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Drying of 'yacon' pretreated by pulsed vacuum osmotic dehydration[1]

Secagem de yacon pré-tratado por desidratação osmótica com pulso de vácuo

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HIGHLIGHTS:
Mathematical models could adjust the drying behavior.
Osmotic pretreatment, higher drying temperature, and vacuum preserve the characteristics of the 'yacon'.

ABSTRACT: In this study, the 'yacon' was dried using pulsed vacuum osmotic dehydration as pretreatment followed by vacuum drying (at different temperatures) or convective drying. The use of osmotic dehydration and vacuum drying had their influence evaluated concerning drying kinetics and quality of the final product, considering fructan retention, color, and water activity. Fick's second law and Page's equation were suitable for the fitting of drying evolution. It was observed that higher temperatures (60 °C) resulted in shorter drying time, higher diffusivity, and higher fructan retention when compared to 40 and 50 °C. The osmotic pretreatment and the vacuum drying differed in fructan retention ($p \leq 0.05$). Moreover, the dried product, osmotically pretreated, presented a shorter drying time. The best condition was vacuum drying at 60 ºC, preceded by pulsed vacuum osmotic dehydration that resulted in fructan retention of approximately 38% in a quicker, higher diffusivity and lighter color product concerning the other tested conditions.

Key words: fructooligosaccharides (FOS), fructan concentration, sorbitol, *Smallanthus sonchifolius*

RESUMO: Neste estudo, o yacon foi seco pelo uso de desidratação osmótica com pulso de vácuo como pré-tratamento seguida por secagem a vácuo (em diferentes temperaturas) ou secagem convectiva. O uso de desidratação osmótica e de vácuo na secagem teve sua influência avaliada com relação à cinética de secagem e à qualidade do produto final considerando a retenção de frutanos, cor e atividade de água. A segunda lei de Fick e a equação de Page se mostraram adequadas para o ajuste da evolução da secagem. Observou-se que temperaturas mais altas (60 °C) levaram a tempos de secagem menores, maiores difusividades efetivas, e maior retenção de frutanos, quando comparada a 40 e 50 °C. O pré-tratamento osmótico e a secagem a vácuo diferiram ($p \leq 0.05$) na retenção de frutanos. Além disto, o produto seco pré-tratado osmoticamente apresentou menores tempos de secagem. A melhor condição foi a secagem a vácuo a 60 ºC precedida por desidratação osmótica com pulso de vácuo, que resultou na retenção de aproximadamente 38% de frutanos em um processo mais rápido, maior difusividade e um produto mais claro que nas demais condições testadas.

Palavras-chave: fruto-oligossacarídeos (FOS), teor de frutanos, sorbitol, *Smallanthus sonchifolius*

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Introduction

The 'yacon' (*Smallanthus sonchifolius*) is a seasonal plant originating from the Andean region (South America), with high concentrations of fructooligosaccharides (FOS) as the main storage carbohydrate. These saccharides are related to prebiotic characteristics, and their maintenance is imperative. The 'yacon' presents high water activity and moisture content; moreover, the FOS hydrolyses quickly after harvesting, which reduces its shelf life (Mendonça et al., 2017). For preservation and retention of its biological activity, special care should be given to the processing technique, which could greatly affect the chemical composition, including the bioactive components (Brochier et al., 2015).

Osmotic dehydration (OD) could minimize nutrient losses and decrease moisture content, preserving food materials (Kaushal & Sharma, 2016; Bakhara et al., 2018). The OD transfers could be intensified with the application of reduced pressure during the process beginning, namely pulsed vacuum osmotic dehydration (PVOD) (Utkucan & Kemal, 2016; Junqueira et al., 2017). Oliveira et al. (2016) optimized PVOD for obtaining a semi-dehydrated product with high FOS concentration but did not obtain a final product by further drying.

'Yacon' was convectively (Lisboa et al., 2018) and vacuum dried (Reis et al., 2012a). The increase in diffusivity with temperature was observed in both cases. Still, none of them used a pretreatment to improve the quality of the final product or even quantified FOS content in the dried product.

This study aimed to evaluate: (i) the effect of different drying temperatures (40, 50, and 60 °C) on the kinetics of osmosed 'yacon' slices during vacuum drying - VD, (ii) the suitability of a diffusional and an empirical equation for predicting the drying behavior; (iii) the quality of the final dried 'yacon'/ and (iv) the influences of osmotic pretreatment and drying conditions (VD and convective drying - CD).

Material and Methods

Fresh 'yacon' tubers (*Smallanthus sonchifolius*) were purchased in a local market (Lavras, MG, Brazil) and stored in a refrigerator at 8 ± 1 °C before the experiments. The tubers were obtained from the same harvest, presenting similar visual aspects of maturity, shape, peel color, and absence of mechanical injuries. The fresh samples presented moisture content of 90.84 ± 0.71 kg of water per 100 kg of sample and fructan concentration of 64.8 ± 0.39 kg per 100 kg of dry matter. These values were similar to those found by Mendonça et al. (2016). The samples were obtained by washing the tubers with tap water, peeling, and slicing them into slices (2 cm length × 2 cm width × 0.05 cm thickness). The samples were convectively and vacuum dried, with and without pulsed vacuum osmotic dehydration as pretreatment, as pointed in Table 1 and detailed as follows.

The osmotic solution was prepared with distilled water and sorbitol [38 kg of sorbitol per 100 kg of solution (w/w)]. The osmotic processing was performed in an osmotic dehydrator with temperature and internal pressure controls. Oliveira et al. (2016) optimized the osmotic solution concentration, absolute pressure, and temperature values. The PVOD conditions were 35 ± 1 °C, sample: solution ratio was 1:25 (w/w), 300 min, with an absolute pressure of 91.4 kPa during the first 10 min of process, followed by the local atmospheric pressure restoration (91.75 kPa). The osmotically dehydrated samples presented a moisture content of 61.73 ± 0.18 kg of water per 100 kg sample.

Table 1. Treatments applied during the drying of 'yacon' slices

Treatments	Drying	PVOD pretreatment
1	VD	No
2	VD	Yes
3	CD	No
4	CD	Yes

CD - Convective drying; VD - Vacuum drying ; PVCD - Pulsed vacuum osmotic dehydration

The VD was performed in a temperature-controlled oven (Solab SL104/40, Piracicaba, Brazil) coupled with a vacuum pump (model DV95, Dosivac, Buenos Aires, Argentina). The temperatures were 40, 50, and 60 °C (temperatures reported in the literature as usual in food drying processes), and the absolute pressure, 91.32 kPa. The CD was done under a standard atmosphere executed in the same oven, in a natural convective way at the same temperatures. The 'yacon' slices were weighed using a digital scale (Marte Científica, AD33000 model, São Paulo, Brazil) at preset times until constant weight. The dried 'yacon' moisture content was determined in a vacuum oven at 70 °C (AOAC, 2010). The treatments were repeated three times. The drying data obtained were fitted according to Fick's second law of diffusion and Page's equation.

The moisture ratio (MR) of the samples during drying experiments was calculated using Eq. 1:

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} \quad (1)$$

where:

X_t, X_0, and X_{eq} - moisture content at any time of drying, initial moisture content, and equilibrium moisture content [kg of water per 100 kg of sample], respectively.

The X_{eq} was experimentally obtained from the moisture content of the samples subjected to a lengthy drying process.

The drying behavior during the treatments has also been modeled using the unidirectional diffusion model (Crank, 1975) that, for an infinite slice, became Eq. 2.

$$MR = \left[\frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left(-(2i+1)^2\pi^2 D_{eff}\frac{t}{4L^2}\right)\right] \quad (2)$$

where:

D_{eff} - effective moisture diffusivity, $m^2 s^{-1}$
t - temp, s; and,
L - the characteristic length (half of the thickness), m.

The activation energy is related to the temperature dependence of the D_{eff} values, described by an Arrhenius-type relationship, as presented by Eq. 3.

$$D_{eff} = D_0 \cdot \exp\left(\frac{E_a}{RT}\right) \tag{3}$$

where:

D_0 - pre-exponential factor of the Arrhenius equation, $m^2 s^{-1}$;
E_a - activation energy, kJ mol;
T - drying air temperature, K; and,
R - universal gas constant, 8.314×10^{-3} kJ (mol K$)^{-1}$.

Eq. 3 can be linearized into the form of Eq. 4, and a plot of ln (D_{eff}) as a function of the reciprocal of absolute temperature (1/T) produced a straight line with a slope equal to (E_a/R), from which the activation energy was estimated.

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \tag{4}$$

Page's equation (Eq. 5) was used to model the drying kinetics (Page, 1949).

$$MR = \exp\left(-kt^n\right) \tag{5}$$

where:

k - drying rate, L s^{-1}; and,
n - unit coefficient, dimensionless.

Quality analyses were performed using fresh and dried 'yacon' slices. All the analyses were performed in at least three replicates. The moisture content of the fresh, osmodehydrated, and dried 'yacon' slices was determined according to AOAC (2010), and the a_w performed using an Aqualab hygrometer (Decagon Devices, Inc., CX-2T model, Pullman, WA, USA). The color variables of fresh and dried 'yacon' slices were measured using a colorimeter (Minolta, CR-400 model, Osaka, Japan). The color variables were used to calculate the chroma (C_{ab}) (Eq. 6) and the total color difference (ΔE) (Eq. 7). Ten samples were used for each treatment.

$$C_{ab} = \sqrt{\left(a^*\right)^2 + \left(b^*\right)^2} \tag{6}$$

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \tag{7}$$

where:

L^* - indicates the lightness;
a^* - indicates red-green; and,
b^* - indicates yellow-blue, and the subscript '0' refers to the fresh samples.

According to the methodology AOAC 997.08 (AOAC, 2010), the fructan concentration was analyzed enzymatically, using the Fructan HK Assay Procedure (Magazyme International Ireland, Ltd., Bray, Ireland) commercial kit. The fructan retention (FR) is given by Eq. 8 (Oliveira et al., 2016).

$$FR = \frac{F_d}{F_f} 100 \tag{8}$$

where:

F_d - fructan concentration of the dried 'yacon' sample; and,
F_f - fructan concentration of the fresh 'yacon' sample.

The parameters of Fick's and Page's equations were estimated using a non-linear regression procedure. The coefficient of determination (R^2) and sum of square error (SE) were evaluated.

The results were evaluated by one-way ANOVA at $p \leq 0.05$, and the means were compared using the Tukey test. These analyses were performed using the software Statistica 8.0 (Statsoft Inc., Tulsa, USA).

Results and Discussion

The drying time for obtaining a 0.15 kg water per kg sample in a VD was 1110, 570, and 300 min for the temperatures 40, 50, and 60 °C, respectively. The drying time decreased 73% with increasing drying air temperature from 40 to 60 °C. This reduction can be related to the enhancement of vapor pressure in the sample that causes faster moisture evaporation from the interior of a solid to the surface with the temperature increase. Reis et al. (2012b) also studied the VD of 'yacon', and those authors reported that an increase in temperature from 45 to 65 °C promoted higher drying rates. The results (Table 2) showed that drying temperature increases the D_{eff}.

The D_{eff} ranged from 0.63×10^{-8} (40 °C) to 3.07×10^{-8} $m^2 s^{-1}$ (60 °C), and the unidirectional model showed good agreement with experimental data, presenting high R^2 and lower SE values.

Eq. 9 presents the effect of the temperature on the D_{eff} of the pretreated 'yacon' slices.

$$D_{eff} = 1736.97 \exp\left(-\frac{8245.4}{T}\right) \tag{9}$$

The activation energy was 68.55 kJ mol^{-1}, and $R^2 = 0.99$.

The statistical results of the modeling with Page's equation, including the drying rate (k) and performance indexes used to evaluate the goodness of fit (R^2 and SE), are summarized in Table 3.

Table 2. Effective moisture diffusivities (D_{eff}) of vacuum-dried 'yacon' at different temperatures

Temperature (°C)	$D_{eff} \times 10^8$ ($m^2 s^{-1}$)	R^2	SE
40	0.63	0.97	0.14
50	1.47	0.99	0.09
60	3.07	0.99	0.07

R^2 - Coefficient of determination; SE - Sum of square error

Table 3. Page's equation regression parameters for vacuum dried 'yacon' at different temperatures

Temperature (°C)	k	n	R^2	SE
40	3.23×10^{-8}	1.61	0.98	2.80×10^{-3}
50	1.70×10^{-6}	1.33	0.99	5.02×10^{-4}
60	4.30×10^{-6}	1.33	0.99	2.05×10^{-4}

R^2 - Coefficient of determination; SE - Sum of square error

The results showed that R^2 values were greater than 0.98 and SE values were lower than 2.80×10^{-3}. The suitability of Page's equation, and its simplest form, has been widely described (Bakhara et al., 2018) in drying processes.

When the drying process is in the falling rate period, the k drying-constant is related to the diffusivity. Therefore, the parameter can be associated with the ease of moisture removal. The k parameter increased with increasing temperature, corroborating the D_{eff} values (Table 2) at different temperatures.

The adjustment parameter n reduced at higher temperatures, and it ranged from 1.61 to 1.33. This parameter could change with initial moisture content or drying conditions to lead to a better fitting. Similar findings were obtained by Reis et al. (2012b) during the VD of 'yacon' slices (ranging from 1.37 to 1.69).

Table 4 presents the influence of drying temperature on water activity and color variables during the vacuum drying of osmosed 'yacon' slices.

The ANOVA revealed no significant effects ($p > 0.05$) in the a_w of the dried 'yacon' (Table 4). All the temperatures provided a_w less than 0.600. These values are considered low enough to provide shelf stability of the final product, preventing the possibility of adverse biochemical changes and microbial growth, which contribute to suitability for long-term storage of the product (Junqueira et al., 2020).

The fresh 'yacon' presented the following color parameters: $L^* = 42.80 \pm 3.32$; $a^* = 0.56 \pm 0.271$; and $b^* = 6.11 \pm 0.73$. The 'yacon' color characteristics were significantly affected by the temperature (Table 4) ($p \leq 0.05$). An increase was observed in L^* values, C_{ab} and ΔE at the highest drying temperature (60 °C). The results indicate that, at this temperature, the final product color is lighter ($L^* = 56.73 \pm 2.53$), and consequently, a higher ΔE (18.29 ± 2.52) was reported.

Reis et al. (2012a) observed an increase in L^* value during the VD of 'yacon' slices (0.6 cm thickness) from 45 to 65 °C. 'yacon' is rich in enzymes (such as polyphenol oxidase and peroxidase). During long process periods, exposure to light and heat could stimulate the enzymatic activity, promoting the oxidation reactions that results in brown pigments (Oliveira et al., 2016).

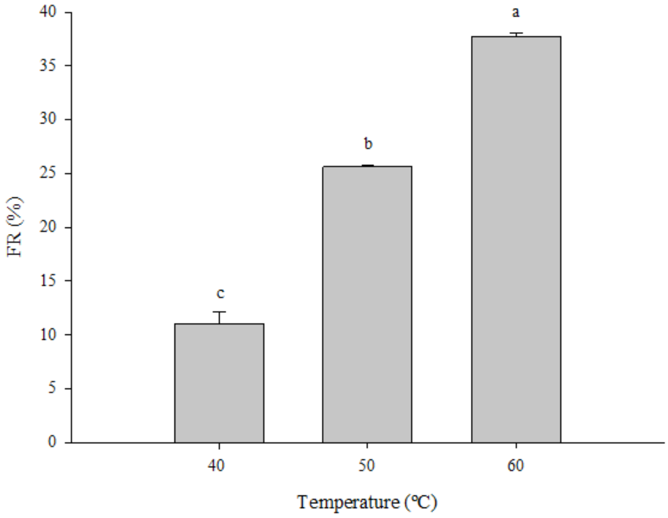
Due to the shorter drying time at 60 °C, less exposure to these triggers may prevent some browning. Significant differences ($p \leq 0.05$) in C_{ab} values (Table 4) were observed. A slight increase in the yellow color of samples treated at 60 °C was observed (data not shown), which probably promoted the increase in color saturation.

The fructan retention (FR) is presented in Figure 1. Significant differences ($p \leq 0.05$) in the FR of dried 'yacon' slices due to the different treatments were pointed.

Table 4. Effect of drying temperature on water activity (a_w) and color variables (L, C_{ab}, and ΔE)

Temp. (°C)	a_w	L	C_{ab}	ΔE
40	0.511 ± 0.076 a	44.32 ± 1.46 c	13.24 ± 0.76 b	7.35 ± 0.78 b
50	0.478 ± 0.007 a	47.99 ± 1.36 b	11.71 ± 0.56 c	8.59 ± 0.83 b
60	0.460 ± 0.003 a	56.73 ± 2.53 a	16.63 ± 1.18 a	18.29 ± 2.52 a
CV (%)	6.87	5.93	4.76	7.07

Mean ± standard deviation; Means followed by different letters in the column differs significantly ($p \leq 0.05$), according to the Tukey test



Mean followed by different letters differs significantly ($p \leq 0.05$), according to Tukey's test

Figure 1. Fructan retention (FR) in 'yacon' slices vacuum dried at different temperatures

A reduction in the FOS concentration during drying treatments was expected, and it ranged from 11.01 ± 1.10 % (40 °C), which corresponds to 8.16 kg of fructan per 100 kg of dry matter, to 37.72 ± 0.35% (60 °C), which corresponds to 24.40 kg of fructan per 100 kg of dry matter. The fructan oxidation causes loss of its content, which is related to exposure to light and heat (Mendonça et al., 2016). The extended process time observed in the treatment at 40 °C (1110 min) promoted the lowest FR. Scher et al. (2009) observed that the inulin content decreased significantly after 'yacon' drying, and they concluded that such a decrease could be due to its hydrolysis, improved by these conditions. As previously mentioned, this degradation is undesirable since fructan presents a wide range of functional properties (Padilha et al., 2017).

According to Table 2 and Figure 1, the air temperature of 60 °C promoted the lowest process time and the highest D_{eff} values and fructan retention. Therefore, this temperature was chosen for the subsequent experiments.

The temperature of 60 °C was chosen, and the effect of osmotic pretreatments and drying conditions (CD and VD) was evaluated. It should also be pointed that the pretreated samples have a lower initial moisture content (61.73 ± 0.18 kg of water per100 kg of the sample), which hinders the comparison of the total drying time. In such cases, the processes should be discussed based on moisture diffusivity during drying. The results of the total drying process (convective or vacuum) time and the effective moisture diffusivities are presented in Table 5.

The pulsed vacuum osmotic pretreatment with sorbitol reduced the drying time, as presented in Table 5. In convective treatments (3 and 4), a reduction of 43% in the processing

Table 5. Effect of different drying conditions on the drying time and effective moisture diffusivities (D_{eff})

Treatment	Drying time (min)	$D_{eff} \times 10^8$ (m^2 s^{-1})	R^2	SE
1	480	1.53	0.98	0.92
2	300	3.07	0.99	0.07
3	690	1.04	0.97	0.75
4	390	1.66	0.96	0.15

R^2 - Coefficient of determination; SE - Sum of square error time was achieved with the immersion of the 'yacon' slices in a hypertonic solution of sorbitol for 300 min. Such an observation was also pointed out in vacuum treatments (1 and 2), in which the pretreatment shortened the drying time by 37%. The lower initial moisture content and the lower density promoted by the expansion of occluded gases and subsequent removal during the PVOD assisted in reducing (Utkucan & Kemal, 2016).

The drying process depends, among other characteristics, on the food microstructure, and the OD causes loss of water and native solutes and solid incorporation that leads to tissue damage such as cell membrane disruption, structural collapse, and shrinkage, which facilitates the moisture removal in a further drying process and promotes energy savings.

Based on the preceding, the OD could improve the drying rate in a subsequent process, in addition to enzymatic browning inhibition, natural color retention, and improvement of the sensory, functional, and nutritional properties of dried products (Mendonça et al., 2017). Those authors observed similar reports during the convective and vacuum drying of pequi (*Caryocar brasiliense*) slices with and without osmotic pretreatments.

Bakhara et al. (2018) studied the OD effect before the convective drying of tender jackfruit and observed that the processing time at 60 °C was 12 hours for the osmosed samples and 18 hours for non-osmosed samples.

Both drying techniques were operated at 60 °C, but due to the low pressures utilized, the vacuum treatments shortened the whole drying process (Table 5). In pretreated samples, a 23% reduction was achieved, and for non-treated samples, the reduction was 30%.

Some authors pointed out higher product quality than CD, and it is especially suitable for fruits and vegetables containing heat-sensitive compounds, as does the 'yacon'. Vacuum application is related to improved drying efficiency and product quality (the oxygen suppression that limits oxidative reactions) and shortens the processing time with low energy consumption (Motevali et al., 2011; Akar & Mazı, 2019).

In the VD process, an increase in the temperature is accompanied by a vapor pressure (inside the sample) increase. Therefore, the pressure gradient between the inner/outer areas of the sample is higher, resulting in a higher drying rate, with a consequent drying time reduction.

According to Table 5, in general, D_{eff} values increased with the osmotic pretreatment. The highest D_{eff} value (3.07×10^{-8} m² s⁻¹) was obtained for OD – VD treatment, followed by OD – CD treatment (1.66×10^{-8} m^2 s^{-1}); while the lowest D_{eff} value (1.04×10^{-8} m^2 s^{-1}) occurred with the IN – CD treatment. For all treatments, the estimated R^2 values were ≥ 0.96.

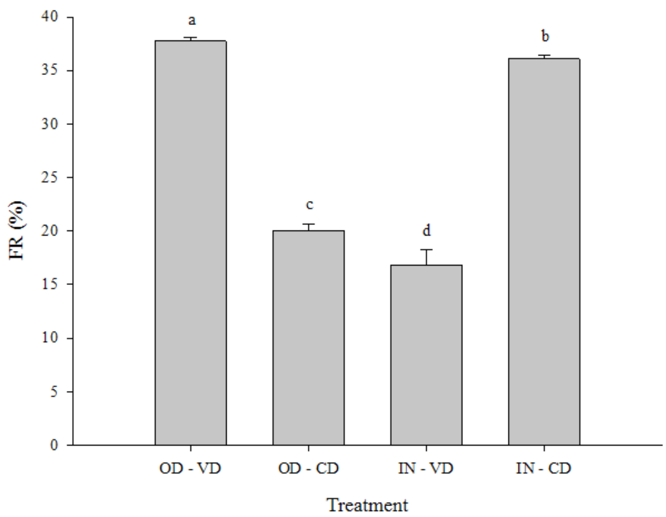
The D_{eff} in 'yacon' increased in the OD - VD treatment probably because of the saturation of the pores with sorbitol from the osmotic solution. During the PVOD, the expulsion of the native fluids from the pores and its filling by osmotic solution could facilitate the moisture removal is an additional drying process, increasing the D_{eff} values (Ahmed et al., 2016).

This might indicate that the moisture removal (and solids incorporation) during the osmotic processes could increase the permeability to vapor, provided that the pore structure remained open (Lyu et al., 2017), increasing the D_{eff} values (Table 5).

The FR of the different treatments is presented in Figure 2.

The ANOVA revealed significant differences ($p \leq 0.05$) in the FR of dried 'yacon' slices due to the different treatments (Figure 2). A reduction in the fructan concentration was expected in all the treatments once fructan oxidation occurs due to the exposure to light and heat, with the FR ranging from 16.84 to 37.72%. Such fructan losses in osmotic experiments (OD – VD and OD – CD) are related to the natural leaching flux that occurs in osmotic processes once this saccharide possesses a hydrophilic nature and migrate from the internal tissue to the osmotic media (Oliveira et al., 2016; Padilha et al., 2017).

The opposite trend was observed for non-osmosed samples (Figure 2). This occurred probably due to possible differences in the composition of the samples. The 'yacon' is a biological sample, and some characteristics may present differences.



Mean followed by different letters differ significantly ($p \leq 0.05$), according to Tukey's test; CD - Convective drying; VD - Vacuum drying; OD - Osmotic dehydration (osmosed samples); IN - fresh (non-osmosed samples)

Figure 2. Fructan retention (FR) in different treatments

Conclusions

1. The pretreatment with pulsed vacuum osmotic dehydration allied with the temperature of 60 °C carried out to a short time drying with higher effective moisture diffusivities values and fructan retention.

2. The decrease of fructan concentration was related to exposure to light, heat, and leaching to the osmotic solution.

3. Fick's second law and Page's equation adjust the drying behavior in both osmotic treated and untreated 'yacon' samples adequately.

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