Australian Journal of
Crop Science
AJCS

AJCS 16(10):1185-1192 (2022) ISSN:1835-2707
doi: 10.21475/ajcs.22.16.10.p3673

Microwave drying of sweet potato: Drying kinetics and energetic analysis

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Abstract

The shelf life of the sweet potato is short due to its high water activity. Therefore, preservative techniques are mandatory. In this sense, the effects of osmotic dehydration (OD) as pretreatment, two different osmotic agents (OA), sucrose and sorbitol, and microwave power density (PD) on the drying kinetics of sweet potato slices (SPS) were studied. The SPS were immersed (pretreated) or not (untreated) in an osmotic solution at $a_w = 0.900$. The samples were placed in the microwave and the drying proceeded until the moisture content was 0.20 ± 0.02 kg water/kg. The results showed that drying time, effective diffusivity, and specific energy consumption (SEC) increased with both increasing the microwave PD and employing OD. The effective diffusivity and SEC ranged from 5.701×10^{-10} to 5.218×10^{-9} m^2/s and from 7.702 MJ/kg_{water} to 15.608 MJ/kg_{water}, respectively. An adapted model was achieved for describing the drying behavior and presented suitable adjustments. According to the results, 10W/g - sucrose must be selected for drying SPS. Drying time, SEC and η at this level were 480 s, 7.702 MJ/kg_{water} and 29.30%, respectively.

Keywords: osmotic dehydration, power density, shrinkage, emerging technology.
Abbreviations: a_w _ Water activity, D_{eff} _ Effective diffusivity, MWD _ Microwave drying, OA _Osmotic agent, OD – Osmotic dehydration, PD _ Power density, SEC _ Specific energy consumption, SG _ Solid gain, SPS _ Sweet potato slices, WL _ Water loss.

Introduction

The sweet potato (*Ipomoea batatas* (L.)) is one of the most important crops in tropical and subtropical regions (Dereje et al., 2020). It is used for human consumption and animal feed. It is also a raw material for starch, ethanol, and lactic acid production. Moreover, sweet potato consumption is associated with controlling blood sugar (Sudhakar et al., 2021). The high water activity of this product requires techniques for its better use (Vithu et al., 2019).

Drying is the oldest process for food preservation and microwave drying (MWD), one of the most effective emerging technologies to accelerate the drying processes of biological products (Khaing et al., 2018; Li et al., 2020). The microwave enhances the drying through dipole rotation and ionic conductance in an electromagnetic field; it has been applied to different food matrices such as vegetables (Çınkır and Süfer, 2020; Souza et al., 2022), fruits (Zielinska et al., 2018), spices (Surendhar et al., 2019) and seafood (Kouhila et al., 2020), with and without osmotic pretreatment. The microwave power density (PD) is an essential variable in MWD that must be considered for improvement to make the process workable (Shivhare et al., 1991; Monteiro et al., 2021).

OD is usually a non-thermic pretreatment that consists of food immersion in a hypertonic solution. The gradient of chemical potential between the solution and the food promotes mass transfers. Osmotic treatment usually reduces the drying time further, contributing to the energetic efficiency of the process (Ciurzyńska et al., 2016; Dash and Balasubramaniam, 2018; Abrahão and Corrêa, 2021). OD coupled with MWD is an effective arrangement for efficient energy use and obtainment of good quality dried foods (Zielinska et al., 2017; Sharif et al., 2018; Li et al., 2020).

For sweet potato drying, many methods are suitable, among which convective drying is the most used technique (Liu et al., 2017). However, this process presents some drawbacks, such as long drying times (Roknul et al., 2014), low energy efficiency (Khaing et al., 2018), and significant physical, nutritional, functional, and chemical modifications (Samoticha et al., 2016).

Thus, novel drying technologies such as microwaving (Lee et al., 2019) and pretreatments such as osmotic dehydration (Junqueira et al., 2017) could enhance the energy efficiency and the quality of dried sweet potatoes. These emerging technologies fill the gaps left by traditional drying methods.

To our knowledge, studies on OD of sweet potato slices (SPS) with nonionic agents preceded by microwave drying are scarce and could offer an interesting response to the effect of the different treatments for obtaining a dried product. This study aimed to evaluate the MWD of non-osmosed (fresh) and osmosed SPS in different power densities (PD), employing two osmotic agents (OA), sucrose and sorbitol. The effects of the use of OD, the OA, and the PD were evaluated in the drying kinetic behavior, mathematical modeling, and energetic analysis.

Results and Discussion

Osmotic dehydration (OD)

The experiments with OD performed in binary solutions of sucrose or sorbitol and their effects are presented in Table 1.

The dehydration reduces the moisture content once the water comes out of the cellular tissue to the osmotic media. The process reduced the initial moisture content by approximately 65%, regardless of the osmotic agent employed. The osmotic processes lead to intermediate moisture products and require further treatments such as drying for microbiological quality assurance (González-Pérez et al., 2021). Similar values were obtained by Junqueira et al. (2018) during the OD of different vegetable structures.

Significant differences ($p \leq 0.05$) in water loss (WL) and solids gain (SG) were found for the different osmotic solutes (Table 1). The WL values were calculated as 0.371 and 0.410 kg water/kg, whereas the SG values were 0.107 and 0.104 kg solid/kg for sucrose and sorbitol, respectively. Apart from the dehydration (WL), the solute incorporation (SG) during the process can make the mass transfer during further drying difficult (Salim et al., 2019).

Such a result indicates that dehydration (WL) is more pronounced than impregnation (SG), preferable in osmotic processes. Osmotic solutes with lower molecular weight (such as sorbitol, 182.17 kg/kmol) can more easily penetrate the tissues than solutes of higher molecular weight (such as sucrose 342.29 kg/kmol). Due to its dehydration efficiency, the use of sorbitol as an osmotic solute is recommended (Brochier et al., 2014).

Microwave drying (MWD)

The influence of OD and PD on the drying kinetics is shown in Figure 1. For all the treatments, the drying rate was higher in the first minutes of the process. In the initial stages, the moisture content is higher, so the sample absorbs more microwave energy, leading to a pronounced generation of internal heat, which implies a higher drying rate. As the process proceeds, the moisture content is reduced, diminishing the microwave energy absorption (Al-Harahsheh et al., 2009).

Regardless of the PD applied, non-osmosed samples required a longer time to be dehydrated. On the one hand, the initial moisture content is lower in the MWD when the samples were previously osmodehydrated, approximately 33% lower than the fresh (non-treated) samples. On the other hand, the osmotic processes lead to cell membrane disruption, which facilitates moisture removal in a different drying process. Another point is that the decrease in the moisture content and the incorporation of solutes could change the food dielectric properties by modifying the interactions between the SPS and the electromagnetic field, consequently reducing the drying process time. During the microwave drying of red radish, Çınkır and Süfer (2020) observed a reduction of approximately 44% to 64% in the drying time, comparing osmosed and non-osmosed samples. Li et al. (2020) studied the effects of OD on the dielectric properties of yams during drying processes. They observed an increase in the loss factor of the samples related to the dielectric properties. Such an improvement in the loss factor facilitated the absorption and dissipation of microwave energy, enhancing the drying. Su et al. (2021) observed improved potato osmotically pretreated dielectric properties, thus intensifying the moisture reduction in the microwave-assisted drying process.

The PD increase leads to a drying kinetic intensification. As observed in Figure 1, at PD 10 W/g, the drying process was faster than obtained at 5.1 W/g. Similar findings were reported by Heredia et al. (2007), who observed a considerable reduction in drying time as microwave power was increased during the microwave drying of cherry tomatoes. Chahbani et al. (2018) observed that the moisture content decreased rapidly at high microwave power during the drying of green peas using different microwave power levels.

According to Figure 1, the drying time for non-osmosed was 990 s in the treatment at 10 W/g and 1500 s in the treatment at 5.1 W/g. Similar behavior was observed for osmodehydrated samples. A lower drying time (360 s) was achieved in the samples pretreated with sucrose at 10 W/g. Such a reduction in drying time was observed by Ghanem et al. (2012), comparing different microwave power levels during the MWD of Thompson, mandarin, and lemon peels. The higher the microwave power, the higher the heat generation inside the material. Therefore, the moisture vaporization increases, improving the pressure difference (driving force related to moisture diffusion, from the inner to the sample surface) (Lüle and Koyuncu, 2015).

The effective diffusivities (D_{eff}) were calculated according to Fick's diffusion theory, and the results are presented in Table 2.

The D_{eff} values ranged from 5.701×10^{-10} to 5.218×10^{-9} m^2/s. The results showed that R^2 values were mainly greater than 0.85, and root mean square error (RMSE) and χ^2 values were lower than 0.109 and 0.012, respectively. Even though the D_{eff} varies for the different treatments, the results presented analogous magnitude orders of food materials subjected to microwave drying (Chahbani et al., 2018).

In general, the values were lower in non-osmosed samples. Lower D_{eff} was observed for the samples treated at 5.1 W/g, as presented in Figure 1. The higher D_{eff} observed in samples dried at 10 W/g is related to increasing the water molecules' kinetic activity (Zarein et al., 2015). During the microwave drying of persimmon slices, Çelen (2019) observed higher D_{eff} in the treatments conducted at higher microwave power.

According to Table 2, this analytical resolution of Fick's model

Table 1. Water loss (WL), solid gain (SG) and performance ratio (WL/SG) of osmotically dehydrated SPS.

Osmotic agent	Moisture content [kg water/kg]	WL [kg water/kg]	SG [kg solid/kg]
Sucrose	0.503 ± 0.019a	0.371 ± 0.006b	0.107 ± 0.001a
Sorbitol	0.497 ± 0.022a	0.410 ± 0.002a	0.104 ± 0.001b

Mean followed by different letters in the column differs significantly ($p \leq 0.05$), according to Tukey's test. CV - 6.21%.

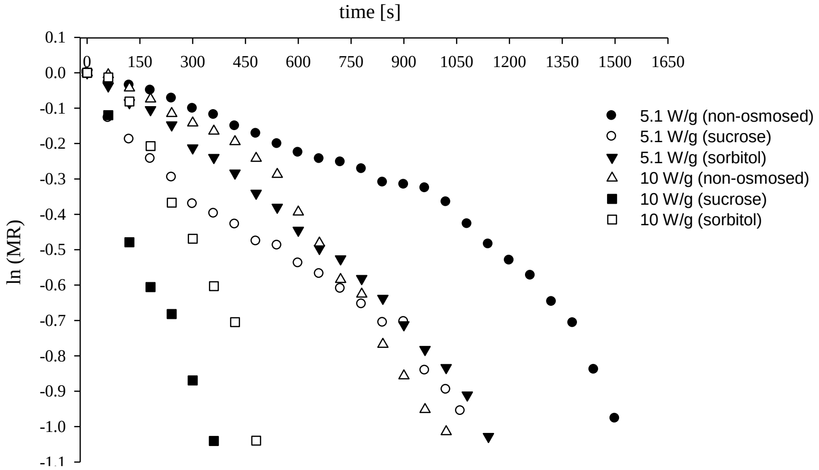

Figure 1. Variation in the moisture content *versus* time during the microwave drying of SPS.

Table 2. Effective diffusivities (D_{eff}) [m^2/s] of microwave dried SPS at different microwave power densities according to the use of the OD process.

Treatment	$D_{eff} \times 10^9$	R^2	$\chi^2 \times 10^3$	RMSE × 10^2
5.1 W/g (non-OD)	0.570	0.872	7.234	8.340
5.1 W/g (sucrose OD)	1.475	0.993	0.363	1.853
5.1 W/g (sorbitol OD)	1.139	0.934	4.454	6.496
10 W/g (non-OD)	1.099	0.855	12.687	10.946
10 W/g (sucrose OD)	5.218	0.957	4.002	6.078
10 W/g (sorbitol OD)	2.327	0.873	10.767	10.066

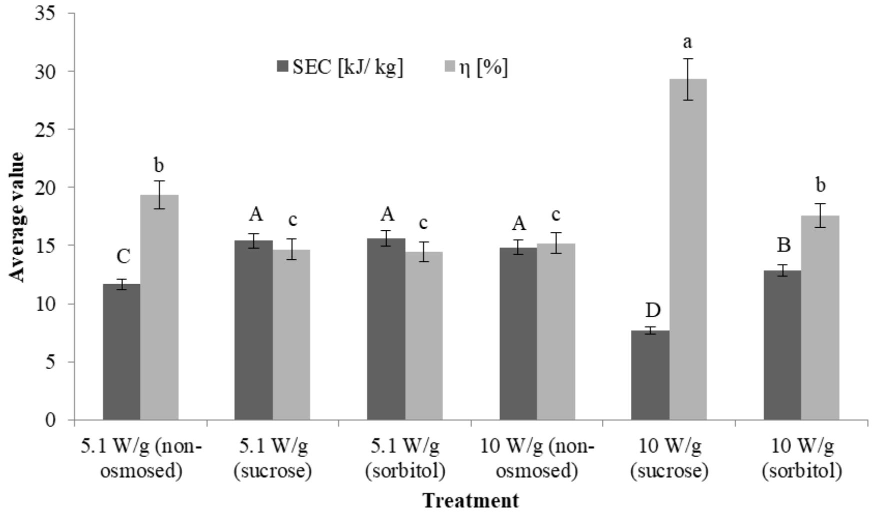

Figure 2. Specific energy consumption (SEC) and efficiency (η) for microwave drying of SPS. Mean followed by different uppercase letters (SEC) and lowercase letters (η), shows significant differences ($p \leq 0.05$), according to Tukey's test.

Table 3. Parameters of the adapted drying kinetics model.

Parameters	Non-osmosed	Sucrose	Sorbitol
a	22.219	11.211	0.992
k	0.0683	0.0046	0.00002
n	0.6188	1.0095	1.6849
R^2	0.938	0.971	0.973
$\chi^2 \times 10^3$	1.054	1.410	2.051
RMSE × 10^2	3.164	4.304	3.595

showed lower R^2 values (even 0.85), indicating its low acuity for portraying the experimental data. This diffusional model is widely employed for describing drying processes (Corrêa et al., 2017; Balzarini et al., 2018; Vallespir et al., 2018). Due to the heterogeneous food composition associated with the complexity of the mass transfer process, this diffusive model may occasionally present a lower fitting capacity (Simpson et al., 2015; Junqueira et al., 2017).

The analytical development of the model's initial and boundary conditions such as uniformity of initial moisture content, negligible shrinkage, and the D_{eff} value constant may be the reasons for the low acuity in some treatments. The food material is not homogeneous, and other mechanisms than diffusion are related to the mass transfer, mainly in microwave drying. These physical alterations affect the development and suitability of the models to represent the process (Miano and Augusto, 2018; Junqueira et al., 2021).

Adapted drying kinetics model

Table 3 shows the results for the parameters R^2, χ^2, and RMSE of the adapted drying kinetics model adjusted to the experimental results. R^2 values were mainly greater than 0.97, χ^2, and RMSE were lower than 0.002 and 0.004, respectively. This means a high agreement between the experimental drying results to the proposed model.

In this model, the size of the solute molecule and water activity influence the "a" parameter since the pretreatment step greatly influences drying.

The "k" parameter of Page's model, according to Simpson et al. (2017), is related to the diffusion coefficient and the geometry of the sample. Thus, the reduction in "k" values for materials submitted to OD may be related to the significant increase in effective diffusivity compared to the non-osmosed drying. However, the heating power of the microwaves, as it directly influences the reduction of drying time and temperature increase, also directly affects the "k" parameter.

The "n" parameter from Page's model is directly related to the type of diffusion and structure of the food material (Simpson et al., 2017). Therefore, by the values of "n" it is possible to verify that for non-osmosed drying, the process is considered sub-diffusion ($n < 1$). Still, when using an OD process, the system becomes super-diffusion ($n > 1$). The diffusion process is greater for large solute molecule sizes; that is, the "n" value is greater.

Therefore, it is possible to verify that, even with significant changes in Page's model, the parameters of the proposed model still follow the behavior of the original model.

To verify the application potential of the model with other experimental data, the drying adapted kinetics model was applied in other works in the literature. The adjustment has been made in works with MWD. Analyzing the R^2 of the adjustment in the studies of Aamir and Boonsupthip (2017), Zhao et al. (2019), and Khodabakhshi et al. (2015), the values obtained were 0.996, 0.985, and 0.964, respectively. This demonstrates the good applicability of the drying kinetics model adapted to different foods as an up-and-coming model for the industry.

Energetic analysis

Figure 2 presents the average values of SEC and η for the microwave drying of SPS.

The SEC ranged from 7.702 MJ/kg_{water} to 15.608 MJ/kg_{water}. This quantitative parameter is related to the drying time process, microwave power, and mass of evaporated water (Eq. 9). Even though the increase in the PD results in more power production and shorter drying duration, the relation of each cited variable makes a comparison among the treatments difficult, and no trend was observed. The differences in the results are related to differences in the drying conditions, equipment, and intrinsic properties of the products (Beigi et al., 2020).

At higher PD, the drying duration was reduced (Figure 1). The fastest treatment was 10 W/g - sucrose (360 s), which presented a lower SEC (Figure 2). The necessary time for the water molecules to reach evaporation temperature is enhanced at higher PD, and theoretically, the energy spent on the evaporation process could decrease (Çelen, 2019; Beigi and Torki, 2020).

During the microwave drying of persimmon slices with different thicknesses, Çelen (2019) obtained SEC ranging from 12.18 to 27.66 MJ/kg_{water}. Beigi and Torki (2020) evaluated the MWD of onion slices and observed values for SEC ranging from 0.82 to 5.43 MJ/kg_{water} under different conditions. Darvishi (2012) obtained values for the microwave drying of potato slices ranging from 4.22 MJ/kg_{water} (PD = 15.0 W/g) to 10.56 MJ/kg_{water} (PD = 5.0 W/g). Surendhar et al. (2019) found SEC values for microwave drying of turmeric at various microwave power levels ranging between 9.78 and 24.61 MJ/kg_{water}.

The microwave drying efficiency (η) is shown in Figure 2. The values ranged from 14.45% to 29.30%. The higher the SEC, the lower the η. It is related to the thermal efficiency of the dryer as the ratio of energy absorption ($m_w \times \lambda_w$) and energy consumption ($P \times t$) (Darvishi et al., 2016).

As seen in Figure 2, the osmotic process is related to the energetic analyses. The solute incorporation may hinder the real effect of the microwave power in the water evaporation, and similar to the SEC, no trend was observed.

During the microwave drying of kiwifruits, Darvishi et al. (2016) obtained η values ranging from 15.1% to 32.7%, evaluating different thickness samples and microwave power levels. The results obtained in this experiment align with Azadbakht et al. (2018) during the microwave drying of orange slices.

The best result concerning energy aspects (SEC = 7.702 MJ/kg_{water} and η = 29.30%) was obtained from the treatment of 10 W/g - sucrose (Figure 2), combined with a lower process time at this condition (Figure 1).

Materials and Methods

Sample preparation

Sweet potatoes (*Ipomoea batatas* (L.)) Braslandia branca cv. were obtained in a local market (Lavras, Brazil) and stored in a refrigerator before the experiments (7 ± 1ºC). The roots were selected based on their appearance, firmness, weight, and size. The moisture content of the roots was determined using a vacuum drying oven (SL104/40; Solab, Piracicaba, Brazil) at 70°C until a constant weight was achieved (AOAC, 2016). Water activity (a_w) was determined using a hygrometer (Aqualab, 3-TE model, WA, USA). The analyses were performed in triplicate. The initial moisture content was 0.758 ± 0.014 kg water/kg and the a_w was 0.988 ± 0.002, similar to those obtained in preliminary studies (Junqueira et al., 2016).

The sweet potatoes were washed in tap water, peeled, and sliced (20.0 mm length × 20.0 mm width × 5.00 mm thickness) using a stainless-steel mold. Then, the SPS were soaked in an aqueous citric acid solution of 1% (w/v) for three minutes to prevent enzymatic browning (Mendonça et al., 2017).

Osmotic processes

The osmotic solutions were prepared with distilled water and the selected osmotic agents, sucrose and sorbitol. The solution concentration was 60.0 and 52.4 kg/100 kg (w/w), respectively. Different concentrations of the agent were used to maintain the same a_w for both solutions, 0.900 ± 0.002.

The OD experiments were conducted in a chamber with temperature control (ELETROlab, EL 111/4 model, Brazil) at local atmospheric pressure (755 mbar). The temperature was set at 30.0 ± 0.5ºC, and the ratio of root to solution was 1:10 (w/w) to prevent the dilution of the osmotic solution during the experiments.

The samples were weighed and soaked in the osmotic solution for 180 minutes (Junqueira et al., 2016). After that, each SPS was removed from the osmotic solution and immersed in a cold-water bath for ten seconds to halt the mass transfer. Finally, the samples were weighed, and the moisture content was obtained according to AOAC (2016). The experiments were performed in four replicates. WL and SG were calculated following Equations 1 and 2, respectively

$$WL = \frac{(M_0 \times X_{w0}) - (M_t \times X_{wt})}{M_0} \tag{1}$$

$$SG = \frac{(M_t \times X_{st}) - M_0(1 - X_{w0})}{M_0} \tag{2}$$

where X_{w0} is the initial moisture content (on a wet basis) [kg water/kg], X_{wt} and X_{st} are the water and soluble solids content, respectively, at any time, and M_0 and M_t are the initial and final sample mass [kg], respectively. The performance ratio was calculated as the relation WL/SG.

Microwave drying (MWD)

A microwave system (Electrolux, MEC41, Curitiba, Brazil) with a maximum output of 1550 W at 2450 MHz was used for the MWD experiments. For each test, approximately 0.35 kg of SPS were placed in a single layer in a polyethylene dish. The microwave power levels were 180 W and 350 W, corresponding to initial power densities (PD) of 5.1 and 10.0 W/g, respectively. A digital balance (OHAUS, ARC120, China, 3,100 g) coupled to the system continuously recorded the sample mass reduction each 60 s during the process. The final moisture content was set at 0.20 ± 0.02 kg water/kg for all the treatments. Drying runs were done in triplicate, and the average values were reported.

Kinetic and mathematical modeling

Drying kinetic

The moisture was recorded during the MWD, and the moisture ratio (MR) was calculated according to Equation 3.

$$MR = \frac{X_t - X_e}{X_0 - X_e} = \frac{X_t}{X_0} \tag{3}$$

where MR is the moisture ratio [dimensionless], X_t is the moisture content at a specific time [kg water/kg], X_0 is the initial moisture content [kg water/kg], and X_e is the moisture content in equilibrium conditions [kg water/kg]. In microwave drying, the X_e value is generally much lower than X_t and X_0. Therefore, its value was set to zero (Çınkır and Süfer, 2020).

Effective diffusivity

Fick's second law of diffusion has been extensively used for describing the drying behavior of agricultural products (Molina Filho et al., 2016; González-Pérez et al., 2021). Although the MWD is not a pure diffusional process, Fick's model could greatly adjust MWD in several microwave power densities (Du et al., 2020).

The unidirectional unsteady-state diffusion, based on Fick's second law is given by Equation 4:

$$\frac{dX_t}{dt} = D_{eff} \nabla^2 X_t \tag{4}$$

where D_{eff} is the effective diffusivity [m^2 /s].

The solution to Equation 4 is obtained using the Fourier series, following certain assumptions (Crank, 1975):

- Uniform initial moisture content, $X_{(z,0)} = X_0$;
- Moisture concentration symmetry, $\frac{dX_t}{dt} = 0$;
- Equilibrium content at the surface, $X_{(L,t)} = X_e$;
- The samples are infinite slabs (length and width much greater than thickness);
- The process is isothermal;
- Shrinkage and external resistance to mass transfer are neglected.

Considering a brief process and unidirectional moisture diffusion, the D_{eff} is calculated according to Equation 5

$$MR = \left(\frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left(-(2i+1)^2 \pi^2 D_{eff} \frac{t}{4L^2}\right)\right) \tag{5}$$

where L is the characteristic length (half of the thickness) [m].

Adapted drying kinetics model

Drying kinetics models are quite useful in the food industry; however, it is only possible to adjust the behavior of the moisture with time and temperature with the classic models. In addition, it is known that other factors influence such behavior, microwave PD, and pretreatment steps. For instance, in the case of OD as pretreatment, it is essential to consider the size of the solute molecule and the water activity of the solution.

To include the effects of the microwave PD, water activity (a_w), and molecular mass of the solute (M_{solute}) and solvent ($M_{solvent}$) from osmotic solutions, the model of drying kinetics, adapted from Page's model, was proposed in Equation 6.

$$MR = \frac{a_w}{\left(\frac{M_{solute}}{M_{solvent}}\right)}\, a \exp(-k\, P\, t^n) \qquad (6)$$

where a [-], n [-], and k [$min^{-n} \times kW^{-1}$] are the parameters of the drying kinetics models.

Page's equation is an empirical equation applied to describe water migration throughout food drying processes. In processes with pretreatment by OD and MWD, the water migration process may have specific influences. Thus, it is necessary to implement new parameters to the empirical models, such as Page's, to describe these influences. This has been largely accomplished in the literature, showing that classic empirical models can be adapted according to certain special drying characteristics (Silva Mota et al., 2020).

Statistical evaluation of the models

Experimental results were analyzed using the Statistica 8.0 (Statsoft Inc., Tulsa, USA) software, with equation parameters estimated using a non-linear regression procedure. The adjusted correlation coefficient (R^2), reduced Chi-square (χ^2), and RMSE were calculated to evaluate the goodness of fit. The model fit is better if the value of R^2 is closer to 1.0 and the χ^2 and RMSE values are closer to 0 (Cano-Lamadrid et al., 2017).

Energetic analysis

For the energetic analysis, some parameters were evaluated. The specific energy consumption (SEC) of the MWD processes was obtained as the consumed energy [kJ] for the removal of 1.0 kg of water from the sample, according to Equation 7 (Çelen, 2019; Beigi and Torki, 2020).

$$SEC = \frac{P \times t \times 10^{-6}}{m_{ev}} \qquad (7)$$

where SEC is specific energy consumption [MJ/ kg $_{water}$], P is the microwave power level [W] and m_{ev} is the total mass of evaporated water [kg].

The MWD efficiency (Equation 8) was calculated as the ratio between the heat energy used for evaporating water and the heat supplied by the microwave system (Darvishi, 2012).

$$\eta = \frac{m_{ev} \times \lambda_w}{P \times t} \times 100 \qquad (8)$$

where η is the microwave drying efficiency [%] and λ_w is the latent heat of water vaporization [kJ/kg], which corresponds to approximately 2,257 kJ/kg (at 100ºC) (Zarein et al., 2015). All the analyses were performed in triplicate, and average values were reported.

Statistical analysis

The results were evaluated by one-way analysis of variance (ANOVA) at the 95% probability level. In the case of significant effects ($p \leq 0.05$), the means were compared using Tukey's test. These analyses were performed using Statistica 8.0 (StatSoft Inc., Tulsa, OK, USA).

Conclusion

The microwave drying of SPS was achieved. A reduction in the drying time was observed for osmodehydrated samples. The drying time was also shortened with an increase in the power density. According to the results, 10W/g - sucrose must be selected for drying SPS. Drying time, SEC and η at this level were 480 s, 7.702 MJ/kg_{water} and 29.30%, respectively.

The adapted drying kinetics model proved to be satisfactory to predict the influence of moisture reduction as a function of the molar mass of the solute molecule and water activity of the OD solution and microwave heating power. Thus, the MWD of pretreated samples presents adequate prospects for industrial use as an emerging technology alternative for obtaining quality products.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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