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Microwave-vacuum drying of pulsed vacuum osmotic dehydration-pretreated Yacon as an alternative for preserving fructo-oligosaccharides

Secagem por microondas a vácuo de Yacon pré-tratado por desidratação osmótica pulsada como alternativa de preservação de fruto-oligosacarídeos

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ABSTRACT

Yacon, a perennial plant from the Andean region, is particularly rich in fructo-oligosaccharides (FOS) and inulin. However, these saccharides are rapidly hydrolyzed after harvest, affecting the functional characteristics of yacon. Therefore, a preservation technology such as drying is warranted to preserve the FOS content of yacon products during the off-season. To this end, we dried yacon slices, either untreated or pretreated with pulsed vacuum osmotic dehydration (PVOD), in a microwave vacuum (MWV). PVOD was performed using a sorbitol solution (38 °Brix, 35 °C, and 681 mmHg during the first 10 min). A three-level experimental design with three initial power densities (PDs) of 3.6, 6.3, and 9.9 W.g^{-1} and three vacuum pressures (VPs) of 0, 300, and 600 mmHg was employed to perform the MWV drying experiments. FOS content, drying kinetics, diffusivity, shrinkage, yacon temperature, and rehydration were investigated. We observed that during PVOD, as microwave PD increased, the drying time, moisture, and water activity decreased. Moreover, an increase in PD positively affected FOS retention, diffusivity, temperature, and shrinkage. Furthermore, VP significantly affected FOS retention in pretreated samples and facilitated drying. In addition, microwaves with a higher PD increased the effective diffusivity and facilitated FOS retention. VP also affected the drying and FOS retention of pretreated samples. In general, yacon browning was observed under all treatment conditions, independent of pretreatment. For osmotically dehydrated samples, processing conditions with a PD of 9.9 W.g^{-1} and vacuum pressure of 600 mmHg are ideal for drying yacon slices via microwave vacuum, thereby increasing the FOS content by approximately 40%.

Index terms: Pulsed vacuum osmotic dehydration; prebiotic; fructo-oligosaccharides; tubercle; fructans.

RESUMO

Yacon é uma planta perene da região andina que é uma fonte particularmente rica em fruto-oligossacarídeos (FOS) e inulina. Contudo, estes sacarídeos hidrolisam rapidamente após a colheita, afetando as características funcionais do yacon. Portanto, uma tecnologia de preservação como a secagem é necessária para preservar o teor de FOS dos produtos yacon durante o período de entressafra. Nesse sentido, fatias de yacon, não tratadas ou pré-tratadas com Desidratação Osmótica a Vácuo Pulsado (PVOD), foram secas em vácuo de micro-ondas (MWD). Para tanto, o PVOD foi realizado com solução de sorbitol (38 °Brix, 35 °C e 681 mmHg durante os primeiros 10 min). Os experimentos de MWD foram baseados em um projeto experimental de três níveis com três Densidades de Potência iniciais - PD (3,6, 6,3 e 9,9 W.g^{-1}) e três Pressões de Vácuo - VP (0, 300 e 600 mmHg). Também foram analisados os resultados de FOS, cinética de secagem, difusividade, retração, temperatura yacon e reidratação. Os resultados mostraram que o aumento da PD por micro-ondas reduziu o tempo de secagem, a umidade e a atividade de água com PVOD. Além disso, o aumento da PD teve uma influência positiva na retenção de FOS, difusividade, temperatura e retração. A pressão do vácuo também afetou significativamente a retenção de FOS nas amostras pré-tratadas e ajudou na secagem. Micro-ondas com maior densidade de potência aumentaram a difusividade efetiva e facilitaram a retenção de FOS. A pressão do vácuo também afetou a secagem e a retenção de FOS das amostras pré-tratadas. De modo geral, o escurecimento da yacon ocorreu em todos os tratamentos, independente do pré-tratamento. Condições de processamento com PD de 9,9 Wg^{-1} e pressão de vácuo de 600 mmHg para amostras osmoticamente desidratadas são ideais para secagem de fatias de yacon por micro-ondas-vácuo, aumentando o teor de FOS em até 40%.

Termos para indexação: DOVP; prebiótico; fructo-oligosaccharideos; tubérculo; frutanos.

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Introduction

Yacon (*Smallanthus sonchifolius*) is a perennial plant in the family *Asteraceae* that is present in the Andean region (Reis et al., 2021). It is particularly rich in fructo-oligosaccharides (FOS) and inulin. FOS are a type of prebiotic with a low caloric content and beneficial effects on health, decreasing blood lipids and glucose levels (Surana et al., 2022). However, these saccharides are rapidly hydrolyzed after harvest, affecting the functional characteristics of yacon. Furthermore, yacon is a seasonal plant; therefore, a preservation technology such as drying is warranted to maintain the FOS content of the product available during the off-season (Reis et al., 2021; Graefe et al., 2004).

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Microwave drying confers better energy usage, a shorter processing time, and a low exposure time of the food to high temperatures, yielding a product with superior quality (Nogueira et al., 2023; Koné et al., 2013). The combination of microwave drying with other techniques, including vacuum application, allows the incorporation of the advantages of the different techniques, minimizing the disadvantages and achieving better quality.

Microwave-vacuum (MWV) drying combines heat transfer via microwave and decreased pressure. Therefore, this technology can improve energy efficiency and product quality (Nogueira et al., 2023; Corrêa et al., 2011; Costa et al., 2021). Studies have revealed that MWV drying is suitable for drying temperature-sensitive products, including biopharmaceuticals (Alex et al., 2018) and bioactive compounds (Wojdyło, Figiel, & Oszmiański, 2009) such as FOS. Furthermore, this technology can decrease the phenomena of food browning and shrinkage, as observed by Liu et al. (2020).

Osmotic pretreatment is recommended not only to improve the quality of the dried product but also to decrease the drying time with microwaves (Corrêa et al., 2011; Macedo et al., 2021). In pulsed vacuum osmotic dehydration (PVOD), the system pressure is decreased at the beginning of the process. The vacuum applied to the product during PVOD results in hydrodynamic mechanisms. Furthermore, the vacuum applied during PVOD helps remove occluded gases in the intercellular spaces of vegetal tissues. Once the atmospheric pressure is restored, the pores are filled with the osmotic solution, thereby increasing the surface area for mass transfer (Abrahão & Corrêa, 2021; Carmo et al., 2022; Zhang et al., 2020; Pei et al., 2023).

However, both dehydration techniques, i.e., PVOD as a pretreatment method and MWV drying, have been independently researched; therefore, evaluating the effect of the simultaneous application of these techniques by studying their variables may be interesting. Liu et al. (2020) subjected cranberries to PVOD and microwave drying and achieved excellent results for their physicochemical properties.

Cuervo et al. (2018) have reported the considerable appeal of commercializing this approach internationally. However, studies on the application of these technologies for preserving and conserving yacon are lacking.

In this study, we elucidated the effects of power density, vacuum pressure, and PVOD pretreatment on preserving yacon quality via fructan retention, shrinkage, water activity, diffusivity, color, browning, drying kinetics, rehydration and the final drying time of dried yacon slices.

Material and Methods

Raw material

Tubers of yacon (*Smallanthus sonchifolius*) were obtained from a local market (Lavras, Minas Gerais state, Brazil). The roots were selected based on their maturation degree, mature roots, and uniformity of color and physical appearance. Furthermore, the absence of diseases, physical injuries, and fissures was considered. Owing to variations in fructan content after harvest (Graefe et al., 2004), the tubers were stored in a climate chamber maintained at 6.0 °C ±2.0 °C and with a relative humidity of 90.0% ±1.8% for a maximum of 5 days before conducting the dehydration experiments (Graefe et al., 2004).

The selected tubers were washed in running water and sterilized in a 200 mg L^{-1} sodium hypochlorite solution for 15 min (Carmo et al., 2021; Corrêa et al., 2014). The yacon roots were peeled, followed by cutting the samples into a parallelepiped shape using an electric slicer (Urano, USM1-320, 2010, Brazil) and a stainless-steel mold; the dimensions were as follows: 2.00 × 2.00 × 0.50 cm (length × width × thickness) (Figure 1). A digital caliper (Western, 150 mm-DC-60, China) was used to verify the dimensions of the slices. This geometry facilitated the use of diffusional models in a flat plate for predicting the drying rate and obtaining diffusivity coefficients (Corrêa et al., 2010).

Figure 1: Examples of the (a) yacon tuber and (b) samples used in the experiments.

To prevent enzymatic browning, the samples were dipped in a 1% citric acid solution at ambient temperature for one min (Mothibe et al., 2014).

Sample characterization

The moisture content, fructan content, number of soluble solids, water activity, and color of fresh and dried yacon samples were characterized.

The gravimetric method 934.06 Association of Official Agricultural Chemists - AOAC (2005) was used to measure the moisture content in a vacuum oven (pressure ≤ 100 mmHg) at 70 °C to constant weight. A water activity meter (Aqualab Decagon Devices Inc. Pullman, model CX-2T, Washington, EUA) was used to measure the water activity (a_w) at 25 °C. The sample was macerated until a homogeneous paste was formed; then, a potentiometer was used to directly measure the pH. A digital pH meter (Digimed model DMpH-2, São Paulo, Brazil) was used and calibrated using pH 4.0 and 7.0 solutions, according to the analytical norms of AOAC (2005).

A digital refractometer (Hanna, HI 96801, USA) was used to determine the soluble solid content of the samples. An electronic colorimeter (Minolta CR 400, Minolta Câmera Co. Ltd, Osaka, Japan) was used to determine the color of the samples at 25 °C, according to the standard L^* (lightness), a^* (red intensity), and b^* (intensity of yellow) values. The Hue angle (h°), which expresses the color tone measured with this equipment, and the Chroma value (C^*), which indicates the opacity or vividness of the color, ranging from zero to 60, were expressed using Equations 1 and 2. The total color difference (ΔE) was calculated using Equation 3; an index value of 0 indicates a fresh product (Liu et al., 2019).

$$°\mathrm{h} = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{1}$$

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{2}$$

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{3}$$

An enzymatic method (Method 997.03) (AOAC, 2005) was used to measure the fructan content. The data were evaluated considering fructan index degradation because of its assessment in fresh samples and dried samples.

Digital image analysis was performed to measure the sample volume. Pictures and sample weight were captured after the same drying time. The surface area of the samples was directly measured from the photographs using ImageJ® software (Igathinathane et al., 2008; Ishibashi et al., 2022). A caliper (Western, 150 mm-DC-60, China) was used to determine the arithmetical average of measurements at five different points on the sample to measure the thickness. Volume data were obtained by multiplying the image surface area by the average thickness of the material.

According to Equation 4, shrinkage (S) was calculated with respect to the volume of the dried sample (V) and its initial volume (V_0) (Liu et al., 2019).

$$S = 1 - \left(\frac{V}{V_0}\right) \tag{4}$$

Drying experiments

Yacon was subjected to MWV drying with and without PVOD pretreatment. The procedures are described below.

PVOD

PVOD experiments were conducted in a dehydrator comprising a 50-L jacketed stainless-steel chamber (A-240-304, Biasinox LTDA), with a minimum operating volume of 10 L accessed via the upper part. A thermostat coupled to the chamber was used to monitor the temperature, allowing a working temperature range of 5 °C–70 °C. A vacuum pump was attached to the system to conduct low-pressure processes.

An osmotic solution of 38 °Brix concentration was prepared using distilled water and commercial sorbitol (Singsino Group Ltd., China). The mass ratio of yacon and the solution was 1:10 (w/w). During the first 10 min of the process, osmotic dehydration was conducted at 35°C and a pressure of 681 mmHg. The total operation time was 300 min. The processing conditions were optimized in previous trials. After PVOD, the samples were immediately immersed in an ice bath for 10 s. Then, a paper towel was used to dry the sample surface to remove surface water. This procedure was used to stop dehydration and remove the excess osmotic solution from the sample surface (Corrêa et al., 2014).

MWV drying

A system comprising a domestic microwave oven, vacuum pump, vacuum trap, catheter tube, and polycarbonate sample holder (Figure 2) was used to perform the MWV drying experiments. The microwave oven (a) (Electrolux, MEC41 Inox, BMC38-A model, Manaus, Brazil) had a cavity volume of 31 L and a nominal maximum power of 1500 W. The polycarbonate sample holder (b) was adapted to the inside of the microwave cavity and was attached to a vacuum pump (c) via a catheter tube. To avoid damage to the vacuum pump, water vapor emerging because of drying was sequestered in a condenser (d) (vacuum trap) between the sample holder and vacuum pump. Furthermore, the sample holder was connected to an analytical balance (e) (OHAUS, ARC 120, China, 3000 ±0.001 g) that transmitted weight variations during the drying experiments to a computer (f). This facilitated continuous measurements of the sample weight during the MWV experiments.

In each experiment, a sample weighing approximately 27 g was used. An infrared thermometer (Fluke, Max 62 MAX, USA) was used to measure the surface temperature of the samples at 5–10 min intervals. The average final moisture content of the dried samples was 12.00% ±1.04% (w.b).

To avoid burning of the dried samples, the initial microwave power density (PD) and vacuum pressure (VP) used in the experiments were preliminarily tested. A three-level experimental design was employed to conduct the MWV drying experiments, with or without PVOD pretreatment (Table 1). Three initial PD levels (3.6, 6.3, and 9.9 $\mathrm{Wg^{-1}}$) and three VP levels (0, 300, and 600 mmHg) were used in the preliminary tests (Montgomery, 1991). Table 1 summarizes the conditions used for the treated and untreated samples, resulting in 18 tests. All assays were performed in triplicates of the central points. Fructan retention, shrinkage, rehydration capacity, color (ΔE, h°, C^*, L^*), and processing time were the dependent variables.

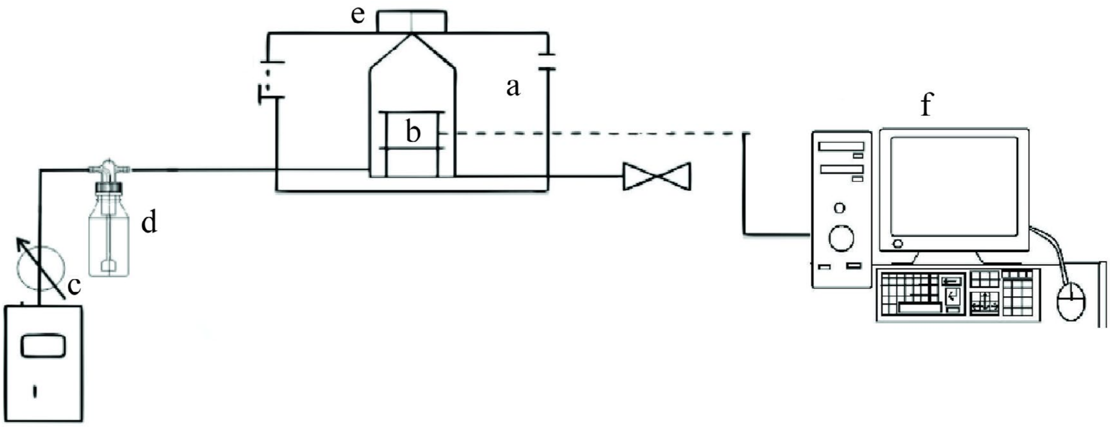

Figure 2: Experimental microwave-vacuum drying system.

Table 1: Experimental design for microwave vacuum drying of yacon.

Assay	Coded variables		Actual variables	
	X_1	X_2	PD [Wg^{-1}]	VP [mmHg]
1 (Without PVOD)	-1	-1	3.6	0*
2 (Without PVOD)	-1	0	3.6	300
3 (Without PVOD)	-1	1	3.6	600
4 (Without PVOD)	0	-1	6.3	0*
5 (Without PVOD)	0	0	6.3	300
6 (Without PVOD)	0	1	6.3	600
7 (Without PVOD)	1	-1	9.9	0*
8 (Without PVOD)	1	0	9.9	300
9 (Without PVOD)	1	1	9.9	600
1 (With PVOD)	-1	-1	3.6	0*
2 (With PVOD)	-1	0	3.6	300
3 (With PVOD)	-1	1	3.6	600
4 (With PVOD)	0	-1	6.3	0*
5 (With PVOD)	0	0	6.3	300
6 (With PVOD)	0	1	6.3	600
7 (With PVOD)	1	-1	9.9	0*
8 (With PVOD)	1	0	9.9	300
9 (With PVOD)	1	1	9.9	600

VP - vacuum pressure; PD - initial power density microwave.
*Vacuum pressure of 0 mmHg corresponds to local atmosphere pressure.

The "IMPI 2-Liter" test method was used to determine the power of the microwave oven, according to the method described by Soysal et al. (2009). The oven was switched on with a nominal voltage network, set at the highest power (100%), and loaded with 2000 ±5.0 g of water present in two 1 L beakers. First, the water was maintained at 20 °C. In the center of the oven, the water beakers were placed side by side across the width of the cavity and touching each other. The microwave oven was switched on for 2 min and 2 s. Thereafter, the beakers were immediately removed from the oven, followed by measuring and recording the final temperature. The microwave power was calculated, based on the method described by Alves and Petri (2021), using Equation 5. This procedure was performed five times.

$$P_m = \frac{mc_p\left(\Delta T_1 + \Delta T_2\right)}{2\Delta t} \tag{5}$$

P_m indicates the average power (W), ΔT_1 and ΔT_2 indicate the increases in water temperature in both beakers, m indicates the total mass of water (kg), c_p indicates the specific heat of water ($J\ kg^{-1}\ K^{-1}$), and Δt indicates time (s).

The oven was preheated by heating the 2 L of water for 5 min; then, the walls were wiped with a damp rag and allowed to cool. The water in each beaker was stirred before measuring the temperature.

Statistical analysis

Using Statistica 8.0 software, analysis of variance (ANOVA) was performed, with a 95% confidence level, to determine the regression coefficients and generate response surfaces. Higher fructan retention, lesser color change, lesser shrinkage, and shorter drying time were used to treat the three-level experimental design and establish the optimum conditions for the drying process. However, the condition that achieved the highest fructan content was considered the optimum.

Statistical reparametrized models were constructed to predict the best conditions. These models were selected because only significant variables were used. Silveira, Mazutti, and Salau

(2016) have reported the usefulness of reparametrized models as a mathematical tool for precisely and reliably performing modeling using fewer parameters, providing more degrees of freedom for statistical analysis and good precision of the results.

The experimental model was validated by performing MWV drying using statistically significant variables at their optimal concentration with the highest fructan retention; an average of three replicates were performed. The rehydration kinetics were determined under the optimal conditions.

Drying kinetics modeling

The drying kinetics were experimentally obtained from the changes in the moisture content with respect to time. The experimental curves were mathematically modeled using a model based on Fick's model (Equation 6). The model was based on a semi-infinite slab; therefore, the diffusion was limited by the smallest dimension; furthermore, it was unidirectional (Junqueira et al., 2022):

$$\frac{\partial M_{(t)}}{\partial t} = \frac{\partial}{\partial z}\left(D_{eff}\frac{\partial M_{(t)}}{\partial z}\right) \tag{6}$$

where $M(t)$ indicates the amount of water at time t, D_{eff} indicates the effective diffusivity, and z indicates the transfer direction.

The effective diffusivity of Fick's model is based on the changes in the moisture with respect to time and space. The sample thickness was $2L$, assuming that the diffusion in a drying process goes from the inside surface, $z = 0$ to the outer surfaces, $z = L$, and $z = -L$. $\left.\frac{\partial M(t)}{\partial t}\right|_{z=0} = 0$ indicates the symmetry of concentration, $M_{(z,0)} = M_0$ indicates the uniform initial amount of moisture, and $M_{(L,t)} = M_{eq}$ indicates the equilibrium moisture content at the material surface.

With these assumptions, Fick's unidirectional diffusion equation for a semi-infinite plate (Junqueira et al., 2022) was as follows in Equation 7:

$$MR = \left(\frac{M_t - M_{eq}}{M_0 - M_{eq}}\right) = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2}{4}\frac{D_{eff}t}{L^2}\right] \tag{7}$$

where D_{eff} indicates the effective diffusivity (m^2s^{-1}) of water, L indicates half the sample thickness (m), n indicates the number of terms (-), M_R indicates the moisture ratio (-), t indicates the drying time (s), M_t indicates the yacon moisture content at each moment (-), M_0 indicates the initial moisture content of the yacon (-), and M_e indicates the equilibrium moisture content (-). Diffusivity was calculated using an iterative method, with n tending to infinity.

The coefficient of determination (R^2), decreased chi-square (χ^2) value (Equation 8), and root mean square error (RMSE) (Equation 9) were used to evaluate the fit of the model (Liu et al., 2020).

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pred,i})^2}{n-N} \tag{8}$$

$$RSME = \left[\frac{1}{n}\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pred,i})^2\right]^{1/2} \tag{9}$$

where $M_{Rexp,i}$ and $M_{Rprev,i}$ indicate the experimental and predicted values, respectively, of the moisture ratio for observation i, n indicates the number of observations, and N indicates the number of parameters in the model.

It is assumed that the shrinkage observed during food drying is a function of the moisture content. The assumption of the linear dependence of the volume shrinkage on the moisture content has been successfully employed previously (Equation 10) (Bernstein & Norena, 2014; Ramallo & Mascheroni, 2013; Corrêa et al., 2012). Assuming that dimension L is a constant can lead to errors (Corrêa et al., 2012).

$$\frac{V}{V_0} = a + b\frac{X}{X_0} \tag{10}$$

V indicates the volume corresponding to the moisture content (m^3) and V_0 indicates the initial volume of the sample corresponding to the initial moisture content of the product (m^3). The terms a and b are the fitted parameters.

Assuming shrinkage in Fick's model, the thickness of the yacon slices (l) was used as the experimental value for each set of the measured data based on Equation 11 (Corrêa et al., 2012). Therefore, the effective diffusivity was obtained assuming sample shrinkage:

$$\frac{l}{l_0} = a + b\frac{X}{X_0} \tag{11}$$

Rehydration kinetics

In a 250 mL beaker, dried samples were immersed in 150 mL of distilled water (25 °C ±1°C). In the first 60 min, samples were weighed at intervals of 20 min and then after 30 min until constant weight was attained. At each weighing, the samples were placed on a paper towel to remove excess surface water. After completing the rehydration process, the moisture content of the samples was determined. The experimental results were expressed as moisture content on a dry weight basis.

Results and Discussion

Physical properties of yacon

For the fresh samples, the moisture, soluble solid content, water activity, and FOS were 91.7 ±0.34 g/100 g of sample, 6.50 ±0.10 °Brix, 0.990 ±0.001, and 63.26% ±1.38% of dry matter, respectively. The color parameters were as follows: a^* = 2.85 ±0.511, b^* = 13.34 ±1.311, L^* = 54.93 ±2.17, C^* = 13.64 ±1.37, and h° = 77.97 ±1.18. These results were consistent with those of Silveira et al. (2024), Corrêa et al. (2021), and Oliveira et al. (2021). On the other hand, for PVOD-treated samples, the moisture content, soluble solid content, water activity, and FOS were 69.42 ±0.04 g/100 g of sample, 10.20 ±0.25 °Brix, 0.976 ±0.001, and 61.11% ±0.42% of dry matter, respectively. The color parameters were as follows: a^* = −0.84 ±0.195, b^* = 13.00 ±0.179, L^* = 49.11 ±0.57, C^* = 13.03 ±0.186, and h° = 93.83 ±1.046 in osmotically dehydrated samples.

We compared the properties of fresh and treated yacon and observed that PVOD decreased the humidity by 24.3%; subsequently, the water activity decreased. However, the soluble solid content increased by 56.9%. This indicates that PVOD causes water loss and solid incorporation in yacon; similar findings were reported by Liu et al. (2020). Furthermore, FOS decreased by 3.4%, suggesting that along with the removal of soluble solids, fructans also exited.

MWV drying

Drying kinetics

Figures 3A, B, and C illustrate the drying kinetics for untreated yacon samples, whereas Figures 3D, E, and F illustrate the drying kinetics for treated samples. Under all conditions, the moisture content of yacon decreased with drying time. Evidently, at any pressure, the moisture ratio decreased with PD. Similarly, Assawarachan and Noomhorm (2011) observed that PD shortened the evaporation time of concentrated pineapple juice.

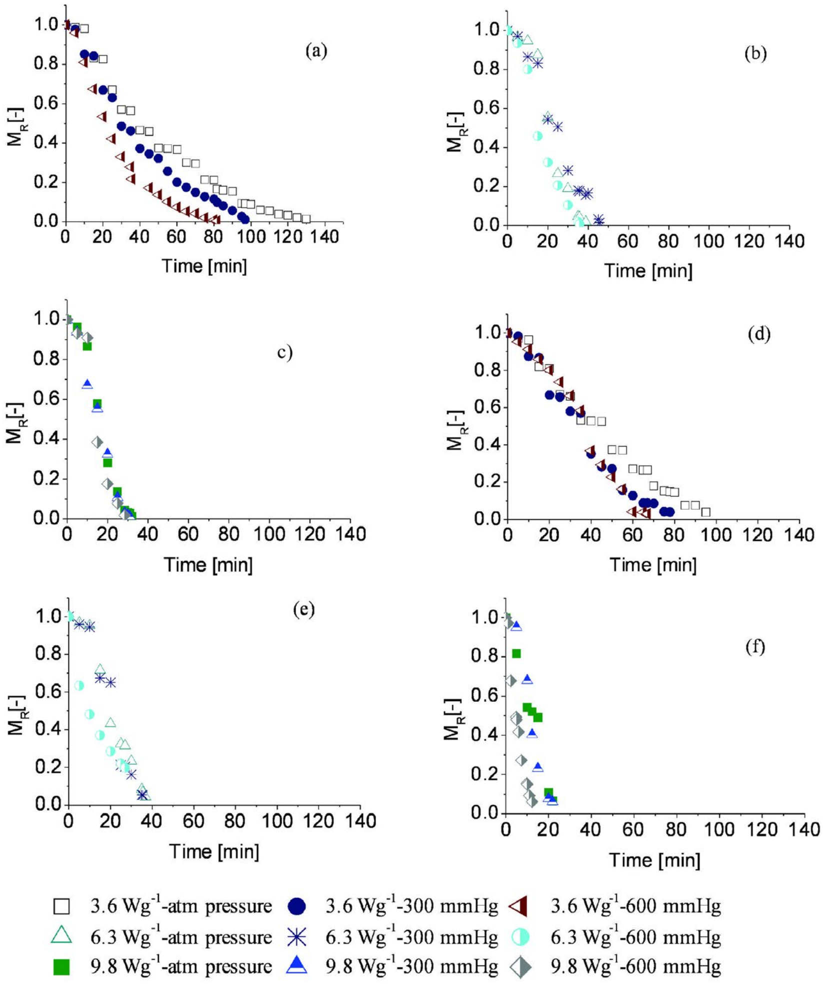

Figure 3: Kinetics of drying of yacon samples without PVOD (A, B, C) and with PVOD (D, E, F).

Sample temperature

Figure 4 illustrates the temperature curves of the samples during MWV drying. Notably, the surface temperature of the osmotically dried yacon samples attained the highest value in less time, shortening the drying time with PVOD (Figure 3B). Pretreatment with PVOD initially decreased the water content in the product and modified the dielectric properties of the material. Moreover, osmotic treatment resulted in structural modifications, including plasmolysis, and a more porous material, which was more suitable for heat and mass transfer. Finally, the sample temperature remained stable, independent of pretreatment. Wang et al. (2013) have reported that this phenomenon occurs because powered microwave heating is equilibrated by evaporative cooling. This finding is extremely interesting for preserving heat-sensitive compounds in yacon, including fructans. Reis et al. (2021) have reported that temperatures more than 70 °C suggest the presence of hydrolyzed FOS in yacon.

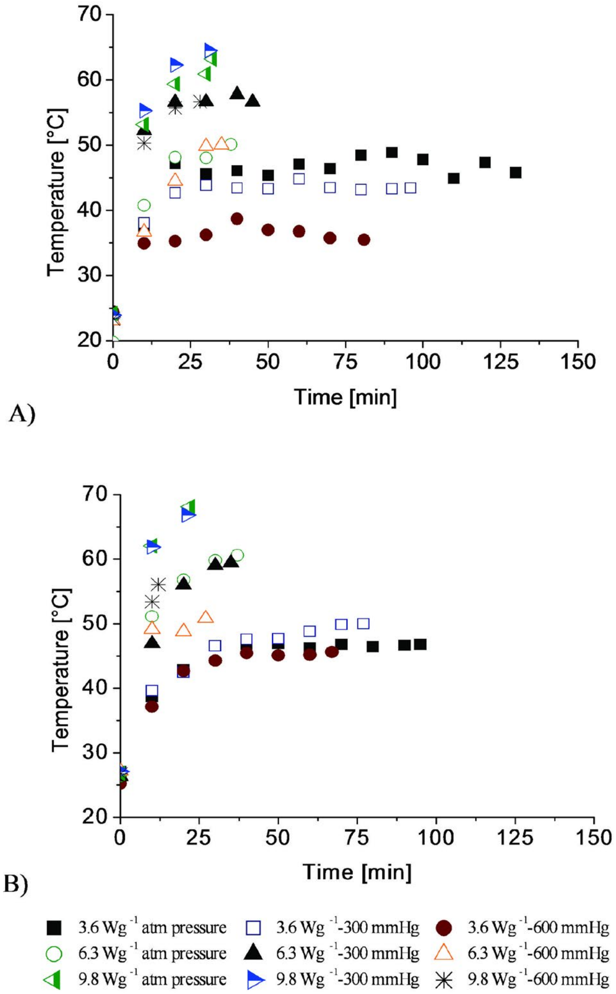

Figure 4: Curves of sample temperature of yacon without PVOD (A) and with PVOD (B) with drying time.

Fructan content in dried yacon

Table 2 summarizes the responses obtained for fructan content and retention with respect to PVOD. For untreated samples, the results were as high as 51.04% and 80.68%, respectively; in contrast, they were approximately 60.57% and 95.74%, respectively, for PVOD-treated samples. Therefore, PVOD pretreatment improved the fructan content and retention by approximately 210% (Assay 3, Table 2).

Table 2: Content of fructans in dry yacons*.

Assay	Content of fructans [%, d.b]		Retention of fructans [%]	
	Without PVOD	With PVOD*	Without PVOD	With PVOD
1	29.20	43.32	46.15	68.47
2	19.73	50.97	31.19	80.56
3	17.95	55.37	28.37	87.53
4	28.87	54.85	45.64	86.70
5	33.91	52.75	53.59	83.38
6	44.87	60.57	70.98	95.74
7	51.04	54.68	80.68	86.43
8	40.63	59.16	64.22	93.51
9	42.87	59.87	67.77	94.64

* The data are on a dry weight basis and products subjected to osmotic dehydration disregarded the gained solids.

Fructans are thermosensitive molecules (Reis et al., 2021; Asquieri et al., 2020). Subsequently, a shorter exposure to a high temperature results in a higher fructan content. Osmotic treatment shortened the drying time as well as decreased the product temperature (Figure 4). Figure 5 illustrates that PDs of 8.05–9.9 Wg^{-1} facilitate FOS retention. Therefore, higher PD values lead to less sample exposure and a higher FOS content at higher temperatures. This helps preserve FOS in the sample. Furthermore, a higher PD value leads to an accelerated drying process. The preferred absorption of microwave energy by the water molecules accelerates the water evaporation in the sample (Al-Harahsheh, Al-Muhtaseb, & Magee, 2009; Zhang, Jiang, & Lim, 2010).

Color representation

Table 3 summarizes that the luminance values (L^*) of the MWV-dried samples decreased with osmotic pretreatment, indicating that PVOD causes yacon browning. Moreover, the color change (ΔE) was higher in treated samples, confirming that osmotic dehydration owing to the penetration of sorbitol solution caused by the vacuum pulse leads to sample browning. In addition, the dimming in the treated samples was 66.48%. Furthermore, the treated yacon samples had a lower Hue angle (h°), expressed in degrees compared to the untreated sample—with pretreatment, the trend was from yellow (= 90°) to red (= 0°). In the absence of PVOD, the chroma, which represents tone intensity or purity, was increased in the samples; however, slight variations in osmotic treatment yielded values similar to those found in fresh yacon.

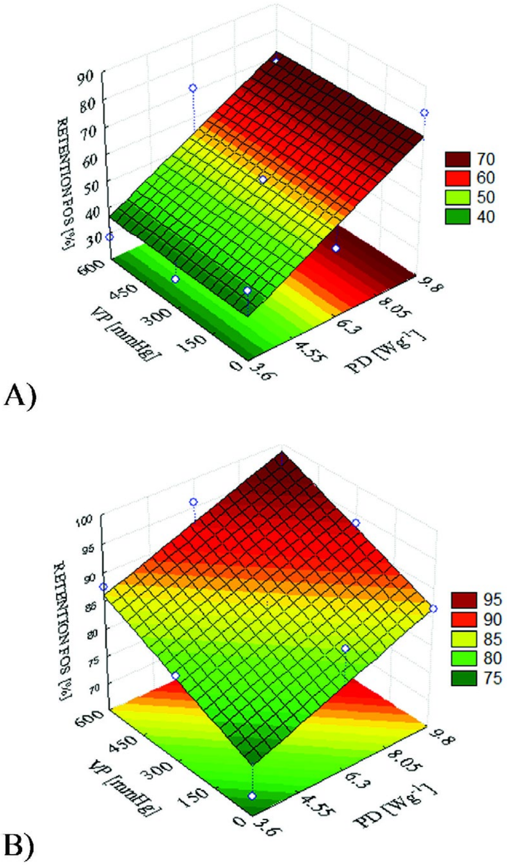

Figure 5: Response surface for FOS retention as a function of vacuum pressure (PV) and power density (PD) for untreated samples (A) and osmotically treated samples (B).

In pretreated samples, the PD of the applied microwave significantly and exclusively regulated the effect of color variation. Furthermore, in untreated samples, the PD was significant. Figures 6A-D and E-H illustrate the response surfaces generated by the proposed model for the color parameters for the untreated and treated samples, respectively. Figures 6A-D illustrate that the least color change was achieved at extreme PD values. Furthermore, at a higher PD value, h° values were lower. These results suggest that a higher PD value preserves tuber color. Moreover, PD significantly affected the chroma parameter, with a PD value of more than 8.05 Wg^{-1} producing values similar to those of fresh yacon (13.64 ±1.37). Figures 6E-H illustrate that PD values of 3.6–6.3 Wg^{-1} resulted in less color variation in the treated samples. Furthermore, a higher Hue angle (h°) was observed (4.55 to 8.05 Wg^{-1}). For lightness (L^*), a higher PD resulted in lower L^* values, indicating the darkening of sorbitol-pretreated samples. In general, all treatments led to yacon browning (i.e., a lower L^*value compared with that obtained for the fresh tuber) independently of the PD values, except for treatments 3, 5, and 9 without PVOD, which exhibited higher luminosity values than fresh samples.

Table 3: Responses of color variation parameters (ΔE), Hue angle (h°), Chroma (C*) and luminosity (L*) of dried yacon.

Assay	ΔE	h°	C*	L^*
	Without PVOD			
1	5.99	76.39	16.34	50.15
2	5.52	75.73	21.16	54.59
3	6.52	84.73	21.62	55.11
4	8.68	73.82	14.21	46.38
5	6.26	74.04	19.18	52.01
6	8.37	79.78	19.66	60.58
7	7.23	69.26	14.76	47.87
8	5.36	73.61	17.53	51.41
9	5.92	77.11	19.39	55.81
	With PVOD			
1	10.95	72.43	11.23	44.33
2	10.48	64.88	12.66	45.06
3	6.72	69.21	17.28	49.48
4	9.72	76.49	11.52	45.28
5	10.08	67.09	12.98	44.98
6	9.89	73.34	13.69	45.07
7	13.69	65.88	10.94	41.83
8	13.70	63.60	12.52	41.29
9	12.41	66.03	12.28	42.87

PVOD-pulsed vacuum osmotic dehydration.

Shrinkage

Table 4 summarizes the volumetric shrinkage in each MWV drying experiment. Under all processing conditions, shrinkage was observed and was associated with product deformation and cellular structure collapse owing to the removal of the moisture occupying some volume of the product. For the untreated and treated samples, shrinkage was 64.06%–81.88% and 40.11%–62.59%, respectively. In addition, osmotic pretreatment resulted in less shrinkage of the dried yacon samples. The material structure begins to change during drying and reaches a critical value, disintegrating and shrinking the tissue cells. In the present study, the osmotic dehydration processing conditions needed to induce shrinkage stress in the samples during drying were less extreme, resulting in lower shrinkage and facilitating water removal.

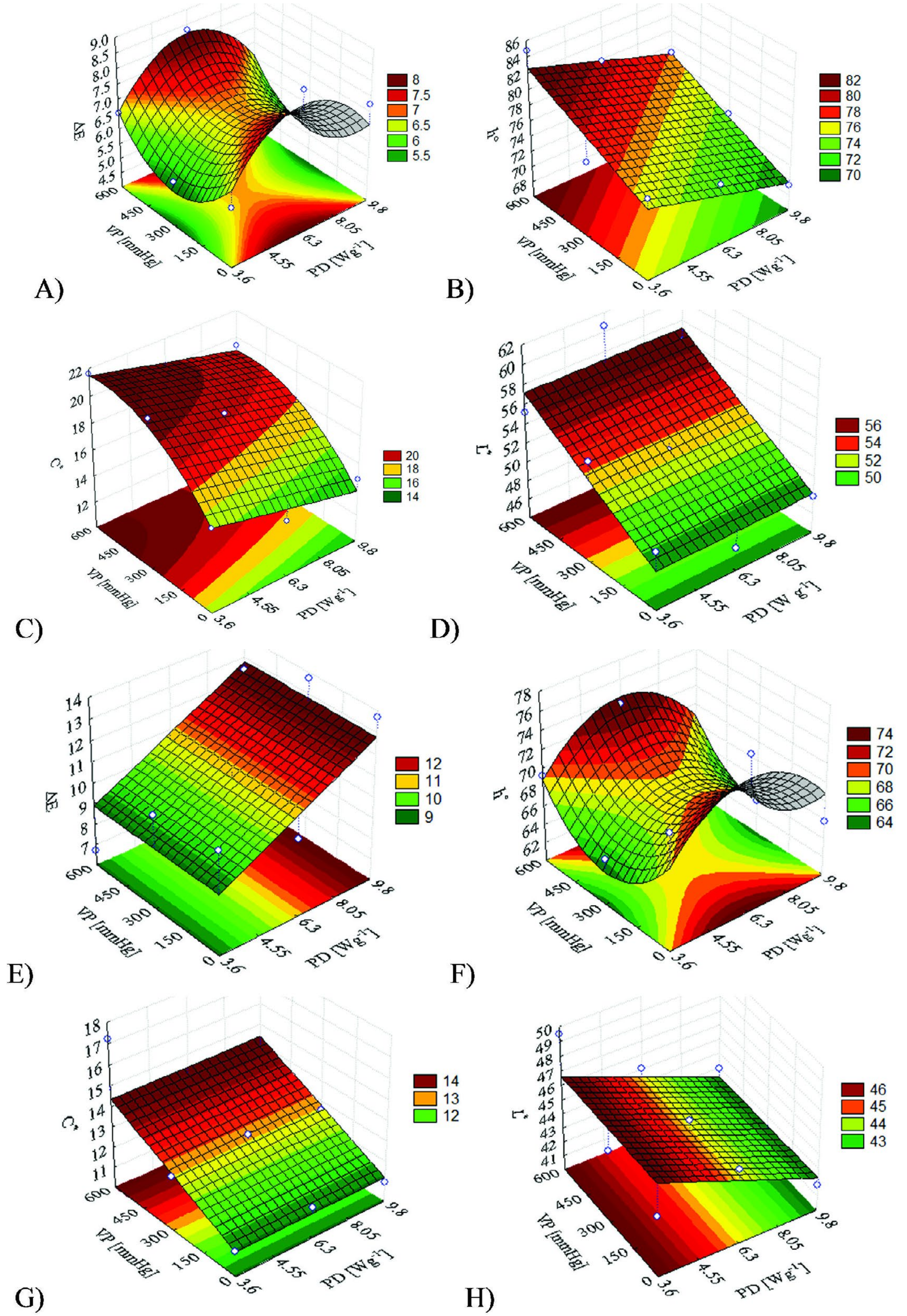

Figure 6: Response surface for Δ*E*, h˚, C* and *L** as a function of vacuum pressure (VP) and power density (PD) for untreated samples (A, B, C, D) and osmotically treated samples (E, F, G, H).

Table 4: Responses of the volumetric shrinkage [%] of dried samples yacon with and without osmotic treatment.

Assay	Shrinkage [%]	
	Without PVOD	With PVOD
1	81.16	60.32
2	81.88	62.59
3	72.12	55.75
4	73.90	51.88
5	74.22	50.25
6	70.27	53.04
7	67.47	48.83
8	64.43	46.15
9	65.06	40.11

Changrue, Orsat and Raghavan (2008) have reported that osmotic dehydration promotes tissue softness and less shrinkage during drying owing to desiccant solution impregnation during processing. This results in a higher solid inlet and lower resistance to product compression compared with non-osmotically dehydrated products. Corrêa et al. (2011) and Al-Harahsheh, Al-Muhtaseb and Magee (2009) have also reported that osmotic dehydration decreases retraction in pineapple and dried tomatoes, respectively, during MWV drying.

Figure 7 illustrates the response surfaces and clearly indicates that PD affects dried yacon shrinkage. Low-power MWV drying decreased shrinkage (Figure 7), possibly favoring volume reduction, corresponding to less stiffening of the cell wall of the product.

Therdthai and Zhou (2009) have elucidated the effects of microwaves on the shrinkage of dried mint. They reported a more porous structure in MWV, allowing rapid moisture vaporization. Furthermore, Han et al. (2010) observed that MWV drying of apple and pineapple pieces resulted in less shrinkage compared with convective drying. The ratio of the lesser shrinkage in MWV compared with convective drying could be a function of the electromagnetic energy absorbed by the water, which directly penetrates the material and leads to volumetric heating (i.e., from the inside to the outside). Rapid energy absorption by water molecules results in rapid water evaporation, resulting in the outward flow of steam. In addition to improving the drying speed, this outward flow helps prevent the shrinkage of the fabric structure, which occurs in most conventional drying techniques. Therefore, the best rehydration characteristics are expected in the microwave (Bórquez, Canales, & Redon, 2010).

Effect of PD

In the presence and absence of PVOD, PD significantly affected the drying time, FOS retention, shrinkage and parameter variation (ΔE), and Hue angle (h°). However, only the presence and absence of the PVOD pretreatment affected luminosity (L^*) and chroma (C^*) values, respectively.

Table 5 summarizes the drying time for each MWV drying condition. The drying time was 28.5–130 and 12.3–95.2 min for untreated and treated samples, respectively. Osmotic pretreatment decreased the drying time by 36.5%. The lowest PD value was 2.31 times faster at higher levels (Assay 9). In addition, the application of PVOD for a short time at the start of dehydration proved beneficial to the kinetic drying process. PVOD application involves a mass transfer operation between a porous solid structure with a liquid phase that is immersed. Pressure gradients generated in the system result in gas expulsion and liquid incorporation into the interior of the porous structure (Fito et al., 2001). The structural changes resulting from PVOD treatment, including complete plasmolysis and membrane lysing (Seguí, Fito, & Fito, 2010; 2012), result in the outward movement of internal liquids. Such changes facilitate further drying via a transfer phenomenon. Moreover, PVOD helped decrease water activity because it facilitated water removal and solute incorporation. Junqueira et al. (2020) also observed this phenomenon during PVOD of different vegetables.

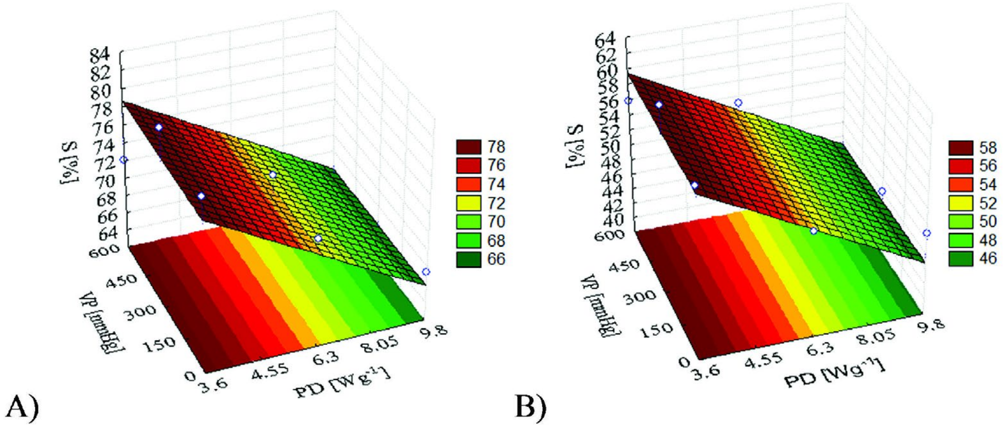

Figure 7: Response surface without PVOD (A) and with PVOD (B) for the shrinkage of dry yacon.

Figure 8 illustrates the response surfaces and indicates that when the microwave PD is higher, the drying time is shorter. PDs of 8.05–9.9 Wg^{-1} shortened the drying time. Wojdyło, Figiel and Oszmiański (2009) and Koné et al. (2013) have reported similar results for drying pineapple, strawberry, and tomato. Microwave heating is because of the dipolar rotation mechanism of polar molecules, which occurs after molecule alignment (which has permanent or induced dipoles) with the applied electric field. Upon removing the field, the molecules return to a disordered state, and the energy absorbed by these dipoles is dissipated as heat. Therefore, microwave absorption induces internal heating and water evaporation, substantially increasing the internal pressure and concentration gradients and thereby affecting water diffusion (Sumnu, Turabi, & Oztop, 2005).

Effect of VP

For PVOD-pretreated samples, PV affected the drying time, FOS retention, color chroma (C^*), and Hue angle (h°). However, for untreated samples, only color (i.e., C^*, h°, L^*, and ΔE) significantly differed ($p < 0.05$) with VP. Furthermore, VP did not affect the drying time of the untreated samples (Figure 8A). In a VP range of 450–600 mmHg, the processing time for the treated samples decreased, exhibiting an even greater effect (Figure 8B). In addition, in the pretreated samples, FOS retention was a function of VP. A VP range of 450–600 mmHg increased FOS retention (Figure 5B). Because polar molecules such as water, fat and sugars better absorb microwaves (Chandrasekaran, Ramanathan, & Basak, 2013), solute incorporation in the pretreatment experiments allowed a larger coupling energy in the presence of microwaves; furthermore, the low pressure generated by the vacuum affected FOS retention. In addition, PVOD-induced tissue changes provided adequate samples for pressure changes in the presence of a vacuum. This also justifies the significant effect of VP on decreasing the drying time for PVOD-treated samples.

Table 5: Drying times for microwave-vacuum drying of yacon with and without pulsed vacuum osmotic dehydration (PVOD) as a pretreatment and Water activity (a_w).

Assay	Drying time [min]			
	Without PVOD	Water activity (a_w)	With PVOD	Water activity (a_w)
1	130.0	0.480±0.055	95.2	0.485±0.026
2	96.8	0.539±0.017	77.8	0.367±0.038
3	81.7	0.560±0.004	67.0	0.376±0.062
4	38.8	0.552±0.021	36.8	0.474±0.064
5	45.7	0.551±0.289	35.5	0.498±0.009
6	35.7	0.533±0.022	27.0	0.460±0.069
7	32.2	0.573±0.019	22.0	0.472±0.021
8	31.0	0.554±0.053	21.8	0.485±0.043
9	28.5	0.549±0.031	12.3	0.407±0.097

Average values ± deviation standard from 3 replicates.

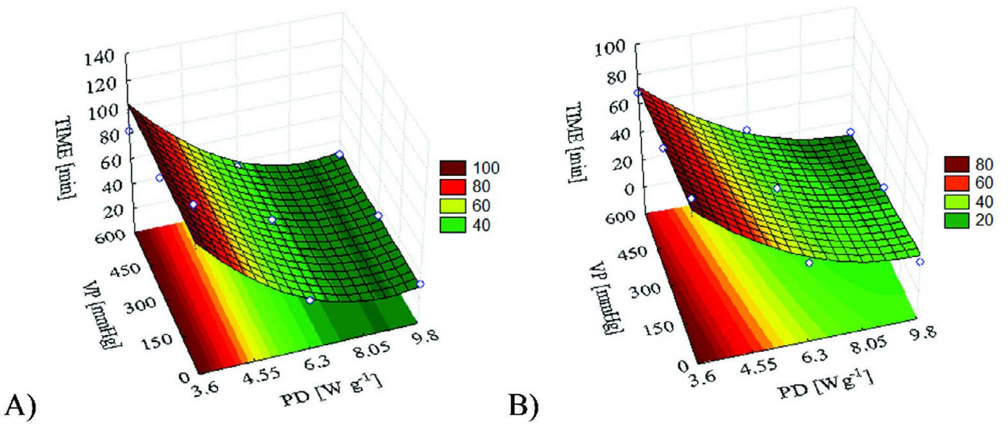

Figure 8: Surface response for yacon drying time in samples untreated with PVOD (A) and pretreated with PVOD (B).

Figures 6A-D and 6E-H illustrate the response surfaces generated by the proposed model for the color parameters for untreated and treated samples, respectively. Figures 6A-D illustrate that the least color change was observed at VP levels similar to 300 mmHg. Additionally, smaller h° values were observed when the VP levels were lower. These results suggest that low pressure preserves tuber color. However, a lower VP value resulted in a low L^* value; therefore, the processing conditions must be carefully selected if pretreatment is not performed. A plausible explanation for this phenomenon is that Maillard reaction products were eliminated owing to the lack of oxygen or that vacuum drying inhibited the activity of heat-sensitive polyphenoloxidase activity. Mothibe et al. (2014) also observed vacuum effects when drying apple cubes in an MWV.

VP significantly affected the chroma parameter; therefore, the application of a VP of <150 mmHg resulted in values similar to those of fresh yacon. Furthermore, a higher h° value was observed at the lowest and highest VP levels. In general, yacon browning (i.e., a lower L^* value when compared with the values obtained for the fresh tuber) was observed in all treatments, independent of PD and VP in the absence of PVOD. Furthermore, luminosity values were higher than those in fresh samples.

Drying kinetics modeling

The effective diffusivity (D_{eff}) was obtained using Fick's diffusion model and is summarized in Table 6. An increase in PD and VP increased the diffusivity coefficient up to 82% when shrinkage was considered, particularly with an increase in PD. In the pretreated samples, shrinkage also increased the diffusivity coefficient. In assay 9, the D_{eff} of PVOD-treated increased by 67% compared with that of others untreated samples. Solution impregnation during osmotic dehydration results in less tissue retraction in the product and facilitates water removal (Corrêa et al., 2011; Macedo et al., 2021). Although the diffusivity differs based on the composition, texture, porosity, sample geometry, temperature, and the type of the drying process, the value range for microwave-dried foods is generally between 10^{-11} and 10^{-6} m^2s^{-1} (Corrêa et al., 2011; Al-Harahsheh, Al-Muhtaseb, & Magee, 2009).

In some cases, the diffusion model failed to exhibit a satisfactory adjustment of the drying kinetics, with R2 values of 99%–71%. However, the RMSE and χ^2 values for shrinkage assumption were lower and better described the drying kinetics. Figure 9A illustrates this lack of fit. However, a fine fit can be observed with PVOD and shrinkage (Figure 9B), with a lower RMSE.

Response surface analysis facilitated the determination of the actual processing conditions that would provide the desired characteristics for MWV drying using the statistically significant variables in their optimum and significant results. These processing conditions were as follows: a PD of 9.9 Wg^{-1} and a VP of 600 mmHg for osmotically dehydrated samples. This combination was selected based on the highest FOS retention.

FOS retention, drying time, and shrinkage were 97.83% ±0.83% 12.5 ±0.33 min, and 42.62% ±2.20% (mean of three replicates), respectively. The chroma value, Hue angle, luminosity, and color variation were 23.34 ±1.08, 80.01 ±2.09, 48.04 ±2.69, and 12.22 ±1.09, respectively. Table 7 summarizes that the model results are similar to the experimental results. The small differences between the predicted values and experimental responses can be attributed to the reparametrized models. Therefore, the validation results are satisfactory and the process is reproducible.

Statistical analysis

The experimental results were analyzed based on the experimental design. Furthermore, the regression coefficients were expressed based on the codified units and coefficients of determination for the four response variables analyzed: drying time, FOS retention, shrinkage, and color parameters.

Although a statistical model contains several parameters, for practical purposes, the simplest model with the fewest parameters reflecting the effects of the principal variables was used. Silveira, Mazutti and Salau (2016) have reported that reparameterization provides an accurate and reliable model with fewer estimated parameters, more degrees of freedom for statistical analysis, and accurate results. Table 8 presents a reparametrized model.

PVOD-pulsed vacuum osmotic dehydration; RE- regression; M/I-means interaction; VP-vacuum pressure; PD- power density microwave; L-significant linear effects and Q-significant quadratic effects.

The ANOVA results for the reparametrized regression model (Table 9) indicated that the model was statistically significant for all responses ($p < 0.05$); the calculated F-values were higher than the tabulated values. All regressions of the responses exhibited a good fit, with an R^2 range of 75.70%–97.8% with PVOD and 76.40%–95.07% without PVOD, allowing the generation of response surfaces.

Kinetics of rehydration

Figure 10 demonstrates the rehydration kinetics of dried yacon in an MWV under optimal conditions.

The product achieved a lower moisture saturation compared with convectively dried yacon: approximately 2.53 kg kg^{-1} dry matter was achieved in approximately 90 min. PVOD-pretreated and convectively dried yacon at 40°C, 50°C, and 60°C exhibited a moisture content saturation of 2.80, 3.35, and 3.45 kg.kg^{-1} dry matter, respectively, between 120 and 240 min. Furthermore, the rehydration rate was higher for PVOD than for the conventional drying process; this has been reported by other researchers (Giri & Prasad, 2007; Nahimana & Zhang, 2011). Rehydration is associated with the structural changes in yacon during drying and osmotic dehydration. PVOD and MWV contributed to cell wall rupture, which was subsequently avoided by preserving the intercellular spaces to fill the pores with water.

Table 6: Effective diffusivity coefficient, coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2) for a Fick model for the various conditions studied with and without shrinkage.

Without PVOD								
Assay	Without shrinkage				With shrinkage			
	D_{eff} [m^2s^{-1}]	R^2	RSME	χ^2	D_{eff} [m^2s^{-1}]	R^2	RSME	χ^2
1	1.05x10^{-10}	0.894	0.102	0.017	3.15 x10^{-10}	0.917	0.062	0.017
2	1.32 x10^{-10}	0.904	0.097	0.003	4.69 x10^{-10}	0.963	0.060	0.011
3	1.99 x10^{-10}	0.916	0.094	0.001	8.16 x10^{-10}	0.965	0.061	0.009
4	2.21 x10^{-10}	0.807	0.101	0.017	6.01 x10^{-10}	0.917	0.013	0.020
5	2.04 x10^{-10}	0.779	0.165	0.009	7.59 x10^{-10}	0.924	0.097	0.011
6	3.03 x10^{-10}	0.887	0.171	0.004	1.36 x10^{-9}	0.938	0.128	0.008
7	3.31 x10^{-10}	0.758	0.194	0.004	1.04 x10^{-9}	0.921	0.111	0.010
8	3.43 x10^{-10}	0.809	0.164	0.003	1.99 x10^{-9}	0.841	0.149	0.002
9	3.21 x10^{-10}	0.713	0.215	0.015	1.06 x10^{-9}	0.877	0.141	0.018
With PVOD								
1	1.06 x10^{-10}	0.853	0.120	0.009	3.00 x10^{-10}	0.922	0.050	0.007
2	1.36 x10^{-10}	0.832	0.138	0.008	3.08 x10^{-10}	0.974	0.054	0.007
3	1.22 x10^{-10}	0.746	0.176	0.017	3.60 x10^{-10}	0.950	0.078	0.007
4	2.29 x10^{-10}	0.750	0.110	0.011	6.42 x10^{-10}	0.922	0.100	0.008
5	2.28 x10^{-10}	0.841	0.202	0.014	6.49 x10^{-10}	0.907	0.114	0.011
6	3.53 x10^{-10}	0.999	0.002	0.001	9.88 x10^{-10}	0.854	0.101	0.001
7	3.87 x10^{-10}	0.814	0.141	0.002	1.08 x10^{-9}	0.982	0.043	0.001
8	3.94 x10^{-10}	0.749	0.183	0.009	1.55 x10^{-9}	0.852	0.140	0.008
9	8.98 x10^{-10}	0.914	0.094	0.003	3.26 x10^{-9}	0.974	0.051	0.002

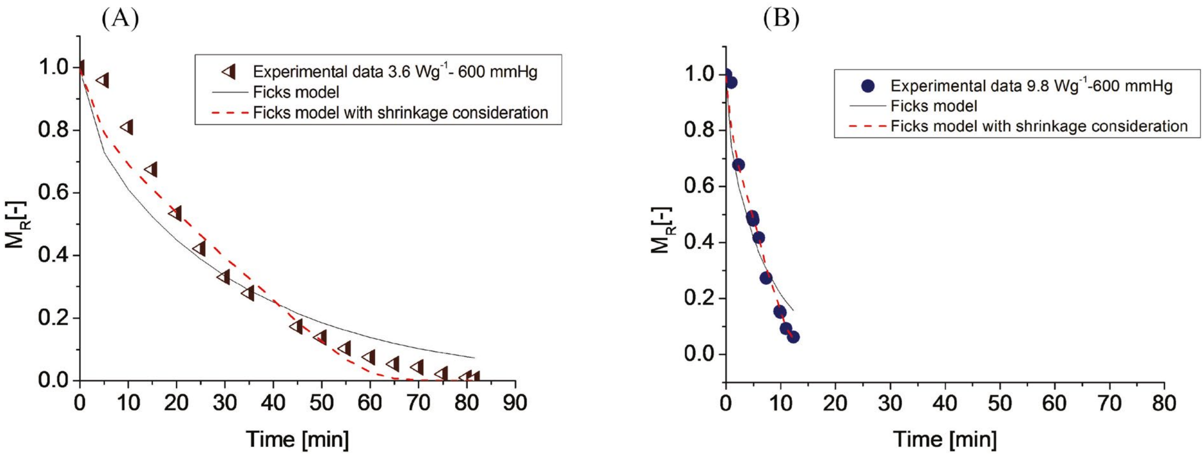

Figure 9: Experimental values and predicted moisture content during drying of yacon slices in experiments without osmotic PVOD (A) and with PVOD (B) treatment.

*The solid line red represents the model with shrinkage, and the solid black lines represent the model without shrinkage.

Table 7: Values predicted by model reparameterization.

Parameters	Predicted values
FOS retention [%]	98.717
Time [min]	10.77
Shrinkage [%]	44.85
C^*	14.37
h°	68.8
L^*	42.32
ΔE	12.79

Table 8: Regression Coefficients for drying time, retention fructans, shrinkage and color parameters (ΔE, h°, $C^*$and L^*).

Factor	Drying time		Retention fructans		Shrinkage		ΔE		h°		C^*		L^*	
	RE	p	RE	p	RE	p	RE	p	RE	p	RE	p	RE	p
Without PVOD														
M/I	400.67	0.003	54.28	0.00	72.28	0.00	6.82	0.00	76.05	2.5 x 10^{-11}	19.29	1.05 x10^{-7}	52.66	1.9 x 10^{-11}
PD (L)	-361.33	0.001	17.83	0.00	-6.37	0.002	-	-	-2.81	0.01	-1.24	0.01	-	-
PD (Q)	266.33	0.042	-	-	-	-	-1.66	0.01	-	-	-	-	-	-
VP (L)	-	-	-	-	-	-	-	-	3.69	0.00	2.56	0.00	4.52	-
VP (Q)	-	-	-	-	-	-	1.40	0.01	-	-	-1.63	0.03	-	-
R²	0.951	-	0.764	-	0.764	-	0.833		0.851		0.951		0.799	
With PVOD														
M/I	331.00	0.0001	86.33	0.00	52.11	0.00	10.85	0.00	68.73	0.00	12.79	0.00	44.47	0.00
PD (L)	-306.50	0.0000	6.34	0.01	-7.26	0.001	1.94	0.02	-	-	-	-	-2.15	0.02
PD (Q)	162.50	0.0078	-	-			-	-	-5.30	0.03	-	-	-	-
VP (L)	-79.50	0.0150	6.05	0.01			-	-	-	-	1.58	0.03	-	-
VP (Q)	-	-	-	-			-	-	5.37	0.03	-	-	-	-
R²	0.978	-	0.806	-	0.822		0.785		0.757		0.750		0.797	

Table 9: Analysis of variance for drying time, retention fructans, shrinkage, and color parameters (ΔE, h°, C*and *L**).

Statistical parameters Drying time Retention fructans		Without PVOD						
		Shrinkage	Δ*E*	h°	C*	*L**		
SS	Regression	9252.38	1906.61	243.20	9.42	129.16	53.81	122.71
Error	1280.58	693.58	75.11	1.88	22.51	2.79	30.77	
Total	10532.96	2600.19	318.31	11.29	151.67	2.79	153.49	
df	Regression	2	1	1	2	2	3	1
Error	6	7	7	6	6	5	7	
Total	8	8	8	8	8	8	8	
MS	Regression	4626.19	1906.61	243.20	4.72	64.58	17.94	122.71
Error	213.43	99.08	10.73	0.31	3.75	0.56	4.4	
F_{cal}	Regression	21.68	19.24	22.66	14.99	17.22	32.15	27.91
p-value	Regression	0.001	0.003	0.002	0.00	0.00	0.00	0.00
F_{tab} 0.05%	Regression	5.14	5.59	5.59	5.14	5.14	5.41	5.59
R²		0.950	0.764	0.764	0.833	0.851	0.950	0.799
		With PVOD						
SS	Regression	6543.87	460.71	316.44	22.66	113.91	15.07	27.61
Error	143.78	111.20	68.78	16.04	40.62	13.36	18.72	
Total	6687.66	571.99	385.23	38.7	154.52	28.42	46.31	
df	Regression	3	2	1	1	2	1	1
Error	5	6	7	7	6	7	7	
Total	8	8	8	8	8	8	8	
MS	Regression	2181.29	230.35	316.44	22.66	56.95	15.07	27.61
Error	28.76	18.53	9.83	2.29	6.77	1.91	2.67	
F_{cal}	Regression	75.85	12.429	32.20	9.89	8.41	7.92	10.33
p-value	Regression	0.00	0.007	0.0007	0.02	0.016	0.03	0.01
F_{tab} 0.05%	Regression	5.41	5.14	5.59	5.59	5.14	5.59	5.59
R²		0.978	0.806	0.821	0.785	0.757	0.751	0.797

PVOD is pulsed vacuum osmotic dehydration.

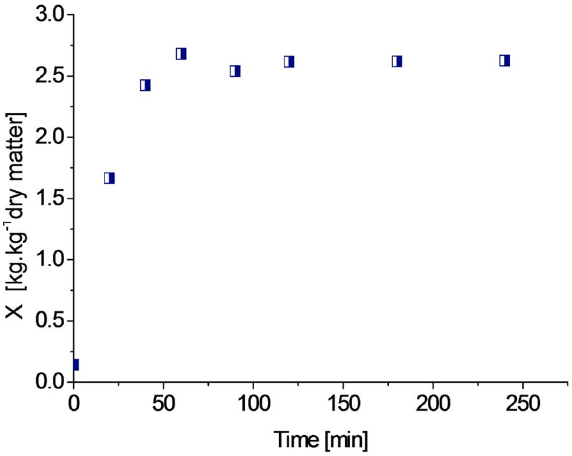

Figure 10: Evolution of moisture content (dry weight basis) for rehydrating dried yacon under 9.9 Wg^{-1} - 600 mmHg optimal conditions.

Conclusions

FOS may be retained in yacon during PVOD and MWV drying. PD significantly decreased the drying time and shrinkage. Microwaves with a higher PD increased the effective diffusivity, resulting in shorter processing times and facilitating FOS retention. In addition, VP affected the drying and FOS retention of pretreated samples. Our data suggest that PVOD-MWV drying at 9.9 Wg^{-1} and 600 mmHg can be an alternative technology for drying yacon, facilitating the rehydration of the product.

Author Contributions

Conceptual Idea: Correa, J. L.G.; Pereira, M.C.A.; Methodology design: Correa, J.L.G.; Mello Junior, R.E.; Data collection: Lopes, F.J.; Mello Junior, R.E.; Souza, A.U.; Data analysis and interpretation: Lopes, F. J.; Souza, A.U. and Writing and editing: Petri Junior, I.; Corona-Jimenez, E.

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