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# How to make a microwave vacuum dryer with turntable

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ABSTRACT

A domestic microwave oven was modified in order to operate as a microwave vacuum dryer with turntable. The dryer performance was assessed with banana, grape tomato and carrot slices, dried under vacuum. Three different levels of microwave power (400, 700 and 1000 W) were tested to evaluate the influence of microwave power on the drying. The experimental results showed that it is possible to produce dried fruits and vegetables with characteristics similar (crisp and crunch) to those produced from a freeze-drying process, in much shorter process times, e.g. 20 min against the 14–16 h, typical of freeze-drying processes. The system presented in this work is a low cost, flexible and ease-to-assemble device, which can be made from domestic microwaves. It works properly with turntable, under vacuum that allows controlling the temperature and leads to uniform food heating, which improves the quality of the dried fruits and vegetables. In this way, this low-cost microwave vacuum drying is very useful to investigate the drying of fruits and vegetables at lab scale, and can be the base for making larger equipment.



## 1. Introduction

Food dehydration processes are used to reduce the moisture content and water activity, in order to inhibit microbial growth, decrease enzymatic activity and chemical reactions rates. Drying extends the shelf life of foods and reduces the costs of transportation and storage, because the products have lower weights and volumes and can be stored at room temperature (Van Arsdel, 1963; Fellows, 2000; Ratti, 2001; Aguilera et al., 2003; Singh and Heldman, 2009). In addition, this food preservation method helps to smooth out (seasonal) variations in consumption oscillations and to develop new food products.

Classically, freeze-drying has been considered an excellent dehydration procedure for thermosensitive fruits and vegetables, because it maintains the structural rigidity during dehydration, avoiding the structure collapse and leads to a preserved porous structure (Ibarz and Barbosa-Canovas, 2003; Ratti, 2008). However, freeze-drying is a time-consuming and relatively costly process, which limits its use to products with high added value (Louka and Allaf, 2002).

Vega-Mercado et al. (2001) considered dehydration processes which involve high-vacuum, microwaves, radio frequency and refractance window as the fourth generation drying technology. These processes can produce dried fruit and vegetables with higher quality. Drying processes based on the application of instant controlled pressure drop (Louka and Allaf, 2002; Mounir and Allaf, 2008) and successive cycles of heating-vacuum pulses (Zotarelli et al., 2012) are reported in the literature as capable of producing dehydrated-and-crunch products.

Microwave drying has the advantages of shortening drying times and improving product quality, resulting in high nutritional and sensory quality products (Datta and Anantheswaran, 2000; Zhang et al., 2006). The energy absorption by the wet material depends on its moisture distribution, which causes selective heating of its interior parts, protecting low moisture parts, e.g. material surface, from overheating (Chandrasekaran et al., 2013). Moreover, microwave heating causes volumetric heating, so vapor is generated inside the product, developing internal pressure gradients that cause water flow from the interior to the surface of the material (drainage). In this way, food shrinkage is reduced (Zhang et al., 2006).

Literature reports many studies on the use of mathematical models in microwave heating (Geedipalli et al., 2007; Salvi et al., 2011; Pitchai et al., 2012), microwave drying (Constant et al., 1996; Boldor et al., 2005; Chatterjee et al., 2007) and microwave assisted drying (Perre and Turner, 1997; Gowen et al., 2008; Kowalski et al., 2010; Rakesh et al., 2010; Malafronte et al., 2012). Furthermore, mathematical models have been used to assess the influence of the main process variables on the final

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product quality, in order to an effective production control (Malafronte et al., 2012).

Vacuum drying is particularly suitable for products that are sensitive to heat, such as fruits with high sugar content and certain vegetables with high added value (Zhang et al., 2006). Microwave heating under vacuum improves the efficiency of drying and prevents or reduces oxidation, preserving product color, texture and flavor, leading to products with quality compared to freeze-dried products (Gunasekaran, 1999; Lin et al., 1998).

On the other hand, one disadvantage of microwave heating is the inherent lack of uniformity of the electromagnetic field inside the microwave dryer, which can lead to non-uniform heating. However, this problem can be partially offset by using wave-guides and a rotating tray (Cohen and Yang, 1995). Literature reports many studies on microwave vacuum drying of fruits and vegetables, as banana (Drouzas and Schubert, 1996; Mousa and Farid, 2002), carrots (Lin et al., 1998), garlic (Figiel, 2009), mint leaves (Therdthai and Zhou, 2009), mushrooms (Giri and Prasad, 2007), potatoes (Song et al., 2009), among others. However, these studies did not report the use of turntables to improve the homogeneity of microwave distribution into the food.

There are several studies that report rotating system for a better distribution of microwaves in fruits and vegetables during drying (Cui et al., 2003; Clary et al., 2005, 2009; Sutar and Prasad, 2007; Puschner, 2012-2015; Calín-Sánchez et al., 2014; Ghazi et al., 2014). Microwave drying of cellulose derivative (hydroxypropyl methyl cellulose, HPMC) was done in a chamber with two integrated mode stirrers for a better distribution of the electromagnetic waves in the drying chamber and samples (Barba et al., 2013). Rinaldi et al. (2015) reported microwave reactors able to operate with rotating vessel under vacuum.

In this context, the present study explains how to adapt a microwave oven with turntable for operating as a microwave vacuum dryer, capable of promoting uniform food heating that leads to high quality dried fruits and vegetables. The developed device was tested for drying bananas, grape tomatoes and carrots. Freeze-dried samples were prepared in order to compare processes and products.

## 2. Materials and methods

### 2.1. Samples preparation

Bananas (*Musa sapientum* L., Prata variety), grape tomatoes and carrots (*Daucus carota*) were purchased in a local market (Florianopolis, SC, Brazil). The fruits and vegetables were selected based on their state of ripeness, evaluated from the visual appearance, soluble solid content (using a digital refractometer, Model AR200, Reichert, USA), and resistance to penetration (using a penetrometer, Model FT 327-∅ = 8 mm, Effegi, Italy). Banana samples presented diameter of 27.6 ± 3.5 mm, with soluble solid content of 22.5 ± 1.6 °Brix and penetration resistance of 5.9 ± 1 N. The grape tomatoes were considered as cylindrical, with length of 29.1 ± 3.6 mm and diameter of 20.2 ± 3.2 mm, presenting soluble solid content of 7.3 ± 0.7 °Brix. The carrots presented diameter of 38.4 ± 4.0 mm. The selected bananas and carrots were washed, peeled and cut into slices of 5 mm of thickness, avoiding fruit and vegetables ends, where diameters are smaller. The grape tomatoes were washed and cut in half, in the axial direction.

### 2.2. Experimental device

A sketch of the microwave vacuum dryer, which operates under vacuum and with turntable, is given in Fig. 1a. A domestic microwave oven (Electrolux, Model MEX55, Joinville, Brazil) with internal space of 45 L, maximum magnetron output power of 1000 W and frequency of 2450 MHz was chosen for making the dryer. A container of polypropylene was used as the vacuum chamber in the interior of the oven Polypropylene was selected because it is a nontoxic material with appropriate dielectric properties (dielectric constant, $\varepsilon' = 2.2$, and loss tangent, $\tan\delta = 0.0003$–$0.0004$)) and good mechanical resistance. The container was connected to a vacuum service line capable of establishing a vacuum pressure of 4 kPa, registered by a pressure transducer (Warme, Model WTP – 4010, Itú-SP, Brazil) connected to a computer. A column of silica gel was used for adsorbing the water vapor at low pressure from the dryer, helping the pump system to maintain the vacuum level. Fig. 1b shows details of the rotary system with mechanical seal, which allows the vacuum chamber to rotate with the turntable.

Roughly, the rotary system consists of a T valve connected to a rotary joint formed by a fixed shaft (connected to the vacuum service line) and a free shaft (connected to the vacuum chamber). As mentioned before, this rotating system helps homogenizing the absorption of microwaves by the fruit samples during drying.

In more detail (see Fig. 1b), the rotary system comprises: (1) T valve; (2) rotary joint (mechanical seal); (3) free axis of the rotary joint; (4) TC (Tri-clamp) silicone gasket; (5) stainless steel bushing with a TC nipple at the top end and a flange at the bottom end; (6) external metal cover of the microwave oven; (7) metal ceiling of the microwave oven; (8) teflon shaft connected to the polypropylene lid by a male thread, and to the rotary joint free axis by a female thread; (9) lid of polypropylene; (10) nylon bushing with TC nipple at the bottom; (11) brass hex nipple screwed laterally to the rotary joint free axis and fixed vertically to the nipple of a Teflon tube; (12) Teflon tube; (13) hex nuts; (14) Teflon nipple. The stainless steel bushing and the nylon bushing with a TC silicone gasket in the middle were coupled by a stainless clamp. The blue dashed line represents the free path that connects the rotating system to the vacuum chamber.

Microwave energy is attenuated as it passes through a circular waveguide having a diameter less than that which allows the power to propagate freely. This circular waveguide is commonly called a "cut-off tube" and is used extensively in the design of window screens, ventilation ports and other such openings for microwave cavities (GAE, 2005-2009). The rate of power attenuation is a function of its wavelength and cut-off tube radius, based on the following equation for the attenuation constant $\alpha$ (dB/m), Eq. (1),

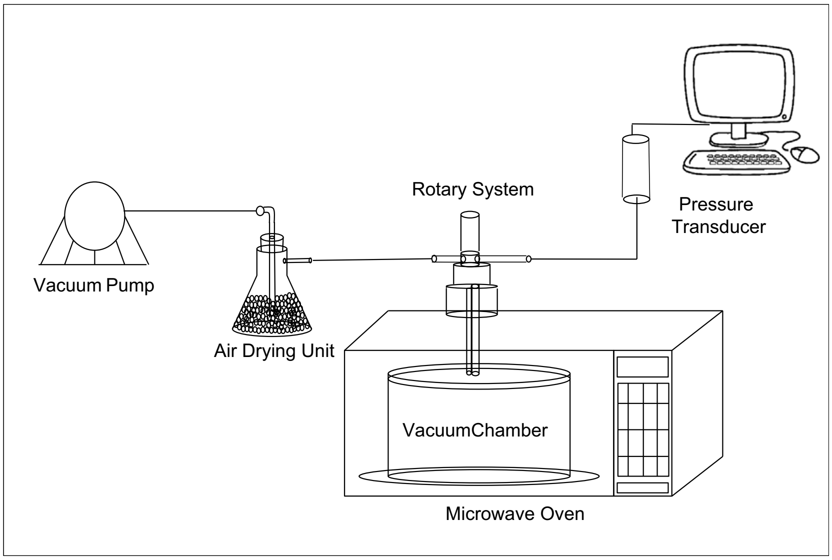
$$\alpha = 8.686\sqrt{\left\{\left(\frac{2\pi}{\lambda_c}\right)^2 - \left(\frac{2\pi}{\lambda_0}\right)^2\right\}} \tag{1}$$

in which $\lambda_c$ (cut-off wavelength) = 3.413 × tube radius (for propagation mode transverse electric dominant for cylindrical wave guide $TE_{11}$, $f = 2.45$ GHz), $\lambda_0$ (wavelength in unbounded medium) = 0.1224 m (for dielectric air) (Meredith, 1998; GAE, 2005-2009).

GAE (2005-2009) application bulletin plots curves of Tube ID vs attenuation from Eq. (1), for ISM frequencies at 915 MHz, 2450 MHz and 5.8 GHz, which are used to find the minimum cut-off tube length given the tube diameter and the entering and exiting power densities, applying only to empty (air filled) cut-off tubes.

The tube radius in this study (part 5, Fig. 1) measures 0.02185 m, which yields attenuation of 580 dB/m from Eq. (1).

The maximum output from industrial equipment and consumer appliances should be limited to 1 mW/cm$^2$, when measured at 5 cm from the source (FDA, 2012). A conservative estimate of the maximum incident power density in a lightly loaded cavity is given by (GAE, 2005-2009).



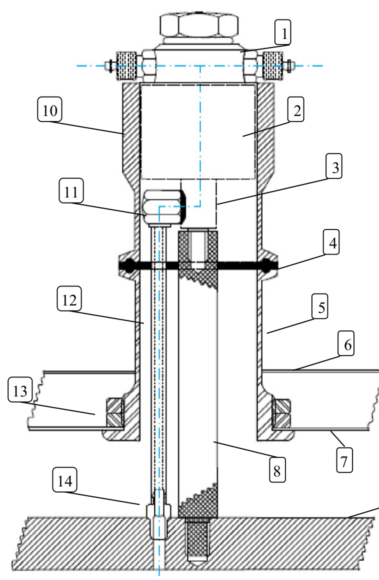




**Fig. 1.** (a) Sketch of the microwave vacuum drying with turntable, (b) Rotary system: (1) T valve; (2) rotary joint (mechanical seal); (3) free axis of the rotary joint; (4) TC (Tri-clamp) silicone gasket; (5) stainless steel bushing with a TC nipple at the top end and a flange at the bottom end; (6) external metal cover of the microwave oven; (7) metal ceiling of the microwave oven; (8) teflon shaft connected to the polypropylene lid by a male thread, and to the rotary joint free axis by a female thread; (9) lid of polypropylene; (10) nylon bushing with TC nipple at the bottom; (11) brass hex nipple screwed laterally to the rotary joint free axis and fixed vertically to the nipple of a Teflon tube; (12) Teflon tube; (13) hex nuts; (14) Teflon nipple.

$$\text{Input} = \frac{4 \times (\text{microwave power delivered})}{(\text{cavity inside surface area})} \tag{2}$$

Thus, for the MEX55 model oven,

$$\text{Input} = \frac{4 \times 10^6 \text{ mW}}{7958 \text{ cm}^2} = 502.6 \text{ mW/cm}^2 \tag{3}$$

The total required attenuation $A$ is given by Eq. (4),

$$A = 10 \log\left(\frac{\text{Input}}{\text{Output}}\right) = 10 \log\left(\frac{502.6}{25}\right) = 13.03 \text{ dB} \tag{4}$$

Thus, the minimum cut-off tube length is (13.03 dB)/(580.0 dB/m) = 0.0225 m. Because of distorted fringing fields at the junction between the cut-off waveguide and the "hot" microwave zone, there is uncertainty of the attenuation rate in this region and it is advisable to allow a length of at least one diameter of cut-off waveguide before the full attenuation is assumed to develop (Meredith, 1998), equivalent to 0.0225 + 0.0437 = 0.0662 m. On the other hand, the influence of Teflon parts 8 (shaft) and 12 (tube) through the cut-off tube is negligible as regards to attenuation, due to the low dielectric constant of Teflon. Thus, the final overall design length of the cut-off tube was chosen as 0.070 m.

After adaptations, the domestic microwave oven was tested with a microwave oven survey meter (Ets-Lindgren model – Holaday EMF Measurement, USA). The equipment do not show detectable leakage of electromagnetic waves and is safe for personnel exposure.

### 2.3. Drying experiments

Sliced samples (of fruits or carrots) were disposed close to the edges of a circular polypropylene tray inserted into the vacuum chamber. The microwave vacuum oven operated at nominal power of 400 W during the drying of tomatoes and carrots. To evaluate the influence of microwave power in the drying of bananas the microwave vacuum oven operated at three nominal powers, i.e. 400, 700 and 1000 W.

Domestic microwave ovens operate by switching from maximum power to zero power in timed cycles (duty cycles). The microwave in study has a cycle period of 29 s. At 1000 W power level, the magnetron is "on" all the time. At power level of 700 W it is "on" for 20 s and "off" for 9 s, while at 400 W the microwave system is "on" for 11 s and "off" for 18 s.

To avoid distortion of the results due to interruption of the drying time, a destructive approach was used, starting always from a new fresh sample for determining each experimental point. Each experiment was performed using approximately 85.55 ± 0.69 g of banana slices, 85.70 ± 0.61 g of grape tomatoes or 85.39 ± 0.68 g of carrots. In this way, each experimental data of the drying curves were determined by removing the samples after the given drying times, and the moisture contents of the sample were determined in a vacuum oven at 70 °C (TECNAL, Model TE-395, Brazil) (A.O.A.C., 2005). Also, the sample water activity ($a_w$) was determined by a hygrometer (Aqualab Model Series 3, Decagon Devices Inc., Pullman, USA). All the drying experiments were performed in triplicate. This procedure was used for each microwave vacuum drying (MWVD) process condition.

To start the drying experiment the vacuum chamber pressure was reduced to approximately 4 kPa and temperature of 30 °C (this period takes approximately 80 s), before the microwave oven was turned on and maintained until the end of the drying, when atmospheric pressure was restored. Fig. 2 shows the temporal evolution of the pressure in the vacuum chamber during the MWVD process, for the three different levels of magnetron power (400, 700 and 1000 W). The temperature was measured off-line and was not higher than 60 °C, for any case.

### 2.4. Freeze drying

Moisture content evolution during freeze-drying (FD) (Freeze dryer, Liotop, Model – L101, São Carlos-SP, Brazil) was determined using a single-point load cell with nominal capacity of 2 kg and sensitivity of 0.1 g (Alfa Instrumentos, Model GL, Brazil), as described by Tribuzi and Laurindo (2014).

### 2.5. Characterization of dehydrated fruits

Scanning electron microscopy (SEM) was used to investigate the internal structure of fruits and vegetables produced by MWVD and FD processes. Before the SEM analysis, the samples were dehydrated by freeze-drying (Liotop, Model – L101, Brazil) during 24 h in order to remove any residual moisture, and were

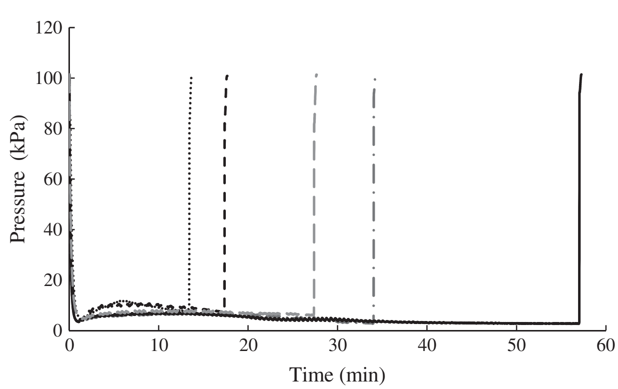



**Fig. 2.** Temporal evolution of the pressure inside the chamber during MWVD drying processes applied to bananas for three magnetron power levels (··· 400, - - 700 and —— 1000 W), carrots (—·— 400 W) and grape tomatoes (— 400 W).

coated with a fine gold layer, using a LEICA device (EM SCD500). Micrographs were obtained with a JEOL JSM 6390LV-Japan scanning electron microscope.

A MiniScan colorimeter (HunterLab, Model – EZ, USA) was used to determine the color parameters of fresh and dried samples. The color was expressed by the CIELAB coordinate system, $L^*$ (whiteness/darkness), $a^*$ (greenness/redness) and $b^*$ (blueness/yellowness), as defined by CIE (*Commission Internationale de L'Éclairage*). Experimental data of color were statistically analyzed with software *Statistica 7.0* (StatSoft, Tulsa, USA), using analysis of variance (ANOVA) and Tukey's test. Mean values were considered significantly different at the 95% confidence level ($p \leqslant 0.05$).

## 3. Results and discussion

### 3.1. Experimental drying curves

Table 2 presents the average moisture and water activities of fresh and dried fruits. Fresh grape tomatoes and carrots showed average moisture content (± standard deviation) of 9.09 ± 0.85 and 8.31 ± 0.38 g g$^{-1}$ (in dry basis, d.b.), respectively before MWVD process with magnetron power of 400 W. The mean moisture content of tomatoes after drying was 0.027 ± 0.006 g g$^{-1}$ (d.b.) while carrots presented moisture of 0.027 ± 0.015 g g$^{-1}$ (d.b.). The water activities (± standard deviation) of fresh tomatoes and carrots were 0.998 ± 0.001 and 0.997 ± 0.001, respectively; after drying these values decreased respectively to 0.302 ± 0.010 and 0.239 ± 0.020. For microwave power of 400 W, the drying times of tomato and carrot samples were approximately 60 min and 35 min, respectively.

The freeze-dried grape tomatoes and carrots presented moisture contents of 0.030 ± 0.002 and 0.029 ± 0.001 g g$^{-1}$ (d.b.), and final water activities of 0.252 ± 0.001 and 0.268 ± 0.006, respectively, similar to the values observed for microwave-vacuum-dried samples.

Figs. 3a and 4a show the drying curves (triplicate) of grape tomatoes and carrots, respectively, while Figs. 3b and 4b shows the evolution of water activity during drying, using microwave power of 400 W. Both, moisture content and water activity curves, showed the good reproducibility of the drying system, even using the destructive sampling approach explained before.

Fresh bananas dried with the MWVD process had average moisture contents (d.b.) of 2.28 ± 0.14 (400 W), 2.28 ± 0.14 (700 W), and 2.40 ± 0.10 g g$^{-1}$ (1000 W). After drying, the mean moisture content were 0.019 ± 0.007, 0.030 ± 0.017 and 0.034 ± 0.003 g g$^{-1}$ (d.b.), for the same sequence of magnetron power. The water activities of fresh samples were 0.981 ± 0.004 (400 W), 0.983 ± 0.003 (700 W) and 0.981 ± 0.006 (1000 W), while the water activities of dried samples, in the same order, were 0.207 ± 0.062, 0.262 ± 0.066 and 0.259 ± 0.006. The drying times were approximately 30 (400 W), 20 (700 W) and 15 min (1000 W). Fig. 5a shows the drying curve of banana slices, while Fig. 5b shows the evolution of their water activity during drying, for processes performed at the three different microwave powers (400, 700 and 1000 W). As expected, higher microwave power led to higher drying rates,

**Table 1**
Constant drying rate and determination coefficients ($R^2$) of the linear fit applied to the experimental data of banana, tomato and carrot dried by MWVD.

| Sample/drying condition | Constant Drying rate (g g$^{-1}$ min$^{-1}$) | $R^2$ |
|---|---|---|
| Banana – 400 W | −0.119 | 0.971 |
| Banana – 700 W | −0.170 | 0.975 |
| Banana – 1000 W | −0.266 | 0.975 |
| Tomato – 400 W | −0.256 | 0.910 |
| Carrot – 400 W | −0.302 | 0.956 |

**Table 2**
Moisture content and water activities (mean ± standard error) of fresh and dried fruits.

| Samples | Drying condition | $X_{db\ fresh}$ (g g$^{-1}$) | $a_{w\ fresh}$ | $X_{db\ dried}$ (g g$^{-1}$) | $a_{w\ dried}$ |
|---|---|---|---|---|---|
| Banana | MWVD – 400 W | 2.28 ± 0.14 | 0.981 ± 0.004 | 0.019 ± 0.007 | 0.207 ± 0.062 |
| | MWVD – 700 W | 2.28 ± 0.14 | 0.983 ± 0.003 | 0.030 ± 0.017 | 0.262 ± 0.066 |
| | MWVD – 1000 W | 2.40 ± 0.10 | 0.981 ± 0.006 | 0.034 ± 0.003 | 0.259 ± 0.006 |
| | FD | 2.37 ± 0.08 | 0.980 ± 0.005 | 0.031 ± 0.003 | 0.224 ± 0.019 |
| Carrot | MWVD – 400 W | 8.31 ± 0.38 | 0.997 ± 0.001 | 0.027 ± 0.015 | 0.239 ± 0.020 |
| | FD | 8.31 ± 0.38 | 0.997 ± 0.001 | 0.029 ± 0.001 | 0.268 ± 0.006 |
| Tomato | MWVD – 400 W | 9.09 ± 0.85 | 0.998 ± 0.001 | 0.027 ± 0.006 | 0.302 ± 0.010 |
| | FD | 9.09 ± 0.85 | 0.998 ± 0.001 | 0.030 ± 0.002 | 0.252 ± 0.001 |

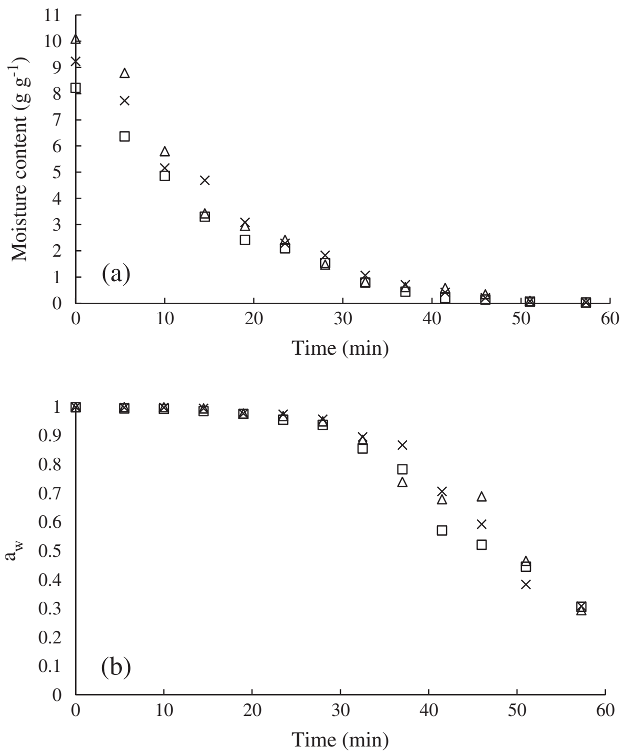



**Fig. 3.** (a) Drying curves of grape tomato samples during the MWVD process (triplicate). (b) Evolution of water activity of grape tomato samples during the MWVD process (triplicate). Magnetron power: 400 W.

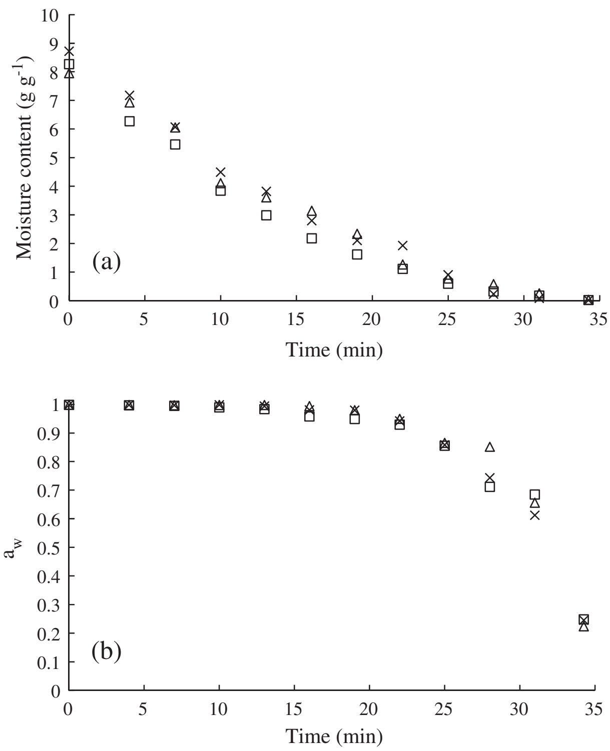



**Fig. 4.** (a) Drying curves of carrot samples during the MWVD process (triplicate). (b) Evolution of the water activity of carrot samples during the MWVD process (triplicate). Magnetron power: 400 W.

which is corroborated by literature results (Drouzas and Schubert, 1996). It is important to remark that the characteristic drying times of MWVD processes was 15–30 min, which is much shorter than the characteristic dehydration times of freeze-drying processes.

For comparison, Fig. 6 presents the temporal evolution of moisture content of banana samples (triplicates) during a FD process. The experimental data recorded by an on-line system showed good reproducibility, and the dried bananas showed moisture content and water activity of 0.031 ± 0.003 g g$^{-1}$ (d.b.) and 0.224 ± 0.019, respectively. The process time was approximately 3 h for freezing the samples and 13 h for the dehydration (freeze-drying). This comparison indicates the huge potential of microwave vacuum drying for many applications.

Fig. 7 shows the drying curves of banana, tomato and carrot samples during the MWVD process, in which the constant drying rate period was marked with a straight line. According to Zhang et al. (2006), the microwave drying has three periods, i.e., a heating period, a rapid drying period and a reduced drying rate period. Initially, the conversion of microwave energy into thermal energy within the moist material increases the product temperature (heating period) up to the boiling point of water (Zhang et al., 2006). However, this period could not be observed from Fig. 7, which can be explained by the relatively minor temperature increase under vacuum condition (the boiling temperature of water at 4 kPa is approximately 30 °C).

In the present study a constant drying rate period and a stable sample temperature were observed, when the microwaves converted to thermal energy provided the latent heat of vaporization of free water (Zhang et al., 2006). This period is clearly perceived from Fig. 7 and represented by a straight line, until the beginning of the falling rate period.

During the falling rate period the moisture was slowly reduced (most of the free water was evaporated in the constant rate period). At this period, the local moisture is reduced and local temperatures may rise above the water boiling point (Zhang et al., 2006). This behavior was reported by Mousa and Farid (2002) from a study on microwave vacuum drying of banana.

The drying rates during the constant period and the determination coefficients ($R^2$) of the linear fits applied to the experimental drying data are presented in Table 1. As expected, for a same food, higher nominal microwave power led to larger drying rates. The

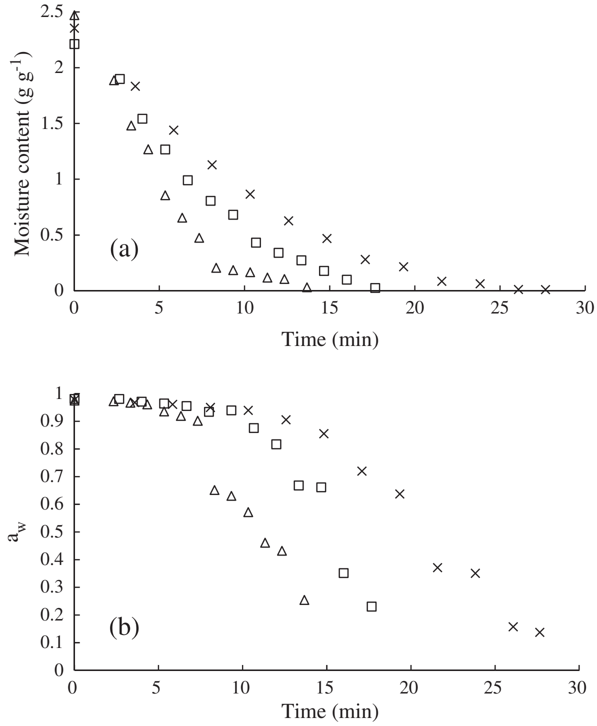



**Fig. 5.** (a) Drying curves of banana samples during the MWVD process. (b) Evolution of the water activity of banana samples during the MWVD process. Magnetron power: 400 W (×), 700 W (□), and 1000 W (Δ).

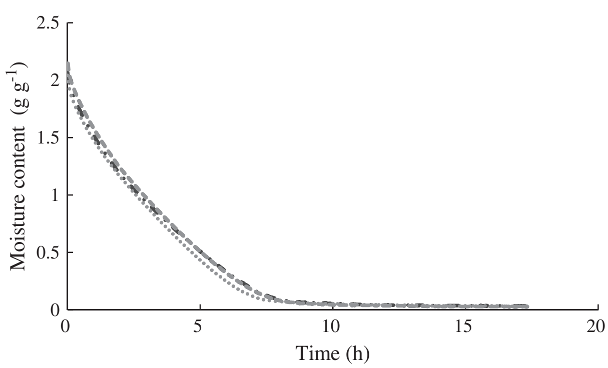



**Fig. 6.** Drying curves of banana samples during the FD process (triplicate).

drying rate of banana using the MWVD with 1000 W was 1.6 times greater than that observed for the 700 W process and 2.2 times greater than that observed for the 400 W process.

Fig. 8 shows the power absorbed by banana, tomato and carrot samples during the MWVD process, calculated from the mass of water evaporated and its latent heat. As expected, reduction of water availability leads to a decrease of the absorbed power. These results indicate that the microwave power must be reduced during drying, to save energy and protect the product and the equipment. A more detailed analysis of the power absorption during drying depends on the influence of moisture on the samples dielectric properties, which is not the objective of the present study.

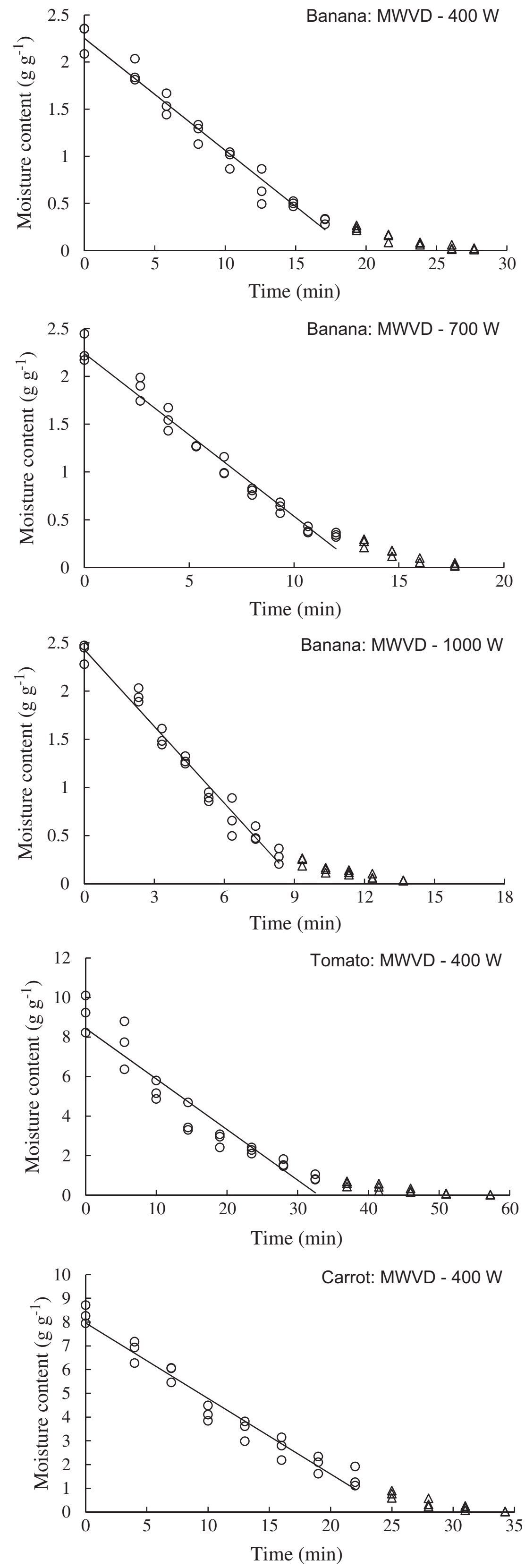



**Fig. 7.** Drying curves of banana, tomato and carrot samples during the MWVD, with straight lines representing the constant drying rate period (○). The falling rate period was represented by (Δ).

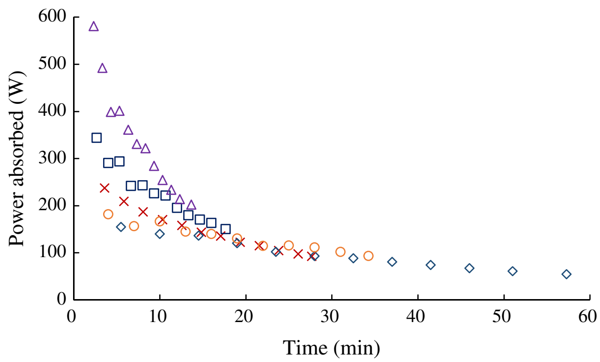



**Fig. 8.** Power absorbed during the MWVD drying processes: Banana: 400 W (×), 700 W (□), and 1000 W (Δ); Tomato: 400 W (◇); Carrot: 400 W (o).

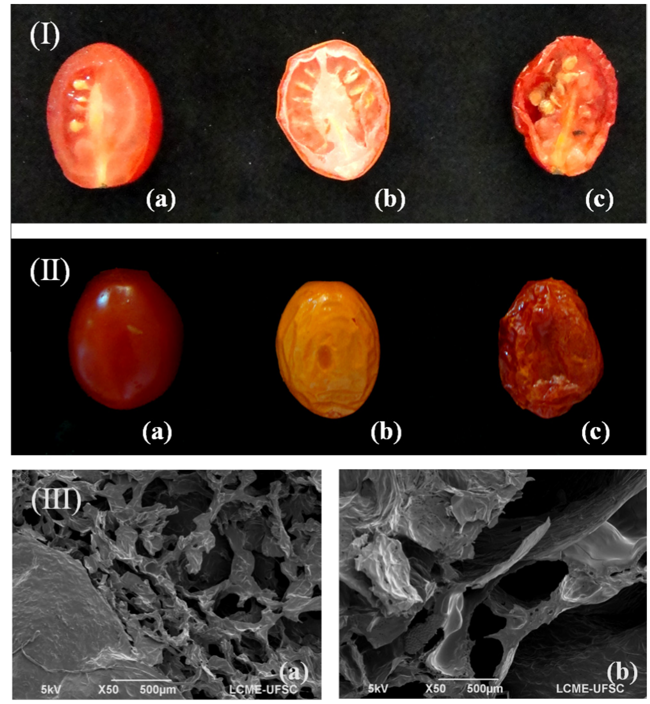



**Fig. 9.** (I) Pictures of tomatoes center: (a) Fresh; (b) FD; (c) MWVD – 400 W. (II) Pictures of tomatoes skin: (a) Fresh; (b) FD; (c) MWVD – 400 W. (III) Scanning electron micrograph of grape tomatoes (magnification of 50 times): (a) FD; (b) MWVD – 400 W.

### *3.2. Color of dried bananas*

Color usually is a decisive attribute for consumeŕs decision and should be considered for choosing a suitable food process. The mean value (± standard deviation) for each color parameter ($L^*$, $a^*$ and $b^*$) resulted from different drying techniques is presented in Table 3.

Pictures of the centers and the skins of fresh tomatoes, FD, MWVD 400 W are shown in Fig. 9(I) and (II). Tomatoes dried by MWVD did not present significantly different to fresh tomatoes, regarding the skin color parameters. The comparison between the center colors of MWVD and fresh tomato showed that only the parameter $L^*$ (lightness) did not differ. From Fig. 9 and the color parameters (Table 3) it is clear that the microwave vacuum process is suitable drying procedure for grape tomatoes, leading to color properties closer to the fresh tomatoes than freeze-dried tomatoes.

Dried carrots by FD presented an increased lightness, while the MWVD carrots got darker than the fresh samples. Both process FD and MWVD resulted in lower values of $a^*$ and $b^*$ parameters, indicating more greenness and blueness samples. Fig. 10(I) present pictures of fresh, FD and MWVD 400 W carrots, showing dehydrated carrot slices with good aspect.

Fig. 11(I) shows banana pictures after FD (a); MWVD – 400 W (b); MWVD – 700 W (c); and MWVD – 1000 W (d). For all drying conditions, dried bananas were darker than the fresh fruit, as well as indicated by the $L^*$ parameter. From Fig. 11 and Table 3 it is possible to evidence that FD process caused less darkening, due to the low process temperature, leading to $L^*$ values closer to the fresh fruits.

The highest magnetron power (1000 W) resulted in a lower darkening when compared with the lower powers (400 and 700 W). Similar results were reported by Alibas (2007), who examined the difference of color of nettle leaves dried by microwave using four power levels (500, 650, 750 and 850 W). He reported slightest changes of color for higher microwave power during drying (850 W). These results could be explained by the shorter drying times observed for higher microwave power Sumnu et al. (2005). Moreover, in the present study, the highest magnetron power (1000 W) resulted in higher values of both $a^*$ and $b^*$ parameters, i.e., samples with higher redness and yellowness.

Drouzas and Schubert (1996) investigated the microwave vacuum drying of banana and reported a lack of heating uniformity (hot spots). Moreover, high microwave power overheated and sometimes burned the samples, increasing the product darkness.

**Table 3**
CIELAB color parameters ($L^*$, $a^*$ e $b^*$) (mean ± standard error) of fresh bananas, grape tomatoes and carrots and dried by MWVD or FD.

| | Samples | $L^*$ | $a^*$ | $b^*$ |
|---|---|---|---|---|
| Banana | MWVD – 400 W | $43.87^b$ (±5.40) | $4.26^b$ (±0.57) | $23.26^b$ (±2.54) |
| | MWVD – 700 W | $40.71^{ab}$ (±5.49) | $4.07^b$ (±0.60) | $21.68^b$ (±2.86) |
| | MWVD – 1000 W | $50.50^c$ (±3.95) | $5.29^c$ (±0.78) | $27.97^d$ (±3.56) |
| | FD | $68.96^d$ (±5.38) | $1.19^a$ (±0.09) | $12.73^a$ (±1.40) |
| | Fresh | $74.42^e$ (±2.30) | $4.43^b$ (±0.93) | $26.48^d$ (±2.38) |
| Carrot | MWVD – 400 W | $43.54^a$ (±4.03) | $21.55^a$ (±2.34) | $41.77^b$ (±3.89) |
| | FD | $65.66^c$ (±2.55) | $27.61^b$ (±0.63) | $36.58^a$ (±1.27) |
| | Fresh | $50.99^b$ (±2.15) | $33.66^c$ (±2.63) | $44.42^c$ (±2.91) |
| Tomato skin | MWVD – 400 W | $7.27^a$ (±1.24) | $10.46^a$ (±0.52) | $5.81^a$ (±0.60) |
| | FD | $11.99^b$ (±1.50) | $12.92^b$ (±4.00) | $14.98^b$ (±2.45) |
| | Fresh | $6.71^a$ (±0.30) | $11.15^{ab}$ (±0.83) | $5.87^a$ (±0.36) |
| Tomato center | MWVD – 400 W | $8.95^a$ (±1.07) | $10.38^b$ (±0.29) | $8.27^b$ (±1.32) |
| | FD | $15.34^b$ (±4.66) | $10.99^b$ (±0.86) | $10.45^c$ (±1.06) |
| | Fresh | $7.84^a$ (±1.12) | $6.86^a$ (±0.95) | $5.69^a$ (±1.03) |

For the same product, different letters represent significant differences ($p < 0.05$) between averages, determined by the Tukey test.

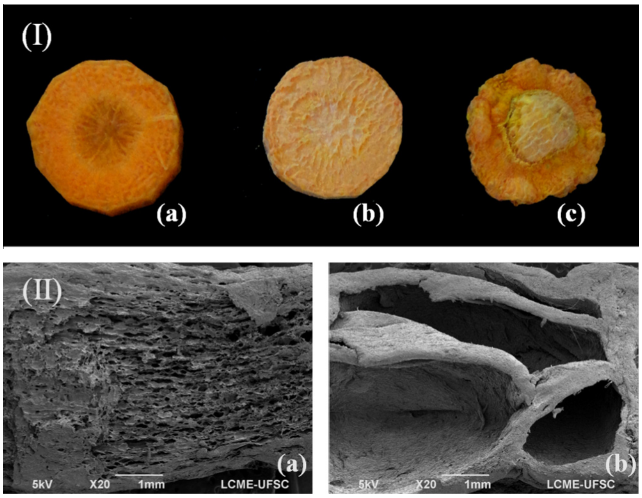



**Fig. 10.** (I) Pictures of carrots: (a) Fresh; (b) FD; (c) MWVD – 400 W. (II) Scanning electron micrograph of grape tomatoes (magnification of 20 times): (a) MWVD – 400 W; (b) FD.

The present study showed that the use of turntable resulted in uniform heating that reduced this problem, as showed by the uniform color and absence of burned parts of dehydrate banana slices.

### 3.3. Microstructure of dried bananas

Scanning electron microscopy Figs. 9(III) and 10 (II) of tomatoes and carrots dried by MWVD showed larger pores than freeze-dried samples.

The microstructure of the fractured sections of dehydrated bananas was examined to explore the effect of microwave power levels on the samples. From the scanning electron micrographs showed in Fig. 11(II) it can be observed that the structures of the samples prepared from MWVD were similar to those of freeze-dried samples, presenting many pores and relatively uniform pore size. The magnetron power level did not affect the internal structure of bananas.

Freeze-drying tends to preserve the product structure, while the MWVD process tends to expand that structure. The volumetric heating and the low pressure lead to vapor production inside the food, creating a puffing effect, due to the high specific volume of water vapor at low pressures. The large vapor pressure gradients between the food interior and its surface is the driving force that drain the water to the surface, resulting in high drying rates (Zhang et al., 2006). The extent of the puffing during the flash-evaporation depends on the food structure and is difficult to predict.

## 4. Conclusions

The microwave oven operating under vacuum with a turntable is a useful tool for investigating the application of microwave vacuum drying to any food, including fruits and vegetables. An experimental device can be made from a domestic microwave oven, a polypropylene vacuum chamber and rotary system with mechanical seal. Slices of fruits and vegetables dried by microwave vacuum drying present structures very similar or better to those produced by freeze drying, with very short drying times. The turntable improves the quality of the final product as result of uniform heating. Fruits and vegetables colors suffer small changes during microwave-vacuum process if adequate processing conditions are

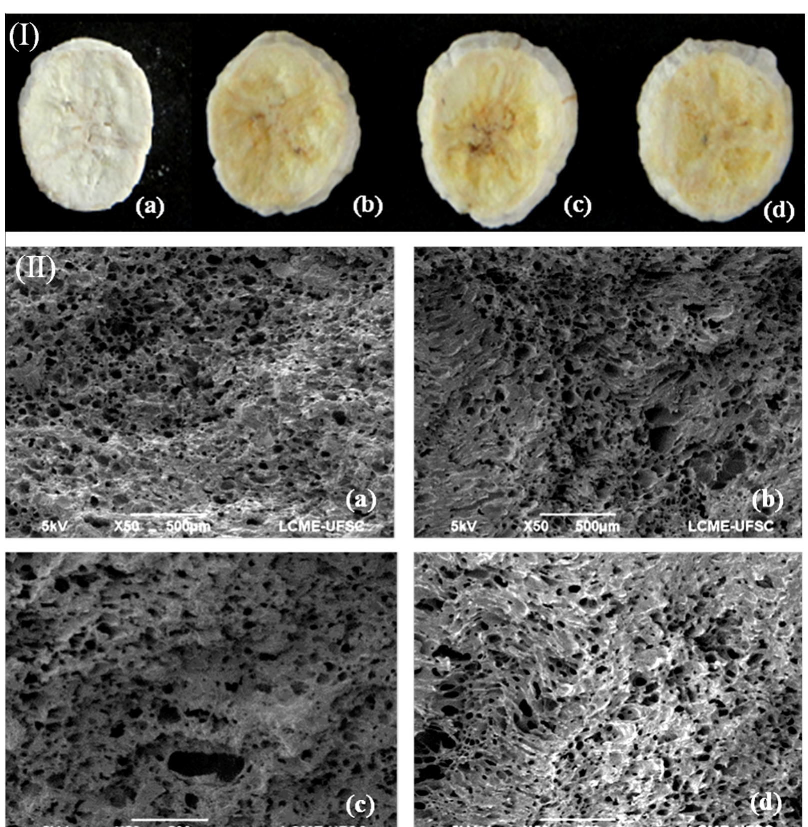



**Fig. 11.** (I) Pictures of dried bananas: (a) FD; (b) MWVD – 400 W; (c) MWVD – 700 W; (d) MWVD – 1000 W. (II) Scanning electron micrograph of dried bananas (magnification of 50 times): (a) MWVD – 400 W; (b) MWVD – 700 W; (c) MWVD – 1000 W; (d) FD.

used. Choosing suitable magnetron power is very important for maintaining the color of the dried product.

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