Effective diffusivity in yacon potato cylinders during drying[1]

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A B S T R A C T

The aim of this study was to obtain the effective diffusivity of yacon potato in fixed-bed dryer at different temperatures (50, 60 and 70 ºC) and drying air velocities (1.0, 1.5 and 2.0 m s^{-1}). Non-linear regression analysis was performed by the Quasi-Newton method using the program Statistica 7.0, where the parameters of the models were estimated as a function of the drying air temperature. Approximation of Diffusion, Two Terms, Henderson & Pabis, and Page models fitted well the experimental data. Drying air temperature and speed influenced the drying time of the samples. The effective diffusivity increased with increasing temperature, ranging from 1.18 x 10^{-9} to 2.15 x 10^{-9} m^2 s^{-1}.

Difusividade efetiva em batata yacon com formato cilíndrico durante a secagem

R E S U M O

Objetivou-se nesse trabalho obter a difusividade efetiva da batata yacon em secador de leito fixo com diferentes temperaturas (50, 60 e 70 ºC) e velocidades do ar (1,0; 1,5 e 2,0 m s^{-1}) de secagem. Foi realizada a análise de regressão não-linear, pelo método Quasi Newton, através do programa Statistica 7.0, onde os valores dos parâmetros dos modelos foram estimados em função da temperatura do ar de secagem. Os modelos de Aproximação da Difusão, Dois Termos, Henderson & Pabis e Page ajustaram-se bem aos dados experimentais. Constatou-se que a temperatura e a velocidade do ar de secagem influenciaram no tempo de secagem das amostras. Verificou-se que a difusividade efetiva aumentou com o aumento da temperatura, variando de 1,18 x 10^{-9} a 2,15 x 10^{-9} m^2 s^{-1} em todas as temperaturas estudadas.

Introduction

Yacon (*Smallanthus sonchifolia*), native to the Andes, began to be cultivated in Brazil through the Japanese colonization, in the region of Capão Bonito, SP, where the root became popularly known as 'batata yacon' or 'batata diet', being cultivated in other regions (Moscatto et al., 2005; Santana & Cardoso, 2008).

Yacon roots are particularly abundant source of fructooligosaccharides (FOS) and inulin, with beneficial effect on human health for having low energetic value, reducing cholesterol and glucose levels in the blood (Genta et al., 2009; Ojansivu et al., 2011).

Despite its nutritive potential, this tuber is still produced on small scale, having fast post-harvest deterioration due to the high moisture content. For this reason, developing new products is highly promising, and one of the main products from this tuber, for instance, is yacon flour, has good possibility of use as functional ingredient in the formulation of various industrialized foods (Rodrigues et al., 2011).

The use of mathematical modeling to predict the drying phenomenon and the evaluation of effective diffusivity in various products has been object of numerous studies (Kingsly et al., 2007; Torregroza-Espinosa et al., 2014; Fernandes et al., 2015; Lopes et al., 2015; Araújo et al., 2017). It is known that effective diffusivity represents the speed with which water moves from the interior to the surface of the product; consequently, the higher the temperature the faster the water movement from the food to the environment (Menezes et al., 2013).

Thus, the drying of this product emerges as a viable alternative to reverse this situation, increasing the storage period because the process reduces water activity, which is higher than 80% in plants (Silva et al., 2013).

This study aimed to evaluate the effective diffusivity in yacon cylinders during the drying process.

Material and Methods

The raw material was yacon (*Smallanthus sonchifolia*), purchased at the Center of Supply and Logistics of Pernambuco - CEASA, in the city of Recife, PE. Samples cut in cylinders approximately 0.5 cm thick and 1.0 cm wide were subjected to a treatment of enzymatic inactivation with 3% citric acid, according to the methodology adopted by Silva et al. (2013). Then, the samples were placed on screen trays and kept at room temperature on the workbenches of the Laboratory of Storage and Processing of Products, at the Academic Unit of Agricultural Engineering, Federal University of Campina Grande (7º 13' S, 35º 52' W). After draining the yacon cylinders, the initial moisture content was determined and the samples were immediately taken to the oven at 105 ºC for 24 h. Then, the cylinders were subjected to drying in a convective tray dryer (fixed-bed) at different temperatures (50, 60 and 70 ºC) and air speeds (1.0; 1.5; and 2.0 m s⁻¹). Drying was conducted in mean times of about 13.3, 10.3 and 7.2 h for the temperatures of 50, 60 and 70 ºC, respectively.

The material was continually weighed, counting from time 0 until reaching constant weight. Moisture content (X) was calculated based on the initial mass (m) and dry mass (m_s) of the yacon cylinders, according to Eq. 1.

$$X = \frac{m - m_s}{m_s} \qquad (1)$$

The experimental data were expressed as moisture ratio (RX), as shown in Eq. 2.

$$RX = \frac{X - X_e}{X_i - X_e} \qquad (2)$$

where:
- X - moisture content of the product, d.b.;
- X_i - initial moisture content of the product, d.b.; and
- X_e - equilibrium moisture content of the product, d.b.

The models Approximation of Diffusion, Henderson & Pabis, Page and Two Terms, evaluated for the fit to the drying kinetics experimental data (Table 1), have also been used by Radünz et al. (2010) and Araújo et al. (2017).

Table 1. Mathematical models used to predict yacon drying kinetics

Models		Equation
Approximation of diffusion	RX = a exp(-kt) + (1-a) exp (-kbt)	(3)
Henderson & Pabis	RX = a exp(-kt)	(4)
Page	RX = exp(-kt^n)	(5)
Two Terms	RX = a exp(-k$_0$t) + b exp(-k$_1$t)	(6)

RX - Moisture ratio (dimensionless); a, b, k, n, k_0, k_1 - Constants of the equation; t - Time (min)

The parameters of the models were obtained by non-linear regression analysis through the Quasi-Newton numerical method for all models and using the program Statistica 7.0. (Statistica, 2005). The model with best fit was evaluated using coefficient of determination (R^2) and mean square deviation (MSD), as presented in Eq. 7.

$$MSD = \sqrt{\frac{\sum \left(RX_{pred} - RX_{exp}\right)^2}{n}} \qquad (7)$$

where:
- MSD - mean square deviation;
- RX_{pred} - moisture ratio predicted by the model;
- RX_{exp} - experimental moisture content; and
- n - number of observations.

The diffusion model based on the Fick's Law (Eq. 8) was applied to estimate effective diffusivity (Def) of yacon cylinders considering the geometry of the product as an infinite cylinder for the four first terms of the series, using the program Statistica 7.0 (Statistica, 2005).

$$RX = 4\sum_{n=1}^{\infty} \frac{1}{\mu_n^2} \exp\left(\frac{-\mu_n^2 Deft}{R^2}\right) \qquad (8)$$

where:
- RX - moisture ratio, dimensionless;

Def   - effective diffusivity, m² s⁻¹;
n   - number of terms;
t   - drying time, s;
R   - cylinder radius, m; and,
μ_n - roots of the Bessel's equation.

Results and Discussion

Table 2 presents the parameters, coefficients of determination and means square deviations of the models Approximation of Diffusion, Two Terms, Henderson & Pabis and Page fitted to the experimental drying data of yacon cylinders, at air speed of 1.0 m s⁻¹ and drying air temperatures of 50, 60 and 70 ºC.

Among the models fitted (Table 2), Approximation of Diffusion showed the highest coefficients of determination and lowest mean square deviations. However, all other models tested can be used to represent the yacon drying process. Torregorza-Espinosa et al. (2014) fitted the Page model to the drying curve of cassava cv. 'Corpoica Verônica', at temperature of 70 ºC with air speed of 1.0 m s⁻¹ and observed good fits of the model to the experimental curve. As to the parameter k, it was observed that between the temperatures of 60 and 70 ºC there was an increase in k and, according to Martins et al.

(2015), the higher its value the higher the effective diffusivity in the drying process.

For the Two Terms model, k_0 and k_1 increased as the temperature increased; on the other hand, the parameters a and b showed undefined behavior. A study conducted by Ruhanian & Movagharnejad (2016), on the drying of potato slices, also found good fit of this same model to the drying data. The parameters k of the models Henderson & Pabis and Page increased with the increment in temperature, corroborating the results of Lopes et al. (2015). The constant n of the Page model increased between 50 and 60 ºC. Reis et al. (2015) observed no clear trend of variation in the parameter k of the Page model with the increase in drying air temperature.

Table 3 presents the parameters, coefficients of determination and mean square deviations of the models Approximation of Diffusion, Two Terms, Henderson & Pabis and Page fitted to the experimental drying data of yacon cylinders, at air speed of 1.5 m s⁻¹ and drying air temperatures of 50, 60 and 70 ºC.

All models satisfactorily represented the drying process of yacon cylinders (Table 3). These results corroborate those of Reis et al. (2015), obtained in the drying of pepper. For the model Approximation of Diffusion, the constant k decreased with the increment in temperature between 50 and 60 ºC,

Table 2. Parameters, coefficients of determination (R²) and mean square deviations (MSD) of the models fitted to the drying curves of yacon cylinders at the different temperatures and at air speed of 1.0 m s⁻¹

Model	Temperature (ºC)	Parameter			R²	MSD
		a	k	b		
Approximation of Diffusion	50	0.0133	0.1124	0.0625	0.9999	0.0049
	60	-1.0031	0.0133	0.8353	0.9998	0.0060
	70	0.0276	0.0858	0.1454	0.9996	0.0093
		a	k_0	b	k_1		
Two Terms	50	0.4930	0.0068	0.4930	0.0068	0.9998	0.0052
	60	0.5246	0.0094	0.4846	0.0094	0.9996	0.0069
	70	0.4962	0.0128	0.4962	0.0128	0.9995	0.0103
		a		k			
Henderson & Pabis	50	0.9918		0.0070		0.9998	0.0052
	60	1.0092		0.0094		0.9998	0.0069
	70	0.9925		0.0128		0.9995	0.0103
		k		n			
Page	50	0.0077		0.9839		0.9998	0.0056
	60	0.0080		1.0342		0.9998	0.0060
	70	0.0143		0.9758		0.9995	0.0738

Table 3. Parameters, coefficients of determination (R²) and mean square deviations (MSD) of the models fitted to the drying curves of yacon cylinders for the different temperatures and at air speed of 1.5 m s⁻¹

Model	Temperature (ºC)	Parameter			R²	MSD
		a	k	b		
Approximation of Diffusion	50	0.0397	0.0829	0.9750	0.9999	0.0027
	60	0.1967	0.0310	0.2756	0.9999	0.0034
	70	0.0109	0.0604	0.2038	0.9999	0.0037
		a	k_0	b	k_1		
Two terms	50	0.0403	0.0849	0.9604	0.0080	0.9999	0.0027
	60	0.8004	0.0085	0.1983	0.0304	0.9999	0.0034
	70	0.4987	0.0124	0.4987	0.0124	0.9999	0.0039
		a		k			
Henderson & Pabis	50	0.9808		0.0083		0.9997	0.0061
	60	0.9678		0.0101		0.9992	0.0134
	70	0.9974		0.0124		0.9999	0.0039
		k		n			
Page	50	0.0109		0.9479		0.9999	0.0047
	60	0.0169		1.8952		0.9999	0.0045
	70	0.0129		0.9917		0.9999	0.0038

and the parameter b decreased as temperature increased. For the Henderson & Pabis model, the constant k increased with the increment in temperature. Similar behavior was observed by Santos et al. (2010) for the drying of potato slices at temperatures of 50 and 60 ºC and air speed of 1.5 m s^{-1}. In addition, the constants k and n of the Page model showed an increase between 50 and 60 ºC, followed by slight reduction when the drying temperature increased from 60 to 70 ºC. Santos et al. (2010) observed, for the Page model, that the value of n increased with the increment in temperature.

Table 4 presents the parameters, coefficients of determination (R^2) and mean square deviations (MSD) of the models Approximation of Diffusion, Two Terms, Henderson & Pabis and Page fitted to the experimental drying data of yacon cylinders, at air speed of 2.0 m s^{-1} and drying air temperatures of 50, 60 and 70 ºC.

Based on the obtained results (Table 4), all models fitted well to the experimental data. Once again, the model Approximation of Diffusion behaved as the best model at the temperatures of 50 and 60 ºC, and the Two Terms was the best model at 70 ºC.

For the model Approximation of Diffusion, the constant k increased between the temperatures of 50 and 60 ºC and decreased between 60 and 70 ºC. For the Two Terms model, the constants k_0, k_1 and b increased with the increment in temperature. For the model Henderson & Pabis, there was an increment in the constant k with the increase in temperature.

Comparing all models at the three drying air speeds, there was a trend of increase in k values, the drying rate constant, which represents the effect of the external drying conditions, with the increase of temperature, a result confirmed in each increment of temperature in the model Henderson & Pabis. For the parameter n, which represents the effects of the internal conditions of the material on the drying process (Perez et al.,

2013), the condition is clearly observed at the air speeds of 1.0 and 1.5 m s^{-1}, possibly denoting a decreasing influence of the internal medium with the increment in air speed.

Based on the results presented in Tables 2, 3 and 4, both drying air speed and temperature influenced the drying time of the samples, which has also been confirmed by Kingsly et al. (2007), Lopes et al. (2015), Araújo et al. (2017), and other authors. There was a gradual reduction in the drying time with the increase in temperature and air speed, proving that these variables significantly influenced yacon drying. According to Shi et al. (2013), the higher the heat transfer rate, the more easily water molecules move, and it facilitates water movement from inside to the surface of the product.

Table 5 presents the values of water effective diffusivity and their respective coefficients of determination (R^2) as a function of temperature and speed of the drying air.

There was a progressive increase in the effective diffusivity with the increase of temperature, at all air speeds (Table 5). The effect of increasing temperature on the increment of effective diffusivity, a consequence of the progressive increase in the molecular agitation in the liquid phase, perhaps followed by increase in cell wall permeability, has been found by various authors, such as Mercali et al. (2008), in the osmotic dehydration of banana cylinders, in which water effective diffusivity increased from 5.37 x 10^{-10} to 6.30 x 10^{-10} m^2 s^{-1} as temperature increased from 25 to 55 °C; and Portela et al. (2014), who dried 2.5-mm-thick slices of macambira (*Bromelia laciniosa*) at temperatures of 43, 49 and 56 ºC, at air speed of 1.0 m s^{-1}, and observed that the increase of temperature caused increment in effective diffusivity, showing values of 1.81 x 10^{-10}, 2.37 x 10^{-10} and 4.09 x 10^{-10} m^2 s^{-1}, respectively.

At the temperature of 60 ºC, the effective diffusivity increased as air speed increased; however, this increment was only observed at 50 ºC between the speeds 1.5 and 2.0 m s^{-1};

Table 4. Parameters, coefficients of determination (R²) and mean square deviations (MSD) of the models fitted to the drying curves of yacon cylinders for the different temperatures and at air speed of 2.0 m s^{-1}

Models	Temperature (ºC)	Parameter			R²	MSD
		a	k	b		
Approximation of Diffusion	50	0.0153	0.0942	0.0689	0.9975	0.0175
	60	0.0074	0.2132	0.0419	0.9999	0.0038
	70	0.1317	0.0438	0.3279	0.9999	0.0036
		a	k_0	b	k_1		
Two Terms	50	0.4959	0.0065	0.4963	0.0065	0.9975	0.0178
	60	0.4882	0.0089	0.5067	0.0089	0.9999	0.0040
	70	0.1303	0.0454	0.8714	0.0143	0.9999	0.0035
		a		k			
Henderson & Pabis	50	0.9922		0.0065		0.9987	0.0178
	60	0.9950		0.0080		0.9999	0.0040
	70	0.9827		0.0159		0.9996	0.0085
		k		n			
Page	50	0.0067		0.9961		0.9986	0.0181
	60	0.0093		0.9938		0.9999	0.0044
	70	0.0207		0.9405		0.9999	0.0043

Table 5. Values of effective diffusivity (Def) in yacon cylinders as a function of the different drying temperatures and air speeds and their respective coefficients of determination (R²)

Air speed (m s^{-1})	Def (m^2 s^{-1})					
	50 ºC	R²	60 ºC	R²	70 ºC	R²
1.0	1.18 x 10^{-9}	0.986	1.28 x 10^{-9}	0.984	1.94 x 10^{-9}	0.980
1.5	0.96 x 10^{-9}	0.985	1.57 x 10^{-9}	0.980	2.15 x 10^{-9}	0.976
2.0	1.08 x 10^{-9}	0.983	1.61 x 10^{-9}	0.983	1.90 x 10^{-9}	0.973

whereas at the temperature of 70 ºC, the diffusivity increased with the increment in air speed between 1.0 and 1.5 m s⁻¹. With this, it was observed that air speed irregularly influenced the values of effective diffusivity among the samples. According to Kingsly et al. (2007), there is a complex of phenomena involved in the simultaneous transfer of heat and mass, such as the structural nature of the material and the magnitude of the moisture content in the product. Fernandes et al. (2015) evaluated the effect of drying air speed on the effective diffusivity of apple cubes dried in convective dryer at the temperatures of 45 and 60 ºC with air speeds of 1, 2, 3 and 5 m s⁻¹, and observed an increase in diffusivity with the increment in air speed at both drying temperatures, and also that the diffusivity increased with the increment in temperature, ranging from 0.58 x 10⁻⁹ to 1.89 x 10⁻⁹ m² s⁻¹.

The reduction in effective diffusivity which occurred as air speed increased at the temperatures of 50 and 70 ºC can be explained by the amount of sugars present in the yacon. The study conducted by Shi et al. (2013), with heat pump drying of 4-mm-diameter yacon cylinders at temperature of 45 ºC and air speed of 1.5 m s⁻¹, found water diffusivity of 7.388 x 10⁻⁷ m s⁻¹, which was much higher than that found in the present study at temperature of 50 ºC for the same air speed. These authors point out that the difference between the values of effective diffusivity is due to a series of factors such as variety, moisture content, sample geometry, chemical pretreatment, type of dryer and temperature used. Alves (2010) also found in the drying kinetics of avocado that the effective diffusivity increased with the increment of temperature, with values of 8.3 x 10⁻¹¹, 11.3 x 10⁻¹¹ and 12.7 x 10⁻¹¹ m² s⁻¹ in the temperatures of 50, 60 and 70 ºC, respectively.

Figure 1 presents the curves fitted with the Fick's diffusion model for the different drying temperatures and drying air speeds.

According to Figure 1, the experimental data at temperatures of 50 and 60 ºC remained very similar along the entire drying process and, at all temperatures, the fitted curves were slightly away from the experimental data from 100 min on, denoting lower predictive accuracy at higher times.

Conclusions

1. The models Approximation of Diffusion, Two Terms, Henderson & Pabis and Page fitted well to the experimental data, with coefficient of determination (R^2) higher than 0.990, and the best fit was represented by the model Approximation of Diffusion.

2. The influence of air speed on the increase in effective diffusivity proved to be more efficient in the increments from 1.0 to 1.5 m s⁻¹ and only at higher drying temperatures.

3. Effective diffusivity increased with the increment of temperature, and the temperature of 70º C is recommended for drying processes aiming at shorter residence times.

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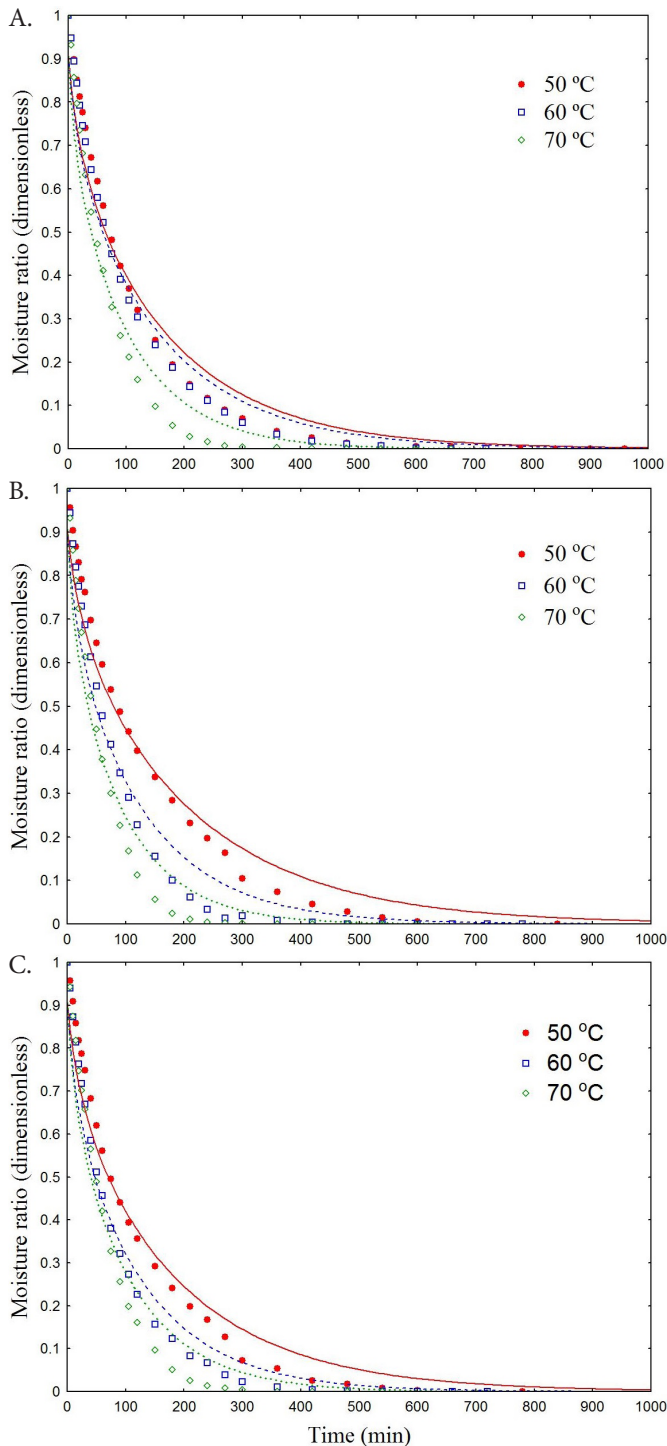

Figure 1. Adjustment of the Approximation of Diffusion model to the experimental drying data of yacon cylinders at the different temperatures and drying air speeds: 1.0 (A) 1.5 (B) 2.0 m s⁻¹ (C)

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