LWT - Food Science and Technology 66 (2016) 503–513

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

Effects of foam mat drying on physicochemical and microstructural properties of yacon juice powder

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ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form
3 November 2015
Accepted 4 November 2015
Available online 10 November 2015

Keywords:
Temperature
Thickness
Hygroscopicity
Color
Density
Solubility

ABSTRACT

Yacon juice powder can be used as a highly nutritious ingredient in several food preparations. To this purpose, factors such as moisture content, density, porosity and solubility should be optimized as they are determinant to the product's ease of reconstitution, stability and sensory quality. In this work, yacon juices with two different concentrations (8°Brix and 24°Brix), both added of egg albumin as foaming agent, were subjected to foam mat drying using different temperatures (50 °C, 60 °C and 70 °C) and thicknesses of the foam layer (0.5 cm, 1.0 cm and 1.5 cm). The resulting juice powders were assessed for color, moisture, chemical composition, water activity, solubility in water, water absorption rate, absolute and bulk densities, intragranular porosity, microstructure and hygroscopicity. The drying conditions did not affect solubility index, density, microstructure and porosity of the particles, however the temperature increase reduced moisture content, water activity and, consequently, hygroscopicity. The powders of concentrate juice resulted lighter and reddish respect to the non concentrate juices, which tended to green. The highest air temperature coupled with reduced thickness for both juices was found to be the best drying condition, yielding juice powders with low water activity and satisfactory physicochemical characteristics.

1. Introduction

The tuberous root of yacon, scientifically known as *Smallanthus sonchifolius* (Poepp. & Endl.) H. Rob., is native to the Andean foothills, where it is commonly cultivated and consumed since the time of the pre-Inca culture (Graefe, Hermann, Manrique, Golombek, & Buerkert, 2004). The global expansion of production and marketing of yacon was launched after studies reported several benefits to human health promoted by this tuber, such as the antioxidant activity associated to the phenolic compounds (Takaneka et al., 2003), reduction of blood glucose levels and prebiotic potential (Mentreddy, 2007; Valentová et al., 2008).

Another big draw is its low caloric value ascribed to its composition rich in water (above 70 g 100 g^{-1} of wet weight). However, the high moisture content and the presence of enzymes such as polyphenol oxidase and peroxidase render it a perishable food, hindering storage, distribution and transport (Shi, Zheng, & Zhao, 2013). Inasmuch as yacon is a seasonal crop, post harvest treatments such as drying are important to preserve its characteristics and make it available either for marketing for longer periods or for further processing (Scher, Rios, & Noreña, 2009).

The reduction of water activity attributed to the moisture removal is one of the most viable alternatives to extend this tuber's shelf life and also to add it value, increasing its market potential and availability (Yemmireddy, Chinnan, Kerr, & Hung, 2013). The foam mat drying (FMD) consists in the transformation of liquid or semi-liquid materials into a stable foam, by incorporation of air or other gases, which is subjected to drying with hot air to the extent that prevents microorganisms growth and development of chemical and/or enzymatic reactions (Falade, Adeyanju, & Uzo-Peters, 2003). It is a relatively simple and low cost method that relies on the use of agents capable of maintaining the foam stability during drying (Widyastutil & Srianta, 2011). Advantages of this method are the

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http://dx.doi.org/10.1016/j.lwt.2015.11.009
0023-6438/

lower drying temperatures and shorter drying time ascribed to the greater surface area exposed to air, allowing higher drying rates respect to other drying techniques to obtain easy rehydration porous particles (Kudra & Ratti, 2008).

In the context of FMD, parameters such as temperature, velocity and relative humidity of the drying air as well as layer thickness and composition of the foam are determining to the quality of the resulting powder, influencing its physicochemical properties, such as moisture content, bulk density, absolute density, particle porosity, solubility and dispensability, which play an important role in both reconstitution and stability of the product (Abadio, Domingues, Borges, & Oliveira, 2004; Kadam et al., 2011).

There are few studies reporting the influence of drying conditions on the physicochemical properties and microstructure of food powders obtained by FMD, thus the main objective of this study was to evaluate the influence of drying air temperature, foam layer thickness and concentration of soluble solids of the yacon juice on color, chemical composition, water activity, solubility, water absorption index, bulk and absolute densities, intragranular porosity, microstructure and hygroscopicity of the juice powders.

2. Materials and methods

2.1. Preparation of the yacon juice

Yacon juice was obtained from processing tuberous roots of yacon purchased in the municipal market of Curitiba, Brazil, in a food centrifuge after being washed and peeled. Immediately after processing, the juice was added of sodium metabisulfite (0.3 g L^{-1} juice) (Maia, Monteiro, & Guimarães, 2001) in order to limit the enzymatic activity. The total soluble solids (TSS) was measured with the aid of 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 on the foam characteristics, part of the juice was freeze concentrated using the modified methodology of Wiecheteck, Nogueira, Drilleau, and Wosiacki (2005), and then was stored under the same conditions presented to the non concentrate juice. The total soluble solids content was 8°Brix and 24°Brix for the yacon juice (YJ) and concentrate yacon juice (CYJ), respectively.

2.2. Preparation and drying of the foams

Foams of YJ and CYJ were obtained with the addition of 200 g of egg albumin per L of juice (Cami, Mizumoto Alimentos Ltda, Guapirama, Paraná, Brazil). After complete homogenization, the solution was incorporated of air by stirring it in a domestic mixer (360 W) at maximum speed for 20 min. The conditions for preparing the foams were obtained in a previous research conducted by these authors (Franco, Ellendersen, Fattori, Granato, and Masson, 2015).

After stirring, the foams were placed in metal beds, not drilled, with thicknesses of 0.5, 1.0 and 1.5 cm, and then forwarded to dehydration in a convective oven (Fabbe-Primar, São Paulo, Brazil) under controlled temperature (50, 60 and 70 °C) and constant air speed (4 m/s), as measured by an anemometer (Testo 405, Testo AG, Lenzkirch, Germany). The moisture loss was determined by weighing the samples every 15 min with an electronic scale until obtaining equal masses in three consecutive weightings (Franco, Perussello, Ellendersen, and Masson, 2015).

The dry foams were then removed from the drying beds, crushed with the aid of a mortar and pestle and then sieved so that the particles were standardized between 250 and 500 μm to carry out further analysis (Barbosa-Cánovas, Ortega-Rivas, Juliano, & Yan, 2005). The crushed samples were packed in polyethylene bags, subjected to vacuum and stored in a home freezer (−6 °C) until use.

2.3. Analysis of the dried juice

2.3.1. Physicochemical characterization

Water activity was assessed by direct measurement in hygrometer (Aqualab, Pullman, United States) according to the manufacturer's specifications.

Color was determined by direct reading with a colourimeter (Color Quest II, Hunter Lab, Reston, United States) according to the international CIE (International Commission on Illumination) color coordinates L*, a* and b*: L* represents brightness, ranging from white (100) to black (0), a* represents the tones between green (−a*) and red (+a*), and b*, between blue (−b*) and yellow (+b*).

The chemical composition was measured using standard methods of analysis for fruit and vegetable products, according to AOAC (2000). Proteins were quantified by the Kjeldahl digestion (Method 930.02), lipids were analyzed by continuous extraction in a Soxhlet-type apparatus (Method 920.39), ashes were determined by incineration in a muffle furnace at 550 °C, and moisture content was assessed by gravimetric analysis in oven set at 105 °C (Method 966.02). Total carbohydrates were calculated by difference.

2.3.2. Physical properties

In order to evaluate the influence of the drying conditions on the dried juice's quality, analyses were conducted on several physical properties of the powders.

2.3.2.1. Solubility in water. Samples of 1 g of powder were diluted by adding 100 mL of distilled water under stirring for 5 min. The solutions were then centrifuged at 3000 g-force for 5 min and 20.0 mL aliquots of the supernatant were transferred to preweighed filters and dried in oven at 105 °C. The weight of dried powder in the filters was used to determine the solubility in water (g of water per 100 g of powder) (Falade and Okocha, 2010).

2.3.2.2. Water absorption index. The water absorption capacity was determined by the method of Sharma Gujral, and Rosell (2011) adapted. A sample of 12.5 g was introduced in a centrifuge with 15 mL of water. After stirring for 30 min, the solution was centrifuged at 3000 g-force for 10 min. The supernatant liquid was collected in a tared filter and placed in oven at 105 °C for 24 h, then the hydrated powder remaining in the centrifuge tube was weighed. The water absorption index (WAI) was determined from the residue of the supernatant evaporation according to Equation (1).

$$WAI = \frac{m_{rc}}{m_a - m_{re}} \quad (1)$$

where m_{rc} is the mass of the residue centrifugation (g), m_a is the sample's mass (g) and m_{re} is the mass of the residue evaporation (g).

2.3.2.3. Bulk density. The bulk density (ρ_a) of the particles was measured according to the methodology of Goula and Adamapoulos (2008) adapted. Approximately 5 g of the powder was discharged in a 25 mL measuring cylinder (1 mL scale). The beaker and its content were agitated manually by repeated vertical movements to a height of 14 cm ± 2 cm until there was no difference in the powder volume. The bulk density was then calculated by the ratio between the known powder's mass (±5 g) and the volume displayed in the tube (Equation (2)).

$$\rho_b = \frac{m_s}{v_s} \quad (2)$$

where ρ_b is the bulk density (g cm^{-3}), m_s is the solid's mass (g) and v_s is the volume occupied by the solid (cm^3).

2.3.2.4. Absolute density. The absolute density (ρ_{abs}) of the yacon juice particles was calculated by the method of Caparino et al. (2012) adapted. Approximately 2.5 g of the powder were placed in an empty cylinder and the total volume was filled with a controlled amount of toluene (used for its ability to penetrate pores extremely connected to the material's surface without dissolving it). The absolute density was then calculated from Equation (3).

$$\rho_{abs} = \frac{m_s}{v_t} \quad (3)$$

where ρ_{abs} is the absolute density (g cm^{-3}), m_s is the solid's mass (g) and v_t is the toluene's volume (cm^3).

2.3.2.5. Intragranular porosity. The intragranular porosity (ε) was determined by the ration between the particle's absolute density and bulk density using Equation (4) (Caparino et al., 2012).

$$\varepsilon = 1 - \frac{\rho_a}{\rho_p} \quad (4)$$

where ε is the intragranular porosity of the powdered juice, ρ_a its bulk density (g cm^{-3}) and ρ_{abs} its absolute density (g cm^{-3}).

2.3.2.6. Hygroscopicity. Hygroscopicity was determined according to the methodology proposed by Tonon, Brabet, and Hubinger (2008), with some modifications. Approximately 10 g of powdered juice samples were set in open containers and then triplicates of each sample were placed in three different desiccators containing aqueous saturated solution of sodium chloride (approximately 75.5 g 100 g^{-1} moisture content), which were stored for 7 days in BOD ovens at 25 °C.

The hygroscopicity (HG) of the juice powders was calculated basing on the mass of water (g) adsorbed per 100 g of dry matter (g 100 g^{-1}):

$$HG = \frac{\Delta m/(m + m_1)}{1 + (\Delta m/m)} \quad (5)$$

where Δm corresponds to the increasing of powder's weight after reaching equilibrium (g), m is the powder's initial mass (g) and m_1 is the free water content of the powder before being exposed to air's humidity (g 100 g^{-1}).

2.3.2.7. Microstructure. The particles' morphology was assessed by scanning electron microscopy (SEM). The powders were set on copper supports with double-sided tape, were vacuum metalized with gold particles and then visualized with a scanning electron microscope (Vega3 LMU, Tescan Orsay Holding, Brno, Czech Republic) operating at a controlled pressure of 15 kV. Micrographs were photographed at magnifications of 250 and 1300 times.

2.4. Statistical analysis

To estimate the effects of air temperature and layer thickness to be dehydrated on the drying behavior of YJ and CYJ foams, a 2^2 design in duplicate with four replicates at the central point was performed, totaling 32 experiments (16 experiments for each one of the foams). Each experimental analysis of microstructural and physicochemical characterization was conducted in triplicate.

The comparison of the average values between treatments was conducted by one-way ANOVA with Tukey test ($p < 0.05$). For evaluating the influence of the independent variables on the characteristics of the dried powder, the Response Surface Methodology (RSM) was applied when statistical differences were detected by the one-way variance analysis (ANOVA). The isolated effects of each factor, their linear interaction and their statistical significance were calculated. Equation (6) shows the relationship between the factors for each dependent variable:

$$E(y) = b_0 + b_1x_1 + b_2x_2 + b_3x_1\,x_2 \quad (6)$$

where b_0 is a constant, b_1 and b_2 are the regression coefficients that represent the isolated effects of factors and b_3 is the regression coefficient of the interaction between variables. Only regression coefficients that were significant when ANOVA was applied remained in the final model presented.

The statistical quality of the proposed models was assessed by the variability percentage explained by the multiple linear regression equation (R^2), the determination coefficient adjusted to the experimental data (R^2_{adj}) and the model's significance (p-value) (Granato, Grevink, Zielinski, Nunes, & van Ruth, 2014).

All statistical analyses were performed using the software Statistica 7.0 (StatSoft Inc. South America, Toulsa, United States).

3. Results and discussion

3.1. Physicochemical characteristics

The moisture content of the juice powders (Table 1) ranged from 6.58 g 100 g^{-1} (SY – 1.5 cm–50 °C) to 3.51 g 100 g^{-1} (SY – 0.5 cm–70 °C), values similar to those for low moisture commercial products like soluble coffee (from 4.18 to 5.25 g 100 g^{-1}) and tomato soup powder (3.4–4.0 g 100 g^{-1}), indicating a very low availability of water for the occurrence of chemical reactions and microbiological growth (Jaya & Das, 2004). Pereira, Barcelos, Pereira, and Ferreira (2013) produced juices with 8.09 g 100 g^{-1} of moisture content from grinded dehydrated slices of yacon after 96 h of drying at 55 °C, a period 16 times longer than that needed for drying a 1.5 cm layer of yacon juice at 50 °C, which generated powder particles with moisture content of 6.58 g 100 g^{-1}.

The moisture content of a food is strongly linked to its stability, however it cannot be related only to water content, but mainly to the availability of water to be used for chemical reactions (Lewicki, 2004). This parameter, known as water activity (Aw), is defined as the ratio between the water vapor pressure of the food and the vapor pressure of pure water at the same temperature (Berk, 2009). A decrease of Aw prevents from development of microorganisms, reduces the rate of enzymatic reactions and retards non-enzymatic browning (Belitz, Grosch, & Schieberle, 2009). All samples showed Aw below 0.25 (Table 1), values much lower than those of the foams (0.96–0.98), which is quite favorable to the stability of the juice powders since Aw rates between 0.2 and 0.3 minimize microbial proliferation and oxidative and enzymatic activity (Rao, Rizvi, & Datta, 2005).

The Aw determined for the yacon juice powders (Table 1) is in agreement with other studies involving FMD. For instance, guavira juice powders showed Aw in the range of 0.2–0.3 (Breda, Sanjinez-Argandoña, & Correia, 2012) and yogurt with egg albumin foams dried at 50, 60 and 70 °C resulted in Aw from 0.32 to 0.35 (Krasaekoopt & Bhatia, 2012).

The fixed mineral residue (or ash) is the inorganic material that remains after burning an organic matter sample, which is transformed into carbon dioxide, water and nitric oxide (Cecchi, 2009). Mineral elements are present in the form of oxides, sulfates,

Table 1
Physicochemical characteristics of yacon juice (YJ) and concentrate juice (CYJ) powders obtained by foam mat drying under different conditions.

Sample	Drying condition	Physicochemical characteristics					
		Moisture (g 100 g^{-1})	Aw	Ashes (g 100 g^{-1})	Proteins (g 100 g^{-1})	Fats (g 100 g^{-1})	Carbohydrates (g 100 g^{-1})
YJ	0.5 cm/50 °C	6.24 ± 0.16^a	0.19 ± 0.001^a	4.53 ± 0.11^a	47.72 ± 0.09^a	0.28 ± 0.01^a	41.23 ± 0.20^a
	1.5 cm/50 °C	6.58 ± 0.04^a	0.19 ± 0.001^a	4.37 ± 0.09^a	47.50 ± 0.29^a	0.25 ± 0.01^a	41.30 ± 0.25^a
	1.0 cm/60 °C	5.50 ± 0.03^d	0.15 ± 0.001^d	4.49 ± 0.09^a	48.20 ± 0.53^a	0.2 ± 0.01^a	41.63 ± 0.45^a
	0.5 cm/70 °C	3.51 ± 0.02^b	0.10 ± 0.001^b	5.08 ± 0.31^a	49.19 ± 0.23^a	0.27 ± 0.01^a	42.06 ± 0.52^a
	1.5 cm/70 °C	4.09 ± 0.05^c	0.12 ± 0.001^c	4.63 ± 0.13^a	49.49 ± 0.15^a	0.28 ± 0.01^a	41.51 ± 0.20^a
CYJ	0.5 cm/50 °C	4.91 ± 0.09^c	0.20 ± 0.001c	5.68 ± 0.06^a	29.37 ± 0.09^a	0.30 ± 0.01^a	59.74 ± 0.02^a
	1.5 cm/50 °C	6.19 ± 0.05^a	0.22 ± 0.001^a	5.38 ± 0.12^a	29.13 ± 0.55^a	0.28 ± 0.02^a	59.00 ± 0.62^a
	1.0 cm/60 °C	5.70 ± 0.07^b	0.21 ± 0.001^b	5.50 ± 0.14^a	30.29 ± 0.36^a	0.32 ± 0.02^a	58.19 ± 0.49^a
	0.5 cm/70 °C	4.11 ± 0.05^e	0.12 ± 0.001^e	5.67 ± 0.06^a	30.13 ± 0.61^a	0.27 ± 0.01^a	59.82 ± 0.55^a
	1.5 cm/70 °C	4.31 ± 0.14^d	0.17 ± 0.001^d	5.73 ± 0.05^a	31.03 ± 0.44^a	0.26 ± 0.01^a	58.69 ± 0.32^a

The results comprise means ± standard deviation. Each analysis was conducted three times and each experiment was composed of 4 replicates in the central point and two replicates in the levels −1 and +1 of the experimental design (see Section 2.4). For samples of the same juice, different letters in the same column indicate significative difference ($p < 0.05$) between treatments according to the Tukey test.

phosphates, silicates and chlorides, depending on the conditions of incineration and food composition (Campbell-Platt, 2009). Although the fixed mineral residue (FMR) indicates the mineral content in the sample, it does not necessarily represents the same composition than the mineral matter originally present in the food as there may be loss by evaporation or some interaction between the sample's constituents (Adolfo Lutz Institute, 2008). The samples of YJ and CYJ powders showed FMR ranging from 4.37 to 5.08 g 100 g^{-1} and 5.38 and 5.73 g 100 g^{-1}, respectively (Table 1). Fruits, vegetables and tubers have relatively high mineral content, and yacon is especially rich in calcium and phosphorus. However, it is important to consider that egg albumin, used as foaming agent, interfere in the FMR of the powders for their average FMR is 6.0 g 100 g^{-1} (information provided by the manufacturer).

Due to the need of adding egg albumin for forming the foam and maintaining its stability during drying, the juice powders showed significant protein contents (Table 1) that are not natural to yacon, whose average value is between 0.2 and 2.0 g 100 g^{-1} (Valentová & Ulrichová, 2003).

The low fat content of the dried samples was influenced by the composition of both yacon and egg albumin, which are low fat foods. The average fat content is 0.35 g 100 g^{-1} for egg albumin (information provided by the manufacturer) and between 0.1 and 0.3 g 100 g^{-1} for yacon (Valentová & Ulrichová, 2003), so it would not be possible that the blend of these two compounds resulted in a high lipid profile product.

Powders of CYJ showed higher concentrations of carbohydrates than those of YJ (Table 1), a variation ascribed to the different TSS between juice (8°Brix) and concentrate juice (24°Brix). Forasmuch as the carbohydrate content of yacon consists essentially of inulin and FOS (40–70 g 100 g^{-1}) (Delgado, Thomé, Gabriel, Tamashiro, & Pastore, 2012), it is important that the juice powders presents a high-carbohydrate profile as this may indicate the functionality the powders can play when consumed directly or as formulation ingredients. Nonetheless, the functionality of juice powders can only be confirmed from the determination of oligofructans, which indeed indicate the actual content of these compounds among total carbohydrates.

Results published by other researchers confirm the important role of FOS as main constituents of the yacon roots' carbohydrate fraction. Vasconcelos, Silva, Teixeira, Chaves, and Martino (2010) produced flour by convective drying yacon slices with 39.71 g 100 g^{-1} carbohydrates, 19.43 g 100 g^{-1} FOS and 9.84 g 100 g^{-1} inulin, Campos et al. (2012) used yacon extract with 63.7 g 100 g^{-1} of FOS as a substrate for fermentation by probiotic microorganisms, and Lago, Bernstein, Brandelli, and Noreña (2012) spray dried concentrate yacon juice containing 31.5 g 100 g^{-1} inulin.

The influence of drying conditions (thickness of the foam layer and air temperature) on the physicochemical characteristics of juice powders was evaluated by the response surface methodology. The variables did not exert significant effect on ashes, lipids, proteins and carbohydrates, but influenced Aw and moisture content.

Mathematical models that represent the effect of process parameters on water activity and moisture content (Table 2) were obtained by applying SRM. The models showed R^2 and R^2-adj greater than 0.75, that is, these models can account for over 75% of the responses variability. It is also noted that the lack of adjustment for all answers was not significant ($p > 0.05$) indicating that the models have adjusted well to the experimental data and can be used for predictive purposes.

As indicated by the equations obtained for the YJ powder (Table 2), thickness and temperature influenced Aw either isolatedly or interacting one to the other for x_1 is positive, x_2 is negative and $x_1.x_2$ is positive. This means that Aw decreases with a higher temperature and a less thick layer. As regard to moisture content, thickness did not affect the result, in opposition to temperature and the interaction between temperature and thickness. Thus, higher drying temperatures yielded juice powders with lower moisture content, and the interaction between temperature and thickness had minor influence on moisture content respect to temperature alone, given the lower value of the coefficient attributed to it (x_2).

For the YJC powders, an increase in temperature led to a reduction of Aw and the interaction between temperature and thickness did not influence Aw as strongly as temperature alone (Table 1). As regard to moisture content, only thickness and the interaction between thickness and temperature influenced the results: an increase in thickness increased moisture content.

The influence of drying air temperature on Aw was also verified by other authors (Lago et al., 2012; Reddy et al., 2014) for the use of higher temperatures imply a higher heat transfer rate, leading to increased evaporation of water from the product, resulting in powders with a lower Aw.

Temperature also influenced moisture content of dried powders of mango juices (Wilson, Dattatreya, Chadha, Grewal, & Sharma, 2014) and açaí (Tonon et al., 2008) since a temperature rise increases the driving force for evaporation of water as a consequence of the larger temperature gradient between product and drying air.

3.2. Physical properties

Some quality aspects require special attention during food dehydration as partial or complete compromise of the product quality may occur (Ratti, 2009). The parameters used to assess the

Table 2
Mathematical models for water activity and moisture content of yacon juice (YJ) and concentrate juice (CYJ) powders as a function of foam layer thickness (x_1) and temperature (x_2).

Parameter	Type of powder	Mathematical model	R^2	R^2-adjusted	p-value
Water activity	YJ	$y = 0.4245 + 0.0323x_1 - 0.0046x_2 + 0.0006x_1.x_2$	0.9964	0.9954	$p < 0.001$
	CYJ	$y = 0.3663 - 0.0036x_2 + 0.0006x_1.x_2$	0.8912	0.8738	$p < 0.001$
Moisture content	YJ	$y = 13.0001 - 0.1380x_2 + 0.0073x_1.x_2$	0.9739	0.9696	$p < 0.001$
	CYJ	$y = 4.3069 + 4.6025x_1 - 0.0644x_1.x_2$	0.8085	0.7769	$p < 0.001$

quality of a food product may be physical, chemical and biochemical, since the water removal during drying can affect food composition and structure (Van't Land, 2012). Some physical parameters are porosity, solubility, hydration capacity, while biochemical changes include loss of vitamins and proteins, browning reactions and degradation of nutraceutical compounds (Chen & Mujumdar, 2008).

Drying processes also cause changes in the microstructure and distribution of components, influencing reconstitution and mainly affecting their function as food ingredients and the way they can be added to other foods (Chen & Mujumdar, 2008).

3.2.1. Solubility in water, water absorption index and hygroscopicity percentage

Solubility is an important indicator of the powder's ability to remain homogeneously mixed with water, i.e., the stability of the mixture composed by particles dissolved in liquid. Presenting percentage solubility above 80 g 100 g^{-1}, the yacon juice powders were more soluble than mango juice powder obtained by FMD using egg albumin as foaming agent, which showed values between 51.83 and 66.65 g 100 g^{-1} (Wilson et al., 2014), but were less soluble than inulin crystals extracted from yam roots by the same technology, showing solubility between 100 and 98.61 g 100 g^{-1} (Harmayani, Winarti, & Nurismanto, 2011).

The solubility of the particulates produced with YJ and YCJ was not influenced by the variation in drying conditions (Table 3). Various works report similar trends: Mishra, Mishra, and Mahanta (2014) observed no interference of dehydration temperature on the solubility of atomized juice of amla (*Emblica officinalis*), Souza, Borges, Magalhães, Ricardo, and Azevedo (2008) found that drying conditions did not affect this property when working with tomato juice, as well as observed by Kha, Nguyen, and Roach (2010) for juice of gac (*Momordica cochinchinensis*). Probably there was no change in solubility because it is strongly affected by the foaming agent added (Yousefi, Emam-Djomeh, & Mousavi, 2011), a factor that has been maintained the same in all experiments.

The good solubility of the dried juice obtained in this study may be attributed to the significant amount of carbohydrates and proteins and low level of lipids in its composition (Mishra et al., 2014), as well as the low moisture content of the powders, since the lower the moisture content, less sticky is the final product, which has in addition a higher surface area available for contact with hydration water (Fazaeli, Emam-Djomeh, Ashtari, & Omid, 2012).

The water absorption index (WAI) relates to the amount of water the dry food is capable of absorbing and is directly related to its hydration capacity (Barbosa-Cánovas et al., 2005). During rehydration, the dried material, which is submerged in water or other aqueous medium, undergoes through multiple simultaneous physicochemical changes (moisture content, total solids content, porosity, volume, gelatinization and texture). Rehydration involves several processes which occur in parallel, including liquid soaking into the dry material, transport of liquid though the pores network and subsequent distribution within the solid matrix, causing swelling of the matrix and leaching of soluble solids to the medium (Ratti, 2009).

Water absorption is an important property for applications in meat products, bread and cakes, for high WAI values may help retain moisture within them, improving handling characteristics and preventing dryness during storage (Oliveira, Pirozi, Borges, Germani, & Fontes, 2009). In addition to the applications already mentioned, powdered products with high WAI are listed as ingredients adequate for rapid preparation of products given its ability to absorb large amounts of water even at low temperatures (Clerici & El-Dash, 2008).

The water absorption capacity of the YJ and CYJ powders varied from 148.76 to 181.08 and 118.15 to 150.87, respectively, indicating good rehydration capacity (Table 3). The somewhat higher hydration capacity of the YJ powders can be explained by its composition richer in protein respect to YCJ. Harmayani et al. (2011) observed that the WAI of inulin powder was affected by the foaming agent composition (egg albumin) given the number of free hydroxyls present on egg albumin, which are able to bind to water molecules from the surrounding medium.

Considering there was significant difference ($p < 0.5$) between responses of WAI, the SRM was applied for proper assessment of

Table 3
Physicochemical properties of yacon juice (YJ) and concentrate juice (CYJ) powders obtained by foam mat drying under different conditions.

Sample	Drying condition	Properties		
		Solubility in water(g 100 g^{-1})	Water absorption index	Hygroscopicity (g 100 g^{-1})
YJ	0.5 cm–50 °C	84.16 ± 0.40^a	181.08 ± 2.86^a	18.61 ± 0.34^c
	1.5 cm–50 °C	80.49 ± 0.13^a	170.94 ± 0.84^b	18.06 ± 0.11^c
	1.0 cm–60 °C	81.99 ± 1.48^a	162.18 ± 0.96^c	20.21 ± 0.01^b
	0.5 cm–70 °C	80.97 ± 0.40^a	150.52 ± 1.31^d	22.31 ± 0.08^a
	1.5 cm–70 °C	81.51 ± 1.27^a	148.76 ± 0.87^d	21.49 ± 0.18^a
CYJ	0.5 cm–50 °C	83.07 ± 0.13^a	150.87 ± 1.26^a	18.86 ± 0.27^b
	1.5 cm–50 °C	81.44 ± 0.20^a	152.69 ± 0.63^a	15.24 ± 0.04^c
	1.0 cm–60 °C	80.89 ± 0.32^a	139.40 ± 0.37^b	18.12 ± 0.12^b
	0.5 cm–70 °C	83.24 ± 0.24^a	118.15 ± 1.15^c	20.39 ± 0.09^a
	1.5 cm–70 °C	82.87 ± 0.51^a	118.90 ± 1.55^c	18.78 ± 0.26^b

The results comprise means ± standard deviation. Each analysis was conducted three times and each experiment was composed of 4 replicates in the central point and two replicates in the levels −1 and +1 of the experimental design (see Section 2.4). For samples of the same juice, different letters in the same column indicate significative difference ($p < 0.05$) between treatments according to the Tukey test.

Table 4
Mathematical models for water absorption index and hygroscopicity of yacon juice (YJ) and concentrate juice (CYJ) powders as a function of foam layer thickness (x_1) and temperature (x_2).

Parameter	Type of powder	Mathematical model	R^2	R^2-adjusted	p-value
Water absorption index	SY	$y = 272.9022 - 31.0816x_1 - 1.7376x_2 + 0.4189x_1.x_2$	0.9678	0.9590	$p < 0.001$
	SYC	$y = 235.7730 - 1.6629x_2 + 0.0005x_1.x_2$	0.9752	0.9733	$p < 0.001$
Hygroscopicity	SY	$y = 10.1282 - 0.6845x_1 + 0.1782x_2$	0.9743	0.9699	$p < 0.001$
	SYC	$y = 20.8998 - 9.9068x_1 + 0.1214x_1.x_2$	0.9721	0.9674	$p < 0.001$

the drying conditions' influence. The correspondent models are presented in Table 4. As these models could explain more than 96% of the responses variability (R^2>0.96) and showed good fitting to the experimental data ($p > 0.5$), they may be used for predictive purposes.

The increase in foam layer thickness (x_1) and drying temperature (x_2) reduced hydration capacity for the YJ powders (Table 4). With respect to the CYJ powders, in turn, only temperature caused a reduction in hydration capacity. Wilson et al. (2014) observed similar effect during FMD of mango pulp, for which there was a decrease in the water absorption rate when increasing drying temperature. This fact can be explained by the lower moisture content of powders processed at higher temperatures, forasmuch as higher moisture contents can contribute to the absorption of water, since the liquid penetrates the pores more easily, allowing a better moisture dispersion (Ghosal, Indira, & Bhatacharya, 2010).

Hygroscopicity is the ability of a food powder to absorb water from an environment with relative humidity higher than the equilibrium moisture content and it is linked to their physical, chemical and microbiological stability. The knowledge of the hygroscopic behavior of these products is essential mainly when it comes to establish drying, packaging and storage conditions (Oliveira, Clemente, & Costa, 2014).

The YJ powders showed hygroscopicity values from 18.06 (thickness 1.5 cm and drying temperature 50 °C) to 22.31 g 100 g^{-1} (0.5 cm and 70 °C). In turn, the CYJ powders ranged from 15.24 to 20.39 g 100 g^{-1} in the same conditions of thickness and temperature.

Our results are far above those outlined by Jaya and Das (2004) as ideal for instant products, between 5.13 g 100 g^{-1} (instant coffee) and 9.38 g 100 g^{-1} (tomato soup instant powder). The high values obtained are ascribed to the chemical nature of the product. It is known that in foods such as powdered fruit juices (sucrose, glucose and fructose) sugars are the main responsible for water absorption due to the ability of hydroxyl groups to form hydrogen bonds with water molecules (Jaya & Das, 2004). Regarding to the yacon juices produced in the current work, the structure of egg albumin must be considered for its polar conformation increases the capacity of the powder to attract water molecules when in contact with surrounding air.

Another factor that must be considered is that most juice powders are produced by spray-drying and added of maltodextrin, a compound with low hygroscopicity applied as a carrier agent to prevent agglomeration of particles (Tonon et al., 2008). This feature is regarded in the work of Caparino et al. (2012), which demonstrated the effects of different drying methods on the physical properties and microstructure of mango puree powders. According to the authors, the lowest hygroscopicity ascribed to the spray-dried powder (16.5 ± 0.06 g 100 g^{-1}) is a consequence of the addition of maltodextrin, which was not used in the other dehydration methods, drum drying (20.1 ± 0.88 g 100 g^{-1}), lyophilization (18.0 ± 0.19 g 100 g^{-1}) and refractive window drying (18.0 ± 0.36 g 100 g^{-1}).

In a study comparing different drying methods applied to apple purees, Jakubczyk, Gondek, and Tambor (2011) obtained a product with 17 g 100 g^{-1} hygroscopicity by convective dehydration, 19 g 100 g^{-1} by lyophilization, 14 g 100 g^{-1} when 6% maltodextrin was added to the foam to be lyophilized and 11 g 100 g^{-1} when the concentration of maltodextrin was increased to 15%, suggesting again the maltodextrin's ability to decrease water absorption for powdered foods.

RSM was also applied to evaluate the effects of drying conditions on hygroscopicity. The models obtained (Table 4) could explain more than 97% of the variability of responses and showed good fitting to the experimental data ($p > 0.05$), hence can be used for predictive purposes. The increase in thickness of the foam layer (x_1) caused a reduction of hygroscopicity, while drying temperature (x_2) increased this response. The influence of temperature is in agreement with the results found by Tonon et al. (2008) and Frascareli, Silva, Tonon, and Hubinger (2012) on drying of tomato pulp, açaí juice and coffee oil, respectively, but contradicts the studies of Moreira et al. (2009) on dehydration of acerola juice and Mishra et al. (2014) on amla juice. For the CYJ powders, the increase in thickness of the foam layer caused a stronger reduction in

Table 5
Physical properties of yacon juice (YJ) and concentrate juice (CYJ) powders obtained by foam mat drying under different conditions.

Type of powder	Drying conditions	Properties		
		Apparent density (g cm^{-3})	Absolute density (g cm^{-3})	Intragranular porosity
YJ	0.5 cm–50 °C	0.69 ± 0.01^a	1.18 ± 0.01^a	0.413 ± 0.002^a
	1.5 cm–50 °C	0.67 ± 0.02^a	1.20 ± 0.01^a	0.442 ± 0.011^a
	1.0 cm–60 °C	0.66 ± 0.01^a	1.20 ± 0.001^a	0.445 ± 0.008^a
	0.5 cm–70 °C	0.65 ± 0.01^a	1.20 ± 0.01^a	0.461 ± 0.004^a
	1.5 cm–70 °C	0.65 ± 0.01^a	1.19 ± 0.01^a	0.450 ± 0.002^a
CYJ	0.5 cm–50 °C	0.50 ± 0.01^a	1.21 ± 0.01^a	0.588 ± 0.001^a
	1.5 cm–50 °C	0.47 ± 0.01^a	1.21 ± 0.01^a	0.606 ± 0.003^a
	1.0 cm–60 °C	0.51 ± 0.01^a	1.20 ± 0.01^a	0.577 ± 0.001^a
	0.5 cm–70 °C	0.52 ± 0.01^a	1.20 ± 0.01^a	0.567 ± 0.003^a
	1.5 cm–70 °C	0.51 ± 0.01^a	1.19 ± 0.01^a	0.567 ± 0.003^a

The results comprise means ± standard deviation. Each analysis was conducted three times and each experiment was composed of 4 replicates in the central point and two replicates in the levels −1 and +1 of the experimental design (see Section 2.4). For samples of the same juice, different letters in the same column indicate significative difference ($p < 0.05$) between treatments according to the Tukey test.

Table 6
Color coordinates of yacon juice (YJ) and concentrate juice (CYJ) powders obtained by foam mat drying under different conditions.

Type of powder	Drying conditions	Color coordinates		
		L*	a*	b*
YJ	0.5 cm–50 °C	77.88 ± 0.01[b]	−1.89 ± 0.01[b]	45.86 ± 0.05[e]
	1.5 cm–50 °C	77.75 ± 0.01[b]	−1.16 ± 0.01[e]	47.97 ± 0.03[d]
	1.0 cm–60 °C	77.69 ± 0.01[b]	−2.23 ± 0.02[a]	54.99 ± 0.01[a]
	0.5 cm–70 °C	78.60 ± 0.02[a]	−1.59 ± 0.01[c]	49.04 ± 0.04[c]
	1.5 cm–70 °C	75.91 ± 0.02[c]	−1.31 ± 0.02[d]	50.65 ± 0.09[b]
CYJ	0.5 cm–50 °C	82.99 ± 0.01[b]	0.54 ± 0.01[e]	26.51 ± 0.01[d]
	1.5 cm–50 °C	83.12 ± 0.01[a]	1.30 ± 0.01[d]	22.57 ± 0.01[e]
	1.0 cm–60 °C	79.09 ± 0.01[c]	3.09 ± 0.01[b]	31.23 ± 0.01[b]
	0.5 cm–70 °C	72.19 ± 0.05[d]	1.45 ± 0.01[c]	27.80 ± 0.02[c]
	1.5 cm–70 °C	62.60 ± 0.03[e]	14.72 ± 0.02[a]	41.87 ± 0.07[a]

The results comprise means ± standard deviation. Each analysis was conducted three times and each experiment was composed of 4 replicates in the central point and two replicates in the levels −1 and +1 of the experimental design (see Section 2.4). For samples of the same juice, different letters in the same column indicate significative difference ($p < 0.05$) according to the tests of Tukey and t-Student.

hygroscopicity (highest coefficient) than the interaction between the two factors, which caused a slight increase.

The low hygroscopicity found at low temperatures and higher thicknesses can be explained by the fact that powders obtained under these conditions have higher moisture content and, as a consequence, lower moisture gradient between product and ambient.

Regarding the quality parameters of food powders, lower values of hygroscopicity, water content and water activity, and greater solubility and water absorption index are desirable characteristics for them to be used in food formulations due to the storage stability (Bakar, Muhammad, Hashim, & Adzahan, 2013).

Predominantly, all powders had satisfactory characteristics. The combination of thinner layers of foam with higher drying temperatures allowed the production of yacon juice powders with low moisture content and water activity, increasing their storage stability. All particulates were soluble in water (above 80%), factor that was not influenced by the drying conditions, and also showed good rates of water absorption, especially those dried at higher temperatures. Regarding the hygroscopicity, the particles had characteristics similar to those of many fruit juices powders. Drying temperature exerted greater influence on hygroscopicity respect to layer thickness.

3.2.2. Bulk density, absolute density and intragranular porosity

Physical low cost determinations such as bulk and absolute densities are useful to predict the quality of particulates (Shishir, Taip, Aziz, & Talib, 2014). Bulk density is a factor directly correlated with the ease of reconstitution, packaging, transportation and marketing of powdered foods (Marques, Borges, Mendonça, Fernandes, & Menezes, 2014). A dehydrated product with a high bulk density can be stored in smaller containers than low density products.

Bulk density varied between 0.65 and 0.69 g 100 g^{-1} for the yacon juice powder and between 0.47 and 0.52 g 100 g^{-1} for the concentrate juice powder. Absolute density ranged from 1.18 to 1.20 g 100 g^{-1} and from 1.19 to 1.21 g 100 g^{-1} for the YJ and CYJ powders. Similar results were found by Oguntunde and Adeojo (1992) for the foam mat drying of whole milk and by Falade and Omojola (2010) for the dehydration of okra foams.

The large reduction in bulk density compared to absolute density may be related to the air incorporated to the juice during preparation of the foams. Similar behavior was reported by Jakubczyk et al. (2011) for apple juice powder obtained by FMD, resulting in bulk and absolute densities of 0.54 and 1.43 g 100 g^{-1}, respectively.

The powder samples of YJ showed the highest values for bulk

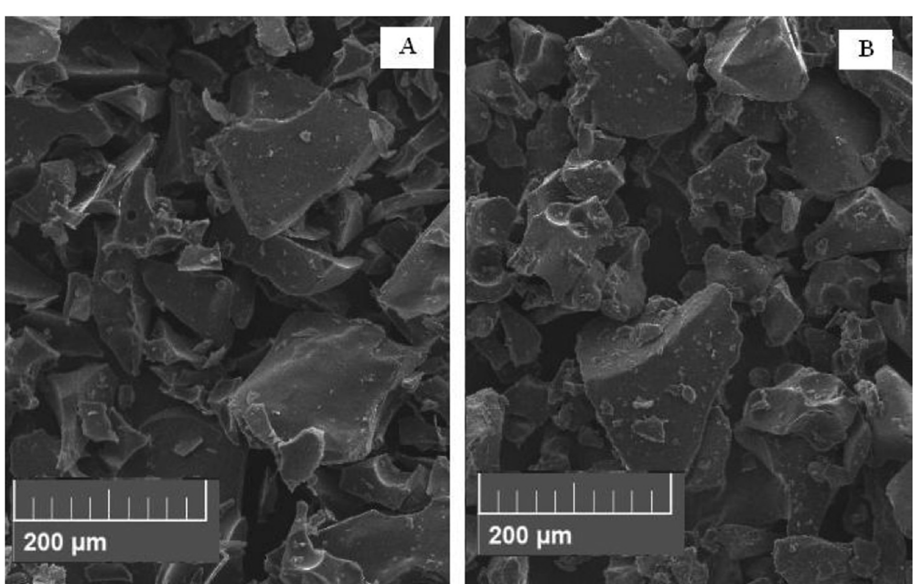

Fig. 1. Scan electron microscopy of powder particles of (A) yacon juice (YJ) and (B) yacon concentrate juice (YCJ) foam mat dried (width 1.0 cm and temperature 60 °C).

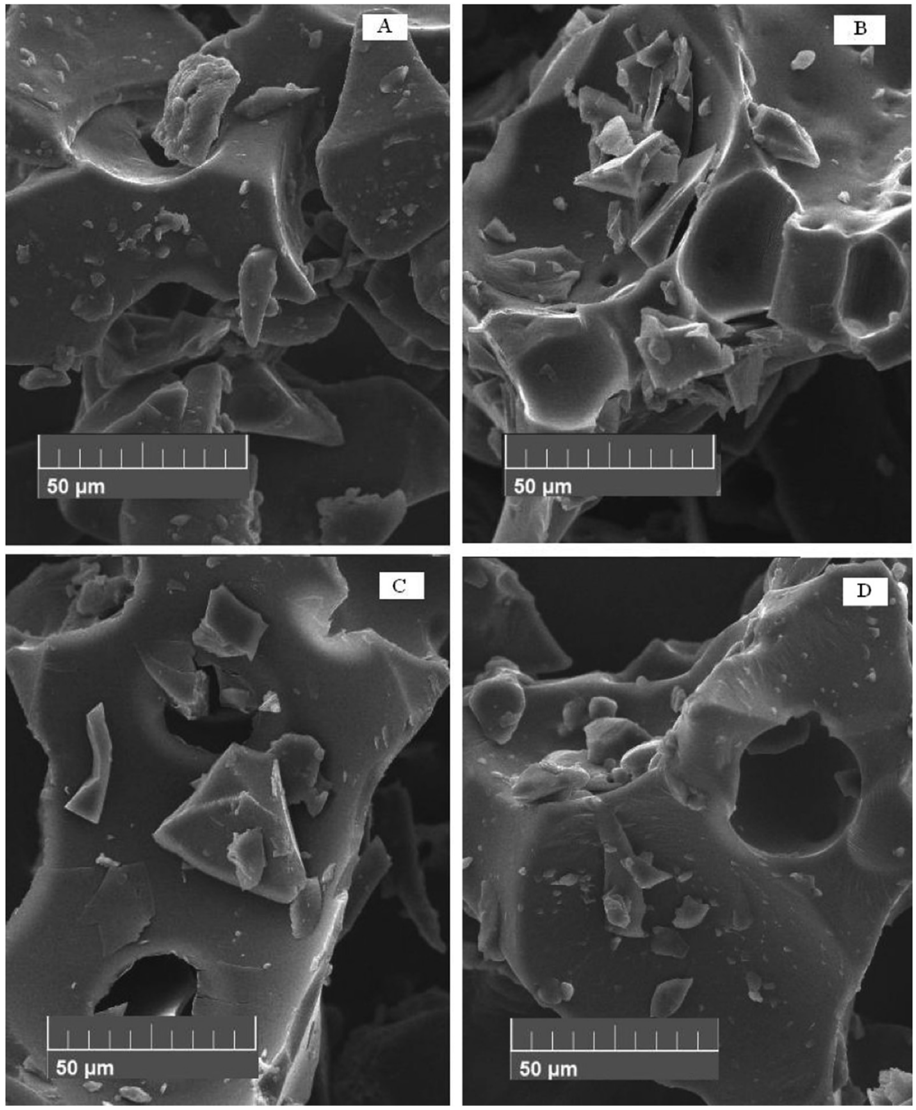

Fig. 2. Scan electron microscopy of powder particles of yacon juice (YJ) and yacon concentrate juice (YCJ) foam mat dried at different conditions: (A) YJ, 0.5 cm and 50 °C; (B) YJ, 1.5 cm and 70 °C; (C) YCJ, 0.5 cm and 50 °C; and (D) YCJ, 1.5 cm and 70 °C).

density. Although all samples are composed of yacon juice and egg albumin, the slight difference on the physicochemical characterization (Table 1) reflected on density. The higher density of the YJ powders in comparison to the CYJ powders can be related to their higher percentage of proteins respect to carbohydrates, as proteins have higher molecular weight (Nelson & Cox, 2004). Such behavior was also observed by Martin (2013) during spray drying of cupuaçu pulp.

The drying conditions did not influence significantly ($p < 0.05$) on density for both powders (YJ and CYJ) (Table 5). This behavior differs from other studies (Fazaeli et al., 2012; Reddy et al., 2014) where higher dehydration temperatures decreased the particles' bulk density. In the current work, however, drying temperature ranges from 50 to 70 °C and higher temperatures (above 100 °C) are required so that evaporation rates are increased to the point where the removal of water causes structural breakage and fragmentation, resulting in lower density powders (Walton, 2000).

Porosity, which indicates the volume fraction of voids in a material, is an important property for particulate materials because a great number of voids implies the presence of higher amount of oxygen that may cause a fast material degradation (Ratti, 2009).

The porosity for the YJ and CYJ powders ranged between 0.413 and 0.461 and between 0.567 and 0.606, respectively, and was affected by the drying conditions employed. Very similar values were reported by Caparino et al. (2012) for the freeze drying (0.43–0.52) and spray drying (0.47) of mango juice and by Souza et al. (2009) for spray dried tomato pulp (0.5–0.59), but smaller rates were found by Jinapong, Suphantharika, and Jamnong (2008) for atomized soybean soluble extract (between 0.70 and 0.74).

The intragranular porosity is inversely proportional to density, indicating that incorporation of air into the foam induced accumulation of air within the dried particles, making them more porous and less dense (Goula & Adamapoulos, 2008).

3.2.3. Color

Color is one of the most important parameters in foods because it reflects their sensory attractiveness and quality. Color is influenced by many factors, including the variety of the fruit, its ripeness and mainly the impact of drying processes (Viuda-Martos et al., 2012). During dehydration, fruit pulps are subjected to high temperatures that cause enzymatic and non-enzymatic browning (Maillard reactions) and become dark at the end of the process

(Damodaran, Parkin, & Fennema, 2010).

Lightness (L^*) in foods is related to several factors, such as concentration and type of pigments present, water content and concentration of water on the surface (Viuda-Martos et al., 2012). The juice powders showed L^* of 75.91–78.60 for YJ and 62.60–83.12 for CYJ, and the results were influenced ($p < 0.05$) by the drying conditions (Table 6). Almost all YJ powders were a little less bright than the CYJ ones, which can be attributed to the drying time slightly longer needed to dry the YJ foams. Reis, Lenzi, and Masson (2012) found the same behavior during drying of yacon slices in vacuum oven: L^* decreased as drying time increased. However, all samples obtained in this work can be considered light, since within a brightness scale from 0 to 100 these exhibited $L^* > 50$ (Vasconcelos, Minim, & Chaves, 2012).

With regard to the a^* coordinate (from green to red), the powders of YJ exhibited negative coefficients of −2.23 to −1.16, representing a green tone, while the particulates of CYJ tended to red (positive coefficients), with values between 0.54 and 14.72. The drying conditions (layer thickness and air temperature) significantly influenced on the quality responses (Table 6). The sharp difference found between concentrate and non concentrate juices may have been caused by their concentration, as this coordinate is affected by the structural integrity of the food fibers, amount of pigments present and their solubility (hydro or liposoluble) (Fernandéz-López, Zhi, Aleson-Carbonell, Pérez-Alvarez, & Kuri, 2005).

The drying conditions also affected the yellow – blue coordinate (b^*), with results corresponding to yellow for all samples: b^* ranged from 45.86 to 54.99 for the YJ powders and between 22.57 and 41.87 for the CYJ ones. The yellow tone may be ascribed to the presence of carotenoids in the roots of yacon.

3.2.4. Microstructure

Through evaluation of the food microstructure, it is possible to assess details of each component (water, starch, carbohydrates, lipids, sugars, proteins, lipids and salts) at microscopic level and their connections inside the cell at molecular level. As a food undergoes various treatments or processes, its microstructure can be preserved or destroyed for the development of new products (Ratti, 2009).

The scanning electron microscopy revealed data on the morphological and structural characteristics of powders of YJ and CYJ. In general, the particle morphology was not affected by the juice concentration or the drying conditions applied: they all presented a porous and irregular structure similar to freeze-dried mango juice (Caparino et al., 2012), which maintained structure and shape without shrinking or collapsing (Fig. 1A and B).

Forasmuch as the juices were dried after the cells of the yacon roots' tissues were ruptured, visible changes were not observed as a result of dehydration, unlike reported by Bernstein and Noreña (2014), who observed changes to macroscopic (volume and format) and microscopic (wall and cell membranes) levels in the yacon slices caused by the treatments applied.

There was a lack of uniformity for all samples. However, the SEM photomicrographs indicate that all samples had cavities in their structure derived probably from the spaces left by the air bubbles contained in the yacon foams, which contributed to the porosity of the juice powders (Fig. 2).

4. Conclusions

The investigation of new attributes and/or new uses from raw materials is of great relevance, given their key impact on economy, society and environment. In fact, the better use of natural resources can contribute to fight world hunger, given the globalization of the food market.

Foam mat drying proved to be an efficient alternative for the processing of yacon juice, since it allowed the development of a product with appropriate features for pure consumption or addition as a food ingredient. Although several drying technologies have been applied to yacon in the literature, there is no paper regarding the FMD. The results obtained in this paper may expand the industrialization of yacon, aiding small producers and industries to develop new yacon-based products.

The drying conditions did not affect significantly the solubility in water, bulk density, absolute density and intragranular porosity of the particles, however the temperature rise reduced moisture content and water activity of the samples. The powders obtained from yacon juice showed greater capacity of water absorption respect to the concentrate juice, which was lower for higher temperatures and lower layer thicknesses. Hygroscopicity was also positively affected by temperature. Brightness decreased with drying time and the color coordinates a^* and b^* indicated colour difference between powders of YJ (reddish) and CYJ (yellowish). The images obtained by scanning electron microscopy indicated that the morphologic characteristics of the particulates were not affected by the drying conditions: all samples presented irregular morphology and cavities that contribute to porosity.

The combination between the higher drying temperature (70 °C) and the smallest thickness (0.5 cm) led to a shorter drying time and consequent lower energy demand to produce a powdered yacon juice with high stability (low moisture content and water activity). These process conditions did not affect the physical and chemical characteristics of the final product.

Acknowledgments

The authors would like to thank CAPES – Coordination for the Improvement of Higher Education Personnel – for the financial support.

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