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Mathematical modeling of the drying of orange bagasse associating the convective method and infrared radiation

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ABSTRACT
Mathematical modeling enables dimensioning of dryers, optimization of drying conditions and the evaluation of process performance. The aim of this research was to describe the behavior of orange bagasse drying using Page's and Fick's second law models, and to assess activation energy (using Arrhenius equation), moisture content, water activity and bulk density of product at the end of the process. The drying experimental assays were performed in 2011 with convective air temperature between 36 and 64 °C and infrared radiation application time in the range from 23 to 277 s in accordance with the experimental central composite rotatable design. Analysis of variance and F-test were applied to results. At the end of the drying process, moisture content was about 0.09 to 0.87 db and water activity was between 0.25 and 0.87. Bulk density did not vary under studied conditions. Empirical Page's model demonstrated better representation of experimental data than the Fick's model for spheres. Activation energy values were about 18.491; 14.975 and 11.421 kJ mol^{-1} for infrared application times of 60; 150 e 244 s, respectively.

Palavras-chave:
difusividade efetiva
atividade de água
modelo de Fick
modelo de Page
energia de ativação

Modelagem matemática da secagem de bagaço de laranja associado ao método convectivo e radiação infravermelha

RESUMO
A modelagem matemática permite o dimensionamento de secadores, otimização das condições de secagem e avaliação do desempenho do processo. O objetivo deste trabalho foi descrever o comportamento da secagem de bagaço de laranja utilizando-se os modelos de Page e a segunda lei de Fick, avaliar a energia de ativação (equação de Arrhenius), o teor de água, a atividade de água e a massa específica aparente do produto ao final do processo. Realizou-se a secagem de bagaço de laranja com temperatura do ar convectivo entre 36 e 64 °C e tempo de aplicação da radiação infravermelha na faixa de 23 a 277 s de acordo com planejamento experimental central composto rotacional. Análise de variância e teste F foram aplicados aos resultados. Ao final dos ensaios de secagem foram observados o teor de água entre 0,09 a 0,87 bs e a atividade de água entre 0,25 e 0,87. A massa específica aparente não variou nas condições estudadas. O modelo empírico de Page demonstrou melhor representação dos dados experimentais do que o modelo de Fick para esfera. A energia de ativação obtida nos tempos de infravermelho de 60; 150 e 244 s foi, respectivamente, 18,491; 14,975 e 11,421 kJ mol^{-1}.

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Introduction

Brazil is the largest processor of orange juice, contributing with 50% of world production. It is considered that 100 kg of orange produce 55 kg of juice, and the remaining 45 kg are residues of the process, such as discarded oranges, zest, seed, and waste resulting from the extraction of essential oil and washed pulp (Cavichiolo, 2010).

Because of its nutritional value, the orange bagasse can be used in the production of animal feed after undergoing drying. Thus, different methods for drying and dryers (cyclone dryer, pneumatic dryer, rotary dryer, flash dryer, among others) have been researched recently (Cavichiolo, 2010; Fiorentin et al., 2010a). Costa et al. (2015) studied sugarcane bagasse drying in a fixed bed and its desorption isotherm.

The use of artificial drying in preservation of agricultural products has expanded, creating the necessity for faster methods and more energy-saving processes. Drying using infrared radiation is a method that offers lower power loss compared with convective drying, since the energy in an electromagnetic wave is directly absorbed by the product (Mongpraneet et al., 2002). This happens because the material is heated quickly and uniformly, and infrared radiation energy is transferred to the product without heating surrounding air (Swasdisevi et al., 2007). Celma et al. (2009) researched about the experimental modelling of infrared drying of industrial grape by-products.

Drying modeling requires the understanding of the mechanisms of water transportation inside food and of the interface between the surface of food and drying air. Transfer of energy (heat) depends mainly on the temperature of air and food, the flow rate of drying air and the exposed area of food. The internal transfer of water is governed by the nature and inherent characteristics of food, including its composition and structure, temperature, pressure and, especially, its moisture content. In turn, transfer of water from the interface food/drying air depends on the water activity on the surface, relative humidity, air flow rate, exposed area of food and pressure.

According to Berg (1986), water activity is the only parameter that can be used as a reliable indicator for predicting food degradation or determining the end point of the drying required to ensure a stable product.

Drying food products are divided into two distinct parts called constant rate period and falling rate period. Food drying occurs mainly in the falling rate period, and the moisture diffusion represents all the mechanisms of water transfer during this period such as: capillary flow (diffusion in liquid phase), migration of moisture from adsorbed layer, vaporization-condensation and diffusion of vapor in the air. The water mass balance equation inside product, proposed by Fick's second law, expresses the flow of mass per unit area as being proportional to water concentration gradient. This fact has been widely used to describe drying processes during the falling rate period for most biological materials (Srikiatden & Roberts, 2006; Hassini et al., 2007).

Effective moisture diffusivity represents the conducting term of all the mechanisms of moisture transfer and is normally determined by experimental drying curves. Drying limited to the mass transfer and the isothermal conditions all over the sample for entire drying period are important to the hypothesis formulation for this determination (Srikiatden & Roberts, 2006). The Page model is often used in the representation of drying curves (Doymaz, 2004; Oliveira et al., 2006; Fiorentin et al., 2012), especially in cases in which the diffusion theory is not appropriate to adjust the behavior of the drying process because of the interference in the internal resistance effect of material.

Due to the importance of drying orange bagasse in a quick and uniform manner for animal feed use, this paper proposed to assess the conditions of drying operation, air temperature and infrared radiation application time in relation to the behavior of moisture content. These independent variables were adjusted by the empirical Page's model and Fick's second law model for spheres for the experimental data. As well, water activity, bulk density, and activation energy using the Arrhenius equation of the orange bagasse were determined in order to establish the effectivity of the drying process.

Material and Methods

Orange bagasse results from the processed juice extraction. The non-uniformity nature of the product in relation to the size of particles of bagasse, makes necessary a previous grinding process with a mill. Then, the samples were placed in plastic bags and stored under the temperature of 5 °C until the tests.

Moisture content was determined in a forced air oven under temperature of 105 ± 5 °C for 24 h (AOAC, 1995).

Water activity (a_w) was measured with the equipment Decagon (Pawkit model), with resolution from 0.01 to 25 °C. The samples were placed in the sample cup of the equipment, and the final result was expressed as the mean of three consecutive readings.

Bulk density was determined using the density meter, composed of a funnel positioned above a cylindrical container of known volume. The analysis procedure consisted of filling the funnel with the orange bagasse sample and then its subsequent opening for sample flow at constant and free flow to inside of cylinder. Then, the container was weighted with product and then its mass was obtained. Bulk density (ρ_a) was obtained by the mean of three replicates using the Eq. 1.

$$\rho_a = \frac{\text{mass}\left(\text{container} + \text{sample}\right) - \text{mass of the container}}{\text{volume of the container}} \quad (1)$$

The experimental runs of orange bagasse drying were performed in the agitator/mixer dryer, in which it was possible to use the convective drying method associated with the application of infrared radiation. The drying chamber dimensions correspond to 0.50 m in diameter and 1.20 m in length, positioned horizontally. The dryer is composed of centrifugal fan (Asten - 1500 W), set of electric resistances (5000 W) and infrared radiation emitters (4500 W).

Air temperature was automatically controlled for the studied range intensities. The infrared radiation application time was manually controlled using a timer. A frequency inverter was used in the adjustment of fan rotation in order to provide constant air velocity of 0.93 m s^{-1}.

Three samples of 100 g of orange bagasse were stored in perforated rectangular containers used to perform the drying experimental assays. Each container had the dimensions of 0.135 x 0.135 x 0.030 m. The containers were placed on a tray (also perforated) at 0.42 m of distance in relation to infrared radiant heaters. A product layer height of approximately 0.015 ± 0.005 m was used.

After the stabilization of drying air temperature, the samples were placed inside the dryer and radiant heaters were turned on until the period determined by experimental planning. The trays containing orange bagasse were weighed every twelve minutes to determine their moisture content. This procedure was repeated until there was no significant mass variation of the samples.

A spherical format was considered for the particles of orange bagasse after processing (grinding). Thus, the solution model of Fick's second law for spheres (Eq. 2) was used to describe drying process. The radius of these spheres were estimated by determining the mean geometric particle diameter, obtained by granulometry test (Handerson & Perry, 1955). The results showed diameters of 1589.3 μm and 1040.5 μm for wet and dry samples, respectively. In order to measure the shrinkage of the samples, the dimensions at specific moments of drying process were interpolated between wet and dry samples data and the respective intermediate drying times. The following equation was used:

$$Y = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-n^2\pi^2 D_{ef}\frac{t}{r^2}\right] \quad (2)$$

where:

r - radius of the sphere, m;
Y - dimensionless moisture content;
n - number of terms;
t - time, s; and
D_{eff} - effective diffusivity, $m^2\,s^{-1}$.

The empirical Page's model (Eq. 3) is also often used in the representation of drying curves (Doymaz, 2004), especially in cases in which the diffusion theory is not appropriate to adjust drying behavior because of the interference in internal resistance effect of material. The following is the equation of Page model:

$$Y = \frac{X - X_{eq}}{X_0 - X_{eq}} = \exp\left(-kt^n\right) \quad (3)$$

where:

Y - dimensionless moisture content;
X - average moisture content;
X_{eq} - equilibrium moisture content;
X_0 - initial moisture content;
k and n - model constants; and
t - time.

The coefficients of the Page model were obtained by nonlinear regression of experimental data, using software Statistica (2001) and Gauss-Newton adjustment method.

The dependence of effective diffusivity in relation to temperature and moisture content is usually described by the Arrhenius equation (Eq. 4) (Botelho et al., 2011):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R_c T}\right) \quad (4)$$

where:

E_a - activation energy, kJ mol^{-1};
D_0 - pre-exponential factor, $m^2\,s^{-1}$;
T - absolute temperature, K; and
R_c - universal gas constant, 8.314 J $mol^{-1}\,K^{-1}$.

A 2^2 full factorial experimental design was used to study the effects of the independent variables: drying air temperature (T) and infrared radiation exposure time (t) in relation to the responses or dependent variables: effective diffusivity (D_{eff}), moisture content (U_{db}) and water activity (a_w) on orange bagasse drying (Table 1).

To evaluate the effect of the factors on the responses with 95% confidence level ($p \leq 0.05$), the software Statistica (2001) was used. Analysis of Variance (ANOVA), coefficient of determination (R^2), and the F-test were used for the experimental results.

Table 1. Experimental design for orange bagasse drying

Points	Assays	Independent variables			
		Real		Coded	
		T (°C)	t (s)	T (°C)	t (min)
Factorial	1	40	60	-1	-1
	2	40	240	-1	1
	3	60	60	1	-1
	4	60	240	1	1
Axial	5	36	150	-1.41	0
	6	64	150	1.41	0
	7	50	23	0	-1.41
	8	50	277	0	1.41
Central	9	50	150	0	0
	10	50	150	0	0
	11	50	150	0	0

Results and Discussion

Table 2 shows the means and standard deviation (SD) obtained, accordingly with the experimental design for moisture content, water activity and bulk density.

Table 2. Moisture content (U_{db}), water activity (a_w) and bulk density (ρ_a) of orange bagasse samples after drying experimental assays

Experimental runs	U_{bs} (kg kg^{-1})	SD - U_{bs}	a_w	SD - a_w	ρ_a (g mL^{-1})	SD - ρ_a
1	0.87	0.17	0.87	0.02	0.233	1.15
2	0.21	0.08	0.64	0.16	0.197	0.58
3	0.36	0.14	0.78	0.07	0.201	0.58
4	0.10	0.02	0.36	0.05	0.197	1.53
5	0.33	0.08	0.72	0.03	0.201	0.58
6	0.09	0.01	0.25	0.08	0.193	1.00
7	0.32	0.26	0.68	0.17	0.197	1.53
8	0.10	0.01	0.36	0.06	0.193	0.00
9	0.18	0.01	0.57	0.09	0.201	0.58
10	0.16	0.03	0.54	0.09	0.197	0.58
11	0.13	0.04	0.42	0.10	0.208	0.58

The highest moisture content and water activity at the end of drying were related to assay 1. This happens because, in this run, low air temperature (40 °C) and infrared radiation time (60 s) were used, providing higher equilibrium moisture content than the remaining assays and removal of 52.71 g of water. On the other hand, assay 6 presented the lowest values of moisture content (0.09 db) and water activity (0.25), because of operational drying conditions that consisted on higher air temperature and infrared time, 64 °C and 150 s, respectively. Such results show that these conditions provided higher removal of water (72.94 g). The orange bagasse showed bulk density values between 0.193 and 0.233 g mL^{-1}.

According to Cavichiolo (2010), orange bagasse after the extraction of juice has moisture content of approximately 101% (db), and after the processing it is generally ground and dried to the moisture content of 16% (db). Considering that industry uses this water content value of dried product, drying conditions of run 10 (50 °C; 150 s) were those that the appropriate final moisture content provided.

According to Celestino (2010), in food with water activity close to 0.6, there is little or no growth of microorganisms. Thus, assays 2; 4; 6; 8; 9; 10 and 11 can be considered under this requirement, with water activity values for the orange bagasse of 0.64; 0.36; 0.25; 0.36; 0.57; 0.54 and 0.42 db, respectively. However, when considering the two factors, the recommended final moisture content for the product (16% db) and the water activity (0.6) favorable for its conservation, it was realized that the drying conditions of assay 10 (50 °C; 150 s) are indicated for orange bagasse.

The statistical analysis of the experimental results allowed the calculation of the regression coefficients of the factors studied (temperature and infrared application time) and their interactions on the responses of moisture content, water activity and apparent density, which are presented in Table 3.

Table 3 shows that only the infrared linear time factor (tL) was statistically significant ($p < 0.05$) for the moisture content response. Whereas, for the water activity response, the global mean and the linear factors of air temperature (TL) and infrared application time (tL) were significant. It is also highlighted that the effect of these factors is negative in the responses, indicating that increased air temperature and infrared application time causes a reduction in moisture content and water activity. In relation to bulk density, it can be observed that none of the factors presented significant effect on this response.

Table 3. Regression coefficients of the factors linear (TL) and quadratic (TQ), air temperature and infrared linear (tL) and quadratic (tQ) time on the responses water content (U_{bs}), water activity (a_w) and bulk density (ρ_a)

Response	Factor	Regression coefficient	Standard error	t – value	p – value
U_{bs} (kg kg^{-1})	Mean	0.16	0.09	1.75	0.14
	TL	-0.12	0.06	-2.19	0.08
	TQ	0.07	0.07	1.06	0.34
	tL	-0.16*	0.06	-2.82	0.04
	tQ	0.07	0.07	1.07	0.34
	TL x tL	0.10	0.08	1.28	0.26
a_w	Mean	0.51*	0.07	6.96	0.001
	TL	-0.13*	0.05	-2.90	0.034
	TQ	0.03	0.05	0.50	0.641
	tL	-0.14*	0.05	-3.07	0.028
	tQ	0.04	0.05	0.81	0.456
	TL x tL	-0.05	0.06	-0.77	0.475
ρ_a (g mL^{-1})	Mean	2.02E-01*	0.006	34.98	3.60E-07
	TL	-5.30E-03	0.007	-1.50	1.94E-01
	TQ	2.99E-04	0.008	0.07	9.46E-01
	tL	-5.56E-03	0.007	-1.57	1.76E-01
	tQ	-5.97E-04	0.008	-0.14	8.93E-01
	TL x tL	8.06E-03	0.010	1.61	1.68E-01

*Statistically significant values: $*p < 0.05$

After the identification of statistically significant regression coefficients, the validity of the models and their adjustments to the experimental data were verified by analysis of variance (ANOVA), based on the F-test and on the percentage of variance explained (R^2). Table 4 shows these results.

The analysis of variance (Table 4) for the moisture content response indicates that the regression was not significant, since the F_{cal} value is lower than the F_{tab} value. The coefficient of determination (R^2) obtained is also unsatisfactory, as it represents only 38% of the variation in experimental data. Thus, it can be affirmed that the infrared radiation application time has not affected significantly the orange bagasse drying and a valid model that represents the experimental data for the studied conditions could not be generated.

However, in Table 4 it is shown that the model obtained for water activity explains 74% of the variation of the observed data. The F_{cal} value was superior to the F_{tab} value, implying that the regression was significant and the model is valid to describe experimental data (Eq. 5). This way, it became possible to generate the response surface (Figure 1).

$$a_w = 0.56 - 0.13T - 0.14t \quad (5)$$

The results for the effective diffusivity and the Page equation coefficients are presented in Table 5.

The effective diffusivity values ranged from 3.57×10^{-10} to 8.14×10^{-10} $m^2 s^{-1}$, which corresponds to assays 1 (40 °C and 60 s) and 4 (60 °C and 240 s) respectively (Table 5). Fiorentin et al. (2012) observed similar behavior for drying of orange bagasse in air temperature ranging from 33 to 92 °C, with effective diffusivity values between 9.25×10^{-10} and 2.92×10^{-9} $m^2 s^{-1}$.

Observing Table 5, the Fick's model explained at least 88% of the variation of experimental data (assay 11). Page model presented better fitting, with R^2 of 0.99 in all experimental runs of orange bagasse drying. Similar results were found by

Table 4. Analysis of variance (ANOVA) for the responses moisture content (U_{db}) and water activity (a_w)

Response	Source of variation	Quadratic sum	Degrees of freedom	Mean square	F_{cal}*	F_{tab}*	R^2
U_{bs} (kg kg^{-1})	Regression	0.20	1	0.20	5.55	10.56	0.38
	Residual	0.32	9	0.04			
	Lack of fit	0.32	7	0.05			
	Pure error	0.001	2	0.001			
	Total	0.51	10				
a_w	Regression	0.29	2	0.14	11.26	4.46	0.74
	Residual	0.10	8	0.01			
	Lack of fit	0.09	6	0.02			
	Pure error	0.01	2	0.01			
	Total	0.39	10				

*Calculated (F_{cal}) and tabulated (F_{tab}) values of the F-test at 95% significance

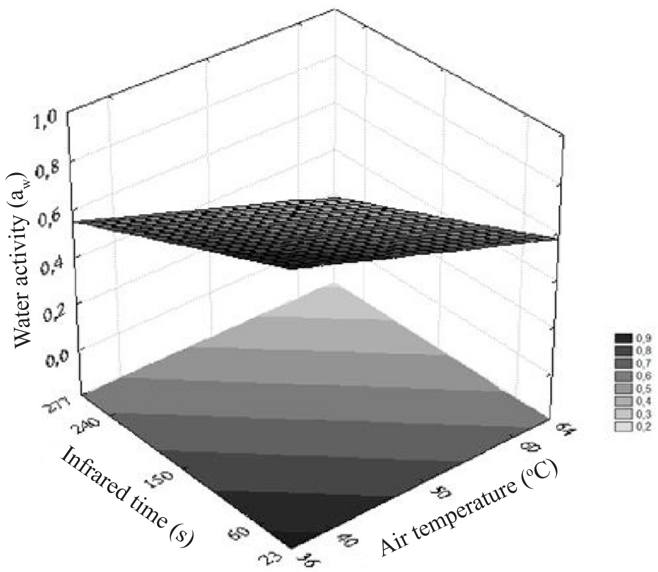

Figure 1. Response surface for water activity as function of air temperature and infrared application time for orange bagasse drying

Table 5. Effective diffusivity (D_{eff}), Page's coefficients and coefficients of determination (R^2) obtained from the drying of orange bagasse

Run	Effective diffusivity [$m^2\ s^{-1}$]		Page's Coefficients		
	D_{ef} ($x10^{-10}$) [$m^2\ s^{-1}$]	R^2	G	j	R^2
1	3.57	0.92	0.0021	1.410	0.997
2	6.26	0.93	0.0049	1.339	0.999
3	5.46	0.93	0.0054	1.301	0.998
4	8.14	0.93	0.0078	1.289	0.999
5	3.99	0.93	0.0027	1.360	0.998
6	6.47	0.91	0.0040	1.366	0.999
7	3.63	0.91	0.0014	1.458	0.998
8	7.44	0.93	0.0073	1.270	0.998
9	5.03	0.97	0.0028	1.391	0.998
10	5.66	0.91	0.0036	1.364	0.998
11	5.30	0.88	0.0018	1.443	0.997

Oliveira et al. (2006), for drying of chicory roots; by Fiorentin et al. (2010b), for orange bagasse; and by Ferreira et al. (2012), for drying of fermented grape bagasse.

Table 6 presents the regression coefficients of studied factors and their interactions on the effective diffusivity response, as a result of statistical analysis.

Table 6 shows that the global mean and the linear factors of air temperature and infrared time presented significant regression ($p \leq 0.05$) on the effective diffusivity response. These factors have had a positive effect on the response, indicating that increasing behavior of effective diffusivity was proportional to the increase in air temperature and infrared application time. As the effective diffusivity is related to how fast water is evaporated, the higher level of the factors caused higher drying mean rates.

Table 6. Estimated effect, standard error and significance level (p) for the effective diffusivity response (D_{eff}, $m^2\ s^{-1}$)

Factors	Regression coefficient	Standard error	t (5)	p-value
Global Mean	$5.33x10^{-10}$*	$2.09x10^{-11}$	25.56	$1.71x10^{-6}$
TL	$9.11x10^{-11}$*	$1.28x10^{-11}$	7.13	$8.42\ x10^{-4}$
TQ	$7.17x10^{-12}$	$1.52x10^{-11}$	0.47	$6.57\ x10^{-1}$
tL	$1.34x10^{-10}$*	$1.28x10^{-11}$	10.53	$1.33\ x10^{-4}$
tQ	$2.21x10^{-11}$	$1.52x10^{-11}$	1.46	$2.05\ x10^{-1}$
TL x tL	$-2.97x10^{-13}$	$1.81x10^{-11}$	-0.02	$9.88\ x10^{-1}$

*Statistically significant regression coefficients: $p < 0.05$

After the identification of statistically significant regression coefficients, the validity of the models and their adjustments to the experimental data was verified by analysis of variance (ANOVA), based on the F-test and on the percentage of variance explained (R^2). Table 7 shows these results.

Table 7 shows that the model obtained for effective diffusivity explains 96% of the variation of observed data. The F_{cal} value was superior to F_{tab} value, implying that, for each variable, the obtained model was significant and valid to describe the experimental data (Eq. 6). So it is possible to generate the response surface (Figure 2).

$$D_{eff} = 5.56\times10^{-10} + 9.11\times10^{-11}T + 1.34\times10^{-10}t \qquad (6)$$

According to Faria et al. (2012), the diffusion approximation method was the model that best adjusted to the drying data obtained; increases in drying temperature promoted higher rate of moisture removal from the crambe seeds.

With the assay data, the drying curve for each set of experimental run (factorial, axial and central) was obtained. These curves are shown in Figure 3 for Fick's model and in Figures 4 for Page's model.

By comparative analysis of the charts using Fick's model for spheres and Page's model, for each run performed, it can be verified that the best fitting of the drying curves occurred with the Page's model.

Table 7. Analysis of variance (ANOVA) for the effective diffusivity response (D_{eff})

Source	Sum of squares	Degree of freedom	Mean square	F_{cal}	F_{tab}*	R^2
Regression	$2.11x10^{-19}$	2	$1.05x10^{-19}$	90.85	4.46	0.96
Residual	$9.29x10^{-21}$	8	$1.16x10^{-21}$			
Lack of fit	$7.32x10^{-21}$	6	$1.22x10^{-21}$			
Pure error	$1.97x10^{-21}$	2	$9.86x10^{-22}$			
Total	$2.20x10^{-19}$	10				

*Calculated (F_{cal}) and tabulated (F_{tab}) value of the F-test at 95% significance

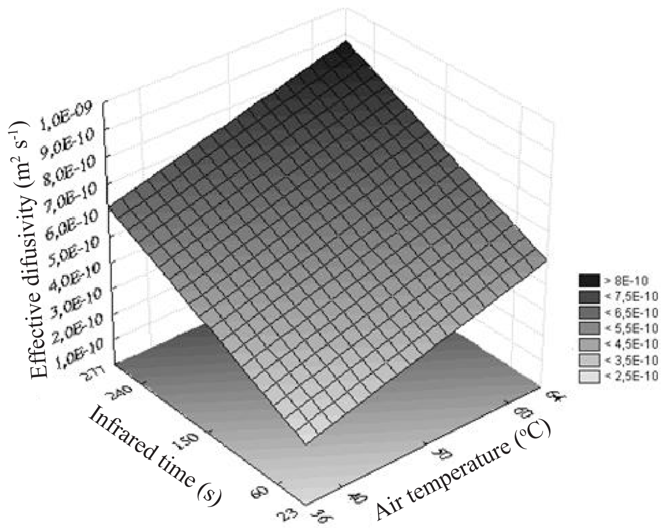

Figure 2. Response surface for effective diffusivity (D_{eff} - $m^2\ s^{-1}$) as function of temperature and infrared application time, obtained in orange bagasse drying

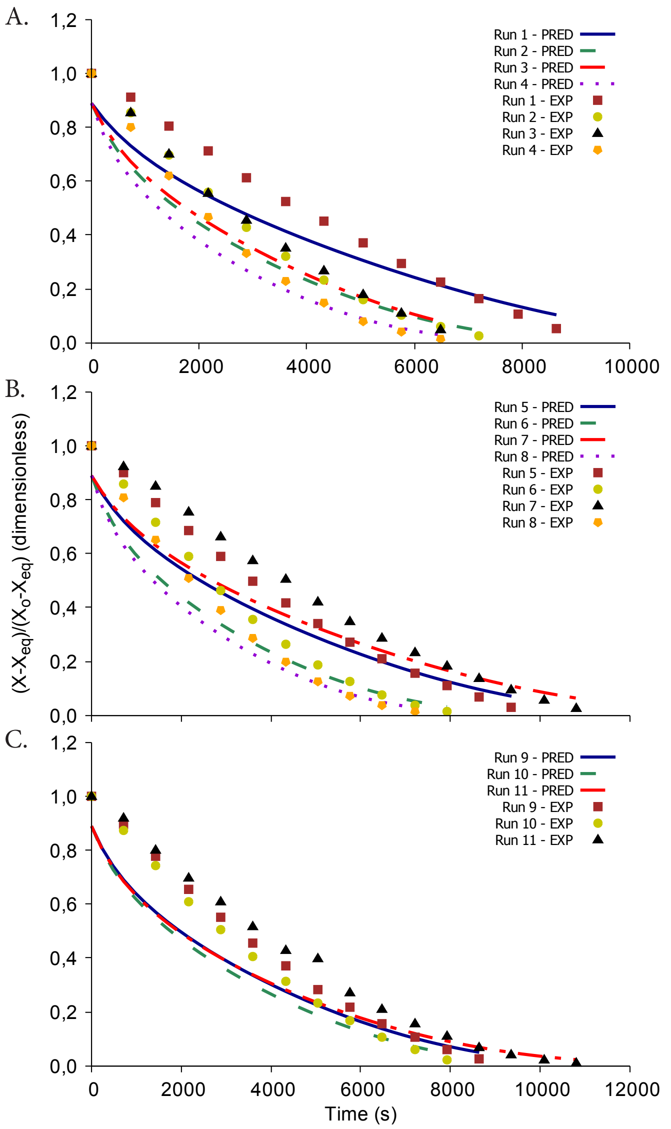

Figure 3. Experimental (EXP) and predicted (PRED) drying curves fitted by the Fick's model for orange bagasse: factorial points (A); axial points (B); central points (C)

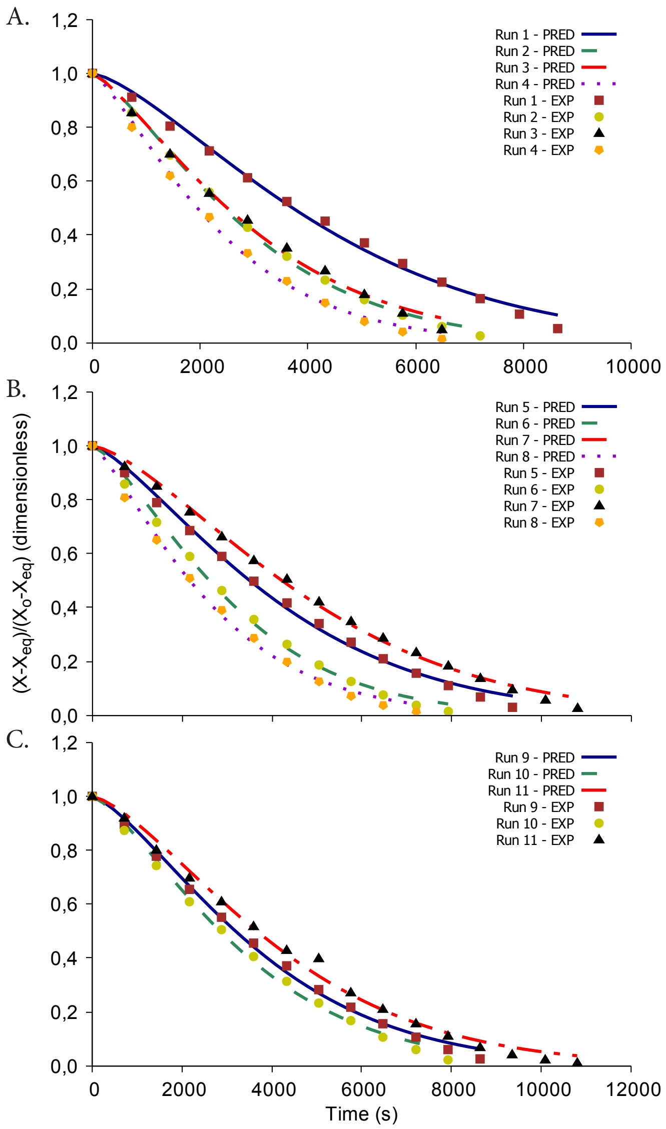

Figure 4. Experimental (EXP) and predicted (PRED) drying curves fitted by the Page's model for orange bagasse: factorial points (A); axial points (B); central points (C)

It was observed in Figures 3A and 4A, for the factorial points experimental assays, that, as temperature varied between 40 and 60 °C and infrared application time varied between 60 and 240 s, the curves showed variation among them. However, as the operational conditions of drying experimental assays of the central points are the same, i.e., there is no variation in the values of the factors, i. e., the curves are close.

For the curves of assays conducted in the axial points, the difference of factor levels is greater, resulting in greater discrepancy between the curves. In addition, the assays with variation in the values of infrared application time (7 and 8) presented a more noticeable difference between themselves compared to assays 5 and 6, which showed variation in air temperature.

The activation energy for the different values of effective diffusivity and infrared application times were determined by linearization of Eq. 4. Longer infrared application times generated lower values of activation energy. Thus, the values of activation energy obtained for infrared application times of 60; 150 and 240 s were 18.491; 14.975 and 11.421 kJ mol^{-1} respectively. Fiorentin et al. (2012) achieved a value of 10.669 kJ mol^{-1} for the activation energy of orange bagasse with convective drying. Ferreira et al. (2012) observed activation energy of 26.440 kJ mol^{-1} in the drying of fermented grape bagasse. Faria et al. (2012) observed the activation energy for liquid diffusion during drying of *Crambe abyssinica* Horts was about 4.97 kJ mol^{-1}.

Conclusions

1. The drying of orange bagasse with air temperature ranging from 36 to 64 °C and infrared time between 23 and 277 s presented a final moisture content in the range from 0.09 to 0.87 (db) and water activity between 0.25 and 0.87. These ranges did not affect the final bulk density of orange bagasse.

2. The best drying operation conditions for drying of orange bagasse were: temperature of 50 °C and infrared radiation application time of 150 s, because the moisture content and water activity are suitable for conservation when the product was stored.

3. The effective diffusivity increases as infrared radiation application time increases and the empirical Page's model was thus assigned the best one to represent the experimental data as

well as it could be recommended as an adequate guide model for the drying process optimization tests of orange bagasse.

4. Effective diffusivity dependence on temperature was described by the Arrhenius equation, with activation energy of 18.491, 14.975 and 11.421 kJ mol^{-1} for infrared application times of 60, 150 and 240 s, respectively.

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