing the best model, i.e. according to this criterion, the most parameterized model is not always the best (Burnham & Anderson, 2004).

AIC (Equation 15) is used to compare non-nested models or when three or more models are being compared. Lower AIC values reflect a better adjustment (Akaike, 1974).

$$\mathrm{AIC} = -2\log like + 2p \tag{15}$$

Where,

p is the number of parameters, and

log*like* is the value of the logarithm of the likelihood function considering the estimates of parameters.

BIC (Equation 16) also considers the degree of parameterization of the model and, similarly, the lower the BIC value is, the better the model adjustment. It is an asymptotic criterion whose adequacy is strongly related to the magnitude of the sample size. In relation to the penalty applied in the number of parameters, it will be more rigorous than AIC for small samples.

$$\mathrm{BIC} = -2\log like + \mathrm{p}\cdot\ln(\mathrm{n}) \tag{16}$$

Where,

n is the number of observations used to adjust the curve.

The effective diffusivity was determined based on the Fick's second law by assuming the geometric shape of an infinite flat plate, which was calculated by [eq. (17)].

$$\mathrm{RX} = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[-\frac{(2i+1)^2\pi^2\mathrm{D.\,t}}{4}.\left(\frac{\mathrm{S}}{\mathrm{V}}\right)^2\right] \tag{17}$$

Where,

RX is the moisture content ratio (dimensionless),

D is the effective diffusion coefficient ($m^2\ s^{-1}$), and i is the number of terms.

Volume and surface area of sweet potato slices were determined by measuring with a digital caliper the three orthogonal axes (length, width, and thickness) in fifteen slices of sweet potatoes before drying them. Volume was calculated by [eq. (18)] and surface area by [eq. (19)].

$$\mathrm{V} = \mathrm{S}\cdot\mathrm{C} \tag{18}$$

Where,

V is the volume (m^3);

S is the surface area (m^2), and

C is the thickness (m).

$$\mathrm{S} = \pi\,\frac{(\mathrm{A.B})}{4} \tag{19}$$

Where,

S is the surface area (m^2);

A is the largest axis (m), and

B is the average axis (m).

The relationship between the diffusion coefficient and the drying air temperature was analyzed by the Arrhenius [eq. (20)].

$$\mathrm{D_{ef}} = \mathrm{D_0}\exp\left(\frac{-\mathrm{E_a}}{\mathrm{R.T_a}}\right) \tag{20}$$

Where,

D_{ef} is the effective diffusion coefficient ($m^2\ s^{-1}$),

D_o is the pre-exponential factor ($m^2\ s^{-1}$),

E_a is the activation energy ($J\ mol^{-1}$),

R is the universal gas constant ($8.134\ kJ\ kmol^{-1}\ K^{-1}$), and

T_a is the absolute temperature (K^{-1}).

RESULTS AND DISCUSSION

The eleven tested models had coefficients of determination (R^2) above 0.96 decimal (Table 2), except for the Verma model (3) for a temperature of 65 °C. According to Sozzi & Ramos (2015), the closer to 1 the R^2 value is, the more elucidative the model and the better it will be adjusted to the experimental data.

TABLE 2. Statistical parameters: coefficient of determination (R^2), Chi-square test (χ^2), relative mean error (P), and estimated mean error (SE) obtained for the models (Mod.) adjusted to the drying of slices of biofortified sweet potato pulp.

Mod.	45 °C			55 °C			65 °C			75 °C		
	P	SE	R^2	P	SE	R^2	P	SE	R^2	P	SE	R^2
2	06.95	0.003	0.992	02.86	0.001	0.999	09.20	0.002	0.996	09.00	0.001	0.997
3	08.82	0.004	0.990	38.07	0.340	0.162	19.45	0.003	0.993	13.17	0.003	0.993
4	22.85	0.012	0.969	21.40	0.008	0.980	34.14	0.006	0.984	33.33	0.015	0.958
5	08.42	0.003	0.990	08.01	0.002	0.996	19.96	0.003	0.993	10.62	0.002	0.994
6	22.84	0.012	0.969	21.40	0.007	0.980	34.14	0.005	0.984	33.33	0.014	0.958
7	05.91	0.003	0.992	03.57	0.001	0.999	04.25	0.002	0.996	06.63	0.001	0.998
8	07.70	0.004	0.992	05.22	0.001	0.998	04.44	0.001	0.996	09.23	0.001	0.997
9	19.09	0.009	0.977	17.89	0.006	0.986	30.48	0.005	0.987	28.17	0.011	0.969
10	22.84	0.012	0.969	21.40	0.008	0.980	34.14	0.006	0.984	33.33	0.003	0.958
11	08.56	0.004	0.990	07.68	0.001	0.997	19.23	0.003	0.993	28.17	0.015	0.969

All drying temperatures presented reduced values (≤ 0.015) when comparing the SE values with each other and only the Verma model (3) presented a discrepant value, with a high magnitude for the temperature of 55 °C (0.340). For temperatures of 45 and 55 °C, the Wang and Singh (2), Verma (3), Page (5), Midilli et al. (7), logarithmic (8), and two-term (11) models presented values lower than 10% for P, while the Wang and Singh, logarithmic, and Midilli et al. models obtained low values of P for 65 and 75 °C, standing out in the representation of the drying phenomenon.

The models considered satisfactory under all the evaluated temperature conditions were Wang and Singh, logarithmic, and Midilli et al. These three models presented an R^2 higher than 99.15% and P values lower than 10%. Thus, through the joint analysis of statistical parameters (R^2, P, and SE), these models presented a better adjustment to the drying process of the potato pulp.

In order to select the best model (Wang and Singh, logarithmic, and Midilli et al.), the Akaike (AIC) and Schwarz's Bayesian (BIC) information criteria were adopted as complementary precepts for selection, as shown in Table 3.

TABLE 3. Akaike (AIC) and Schwarz's Bayesian (BIC) selection criteria for the Wang and Singh, logarithmic, and Midilli models.

Model	45 °C		55 °C		65 °C		75 °C	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
Midilli et al.	−72.33	−68.79	−79.89	−76.35	−56.65	−53.83	−50.82	−48.83
Logarithmic	−66.67	−63.83	−80.01	−77.18	−58.77	−56.77	−47.15	−48.75
Wang and Singh	−68.80	−66.68	−81.47	−79.34	−58.78	−57.09	−49.05	−50.05

The joint analysis of the AIC and BIC criteria, in which the lower values indicate better the model adjustment, showed that the values estimated by AIC had the best adjustment for the Midilli et al. at temperatures of 45 and 75 °C and for the Wang and Singh model at temperatures of 55 and 65 °C. In addition, the values estimated by BIC presented better experimental adjustments for the Midilli et al. model at 45 °C and for the Wang and Singh model at temperatures of 55, 65, and 75 °C.

Thus, the Wang and Singh model was selected to represent the drying kinetics of biofortified sweet potato pulp because it presented the best adjustment for most of the drying conditions. Ribeiro et al. (2014) carried out similar studies with sliced banana and Gomes et al. (2018) with ground jambu mass and also used the AIC and BIC selection criteria to indicate the most suitable model to represent their drying kinetics.

Figure 1 shows that different temperatures influenced water loss from the material and drying was faster for higher temperatures. According to Fiorentin et al. (2010), an increased temperature accelerates the drying process, promoting moisture content reduction more quickly at the beginning of the drying process, which consequently results in shorter drying time.

This behavior was expected and was also recorded by other authors when drying pumpkin slices (Borges et al., 2008), fibrous cassava mass (Castiglioni et al., 2013), lemon slices (Wang et al., 2018), and green banana peel and pulp (Gonçalves et al., 2017). In these cases, the highest rates of water vaporization in a shorter drying time was obtained by raising the temperature.

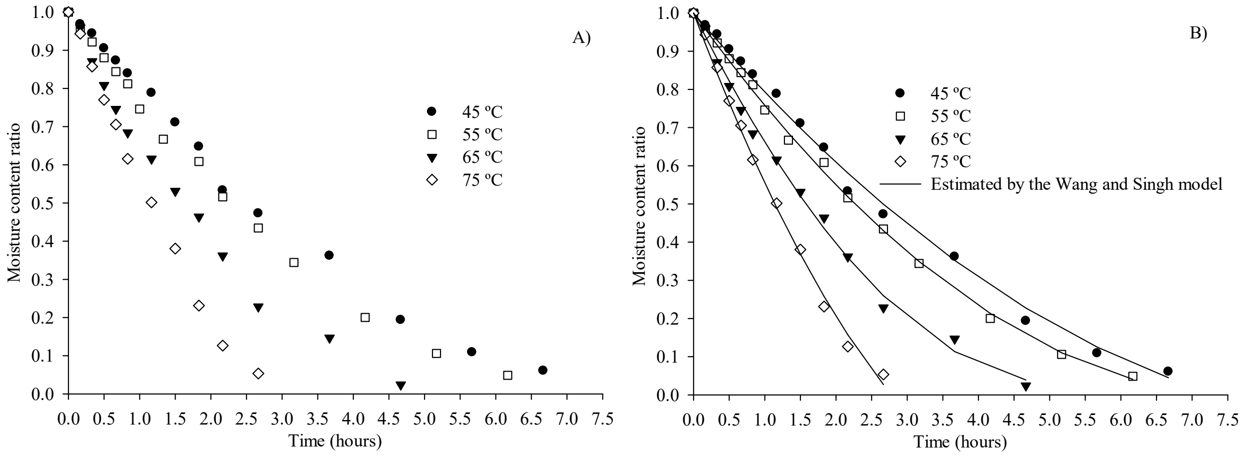

FIGURE 1. A) Moisture content ratio during the drying time to different temperatures and B) experimental values estimated by the Wang and Singh model for the drying of slices of biofortified sweet potato pulp at temperatures of 45, 55, 65, and 75 °C.

The Wang and Singh mathematical model was the best adjustment for the experimental data of drying of biofortified sweet potato pulp at temperatures of 45 to 75 °C. This result is in accordance with Doymaz (2004a), who studied the drying of plums, and with Sousa et al. (2016), who studied the drying of malt bagasse.

Table 4 shows the coefficients of the Wang and Singh model. The values found for the parameter b increased as temperature increased, while the parameter a decreased as water removal increased.

TABLE 4. Coefficients a and b obtained from the Wang and Singh model for the drying kinetics of slices of biofortified sweet potato pulp at temperatures of 45, 55, 65, and 75 °C.

Temperature (°C)	Parameters of the Wang and Singh Model	
	a	b
45	−0.2219	0.0117
55	−0.2438	0.0153
65	−0.3732	0.0359
75	−0.4928	0.0480

The diffusion coefficient increased linearly as the temperature of the drying air increased and its influence can be described by means of the Arrhenius representation, as shown in Figure 2B. During the drying, the diffusion coefficients showed magnitudes of 7.55 × 10^{-11}, 8.9 × 10^{-11}, 13.01 × 10^{-11}, and 19.24 × 10^{-11} $m^2\ s^{-1}$ for temperatures of 45, 55, 65, and 75 °C, respectively. These results are in accordance with those obtained by Fernando et al. (2011), who dried slices of banana, cassava, and pumpkin and found values ranging from 0.69 × 10^{-10} to 0.52 × 10^{-10} $m^2\ s^{-1}$ for banana, 0.80 × 10^{-10} to 1.12 × 10^{-10} $m^2\ s^{-1}$ for cassava, and 5.76 × 10^{-10} to 5.60 × 10^{-10} $m^2\ s^{-1}$ for pumpkin.

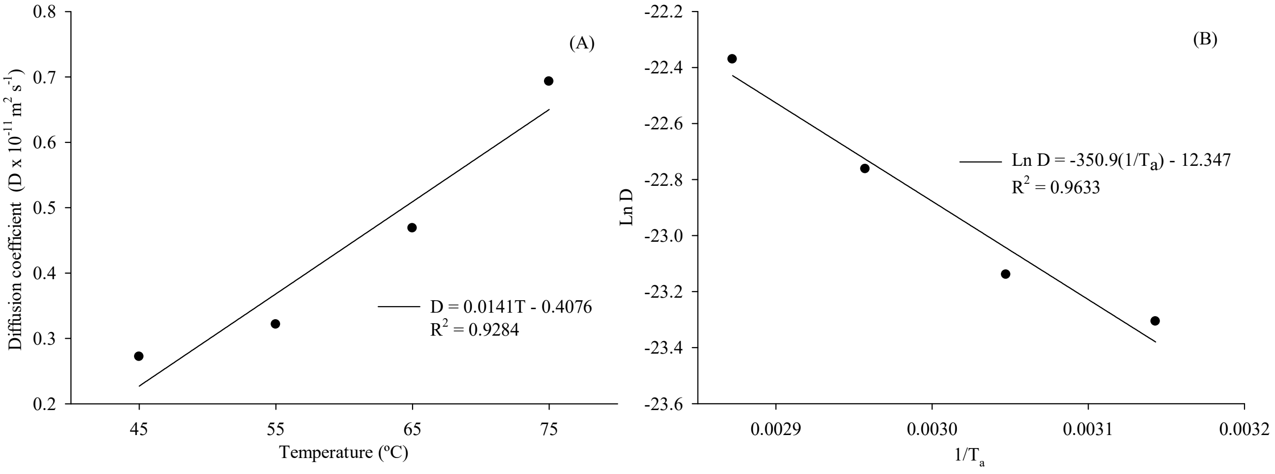

FIGURE 2. Effective diffusion coefficient (A) and Arrhenius representation for the effective diffusion coefficient (B) obtained for the drying of biofortified sweet potato pulp at temperatures of 45, 55, 65, and 75 °C.

The activation energy for the liquid diffusion of biofortified sweet potato pulp was 29.18 kJ mol^{-1} for the temperature range between 45 and 75 °C, which is in accordance with the results obtained by Doymaz (2004b), who studied the drying of sliced carrots with an activation energy of 28.36 kJ mol^{-1}. According to Corrêa et al. (2010), the lower the activation energy in the drying processes is, the higher the water diffusivity in the product, i.e. the lower the energy required for the physical transformation to occur and for the liquid water pass to steam (drying of the product).

CONCLUSIONS

Among the studied models, the Wang and Singh model was selected to represent the drying kinetics of biofortified potato pulp since it exhibits the best adjustment for most conditions. The AIC and BIC criteria were suitable for selecting a single model. The effective diffusion coefficient increased as the temperature of the drying air increased and the activation energy for the liquid diffusion was 29.18 kJ mol^{-1}.

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ERRATUM

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