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Hybrid microwave-hot air drying of the osmotically treated carrots

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ABSTRACT

The influence of the hot air drying (HAD) and the hybrid drying (microwave drying followed by HAD) with (MWODHAD) or without (MWHAD) previous osmotic dehydration (OD) was evaluated on the effective moisture diffusivity (D_{eff}), volumetric shrinkage (Sh), rehydration, carotenoid content and color of sliced carrots. The OD was performed with a ternary solution of sucrose and sodium chloride (35 °C; 300 min). The HAD procedure was carried out at 70 °C (1.5 m/s) and the MWHAD was tested using three different power levels (55.7, 167.9, 336.8 W) until the final moisture content of 0.13 ± 0.01 kg H_2O/kg dry matter (DM). The results showed that the use of MWHAD with the highest power, reduced ($p < 0.05$) the total drying time (144 min) and increased the D_{eff} compared to the HAD. Moreover, the MWHAD treatment showed the highest values of Sh, rehydration and carotenoid content. The sliced carrots dried using these three drying arrangements had no significant differences in color. In general, the combined treatment MWHAD could improve the drying rate and the quality.

1. Introduction

Carrot (*Daucus carota* L.) is a source of functional components such as vitamins (A, D, B, E, C, and K), minerals (calcium, potassium, phosphorus, sodium, and iron), carotenoids and antioxidants, being an important vegetable in the prevention of cancer and cardiovascular diseases (Singh, Kulshrestha, & Kumar, 2013). Due to its high perishability, the transformation of fresh carrots into a dehydrated product is an alternative to reduce microbial spoilage and chemical reactions (Gong et al., 2019).

Hot air drying (HAD) is among the simplest methods for food preservation (Isquierdo et al., 2013). However, due to the usual high temperatures used in a HAD, it is common occur degradation of flavorings and nutritional compounds, as well as, structural collapses and color change (Ángel;Calín-Sánchez et al, 2014; Md Salim et al., 2019). Therefore, the use of hybrid drying techniques is an alternative to reduce these changes because the combined technology receives the benefits of the individual processes (Zielinska, Ropelewska, Xiao, Mujumdar, & Law, 2019). Advances in the use of emerging food processing technologies have favored the employment of microwave energy, mainly to speed up the conventional drying process, maintaining the quality of the dried product. Among the factors that interfere with microwave drying (MWD), the power level used has a direct effect on the drying rate. Low levels can lead to a reduced drying rate, while high levels could increase it, but could also depreciate the quality of the final product (C. Kumar & Karim, 2019; Q. Wang et al., 2019).

On the other hand, osmotic dehydration (OD) is a widely used method for the partial removal of moisture from plant tissues by the immersion of the food in a hypertonic solution (Oliveira, Corrêa, Botrel, et al., 2017). The OD has been used as a pre-treatment in the hybrid drying of some fruits and vegetables as yacon (Oliveira, Corrêa, Silveira, Vilela, & Junqueira, 2017), black chokeberry (Ángel Calín-Sánchez, Figiel, et al., 2014), carrot (Mierzwa, Kowalski, & Kroehnke, 2017) apple (Dehghannya, Farshad, & Heshmati, 2018), among others, attaining products with high quality. Moreover, OD favors the homogeneous heating in a further MWD by the change in dielectric properties, due to solute absorption, reducing shrinkage, porous structure and improving the rehydration characteristics (Torringa, Esveld, Scheewe, Van Den Berg, & Bartels, 2001).

Nevertheless, there is a lack of information in the literature of studies of hybrid drying techniques of HAD with MWD, pretreated with OD. Therefore, the present study was carried out to evaluate the influence of

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the hot air drying (HAD) and the hybrid drying (microwave drying followed by HAD) with (MWODHAD) or without (MWHAD) previous osmotic dehydration (OD) in some quality parameters of sliced carrots.

2. Materials and methods

2.1. Material and sample preparation

Fresh carrots were purchased in a local market (Lavras, MG state, Brazil) and randomly chosen with a uniform appearance, size, color intensity and firmness. Then, the vegetables were stored at 8 ± 1 °C until use. The mean moisture content and water activity of the fresh carrot were 7.93 ± 0.12 kg H_2O/kg DM and 0.980 ± 0.003, respectively. Subsequently, the carrots were cut with the aid of a stainless-steel mold into slices of 2.00 cm × 2.00 cm × 0.55 ± 0.04 cm (length × width × thickness). The samples presented parts of the xylem, phloem and cortex, but not the peel. Thus, for all analyzes performed, the samples comprised all of these parts.

2.2. Experimental design

Three types of experiments were carried out (Fig. 1). On the one hand, samples were submitted a direct HAD at 70 °C and 1.5 m/s. On the other hand, a hybrid drying process of the sliced carrots was carried, this process consisted of microwave drying at different powers (55.7, 167.9, 336.8 W) followed by HAD. Finally, the third type of experiment was performed with the hybrid drying process with an osmotic pretreatment in a solution of sucrose and sodium chloride. Details of each process are described as follows.

2.2.1. Osmotic dehydration (OD)

The OD was performed using a ternary solution prepared with distilled water, sucrose [40 kg/100 kg (w/w)], and sodium chloride [10 kg/100 kg (w/w)] [a_w 0.836 ± 0.001]. The samples were immersed in the osmotic solution at 35 °C for 300 min in a temperature-controlled chamber without mechanical agitation (ELETROlab, EL 111/4 model, Brazil). This condition was optimized by Junqueira, Corrêa, Mendonça, Mello Junior, and Souza (2018) to higher water loss and lower solid and sodium incorporation. The ratio of the weight of the product to the weight of the solution was about 1:10 to avoid dilution of the osmotic solution (Corrêa, Dev, Gariepy, & Raghavan, 2011). After completing the OD time, samples were removed from the solution, quickly rinsed in a bath of distilled water the surface of the sample was dried with absorbent paper (Viana, Corrêa, & Justus, 2014). The tests were carried out in quintuplicate.

2.2.2. Microwave drying (MWD)

The MWD was carried out in a microwave oven (Electrolux, Model MEC41, Joinville, Brazil) with a nominal power of 1500 W and an internal capacity of 31 L. The power used in each level studied was measured by IMPI 2-liter test (Buffler, 1993), describe in detail by Soysal, Ayhan, Eştürk, and Arikan (2009), therefore, three different microwave power levels were used [55.7, 167.9, 336.8 W] (Table 1). The carrots were placed in a perforated tray on the oven turntable of the

Table 1
Initial and final power density (PD), power level of microwave drying step with (MWODHAD) or without (MWHAD) pretreatmen osmotic dehydration (OD).

Code	Initial PD [W/m^2]	Final PD [W/m^2]	Power [W]
1MWHAD	0.65 ± 0.01	1.58 ± 0.02	55.7 ± 2.0
2MWHAD	1.77 ± 0.02	4.08 ± 0.06	167.9 ± 6.6
3MWHAD	3.43 ± 0.03	7.86 ± 0.17	336.8 ± 4.0
1MWODHAD	0.65 ± 0.00	1.19 ± 0.00	55.7 ± 2.0
2MWODHAD	1.89 ± 0.21	3.86 ± 0.47	167.9 ± 6.6
3MWODHAD	3.45 ± 0.01	6.47 ± 0.25	336.8 ± 4.0

Average value ± standard deviation (n = 5). The numbers 1, 2 and 3 represent different microwave power levels of microwave drying step with (MWODHAD) or without (MWHAD) pretreatmen osmotic dehydration (OD).

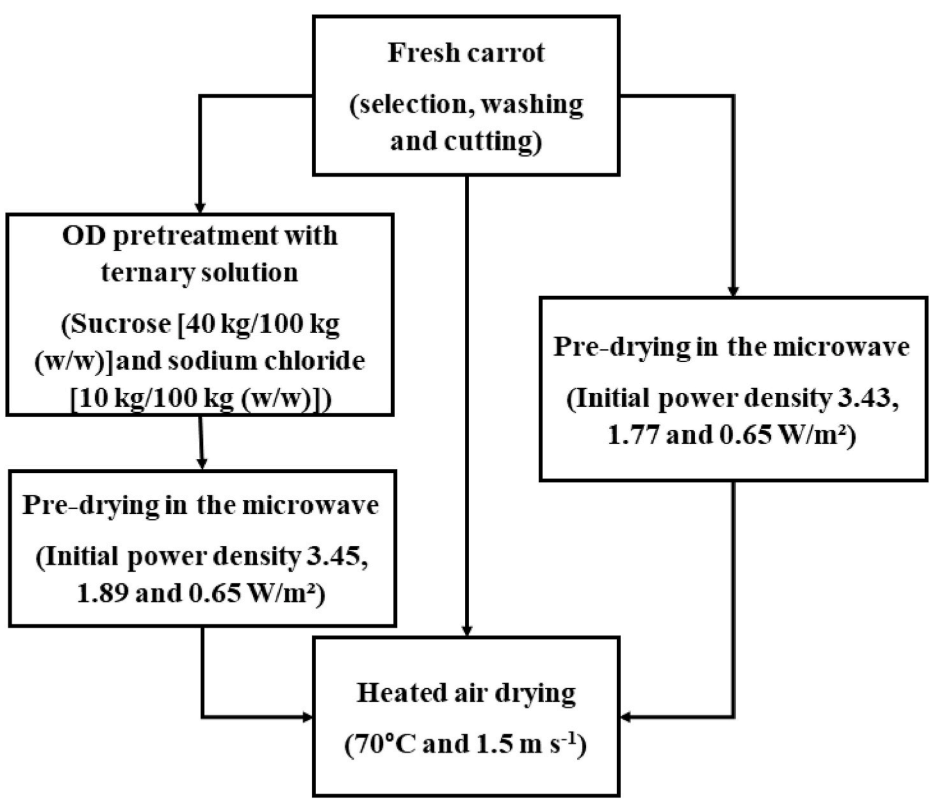

Fig. 1. Drying process of carrots by hybrid drying with (MWODHAD) or without (MWHAD) previous osmotic dehydration (OD) at different power levels.

oven and the mass of the samples was periodically measured (Ohaus, model Adventure ARC120, Nanikon, Switzerland). The residence time of the product in the microwave was previously established based on the longest duration of microwave heating with no charring of the samples (Dehghannya et al., 2018). Measurements of power level [W], power densities [PD] [W/m^2], total drying time [TD] [min] and final temperature [°C] (Fluke, 62 MAX model, Eindhoven, Netherlands) were determined.

2.2.3. Hot air drying (HAD)

After pre-drying with microwave, samples were submitted to HAD in a tunnel dryer (Eco Engenharia Educacional, MD018 model, Brazil) with the parallel flow at 70 °C and 1.5 m/s. In each batch, about 101.06 ± 0.89 g of carrots were dried. The drying occurred until the minimum moisture content of 0.13 ± 0.01 [kg H_2O/kg DM].

2.3. Mathematical modeling

The moisture ratio (M_R) of the sample was calculated from the experimental moisture data using Eq. (1):

$$M_R = \frac{(M - M_e)}{(M_0 - M_e)} \approx \frac{M}{M_0} \tag{1}$$

where M is the moisture content [kg H_2O/kg DM] at any time, M_0 is the initial moisture content [kg H_2O/kg DM]. The M_e is the equilibrium moisture content [kg H_2O/kg DM] in which the value was much lower with relation to initial moisture content and moisture content at the time [t]. Therefore, its value was assumed to be zero for the drying conditions (Faruq, Zhang, & Fan, 2019).

The effective moisture diffusivity (D_{eff}) of carrots slices was estimated by Fick's second diffusion law for slab geometry Eq. (2):

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

where D_{eff} is the effective diffusivity of the water [m^2/s], n is the number of series terms, L is the characteristic length (sample half-thickness) [m], t is the time [s], and M_R is the dimensionless moisture content.

The effective diffusivities were obtained using the non-linear regression (Quasi-Newton) from software Statistica 8.0 (Statsoft Inc., Tulsa, USA) considering the expansion of the equation with five terms. The fitting of the model was evaluated by the coefficient of determination [R^2] (Eq. (3)), chi-square [χ^2] (Eq. (4)) and root mean square error [RMSE] (Eq. (5)). The higher the values of the R^2, and the lower the values of the RMSE and χ^2, the better the goodness of the fit (Faruq et al., 2019).

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N}\left(M_{Rpre,i} - M_{Rexp,i}\right)^2}{\sum_{i=1}^{N}\left(M_{Rpre,i} - M_{Rexp,i}\right)^2}\right] \tag{3}$$

$$RSME = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{Rexp,i} - M_{Rpre,i}\right)^2\right]^{1/2} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(M_{Rexp,\ i} - M_{Rpre,i}\right)^2}{N - n} \tag{5}$$

where, $M_{Rexp,i}$ is the ith experimental moisture ratio, $M_{Rpre,i}$ the ith predicted moisture ratio, N is the number of observations and n is the number constants.

2.4. Quality analysis

2.4.1. Moisture content and water activity

The moisture content [kg H_2O/kg DM] of the samples was determined in a vacuum drying oven at 70 °C until constant weight (AOAC, 2010). The water activity [a_w] was measured with a dew-point hygrometer (Decagon Devices Inc., Aqualab Series 3, USA). Both analyses were carried out in triplicate.

2.4.2. Volumetric shrinkage (Sh)

The thickness of the samples was obtained as an arithmetic average of measurements at five different points with the use of a digital caliper (Western, 150 mm-DC-60, China). The surface area of the samples was directly measured from photographs with the software ImageJ®. The area and thickness measurements were run in quintuplicate. The volume was calculated by multiplying the surface area by sample thickness. The volumetric shrinkage [Sh] was expressed as the ratio between the volume after and before drying, and the closer to unity, the smaller the volumetric ratio of the sample (Junqueira et al., 2018) Eq. (6):

$$\text{Sh} = \frac{V_i - V_f}{V_i} \tag{6}$$

Where V_i is the initial volume of carrots (m^3) and V_f is the volume after drying (m^3).

2.4.3. Rehydration experiments

The dried carrot was rehydrated in 100 ml of water at 25 °C. The change in the mass of rehydrated slices was measured after 50 min of immersion. Five samples were tested and the average values were reported. The rehydration of the dried carrots was then calculated with Eq. (7) (Levi, Ben-Shalom, Plat, & Reid, 1988):

$$\text{Rehydration}\quad [\%] = \frac{W_r - W_d}{W_d} x100 \tag{7}$$

Where W_d is the mass of dried carrot [kg] and W_r is the mass of rehydrated carrot at time t [kg].

2.4.4. Carotenoid content

The carotenoid content was obtained according to the methodology described by Rodriguez-Amaya (2001) based on extraction with acetone and separation in petroleum ether. Absorbance was measured by UV/Vis spectrophotometry (Cary 50, Varian, Australia) at 444, 450 and 470 nm, which correspond to α-carotene, β-carotene, and lycopene determination, respectively. The carotenoid content was expressed as micrograms of carotenoid per gram of dry matter [μg/g DM].

2.4.5. Color

The measurement of color parameters was based on the CIELAB coordinates (L*, a*, b*) evaluated with D65 illuminant. The measurements were done directly with a Minolta (CR300) in five samples and the average values were reported. The color values were expressed as L* (lightness/darkness), a* (redness/greenness) and b* (yellowness/blueness). The global color change (ΔE) was determined by Eq. (8) (Kroehnke et al., 2018):

$$\Delta E^* = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \tag{8}$$

where L* indicates the lightness (100 for white to 0 for black), a* indicates red when positive and green when negative, and b* indicates yellow when positive and blue when negative. The subscript '0' refers to the fresh fruit color parameters.

2.5. Statistical analysis

The quality analysis results were analyzed by one-way ANOVA at the 95% probability level and the significant effects ($p < 0.05$) between means were determined by Tukey's test using the software Sisvar 5.6 (Ferreira, 2011).

3. Results and discussion

3.1. Osmotic dehydration (OD)

The use of OD led to a water loss (WL) of about 40.5 ± 1.31%, a solid gain (SG) of 12.6 ± 1.31% and a moisture content of 1.92 ± 0.20 [kg H_2O/kg DM], resulting in a product with a_w of 0.885 ± 0.003. According to (Dehghannya et al., 2018), the range of WL commonly reached by OD is between 25 and 84%. The carrots obtained from OD have fit in a group of food called intermediate moisture foods (IMF), that present a_w values from 0.70 to 0.90 (Vermeulen et al., 2015). The OD has several advantages that are related, mainly, to the decrease in the energy cost and maintenance of the sensorial and nutritional characteristics of the finished product (Ramya & Jain, 2016). Therefore, it is already a very widespread partial dehydration technology in the production of dried foods.

3.2. Drying behavior and effective moisture diffusivity (D_{eff})

The dehydration process developed was composed of three different individual processes and, in the case of MWD, the use of three different PD. For analyzing the diverse situations, the DT of MWD and HAD and the D_{eff} were considered.

Fig. 2 shows the evolution of moisture content with time during the different hybrid drying treatments up to 0.13 g ± 0.01 [kg H_2O/kg DM], with a similar a_w of 0.553 ± 0.036, which is below the critical of 0.6. So, it can be said the processing can contribute to retain microbial growth, enzymatic activity, and non-enzymatic blackening at a minimum, and allowing to achieve the maximum stability of carotenoids (Cuccurullo, Metallo, Corona, & Cinquanta, 2019). It is important to remind that the initial moisture content of the samples pretreated by OD (1MWODHAD, 2 MWODHAD and 3MWODHAD) was lower than the other ones, due to the water loss of the samples by the osmotic treatment (Table 1).

The drying experiment performed only with hot air without osmotic pretreatment was used as a control for observing the alterations by the use of OD and MWD. The use of MWD, with or without previous OD,

Table 2
Microwave drying time (MW-DT), hot air drying time (HA-DT), total drying time (Total DT), final temperature and effective diffusivity (D_{eff}) of carrot dried by hybrid microwave hot air drying (MWHAD), pretreated or not by osmotic dehydration (OD).

Code	MW-DT [min]	HA-DT [min]	Total DT [min]	Final Temperature [°C]	D_{eff} x10^7[m^2/s]
HAD	–	313 ± 12^{a}	313 ± 12^{a}	–	0.57^{cd}
1MWHAD	73 ± 1^{a}	140 ± 10^{a}	206 ± 6^{cd}	35.14 ± 0.96^{a}	0.85^{c}
2MWHAD	20 ± 0^{a}	147 ± 15^{a}	167 ± 15^{e}	42.47 ± 1.86^{a}	1.95^{b}
3MWHAD	11 ± 0^{a}	133 ± 6^{a}	144 ± 6^{de}	41.78 ± 1.45^{a}	2.37^{a}
1MWODHAD	69 ± 3^{a}	177 ± 6^{a}	246 ± 9^{b}	47.02 ± 0.85^{a}	0.66^{c}
2MWODHAD	19 ± 1^{a}	137 ± 15^{a}	156 ± 14^{e}	46.98 ± 0.79^{a}	0.23^{ab}
3MWODHAD	10 ± 1^{a}	213 ± 15^{a}	227 ± 15^{bc}	49.13 ± 1.23^{a}	2.55^{a}

Average value ± standard deviation (n = 3 for the total drying time, drying time of the microwave step and hot air step and for the effective diffusivity; n = 5 for the final temperature). The numbers 1, 2 and 3 represent different microwave power levels of microwave drying step with (MWODHAD) or without (MWHAD) pretreatmen osmotic dehydration (OD). Different letters in the same column show statistical difference ($p < 0.05$) according to Tukey's test.

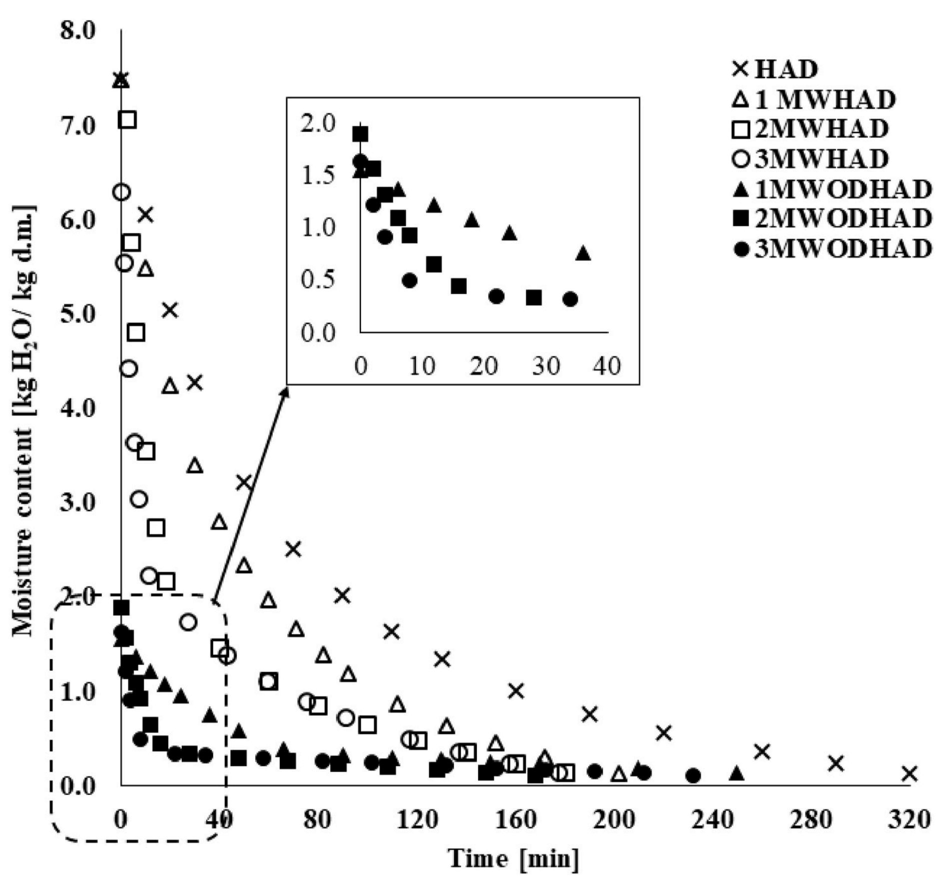

Fig. 2. Change of moisture content with drying time for apple fruits. The numbers 1, 2 and 3 represent different microwave power levels of microwave drying step with (MWODHAD) or without (MWHAD) pretreatmen osmotic dehydration (OD).

resulted in a total DT reduction between 21 and 54% (Table 2). It could be said that this reduction mainly comes from microwave energy. In the MWD the materials are heated through the microwave energy coupling with food, promoted by volumetric heating, while in a HAD the heat transfer comes from the surface to the interior of the food (Cuccurullo et al., 2019). In addition, the initial PD also influenced the DT, inversely. This means that the reduction of the DT is a direct function of the amount of supplied microwave energy, generating, consequently, an increase in the mass transfer (Saha, Dey, & Chakraborty, 2019). It is interesting to note that the time the samples were submitted to MWD was reducing with the increase in the PD, being this time determined in function of the "burning". This condition of drying led to the moisture of 1.89 ± 0.24 [kg H2O/kg DM] to the samples untreated by OD, while the ones treated presented moisture of 0.40 ± 0.04 [kg H2O/kg DM].

The use of OD was not efficient in the reduction of DT when used the highest power level studied (3MWODHAD), presenting an increase of 15% when it is compared with microwave treatment without OD (3MWHAD) (Table 2). It could be attributed due to higher sucrose gained through the OD which changed the dielectric properties of carrots, along with the loss of native compounds leading to an increase in drying time. Similar behavior was observed in a study with kiwi slices (Zhou, Lyng, & Wang, 2018) and apple slices (Dehghannya et al., 2018). In addition, the incorporation of solids into a food can act as the bonding agent of moisture, becoming renders moisture removal more difficult during drying (Dehghannya et al., 2018). This behavior was not observed in the intermediate power levels (2MWHAD and 2MWODHAD), since presented the drying time was similar regardless of the use or not of OD, besides being the treatment that presented the lowest DT. Among the experiments with MWD, the use of lower microwave power levels (1MWHAD and 1MWODHAD), also contributed to obtaining higher drying times using or not the osmotic pretreatment. This can be justified by the lower energy provided concerning the treatments that use the higher microwave power level (Saha et al., 2019).

The values of effective diffusivity (D_{eff}) were listed in Table 2. The obtained D_{eff} values were in the range from 2.32×10^{-8} to 2.55×10^{-7} m^2/s ($R^2 = 0.849$ and 0.996, respectively, $\chi^2 < 0.034$ and RSME <0.150), which are common values for food materials (Zarein, Samadi, & Ghobadian, 2015). Although the MWD and the HAD are not pure diffusional phenomena, the adjustment of Fick's model endorses its use for fitting such processes. HAD showed the lowest effective diffusivity value together with the treatments with the low power level of microwave, which leads to the realization that the use of lower power levels leads to low diffusivity of moisture. The D_{eff} of the samples was mainly influenced by the power levels. In this sense, the lower power level provides less energy for the removal of water and, consequently, there is less diffusion of it (Demiray, Seker, & Tulek, 2017). Thus, it is also important to highlight that the use of microwaves increased diffusivity when compared to HAD, confirming that it is a good technique to reduce moisture, which by the results obtained by Ashtiani, Sturm, and Nasirahmadi (2018) in a hybrid drying (MWHAD), of nectarine slices. When adding solute to the food matrix, it is common for these to associate with water molecules, which makes it difficult to remove moisture, which also reduces effective diffusivity. This behavior was not observed. The treatments presented Deff similar to its treatment with osmotic dehydration. In addition, it is worth noting that, although without significant difference, an increase in the power level was able to overcome the moisture retention caused by the incorporation of solutes, increasing the D_{eff}. The obtained values of D_{eff} in this study are comparable with the ones of nectarine slices drying using a hot-air (50 °C and 0.5 m/s), hybrid drying (MWHAD) with 80, 160, 240, and 320 W (Ashtiani et al., 2018), and with pistachio kernel during the convective drying assisted by microwave at 100W (Jahanbakhshi et al., 2020).

3.3. Volumetric shrinkage (Sh)

The Sh of carrot slices was measured after each process step: MWD step and in the hybrid drying with (MWODHAD) or without (MWHAD) OD (Table 3). The results showed that all treatments exhibited Sh. Also, the results obtained show that carrots submitted to OD pretreatment had shrinkage of 0.381 ± 0.027, due to the contracting stress caused by pressure imbalance between the interior and exterior (Junqueira et al., 2018). After MWD, the Sh did not show a significant difference concerning power levels and the use of OD, presenting a value of about 0.631 ± 0.027.

When the whole process is evaluated, that is, hybrid drying with (MWODHAD) or without (MWHAD) OD, it could be observed a significant difference between treatments. The HAD presented the largest Sh, which may be related to the higher time spent in drying, leading to a higher collapse of the cellular structure of the material (Kumar, Devi, Panda, & Shrivastava, 2019). However, the addition of the MWD treatment in the process also did not prevent shrinkage, even with a shorter drying time, being statistically similar to HAD ($p < 0.05$), which can be attributed to large heat generation and accelerated moisture removal, which can cause damage to the cell structure, with consequent shrinkage (Dehghannya, Bozorghi, & Khakb, 2018). No significant differences between variations in power levels were observed concerning this parameter.

In the literature, it is common that microwave drying shows reduced values of food shrinkage. Conte et al. (2019) compared three methods of drying apples (MWD, HAD and MWHAD) and smaller shrinkage was observed when using only MWD, also a more accentuated and similar shrinkage in dried apples by the HAD and MWHAD methods was observed. This behavior was justified by the greater temperature fluctuations during the drying that use HAD, that is, due to the temperature increase occurring gradually, starting from the external part to the internal part of the material, which causes greater damage to the tissue structure.

When assessing punctually the influence of OD in the first drying stage, that is, only in MWD, it can be inferred that its use did not favor the maintenance of the carrot structure. However, when the complete process was evaluated, that is, MWODHAD up to a moisture content of 0.13 g ± 0.01 [kg H_2O/kg DM], it is possible to notice a reduction in shrinkage. The volumetric shrinkage after MWODHAD showed a decrease when used of OD, independent of the power level used, at least 18%. The shrinkage of food materials is commonly related to the drying rate since the rapid moisture removal leads to a pressure imbalance between the inside and the outside of the tissue resulting in compressive stresses for shrinkage, in addition to the collapse of the structure due to the water evaporation in the form of steam (Nahimana & Zhang, 2011; Xu et al., 2020). However, as not possible to correlate the D_{eff} with the shrinkage. The drying time of the treatments that used the drying by MWHAD was shorter than the drying by HAD, but they had the same

Table 3
Volumetric shrinkage after microwave step (MW-Sh), after hybrid drying (Total Sh) treatment and rehydration of carrot dried by hot air drying (HAD) and the hybrid drying with (MWODHAD) or without (MWHAD) previous osmotic dehydration (OD).

Code	MW-Sh [−]	Total Sh [−]	Rehydration [%]
HAD	–	0.820 ± 0.005[a]	253.44 ± 19.45[a]
1MWHAD	0.634 ± 0.024[a]	0.839 ± 0.016[a]	230.81 ± 18.09[a]
2MWHAD	0.603 ± 0.019[a]	0.837 ± 0.011[a]	223.88 ± 1.71[a]
3MWHAD	0.641 ± 0.055[a]	0.824 ± 0.011[a]	257.29 ± 7.13[a]
1MWODHAD	0.672 ± 0.019[a]	0.742 ± 0.018[b]	94.24 ± 12.31[c]
2MWODHAD	0.634 ± 0.058[a]	0.672 ± 0.057[b]	110.65 ± 4.97[bc]
3MWODHAD	0.599 ± 0.032[a]	0.676 ± 0.032[b]	139.56 ± 15.63[b]

Average value ± standard deviation (n = 5 for the volumetric shrinkage, after microwave step and after hybrid drying, and for the rehydration.). The numbers 1, 2 and 3 represent different microwave power levels of microwave drying step with (MWODHAD) or without (MWHAD) pretreatmen osmotic dehydration (OD). Different letters in the same column show statistical difference ($p < 0.05$) according to Tukey's test.

impact on the shrinkage of the samples. Thus, the importance of using DO in the structural maintenance of the carrot is highlighted. This behavior change can be associated with the sucrose gain by the carrot, which, in turn, tends to occupy the empty intracellular spaces. This leads to increased structural strength during drying, reducing shrinkage (Dehghannya et al., 2018). Similar behavior was obtained by Corrêa et al. (2011) in drying of osmodehydrated pineapple by microwave-vacuum, in which they perceived that the presence of solutes led to less shrinkage after drying.

3.4. Rehydration

Dried carrots rehydration was evaluated after 60 min of immersion in water (Table 3). A maximum rehydration ratio was obtained by HAD (249%), being significative similar to those treatments submitted to MWD (about 237%) during the rehydration. Besides that, in this context, the variation in power levels did not influence this response. Therefore, as the rate of rehydration is usually associated with a change in cell structure, the use of MWD in different power levels did not efficient to reduce these changes.

Rehydration properties were not improved by OD, presenting values to half of the rehydration obtained in HAD and MWHAD treatments. This can be attributed to sucrose incorporation which can lead to narrowing or the reduction of the number of empty intercellular spaces of tissue, developing higher resistance to water diffusion, preventing rehydration (An et al., 2013). Besides that, the presence of salt probably inhibits the movement of water in the intercellular spaces due to the accumulation of crystals on the product surface (Wang, Zhang, & Mujumdar, 2010). Relating these results with the shrinkage data, it is possible to consider that this lesser rehydration with the OD use may be more linked to these physical obstacles arising from the addition of solutes than to the cellular tissue damage usually caused by drying processes.

Power level also did not differ significantly ($p < 0.05$) with the use of DO, but a trend was observed, in which the increase in potency increased rehydration. Generally, a reduction in rehydration is observed with the increase in microwave power due to irreversible damage to the cell structure (Ashtiani et al., 2018). However, the presence of solutes may have contributed to the containment of this damage.

3.5. Carotenoid content

The carotenoid content, correspondent to α-carotene, β-carotene and lycopene, are presented in Table 4. These three carotenoids showed similar behaviors when subjected to the treatments, therefore these results were discussed together. The reduction percentage of carotenoids was from 7.88 to 51.80% for α-carotene, 8.02–52.89% for β-carotene and 8.47–57.81% for lycopene when compared to the fresh carrots. The crescent order of carotenoid content after drying was MWODHAD < HAD < MWHAD. For all these treatments, the β-carotene was the predominant carotenoid, which is by the results found by Junqueira et al. (2018).

The carrots dried by HAD, showed a reduction of 32.08, 33.22 and 35.67% for α -carotene, β-carotene and lycopene, respectively, when compared with the fresh carrot. This can be attributed to the high susceptibility of carotenoids to oxidation and isomerization, due to the high degree of unsaturation in the structure (Saini, Nile, & Park, 2015). However, with the presence of microwave energy in the form of hybrid drying (MWHAD) higher retention of carotenoid content was observed, increasing the concentration by 54, 52 and 55%. The use of microwave energy commonly leads to quicker dehydration and shorter drying times and, due to the removal of the reaction medium, which in this case is water, a reduction in the enzymatic activity of lipoxygenase, which is responsible for the degradation of carotenoids (Cui, Xu, & Sun, 2004) can exist.

Some authors report that there is an increase in the degradation of carotenoids with the increase in microwave power due to the increase in the temperature of the product (Kroehnke et al., 2018; Song, Wang, Li, Meng, & Liu, 2017). Nevertheless, in the present study, there was no significant variation in the content of carotenoids with the change of power levels in MWHAD treatments. This result can be supported by the final temperature measured after MWD (Table 2), however, although they were different from each other, did not reach a degree of heating capable of causing significant degradation of the carotenoids.

Dried carrots pretreated by OD showed lower carotenoid content when compared with carrots dried by MWHAD and HAD ($p < 0.05$). By immersing the carrots in a concentrated solution, an osmotic pressure gradient is formed, which results in changes in cellular structure followed by cell turgor loss (Nieto, Vicente, Hodara, Castro, & Alzamora, 2013). Junqueira et al. (2018) also reported carotenoids reduction in carrot slices after osmotic processing, similar to Mendonça et al. (2017) in pequi slices. This structural change due to OD may have caused the degradation of carotenoids in this first stage, which may have maximized the degradation in the subsequent stages of MWD and HAD.

3.6. Color

Table 4 presents the values of the luminosity (L*), redness (a*), yellowness (b*), and total color difference (ΔE) observed for carrots. The ΔE varied between 4.63 and 10.02, being the changes in ΔE were related to changes in L* and a* values after the drying. HAD treatment presented the highest value, suggesting that a longer drying time leads to a greater change in color parameters. However, it was not a significant difference when the MWD and OD were applied in the process. The treatments that presented the lowest variation were those submitted to intermediate microwave power, regardless of the use of OD, suggesting that there is a power threshold to be used without color changes.

Concerning L* parameter, the use of HAD did not significantly affect the luminosity of the carrots. As the dried carrots obtained remained clearer even with the concentration of the substances by the removal of moisture during drying, it can be said that there was a degradation of pigments, corroborating with the carotenoids results. The use of MWD

Table 4
Carotenoid content and color parameters of carrot dried by hybrid drying with (MWODHAD) or without (MWHAD) previous osmotic dehydration (OD).

Code	α-carotene	β-carotene	Lycopene	ΔE	L*	a*	b*
IN	140.28 ± 5.02^a	147.38 ± 2.51^a	89.00 ± 10.56^a	–	63.50 ± 1.67^a	24.41 ± 1.81^a	36.36 ± 2.46^a
HAD	45.00 ± 6.65^c	48.96 ± 6.33^c	31.75 ± 4.91^c	10.02 ± 1.26^a	62.05 ± 2.51^{ab}	17.49 ± 2.13^b	32.51 ± 0.24^a
1MWHAD	70.61 ± 8.22^b	75.86 ± 8.74^b	50.02 ± 5.85^b	9.72 ± 0.37^a	55.93 ± 1.14^c	24.22 ± 0.80^a	32.54 ± 3.35^a
2MWHAD	72.66 ± 4.09^b	77.95 ± 4.57^b	51.45 ± 2.97^b	5.56 ± 1.72^b	57.08 ± 1.71^c	26.50 ± 0.73^a	38.04 ± 0.33^a
3MWHAD	65.48 ± 9.21^b	69.88 ± 9.73^b	46.34 ± 6.60^{cb}	7.40 ± 0.73^{ab}	55.58 ± 1.33^c	23.66 ± 1.10^a	36.23 ± 1.49^a
1MWODHAD	11.77 ± 3.22^d	12.64 ± 3.50^d	8.29 ± 2.25^d	6.29 ± 1.62^{ab}	56.79 ± 1.29^c	26.99 ± 0.89^a	37.12 ± 1.18^a
2MWODHAD	11.05 ± 3.25^d	11.82 ± 3.54^d	7.54 ± 2.29^d	4.63 ± 1.82^b	59.18 ± 2.75^{abc}	25.11 ± 3.87^a	37.11 ± 0.37^a
3MWODHAD	15.73 ± 0.92^d	16.76 ± 1.11^d	10.80 ± 1.25^d	6.63 ± 1.03^{ab}	57.61 ± 1.52^{bc}	24.82 ± 0.63^a	34.48 ± 0.61^a

Average value ± standard deviation (n = 3 for the alpha and beta carotene and licopene; n = 5 for the color parameters). The numbers 1, 2 and 3 represent different microwave power levels of microwave drying step with (MWODHAD) or without (MWHAD) pretreatmen osmotic dehydration (OD). Different letters in the same column show statistical difference ($p < 0.05$) according to Tukey's test.

step and OD pretreatment significantly decreased the L * parameter of carrot slices ($p < 0.05$), in comparison with the fresh samples. It is suggesting that the darkness can be due to the concentration of compounds of the matrix by the water removal. However, the change in power levels did not influence this variable.

For a* parameter, it was observed that HAD presented lesser redness. This can be related to the carotenoid content found, that is, the extent of the bioaccessibility, with consequent degradation, was sufficient to cause changes in the redness of the samples. The other treatments did not present statistical difference with respect to the fresh carrot. Similar results were observed by Wray and Ramaswamy (2015) in a hybrid drying of cranberries, which reported higher maintenance of color in treatments that spent less time in the dryer. The b* parameter was not affected by the treatments used, maintaining similar values to the fresh sample with an average of 31.80 ± 11.95. The color analysis can be correlated with the carotenoids content, since the carrots dried by MWHAD were more reddish than those dried by HAD, suggesting a lesser degradation of the pigment.

4. Conclusion

The MWHAD procedure was the treatment that obtained the best results, due to the drying time being shortened, a higher effective moisture diffusivity, lower degradation of carotenoids and no color changes were observed. The higher tested power level was even the best condition due to shorted the total drying time with both shortest time of MWD and HAD, which means a lower energetic requirement. The findings from this research suggested that combined treatment MWHAD could improve the drying rate and the quality of sliced carrots.

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CRediT authorship contribution statement

Amanda Umbelina de Souza: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Jefferson Luiz Gomes Corrêa:** Supervision. **Douglas Hideki Tanikawa:** Investigation, Data curation. **Fernanda Rezende Abrahão:** Investigation, Visualization. **João Renato de Jesus Junqueira:** Supervision. **Edith Corona Jiménez:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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