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Foam mat drying of yacon juice: Experimental analysis and computer simulation

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ABSTRACT

The foam mat drying of yacon juice (YJ) and concentrate yacon juice (CYJ) was conducted under various conditions of thickness of product (0.5, 1.0 and 1.5 cm) and air temperature (50, 60 and 70 °C). After drying the resulted dry powder was removed from the metallic tray and pulverized. Layer thickness and air temperature influenced statistically ($p > 0.5$) drying time, moisture content and water activity (Aw) of the product. The shortest drying time to reach the desired Aw (0.1–0.3) corresponds to the condition of 0.5 cm and 70 °C for both juices – 59 and 65 min for the YJ and CYJ, respectively. The process was modeled in terms of heat and mass transfer and then simulated by a finite element method software. The model was able to predict the process satisfactorily and the foam drying technique allowed to obtain yacon powder of good quality, which can be inserted in various food formulations.

1. Introduction

The tuberous roots of yacon (*Smallanthus sonchifolius*) are native to the Andean mountains, where they are commonly cultivated and consumed since the pre-Inca culture period (Seminario et al., 2003; Graefe et al., 2004). The global expansion of their production and marketing initiated after studies related their consumption to the promotion of human health benefits, such as the antioxidant activity associated to the phenolic compounds (Yan et al., 1999; Takaneka et al., 2003) and the reduction of blood glucose levels ascribed to the carbohydrate profile (Mentreddy, 2007; Valentová et al., 2008).

For its sensory resemblance to a sweet and refreshing fruit, the root is traditionally consumed in its raw form (Maldonado et al., 2008). The sweet taste is related to its composition rich in carbohydrates. Unlike other tubers, however, yacon stores fructooligosaccharides (FOS) and inulin instead of starch. These sugars provide prebiotic properties to the yacon roots, forasmuch these components are poorly broken by the digestive enzymes: reaching the intestinal flora intact, they stimulate the development and activity of microorganisms that are beneficial to human health (Lachman et al., 2003; Ojansivu et al., 2011; Campos et al., 2012).

The yacon roots are passive of accelerated rates of enzymatic browning due to the high content of water (up to 70% of the fresh weight) and the soft and delicate internal tissues. Such combination leads to high losses during post-harvesting and transportation, restricting the sustainable development of the culture and generating economic losses (Manrique and Parraga, 2005; Shi et al., 2013). Inasmuch as yacon is a seasonal crop, it is extremely important to establish processing alternatives that increase the stability and availability of this food (Scher et al., 2009).

The moisture removal with consequent reduction of water activity is one of the most viable alternatives to extend the shelf life of this culture. The application of different drying techniques, such as encapsulation (Lago et al., 2012), convective drying (Vasconcelos et al., 2010), dehydration in vacuum oven (Reis et al., 2012), solar drying (Castro et al., 2012), osmo-convective drying (Kotovicz et al., 2014; Perussello et al., 2014) and freeze drying (Bernstein and Noreña, 2014) are reported in literature. Among the various researches about dehydration of yacon published so far, none of them regard to the foam mat drying.

In the foam mat drying, a liquid is converted into a stable foam by incorporation of air (usually by whipping) after addition of a foaming agent. The foam is dried by application of heat and the resulting dried powder is further processed (Raharitsifa et al., 2006; Rajkumar et al., 2007). Because of the porous structure of the foam and the large surface area exposed to the drying air, the

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mass transfer rates are increased when compared to the solid food, leading to a shorter period of dehydration and therefore a final product with higher quality. The nutrients are preserved and the browning rates are lower for the application of high temperatures is not mandatory (Ratti and Kudra, 2006; Muthukumaran et al., 2008). This method can be used on heat sensitive, viscous and high sugar content foods, giving rise to a powder that is easily rehydrated and presents characteristics such as color, flavor, texture and nutritional composition (i.e., antioxidants) similar to the raw material (Fernandes et al., 2013). For these skills, the foam mat drying was applied in various types of foods such as fruit juices (Kadam and Balasubramanian, 2011; Kadam et al., 2012; Chaves et al., 2013), yogurt (Krasaekoopt and Bhatia, 2012), spirulina (Prasetyaningrum and Djaeni, 2012) and beans (Falade et al., 2003).

For an efficient mat drying process, the foams should remain mechanically and thermodynamically stable in order to maintain the efficiency of the water removal and the quality of the product. The use of agents that promote stability is thus required (Bag et al., 2011). Ovalbumin is generally applied as foaming agent in view of the ability of its proteins to form a dense film around the air bubbles, reducing the surface tension instability and retaining the entrapped air (Karim and Wai, 1999; Lomakina and Mikova, 2006).

The use of appropriate drying conditions is of fundamental importance to the quality of the final product and the energy demand required. In the context of the foam mat drying, parameters such as air temperature, velocity and relative humidity, and thickness and composition of the foam determine the quality of the powder obtained toward color, moisture content and preservation of nutrients.

With the purpose of evaluate the application of this technology to yacon roots, drying tests were conducted at different process conditions. The addition of ovalbumin to the yacon juice in order to form a foam that was convective dried resulted in a powder with a high nutritional value in terms of quality and high content of proteins and FOS. As such, this product can be incorporated in the formulation of various foods as a way to facilitate the consumption of yacon and the use of its features. The powder offers a multitude of uses: it can be consumed as a juice after rehydration in water and may also be added to dairy and bakery products to increase their biological value and/or impart texture properties. The statistical analysis of the data showed that the parameters air temperature and thickness of the foam were decisive in the drying rate and, therefore, in the energy demand of the process. As an additional tool to estimate optimal drying conditions, the heat and mass transfer phenomena were modeled to predict the process without the need of driving multiple experimental tests. The computational simulations provided satisfactory results.

2. Material and methods

2.1. Yacon juice

The yacon juice was obtained from roots purchased in the municipal market of Curitiba (Paraná, Brazil). After washed and peeled, they were processed in a food centrifuge. Immediately after processing, sodium metabisulfite was added to the juice (300 mg/L juice) (Maia et al., 2001) to limit the enzymatic activity. The total soluble solids (TSS) were measured using a refractometer (RL3, PZO, Brochowska, Poland). The samples were packed and stored in a freezer (−18 °C) until preparation of the foams.

To evaluate the effect of TSS in the foam characteristics, part of the juice was concentrated by freeze concentration, using the methodology proposed by Wiecheteck et al. (2005). Afterwards, it was stored under the same conditions presented to the non-concentrate juice. The TSS was set as 8°Brix and 24°Brix to the yacon juice (YJ) and concentrate yacon juice (CYJ), respectively.

2.2. Preparation of the foam and drying process

The foams of YJ and CYJ were formed by the addition of ovalbumin powder (20%) (Cami, Mizumoto Alimentos Ltda, Guapirama, Paraná, Brazil) to the liquid phase. After complete mixing, the solution was whipped in a domestic mixer (360 W power) at maximum speed for 20 min to allow the mechanical incorporation of air. The conditions for producing the foams were determined through preliminary tests conducted by the authors.

After whipping, the foams were placed in galvanized steel beds (length 20 cm, width 15 cm and thickness varying from 0.5 to 1.5 cm) and then dried in a convective oven (Fabbe-Primar, São Paulo, Brazil) under controlled air temperature (50, 60 and 70 °C) and speed (4 m/s), which were determined with an anemometer (Testo 405, Testo AG, Lenzkirch, Germany). The moisture loss was assessed by weighing the samples every 15 min on an electronic scale. The criterion for the completion of the process was the stability of the sample's masses in three successive measurements. The moisture content equivalent to the stabilization of the sample's mass was considered as the equilibrium moisture content, which approached 1% w.b. for all drying tests. The ideal moisture for the yacon powder, previously tested by the authors, is the one that provides a light-colored product with low water activity (0.1–0.3).

2.3. Moisture ratio

The moisture ratio (MR) of the samples during drying was calculated by

$$MR = \frac{(M - M_e)}{(M_0 - M_e)} \quad (1)$$

Table 1
Experimental tests resulted from the factorial design.

Test	Yacon juice[a]	x_1 (cm)	x_2 (°C)
1	YJ	0.5	50
2	YJ	1.5	50
3	YJ	1.0	60
4	YJ	0.5	70
5	YJ	1.5	70
6	CYJ	0.5	50
7	CYJ	1.5	50
8	CYJ	1.0	60
9	CYJ	0.5	70
10	CYJ	1.5	70

[a] YJ = non-concentrate yacon juice (8°Brix), CYJ = concentrate yacon juice (24°Brix).

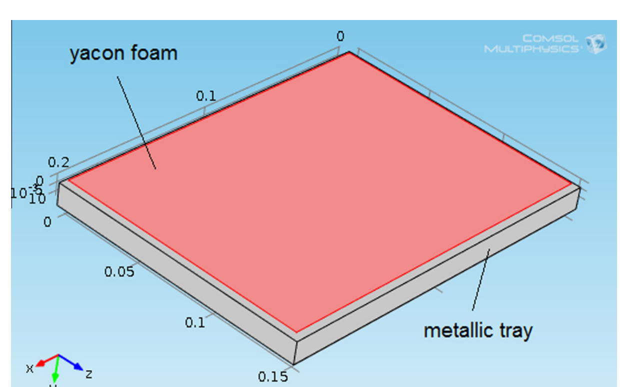

Fig. 1. Computational domain (note: thickness may assume three different values depending on the experimental test).

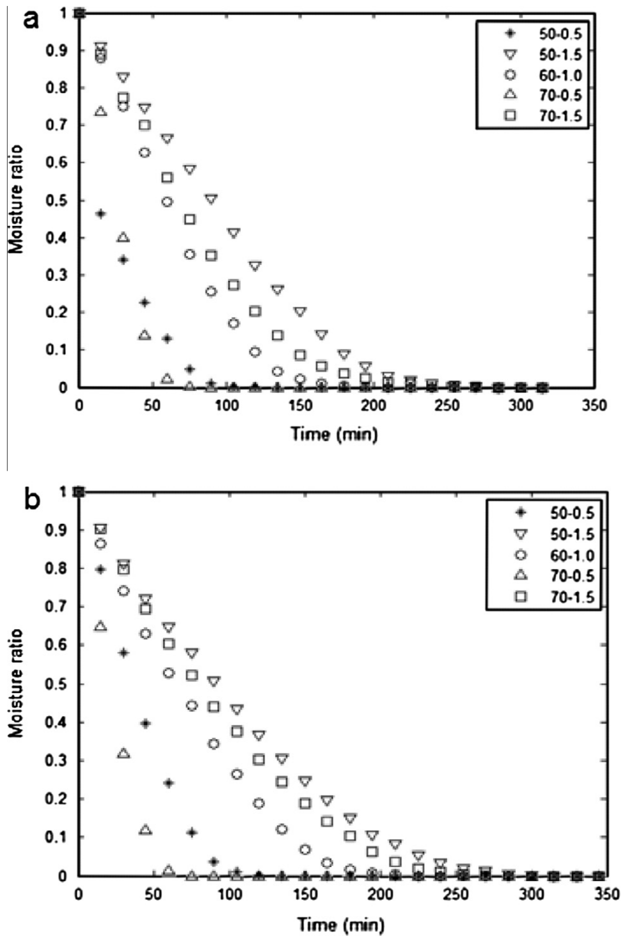

Fig. 2. Drying curves for the foams of (a) yacon juice and (b) yacon concentrate juice at different air temperatures and layer thicknesses.

where M is the moisture content at time t, M_e is the equilibrium moisture content and M_0 is the initial moisture content of the foam, all of them in dry basis (kg/kg).

After drying, the yacon juice foams were scraped off the trays, sprayed, vacuum packed and stored for further studies (Kadam et al., 2010). The water-soluble powder obtained, rich in animal and vegetable proteins and FOS, can be inserted in the formulation of many food products, whether to increase its nutritional value or to assign different textures.

2.4. Statistical analysis

The experiments were planned according to a 2^2 full factorial design with repetition at the central point for both foams (YJ and CYJ), as outlined in Table 1. The effects of two levels of two independent variables, thickness of the foam layer and drying temperature (x_1 and x_2, respectively), were assessed, assuming values of 0.5, 1.0 and 1.5 cm and 50, 60 and 70 °C. The dependent variables analyzed were the drying time (y_1), the moisture content of the yacon powder (y_2) and its water activity (y_3). The factorial design generated 10 experiments, performed in triplicate.

The effect of the independent variables (x_1 and x_2) on the process responses (y_1, y_2 and y_3) were evaluated by the Student's t test at a 95% confidence interval ($p \leqslant 0.05$) using the software Statistica 7.0 (Statsoft Inc. South America, Toulsa, Oklahoma, United States) (Rodrigues and Iemma, 2005).

2.5. Modeling and simulation of the drying process

The mathematical model proposed to represent the transient phenomena of heat and mass transfer during drying of the yacon and ovalbumin foams bases on the diffusional laws of Fourier and Fick, respectively, according to Eqs. (2) and (3). The 3-D computational domain (Fig. 1) is represented by the metallic bed filled with the foam.

$$\rho \mathrm{Cp}\frac{\partial T}{\partial t} + \rho Cpu\nabla T = \nabla(k\nabla T) + Q \quad (2)$$

$$\frac{\partial C}{\partial t} + \nabla(-D\nabla C) = R \quad (3)$$

where ρ, Cp and k are the product's density (kg/m^3), specific heat (J/kg K) and thermal conductivity (W/m K), respectively, T is temperature (K), u is the velocity field (m/s), C is the concentration of water (mol/m^3), Q is the heat generation (W m), D is the mass diffusion coefficient (m^2/s) and R is the mass generation or consumption (kg/m^3).

The following assumptions were considered on the formulation of the model: (a) speed field, thermal and mass generation and consumption are null; (b) thermophysical properties are homogeneous along the foam but variable according to drying time; (c) initial moisture content and temperature of the foam and temperature of the steel bed are homogeneous.

The following mathematical model, written in generalized coordinates, was obtained applying the conditions above to Eqs. (2) and (3). The coupling between heat and mass transfer was performed by the use of thermophysical properties of the food material as a function of its moisture content.

Table 2
Transport coefficients and dimensionless numbers of heat and mass transfer.

Test	Process conditions[a]	Sh[1]	Nu[2]	h (W/m K)[3]	h_m (m/s)[4]	Def (m^2/s)[5]
1	YJ – 0.5 cm, 50 °C	18.5	19.4	108.6	0.113	7.78e−9
2	YJ – 1.5 cm, 50 °C	32.0	33.6	62.7	0.065	2.43e−8
3	YJ – 1.0 cm, 60 °C	25.5	26.9	77.2	0.082	1.70e−8
4	YJ – 0.5 cm, 70 °C	17.8	18.6	109.5	0.117	1.04e−8
5	YJ – 1.5 cm, 70 °C	30.8	32.2	63.2	0.067	3.07e−8
6	CYJ – 0.5 cm, 50 °C	18.5	19.4	108.6	0.113	2.48e−8
7	CYJ – 1.5 cm, 50 °C	32.0	33.6	62.7	0.065	2.0e−8
8	CYJ – 1.0 cm, 60 °C	25.5	26.9	77.2	0.082	1.44e−8
9	CYJ – 0.5 cm, 70 °C	17.8	18.6	109.5	0.117	1.42e−8
10	CYJ – 1.5 cm, 70 °C	30.8	32.2	63.2	0.067	2.54e−8

[1] Sherwood number.
[2] Nusselt number.
[3] Convective heat transfer coefficient (evaluated at the foam's surface, where the moisture evaporation takes place).
[4] Convective mass transfer coefficient.
[5] Mass diffusion coefficient.
[a] YJ = non-concentrate yacon juice (8°Brix), CYJ = concentrate yacon juice (24°Brix).

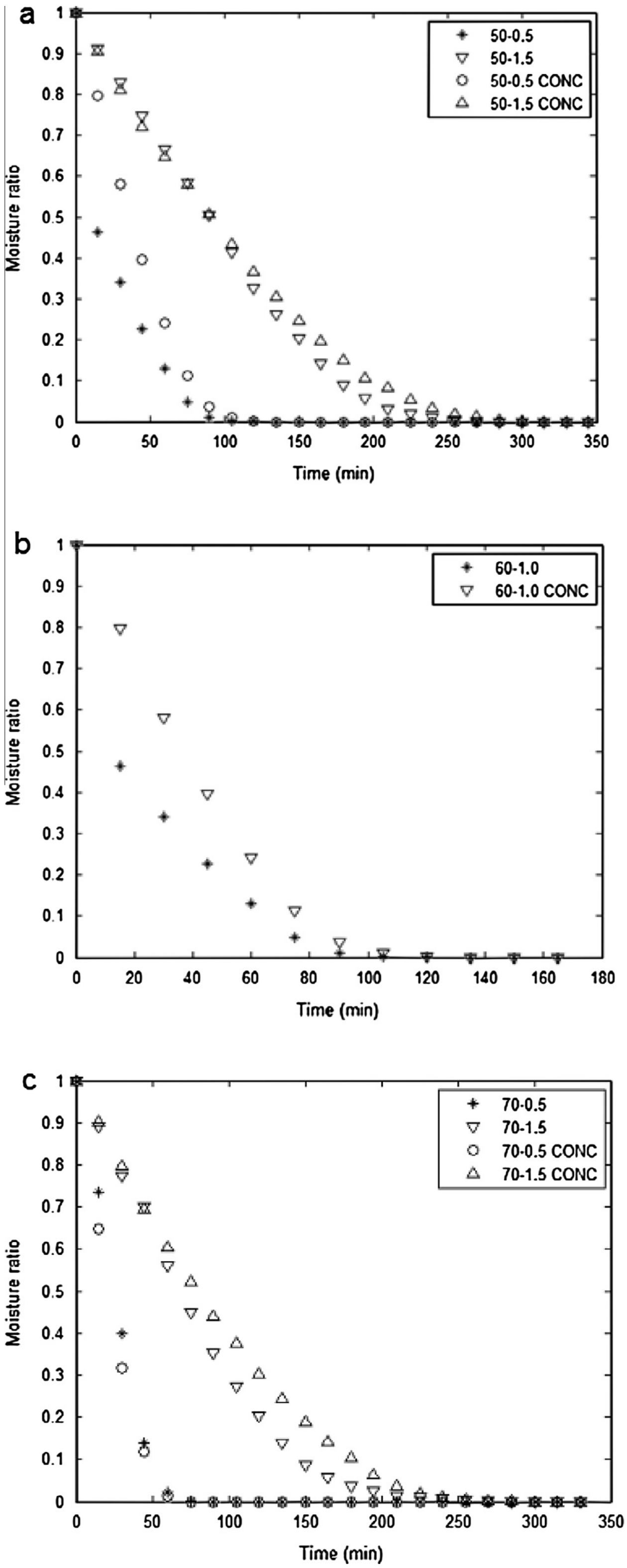

Fig. 3. Comparison of drying curves of the foam produced with yacon juice and concentrate juice (CONC) at: (a) 50 °C, (b) 60 °C and (c) 70 °C.

$$\rho \mathrm{Cp} \frac{\partial T}{\partial t} = \nabla(k \nabla T) \tag{4}$$

$$\frac{\partial C}{\partial t} + \nabla(-D\nabla C) = R \tag{5}$$

The initial and boundary conditions for the heat transfer are: initial temperature known (Eq. (6)), null heat flux in the symmetry region (Eq. (7)), convective heating and evaporative cooling at the surface of the foam (Eqs. (8) and (9), respectively) and convection at the sides of the metallic bed (Eq. (10)). For mass transfer, the initial and boundary conditions are: initial moisture content known (Eq. (11)), null mass flux in the symmetry region (Eq. (12)) and convective mass flow on the foam's surface (Eq. (13)).

$$T = T_0 \text{ for } t = 0 \tag{6}$$

$$\frac{\partial T}{\partial t} = 0 \text{ for } l = L/2 \tag{7}$$

$$\frac{\partial T}{\partial t} = h(T_\infty - T) \text{ for } \tau = T \tag{8}$$

$$\frac{\partial T}{\partial t} = h_m \times \varphi \times (\rho_{\mathrm{wap}-\infty} - \rho_{\mathrm{wap}-wet}) \text{ for } \tau = T \tag{9}$$

$$\frac{\partial T}{\partial t} = h(T_\infty - T) \text{ for } l = 0, l = L, w = 0 \text{ and } w = W \tag{10}$$

$$C = C_0 \text{ for } t = 0 \tag{11}$$

$$\frac{\partial U}{\partial t} = 0 \text{ for } l = L/2 \tag{12}$$

$$\frac{\partial U}{\partial t} = h_m(C_\infty - C) \text{ for } \tau = T \tag{13}$$

where T_0 is the product's initial temperature (K), L, W and T are the length, width and thickness of the metallic bed, respectively (m), h and h_m are the coefficients of convective heat transfer (W/m K) and mass transfer (m/s), respectively, t is the drying time (s) and C_0 and C_∞ are the concentrations of water in the product at time 0 and in the air, respectively (mol/m^3).

The model was implemented in the software COMSOL Multiphysics®, version 4.3, which solves differential equations by the finite element method. For the numerical simulation, a default mesh composed of 19,069 tetrahedral, triangular and edge elements and a step time of 30 s were used. The coupling between the phenomena of heat and mass transfer was conducted using thermophysical properties that are variable over time based on the moisture content of the foam, as mentioned previously. The properties of the product (specific heat, thermal conductivity and density) were estimated according to Singh and Heldman (1993) using equations based on the chemical composition and porosity (Eqs. (14)–(16)), which were determined experimentally. Considering that water is continuously removed from the yacon foam during drying, the product's chemical composition was updated along process time and the properties could be computed as a function of moisture content.

$$\rho = \frac{1 - \varepsilon}{\sum_j \frac{x_j}{\rho_j}} \tag{14}$$

$$\mathrm{Cp} = \sum_j (x_j \mathrm{Cp}_j) \tag{15}$$

$$k = \frac{1}{2}\left[\sum_j x_{vj} k_j + \frac{1}{\sum_j \left(\frac{x_{vj}}{k_j}\right)}\right] \tag{16}$$

where x_j and x_{vj} are the mass and volumetric fractions, respectively, of each pure component of the yacon and egg albumin foam and ε is the porosity (mass fraction of air) of the foam (0.819).

Table 3
Average results of the experimental tests to obtain yacon powder with Aw between 0.1 and 0.3.

Test	Process conditions[a]	Time (min)	Moisture content w.b. (%)	Aw
1	YJ – 0.5 cm, 50 °C	89 ± 0	6.2 ± 0.3	0.19 ± 0.01
2	YJ – 1.5 cm, 50 °C	211 ± 0	6.6 ± 0.1	0.19 ± 0.00
3	YJ – 1.0 cm, 60 °C	156 ± 0	5.5 ± 0.1	0.15 ± 0.00
4	YJ – 0.5 cm, 70 °C	65 ± 0	3.5 ± 0.0	0.11 ± 0.00
5	YJ – 1.5 cm, 70 °C	211 ± 1	4.1 ± 0.1	0.12 ± 0.00
6	CYJ – 0.5 cm, 50 °C	96 ± 1	4.9 ± 0.2	0.20 ± 0.00
7	CYJ – 1.5 cm, 50 °C	242 ± 0	6.2 ± 0.1	0.22 ± 0.00
8	CYJ – 1.0 cm, 60 °C	174 ± 0	5.7 ± 0.1	0.21 ± 0.00
9	CYJ – 0.5 cm, 70 °C	59 ± 0	4.1 ± 0.1	0.13 ± 0.00
10	CYJ – 1.5 cm, 70 °C	224 ± 1	4.3 ± 0.2	0.17 ± 0.00

[a] YJ = non-concentrate yacon juice (8°Brix), CYJ = concentrate yacon juice (24°Brix).

The product's thermal diffusivity was computed by the following correlation:

$$\alpha = \frac{k}{\rho Cp} \tag{17}$$

The coefficients of convective heat and mass transfer, h and h_m, respectively, were obtained according to Holman (1996) (Eqs. (18) and (19)) using the dimensionless numbers given by Eqs. (20)–(23) (Incropera and Dewitt, 1990):

$$h = \frac{\mathrm{Nu} \times k_\infty}{d} \tag{18}$$

$$h_m = \frac{\mathrm{Sh} \times D_{AB}}{d} \tag{19}$$

$$\mathrm{Re} = \frac{\rho_{\infty \times} v_\infty}{\mu_\infty} \tag{20}$$

$$\mathrm{Nu} = 0.664 \mathrm{Re}^{1/2} \mathrm{Pr}^{1/3} \tag{21}$$

$$\mathrm{Sc} = \frac{\mu_\infty}{\rho_\infty \times D_{AB}} \tag{22}$$

$$\mathrm{Sh} = 0.664 \mathrm{Re}^{1/2} \mathrm{Sc}^{1/3} \tag{23}$$

where Re, Nu, Sh and Sc are the dimensionless numbers of Reynolds, Nusselt, Sherwood and Schmidt, respectively, ρ_∞, v_∞, μ_∞ and k_∞ are the density (kg/m^3), velocity (m/s), viscosity (Pa s) and thermal conductivity of air (W/m K), respectively, D_{AB} is the binary diffusion coefficient (water–air) (m^2/s) and d is the bed's characteristic length (m), which depends on the surface at which the convective fluxes take place.

The mass diffusion coefficient was calculated using the analytical solution of Fick's second law for a flat plate (Crank, 1975):

$$\mathrm{MR} = \frac{M_t - M_{eq}}{M_0 - M_{eq}} = \frac{8}{\pi^2} e^{-\left(\frac{D_{if}\pi^2 t}{4\tau^2}\right)} \tag{24}$$

where D_{if} is the mass diffusion coefficient (m^2/s), t is the drying time (s), MR is the dimensionless moisture content as a function of time, M_t is the moisture content at time t (kg/kg), M_{eq} is the equilibrium moisture content (kg/kg), M_0 is the initial moisture content (kg/kg) and τ is the product thickness (m).

One among all 10 experimental tests was randomly selected in order to perform the computer simulations: 1.0 cm, 60 °C, YJ. The physical validation of the model was conducted by comparing experimental and numerical outcomes of average moisture content for the case selected. Afterwards, the numerical validation was assessed by confronting numerical data obtained by different meshes. The default mesh was refined twice, yielding three meshings. The results were considered satisfactory when a determination coefficient (R^2) higher than 0.98 was achieved for both validations, physical and numerical.

3. Results and discussion

3.1. Drying kinetics

The drying curves for the foams of YJ and CYJ are shown in Fig. 2. The data are presented in the form of moisture ratio versus time. The process occurred at a falling rate period, which indicates diffusion as the most likely physical mechanism to govern the movement of moisture through the structure of the product (McMinn and Magee, 1999). The drying rate, nonetheless, is limited by the moisture evaporation from the surface of the foam to the hot air, as indicated by the dimensionless numbers of heat and mass transfer (Table 2). As indicated by the Sherwood number (Sh), the mass convective flow is predominant with respect to moisture diffusion and obviously depends on the air temperature and not on the thickness or concentration of the foam. Inasmuch as the foam has a high porosity (ε = 81.9%), it was expected that the internal migration of moisture was slower than its evaporation into the airflow. The Nusselt number (Nu) confirms that the convective heat transfer is greater than thermal diffusion since the air velocity is high (4 m/s) as well as the high porosity of the food hinders heat conduction.

The lack of a drying period at a constant rate may be ascribed to the nature of the moisture in the foam: the free surface water may be present in the form of suspension and solution (sugars and other molecules), with a vapor pressure below that of the pure water. The same behavior was observed for the foam mat drying of bananas (Thuwapanichayanan et al., 2008).

As expected, drying time was shorter when higher temperatures were applied, behavior caused by the increased drying rate in view of the greater temperature gradient between air and foam (Akpinar et al., 2003). Such effect of temperature on the foam mat drying was observed by Azizpour et al. (2014) as regard to shrimps and by other authors (Erenturk et al., 2004; Doymaz, 2006; Goyal et al., 2007) who studied the thin layer drying of foods.

Another factor that substantially influenced drying time was the thickness of the foam layer. Process time was reduced from 315 min (YJ, 1.5 cm and 50 °C) to 150 min when thickness was changed to 0.5 cm. In turn, for the CYJ, drying time was reduced in 180 min and 225 min when thickness ranged from 1.5 to 0.5 cm at 50 °C and 70 °C, respectively. Similar results were reported for the foam mat drying of mangoes (Rajkumar et al., 2007), tamarindo (Vernon-Carter et al., 2001) and papaya (Kandasamy et al., 2012). The increased thickness reduces the moisture diffusion rate due to the longer path that moisture has to overcome to reach the product's surface. In addition, heat transfer is more efficient at lower thicknesses as the faster heat

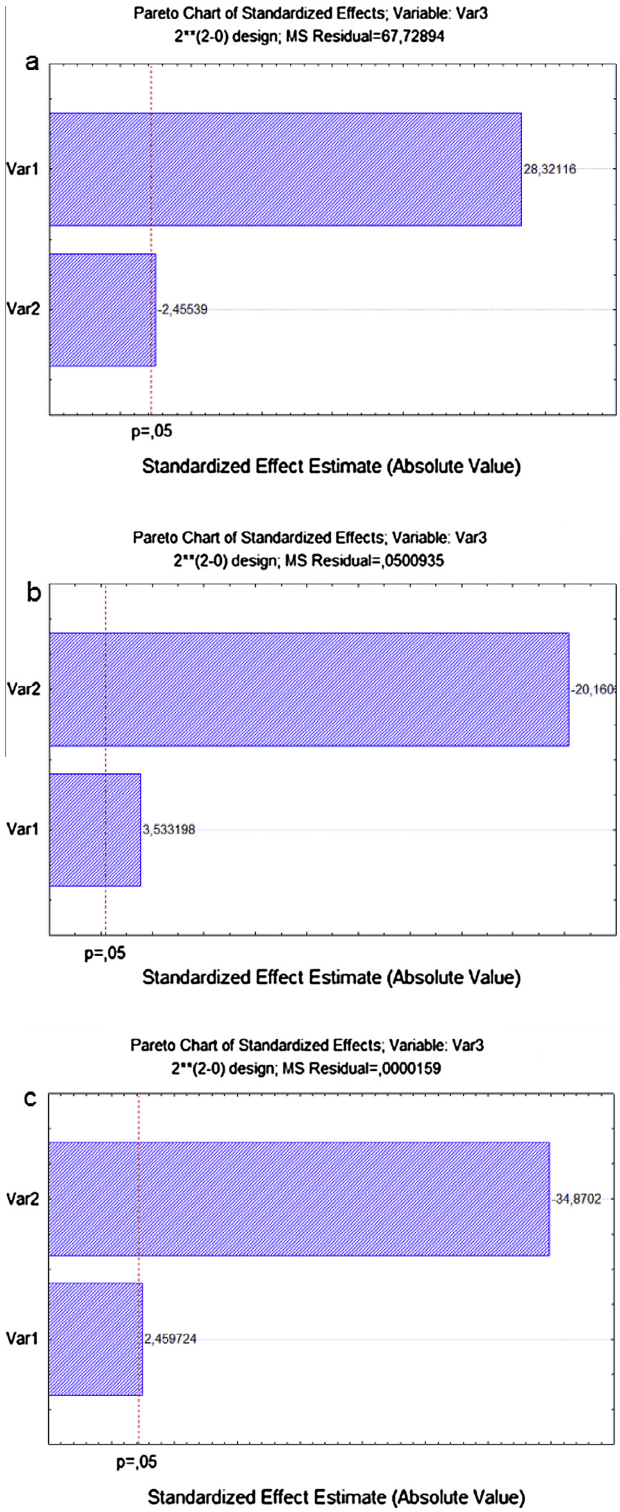

Fig. 4. Pareto charts of the effects of process variables on yacon foams prepared from YJ at a 95% confidence interval: (a) drying time (min); (b) moisture content w.b. (%); (c) Aw (note: Var1 = thickness; Var2 = temperature).

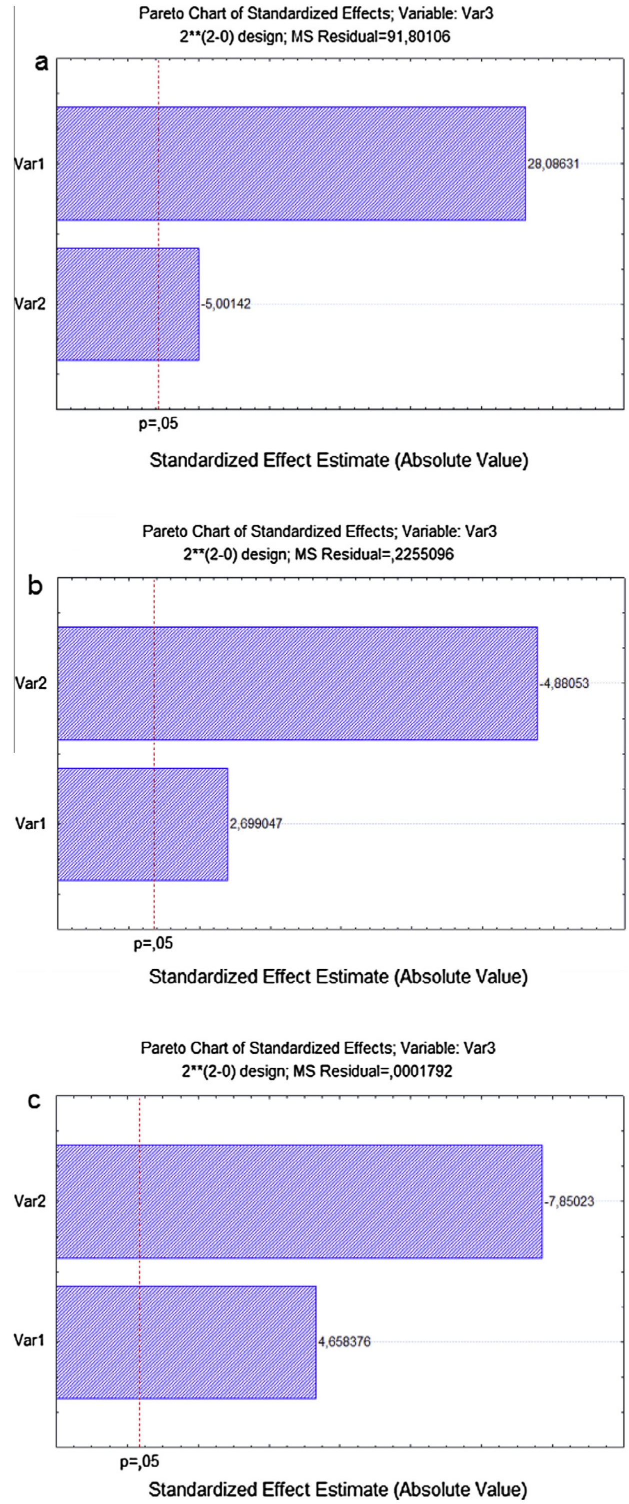

Fig. 5. Pareto charts of the effects of process variables on yacon foams prepared from CYJ at a 95% confidence interval: (a) drying time (min); (b) moisture content w.b. (%); (c) Aw (note: Var1 = thickness; Var2 = temperature).

penetration induces moisture diffusion to begin in a shorter time (Djaeni et al., 2013).

The concentration of soluble solids of the yacon juice influenced the process kinetics only by a small difference in drying time (Fig. 3). The process time at 50 °C was the same (120 min) for both foams (YJ and CYJ) for a thickness of 0.5 cm; for a thickness of 1.5 cm, in turn, the CYJ foam took 30 min less (300 min versus 270 min) to achieve the desired Aw compared with that formulated with YJ. For the central point of the experiment (1.0 cm, 60 °C), the time to reach the ideal Aw was the same for both foams (120 min), as shown in Fig. 3b. For the higher drying temperature applied in this work (Fig. 3c), the foams produced from CYJ and YJ required 60 min and 285 min, respectively, to achieve the

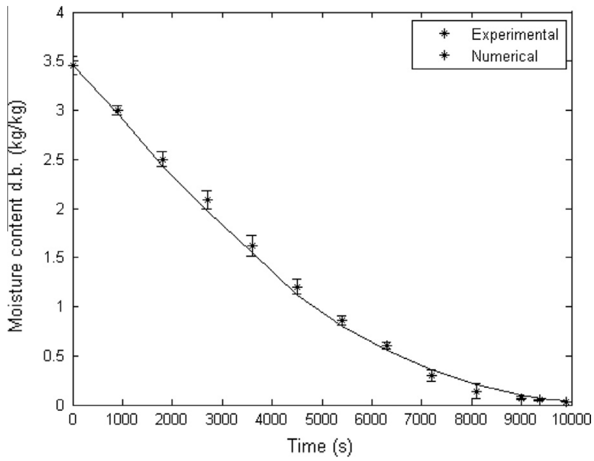

Fig. 6. Average moisture content of the yacon foam during drying at the condition of 1.0 cm, 60 °C, YJ: numerical versus experimental results.

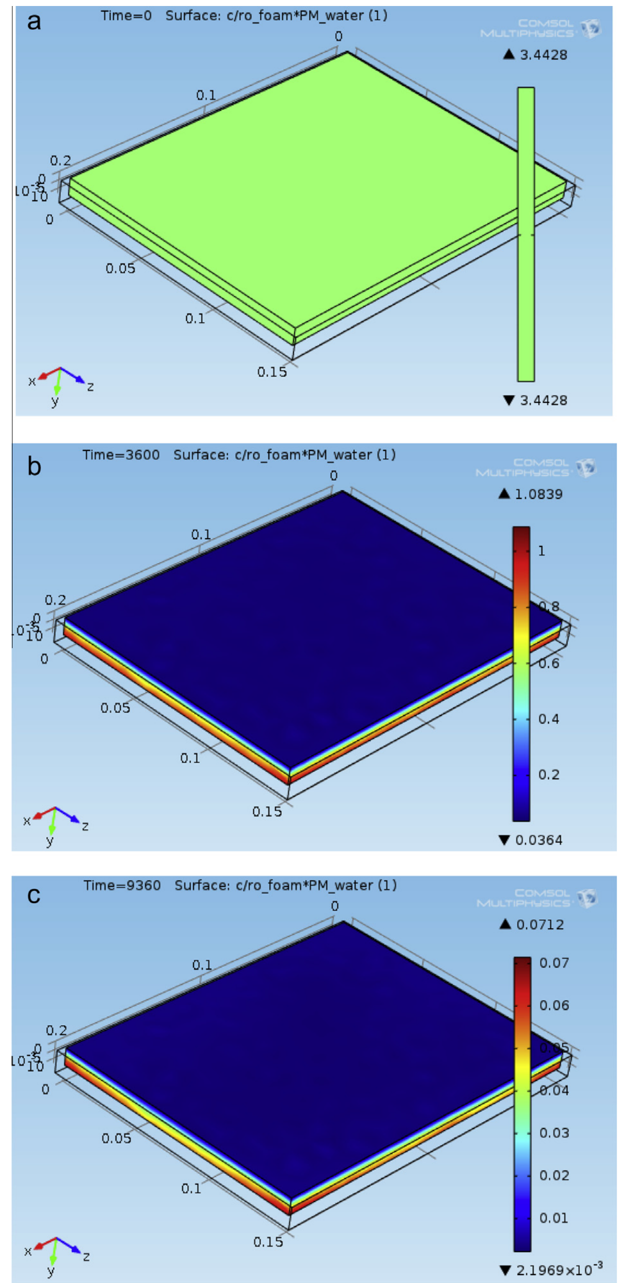

Fig. 7. Moisture profiles of the yacon foam during drying at the condition of 1.0 cm, 60 °C, YJ in: (a) 0 min, (b) 60 min, and (c) 156 min.

desired Aw. This difference can be attributed to the composition of the foams and its influence on the mechanical stability during drying (Ratti and Kudra, 2006). In addition, the solids dissolved in the foam hinder the movement of moisture, mainly by diffusion and capillarity, reducing the drying rate.

3.2. Influence of process variables on the characteristics of the juice powder

The drying time required to achieve an Aw between 0.1 and 0.3 was selected as the final process point. According to Singh and Heldman (1993), the degradative reactions in foods, such as oxidation of fats, browning and microbiological growth, are minimized in this range of Aw. Table 3 presents the mean scores and their respective standard deviations for the moisture content and Aw of the yacon dried powder stored under vacuum, as well as the correspondent drying time.

From Table 3, it is clear that the drying temperature and thickness of the foam layer influenced process time and moisture content and Aw of the dry powder obtained. These outcomes also suggest that this influence occurs at the same way for both juice concentrations, 8°Brix (YJ) and 24°Brix (CYJ). To endorse these observations, Pareto charts were plotted for the powders produced from the foams of YJ (Fig. 4) and CYJ (Fig. 5). These graphs illustrate the statistical effect ($p < 0.5$) of the independent variables on the responses y_1, y_2 and y_3.

Fig. 4 indicates that all process responses are influenced both by the thickness of the foam layer and the drying temperature when the powder is formulated with non-concentrate juice of yacon (YJ). As expected, process time increases for larger thicknesses, as well as the final moisture and Aw. Instead, temperature had a negative effect on all responses, i.e., the higher the drying temperature, the lower the moisture and Aw. Furthermore, the statistical analysis shows that thickness exerts more influence than temperature on drying time (Fig. 4a) as a result of the mechanism of heat and mass transfer prevailing inside the foam, diffusion. The air temperature, in turn, exerts more influence than thickness on final moisture content and Aw. The same conclusions were found for the foam prepared with CYJ (Fig. 5).

In summary, drying temperature and layer thickness influenced statistically the process responses – time, moisture content and Aw – for both foam formulations (YJ and CYJ). Thus, in order to minimize time and energy demand, it would be obvious to choose combinations of factors (x_1 and x_2) which provide a powder of lower Aw in a shorter time. However, an important factor to be also analyzed is the color of the product, which influences the sensory acceptance. Yacon is rich in enzymes such as polyphenol oxidase (PPO) and peroxidase (POD), which use the amino acid L-tryptophan, tannins and phenolic compounds, particularly chlorogenic acid, as substrates. During drying, temperature stimulates the activity of PPO and POD, promoting the enzymatic oxidation of phenolic compounds to quinones, resulting in brown or black pigments after polymerization (Valentová and Ulrichová, 2003). Although sodium metabisulphite has been added to the yacon juice, it minimizes but not completely prevents the enzymatic activity. Thus, it is not enough to find a combination of factors that includes the higher temperature and the smaller foam's thickness: it is mandatory to correlate the outcomes of time, moisture content and Aw with important qualitative parameters, such as color. Furthermore, the enzyme activity consumes substrates, leading

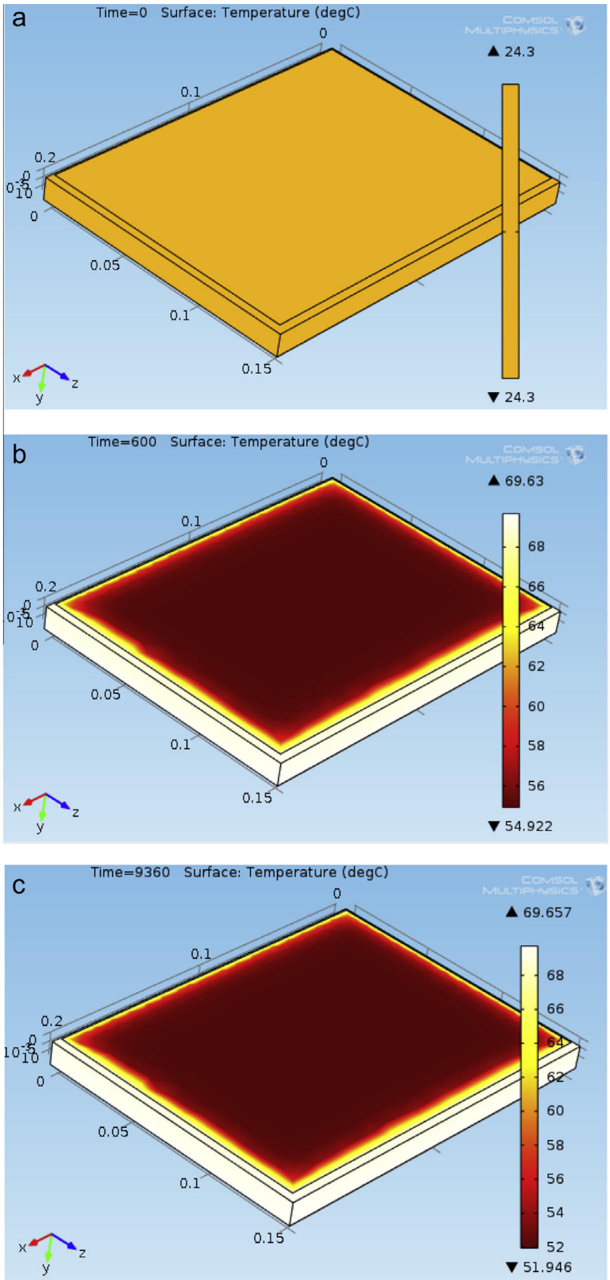

Fig. 8. Temperature profiles of the yacon foam during drying at the condition of 1.0 cm, 60 °C, YJ in: (a) 0 min, (b) 10 min, and (c) 156 min.

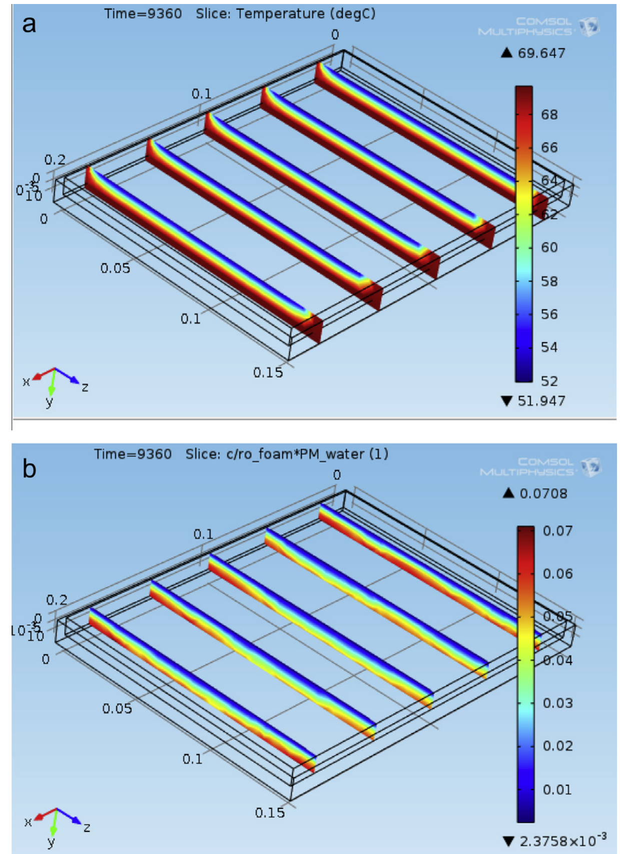

Fig. 9. Internal profiles of (a) temperature and (b) moisture content after completion of drying (156 min) at the condition of 1.0 cm, 60 °C, YJ.

to a reduction of nutritional value of the processed yacon depending on drying temperature.

From a visual investigation, it was found that the drying conditions which generated darker powders were those that combined higher temperatures and thicker layers of foam. During drying of carambola juice, Karim and Wai (1999) observed that the dry foams treated at 90 °C yielded darker products than the ones dried at 70 °C. Kandasamy and collaborators (2012) also addressed the effect of high foam mat drying temperatures in the degradation of the color of papaya juices.

3.3. Drying modeling

The heat and mass transfer phenomena during drying of the foams were mathematically modeled and then simulated in COMSOL Multiphysics®. The comparison between numerical results for the moisture content of a test selected randomly (60 °C, 1 cm, YJ) and the experimental data shows that the model predicts drying successfully. Fig. 6 shows the confrontation between experimental and numerical outcomes of average moisture content of the foam, for which a high coefficient of determination was obtained ($R^2 = 0.998$).

Figs. 7 and 8, in turn, present the three-dimensional profiles of the foam's moisture content and temperature of the system formed by tray and foam, according to the simulation outcomes. Fig. 7 shows that the moisture flow in the foam occurs toward the surface of the tray, as expected, since this is the only contact face between product and air. Within 156 min, the moisture was considerably reduced, nonetheless there was still a water concentration gradient, i.e., the product did not reach the equilibrium moisture content. The model also described coherently the temperature profiles (Fig. 8). Whereas the thermal conductivity of the galvanized steel is very high, the tray nearly reaches the air temperature in the first 10 min. The foam is heated by conduction – in view of the heat flow from the hot tray – and convection – due to the direct contact between product's surface and air. As a result of the evaporative cooling, the foam's temperature, which had reached 54 °C at its free surface after 60 min, suffers a small decrease until the end of drying, reaching a maximum temperature of 52 °C.

Fig. 9 illustrates the internal profiles of moisture and temperature of the product, whose numerical results are physically consistent. The bottom side of the metal mold is in direct contact with the dryer tray, so it is heated only by thermal diffusion. The four sides of the tray, in turn, are heated by convection for there is contact with the hot moving air. The heat flow received by the foam from the walls of the metallic bed raised the temperature of the food material. Meanwhile, the foam's surface received heat by convection from the hot air, but also lost thermal energy due to water evaporation, resulting in the thermal profile shown in Fig. 9a. The maximum temperature reached by the foam in the end of drying is 52 °C, on its surface. The metallic mold, in turn, reaches a temperature near that of the drying air. Moisture is conducted by diffusion toward the surface of the foam thanks to the temperature and water concentration gradients at the interface air-product. The water is removed from the foam across its surface, reason why there is a moisture gradient between base and the top of the bed (Fig. 9b). At the end of 156 min, when the Aw was decreased to the desired value, the product has not yet reached its limit moisture, since air was still drier (in terms of molar concentration of water) than the foam's surface.

These results confirm the possibility of using the proposed model for the prediction of the foam mat drying of yacon. Forasmuch as the model is based on a theoretical study as regard to the heat and mass transport mechanisms, it can be used to simulate other process conditions, namely the thickness and composition of the foam, temperature, velocity and relative humidity of the air, among others. A significant economy of experimental time and costs is ascribed to the predictive ability of such mathematical model.

4. Conclusions

As indicated by the drying curves of the yacon foams (YJ and CYJ), the process took place in a falling rate period, suggesting that diffusion is the governing mechanism of internal moisture movement. While the internal moisture movement occurs mainly by diffusion, the analysis of the transport coefficients indicated that the resistance to convection limits the drying rate.

The drying temperature and the thickness of the foam layers significantly influenced process time and the characteristics of the dry powder (Aw and moisture content). The combination of higher temperatures and lower thicknesses resulted in smaller drying times and powdered juices with lower moisture and Aw, which are characteristics desirable to the product.

The mathematical model proposed was capable of adequately predict the moisture and temperature profiles of the food material, serving as an useful tool for the process optimization.

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References

Akpinar, E.K., Bicer, Y., Yildiz, C., 2003. Thin layer drying of red pepper. J. Food Eng. 59, 99–104.
Azizpour, M., Mohebbi, M., Khodaparast, M.H.H., Varidi, M., 2014. Optimization of foam parameters and investigating the effects of drying temperature on the foam-mat drying of shrimp (*Penaeus indicus*). Drying Technol. 32, 374–384.
Bag, S.K., Srivastav, P.P., Mishra, H.N., 2011. Optimization of process parameters for foaming of Bael (*Aegle marmelos* L.) fruit pulp. Food Bioprocess Technol. 4 (8), 1450–1458.
Bernstein, A., Noreña, C.P.Z., 2014. Study of thermodynamic, structural, and quality properties of yacon (*Smallanthus sonchifolius*) during drying. Food Bioprocess Technol. 7, 148–160.
Campos, D., Betalleluz-Pallardel, I., Chirinos, R., Aguilar-Galvez, A., Noratto, G., Pedreschi, R., 2012. Prebiotic effects of yacon (*Smallanthus sonchifolius* Poepp. & Endl), a source of fructooligosaccharides and phenolic compounds with antioxidant activity. Food Chem. 135, 1592–1599.
Castro, A., Caballero, M., Herbas, A., Carballo, S., 2012. Antioxidants in yacon products and effect of long term storage. Ciência e Tecnologia de Alimentos 32 (3), 432–435.
Chaves, M.A., Barreto, I.M.A., Reis, R.C., Kadam, D.M., 2013. Physicochemical and sensory properties of purple Brazilian cherry (*Eugenia uniflora*, L.) foams. Int. J. Food Sci. Technol. 48, 1688–1697.
Crank, J., 1975. The Mathematics of Diffusion, second ed. Oxford University Press, New York, p. 414.
Djaeni, M., Prasetyaningrum, A., Sasongko, S.B., Widayat, W., Hii, C.L., 2013. Application of foam-mat drying with egg white for carrageenan: drying rate and product quality aspects. J. Food Sci. Technol. http://dx.doi.org/10.1007/s13197-013-1081-0.
Doymaz, I., 2006. Thin layer drying behaviour of mint leaves. J. Food Eng. 74, 370–375.
Erenturk, S., Gulaboglu, M.S., Gultekin, M.S., 2004. The thin layer drying characteristics of rosehip. Biosyst. Eng. 89 (2), 159–166.
Falade, K.O., Adeyanju, K.I., Uzo-Peters, P.I., 2003. Foam-mat drying of cowpea (*Vigna unguiculata*) using glyceryl monostearate and egg albumin as foaming agents. Eur. Food Res. Technol. 217, 486–491.
Fernandes, R.V.B., Queiroz, F., Botrel, D.A., Rocha, V.V., Lima, C.F., Souza, V.R., 2013. Foam mat drying of tomato pulp. Biosci. J. 29 (4), 819–825.
Goyal, R.K., Kingsly, A.R.P., Manikanthan, M.R., Ilyas, S.M., 2007. Mathematical modeling of thin layer drying kinetics of plum in a tunnel dryer. J. Food Eng. 79, 176–180.
Graefe, S., Hermann, M., Manrqiue, I., Golombek, S., Buerkert, A., 2004. Effects of post-harvest treatment on the carbohydrate composition of yacon roots in the Peruvian Andes. Field Crops Res. 86, 157–165.
Holman, J.P., 1996. Heat Transfer. McGraw-Hill, New York, p. 665.
Incropera, F.P., Dewitt, D.P., 1990. Fundamentals of Heat and Mass Transfer, third ed. J. Wiley & Sons, New York, p. 696.
Kadam, D.M., Balasubramanian, S., 2011. Foam mat drying of tomato juice. J. Food Process. Preserv. 35, 488–495.
Kadam, D.M., Wilson, R.A., Kaur, S., 2010. Determination of biochemical properties of foam-mat dried mango powder. Int. J. Food Sci. Technol. 45, 1626–1632.
Kadam, D.M., Wilson, R.A., Kaur, V., Chadha, S., Kaushik, P., Kaur, S., Patil, R.T., Rai, D.R., 2012. Physicochemical and microbial quality evaluation of foam-mat-dried pineapple powder. Int. J. Food Sci. Technol. 47, 1654–1659.
Kandasamy, P., Varadharaju, N., Kalemullah, S., Moitra, R., 2012. Production of papaya powder under foam-mat drying using methyl cellulose as foaming agent. Asian J. Food Agro-Ind. 5 (5), 374–387.
Karim, A.A., Wai, C.C., 1999. Foam-mat drying of starfruit (*Averrhoa carambola* L.) pureé. Stability and air drying characteristics. Food Chem. 64, 337–343.
Kotovicz, V., Ellendersen, L.S.N., Clarindo, M.M., Masson, M.L., 2014. Influence of process conditions on the kinetics of the osmotic dehydration of yacon (*Polymnia sonchifolia*) in fructose solution. J. Food Process. Preserv. 38 (3), 1385–1397.
Krasaekoopt, W., Bhatia, S., 2012. Production of yogurt powder using foam-mat drying. AU J. Technol. 15 (3), 166–171.
Lachman, J., Fernandez, E.C., Orsák, M., 2003. Yacon [*Smallanthus sonchifolia* (Poepp. et Endl.) H. Robinson] chemical composition and use – a review. Plant Soil Environ. 49, 283–290.
Lago, C.C., Bernstein, A., Brandelli, A., Noreña, C.Z., 2012. Characterization of powdered yacon (*Smallanthus sonchifolius*) juice and pulp. Food Bioprocess Technol. 5, 2183–2191.
Lomakina, K., Míková, K.A., 2006. A study of the factors affecting the foaming properties of egg white – a review. Czech J. Food Sci. 24, 110–118.
Maia, G.A., Monteiro, J.C.S., Guimarães, A.C.L., 2001. Estudo da estabilidade físico-química e química do suco de caju com alto teor de polpa. Ciência e Tecnologia de Alimentos 21 (1), 43–46.
Maldonado, S., Santapaola, J.E., Singh, J., Torrez, M., Garay, A., 2008. Cinética de la transferencia de masa durante la deshidratación osmótica de yacón (*Smallanthus sonchifolius*). Ciência e Tecnologia de Alimentos 28 (1), 251–256.
Manrique, I., Párraga, A., 2005. Conservación y uso de la biodiversidad de raíces y tubérculos Andinos: una década de investigación para el desarrollo (1993–2003). Jarabe de yacón: principios y procesamiento, first ed. Centro Internacional de La Papa, Peru, pp. 40–79.
McMinn, W.A.M., Magee, T.R.A., 1999. Principles, methods and applications of the convective drying of food stuffs. Trans. IChemE 77, 175–193.
Mentreddy, S.R., 2007. Review – medicinal plant species with potential antidiabetic properties. J. Sci. Food Agric. 87, 743–750.
Muthukumaran, A., Ratti, C., Raghavan, V.G.S., 2008. Foam-mat freeze drying of egg white – mathematical modeling part II: freeze drying and modeling. Drying Technol. 26, 513–518.
Ojansivu, I., Ferreira, C.L., Salminen, S., 2011. Yacon, a new source of prebiotic oligosaccharides with a history of safe use. Trends Food Sci. Technol. 22, 40–46.
Perussello, C.A., Kumar, C., Castilhos, F., Karim, M.A., 2014. Heat and mass transfer modeling of the osmo-convective drying of yacon roots (*Smallanthus sonchifolius*). Appl. Therm. Eng. 63, 23–32.
Prasetyaningrum, A., Djaeni, M., 2012. Drying spirulina with foam mat drying at medium temperature. Int. J. Sci. Eng. 3 (2).
Raharitsifa, N., Genovese, D.B., Ratti, C., 2006. Characterization of apple juice foams for foam-mat drying prepared with egg white protein and methylcellulose. J. Food Sci. 71 (3), E142–E151.
Rajkumar, P., Kailappan, R., Viswanathan, R., Raghavan, G.S.V., 2007. Drying characteristics of foamed alphonso mango pulp in a continuous type foam mat dryer. J. Food Eng. 79, 1452–1459.

Ratti, C., Kudra, T., 2006. Drying of foamed biological materials: opportunities and challenges. Drying Technol. 24, 1101–1108.
Reis, F.R., Lenzi, M.K., Masson, M.L., 2012. Effect of vacum drying conditions on the quality of yacon (*Smallanthus sonchifolius*) slices: process optimization toward color quality. J. Food Process. Preserv. 36, 67–73.
Rodrigues, M.I., Iemma, A.F., 2005. Planejamento de experimentos e otimização de processos. Uma estratégia sequencial de planejamentos, first ed. Editora Casa do Pão: Itaquaquecetuba, pp. 105–106.
Scher, C.F., Rios, A.O., Noreña, C.P., 2009. Hot air drying of yacon (*Smallanthus sonchifolius*) and its effect on sugar concentrations. Int. J. Food Sci. Technol. 44, 2169–2175.
Seminario, J., Valderrama, M., Manrqiue, I., 2003. El yacón: fundamentos para el aprovechamiento de um recurso promisorio, first ed. Centro Internacional de la Papa, Lima, pp. 13–115.
Shi, Q., Zheng, Y., Zhao, Y., 2013. Mathematical modeling of thin-layer heat pump drying of yacon (*Smallanthus sonchifolius*) slices. Energy Convers. Manage. 71, 208–216.
Singh, P.R., Heldman, D.R., 1993. Introduction to food engineering, second ed. Academic Press, New York, pp. 115–135.
Takaneka, M., Yan, X., Ono, H., Yoshida, M., Nagata, T., Nakanishi, T., 2003. Caffeic acid derivatives in the roots of yacon (*Smallanthus sonchifolius*). J. Agric. Food Chem. 51, 793–796.
Thuwapanichayanan, R., Prachayawarakorn, S., Soponromarit, S., 2008. Drying characteristics and quality of banana foam-mat. J. Food Eng. 86 (4), 573–583.
Valentová, K., Ulrichová, J., 2003. *Smallanthus sonchifolius* and *Lepidium meyenii* – prospective Andean crops for the prevention of chronic diseases. Biomed. Papers 147 (2), 119–130.
Valentová, K., Stejskal, D., Bartek, J., Dvoracková, S., Kren, V., Ulrichová, J., Simánek, V., 2008. Maca (*Lepidium meyenii*) and yacon (*Smallanthus sonchifolius*) in combination with silymarin as food supplements: in *vivo* safety assessment. Food Chem. Toxicol. 46, 1006–1013.
Vasconcelos, C.M., Silva, C.O., Teixeira, L.J.Q., Chaves, J.B.P., Martino, H.S.D., 2010. Determination of the soluble dietary fiber fraction in yacon (*Smallanthus sonchifolius*) root and flour by enzymatic–gravimetric method and high pressure liquid chromatography. Revista Instituto Adolfo Lutz 69 (2), 188–193.
Vernon-Carter, E.J., Espinosa-Paredes, G., Beristain, C.I., Romero-Tehuitzil, H., 2001. Effect of foaming agents on the stability, rheological properties, drying kinetics and flavour retention of tamarindo foam-mats. Food Res. Int. 34, 587–598.
Wiecheteck, F.V., Nogueira, A., Drilleau, J.F., Wosiacki, G., 2005. Effect of cryoconcentration in total phenolic compounds of industrial apple must. Publicatio UEPG: Ciências Exatas e da Terra, Ciências Agrárias e Engenharias 11 (1), 27–34.
Yan, X., Suzuki, M., Ohnishi-Kameyama, M., Sada, Y., Nakanishi, T., Nagata, T., 1999. Extraction and identification of antioxidants in the roots of yacon (*Smallanthus sonchifolius*). J. Agric. Food Chem. 47, 4711–4713.