PAPER

DRYING KINETICS, HEATING UNIFORMITY AND QUALITY CHANGES DURING THE MICROWAVE VACUUM DRYING OF ARTICHOKES (*CYNARA SCOLYMUS* L.)

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ABSTRACT

In this study, our aim was to investigate the effect of process parameters such as the microwave power (450-800 W), system pressure (12.40 – 31.20 kPa) and drying time (0-25 min) on the drying kinetics, quality characteristics and heating uniformity indices during the microwave vacuum (MV) drying of artichokes. The microwave power was found to be more influential than the system pressure, and variations resulted in different drying characteristics. The effective diffusion coefficients were found to range from 2.279×10^{-6} - 3.454×10^{-6} m^2/s and $3.600\times10^{-}$ - $6.297\times10^{-}$ m^2/s for the first and second falling rate periods, respectively. Reducing microwave power and system pressure resulted in higher uniformity in temperature distributions. However, the average temperatures deviated slightly from the targeted drying temperatures at high microwave power. The highest shrinkage coefficient (0.3705±0.0233) and rehydration ratio (3.82±0.091) values were obtained at 800 W and 12.4 kPa. MV drying preserved the fresh colour characteristics of artichokes, and it could be used as an alternative to conventional drying.

Keywords: artichoke (*Cynara scolymus* L.), Microwave Vacuum Drying, Heating Uniformity, shrinkage, rehydration, Browning Index

1. INTRODUCTION

The globe artichoke (*Cynara scolymus* L.), which belongs to the Asteraceae family, is an important crop cultivated primarily in the Mediterranean area. The contribution of artichoke cultivation to the agricultural economy is often accompanied by the fresh consumption of the immature flower heads as a vegetable and the leaf extracts by the pharmaceutical industry (LATTANZIO *et al.*, 2009; LOMBARDO *et al.*, 2010). Several *in vitro* and *in vivo* experiments have shown the biological activity of artichokes, including their anticarcinogenic, anti-cholestatic, anti-inflammatory, and anti-genotoxic properties, which are due to its phytochemical composition, including its phenolic compounds, namely, its caffeoylquinic acids, apigenin, luteolin glycosides and tannins (ABU-REIDAH *et al.*, 2013; BEN SALEM *et al.*, 2017; FRATIANNI *et al.*, 2014). The demand for artichokes is steadily increasing because their associated nutritional characteristics are well suited to the increasing expectations of consumers regarding healthy foods. However, there is a limited season for fresh artichoke consumption, and this crop is highly susceptible to discolouration and nutritional losses due to enzymatic activity, even under cold storage. The canning and freezing of artichokes are the most common methods used in industrial production, but the resulting products do not fully meet consumer expectations due to nutritional losses and concerns about cost effectiveness (GUIDA *et al.*, 2013). Drying artichokes at low temperatures using methods such as freeze-drying and microwave vacuum (MV) drying would be advantageous for existing postharvest techniques in terms of preserving the nutraceutical properties for long periods as well as reducing storage, packaging and transportation costs.

The use of MV drying technology for food dehydration has emerged as an alternative drying method that has attracted the interest of researchers and the food industry in recent years (CLARY *et al.*, 2007; LOMBRAÑA *et al.*, 2010; MEDA *et al.*, 2016). The penetration of the product with microwaves results in rapid volumetric heating, increasing the vapour pressure at the interior and creating a driving force for moisture transfer to the surface. Applying a vacuum creates an additional pressure gradient for moisture transport and allows the user to adjust the temperature to the desired level. These combined effects cause rapid drying and prevent both the shrinkage and case hardening problems often seen in conventional drying methods (TSURUTA *et al.*, 2015; WRAY and RAMASWAMY, 2015).

The MV drying of potato cubes created a porous microstructure from the dried material, and there was low shrinkage of the dried potato particles as well as high rehydration capacity (MARKOWSKI *et al.*,2009). MV-dried green peas were characterized by minimal structural changes in terms of microstructure, shrinkage (43.3±0.1%) and colour changes compared to atmospheric freeze-drying with a heat pump fluidized bed (ZIELINSKA *et al.*,2013). In addition, the aroma, colour, and nutrients or other biologically active ingredients that are sensitive to thermal or oxidative degradation are better protected by MV drying than conventional hot air drying methods (CHAUHAN and SRIVASTAVA, 2009; MICHALSKA *et al.*, 2017; TEIN M. LIN, 1998; WOJDYŁO *et al.*, 2013). A lower degradation of polyphenols and anthocyanins has been reported for MV-dried raspberries compared to hot air-dried samples (SI *et al.*, 2016). LEUSINK *et al.* (2010) found that MV drying and freeze-drying methods had similar effects in preserving the anthocyanin content and antioxidant activity of cranberries, while lower drying times were needed during MV drying. Despite the numerous studies that have demonstrated the superiority of MV drying in terms of product quality, the drying of artichokes using a microwave vacuum has not been studied yet.

Designing an MV drying process is a complicated engineering problem because it is controlled by a large number of variables associated with both the system design (i.e., the cavity size, number and position of magnetrons, power density, duty cycle, and vacuum intensity) and the product properties (shape, size, geometry, dielectric and thermophysical properties) (CHEN *et al.*, 2015; PITCHAI *et al.*, 2012; ROGELIO *et al.*, 2015). Since microwaves are sinusoidal propagating electromagnetic waves and they are reflected from metal surfaces, a complex time-dependent field pattern generally forms in the drying cavity. This pattern results in the uneven heating of the product and the formation of hot spots. Therefore, the prediction of the temperature distributions in addition to the moisture transport in the product is critical to the product quality and process development (FENG *et al.*, 2012). From a practical point of view, empirical models have been used by several authors to simulate the drying curve of various products during MV drying. KIRANOUDIS *et al.* (1997) studied the MV drying kinetics of fruits by using the exponential model and reported that the drying constant is dependent on the microwave power and vacuum pressure. DROUZAS *et al.* (1999) used the Lewis model to predict the MV drying kinetics of model fruit gels and proposed an empirical correlation to estimate the drying rate constant as a function of the microwave power and the absolute pressure of the system. CUI *et al.* (2005) modelled the drying kinetics of carrot slices with a theoretical model and found a linear relationship between the drying rate and the microwave power level. In the same study, the temperature changes were also evaluated but the heating uniformity issues were not. It is obvious that the mathematical form of the proposed model and the drying times significantly changed for each food item in the above mentioned studies. Therefore, determining the heat and mass transfer behaviour simultaneously with the heating uniformity issues and quality characteristics would enhance our knowledge regarding the adoption of this relatively new technology for drying artichokes.
In this study, the use of microwave vacuum drying on fresh artichokes was investigated by determining the drying characteristics and temperature profiles under different drying conditions. For this purpose, the effects of the microwave power, system pressure and drying time on the drying rates, heating uniformity indices, colour changes, shrinkage and rehydration behaviour of artichokes were investigated. In addition, simple mathematical modelling approaches, including Fick's law of diffusion, were tested to predict the moisture transport.

2. MATERIAL AND METHODS

2.1. Materials

Fresh artichokes (*Cynara scolymus* L. cv. Sakız) were purchased from a manufacturer located in the Urla/İzmir area (Aegean coast of Turkey). Samples at the same commercial maturity level (as defined by the compactness of the fully developed buds) were carefully selected. All the globe artichokes were hand-trimmed on the same day using sharp stainless-steel knives to remove the external bracts and leaves and to create a uniform shape and size (10 ±1 cm diameter and 1±0.2 cm thickness). The average moisture content of the fresh artichoke hearts was found to be 6.1466±0.2909 kg H_2O/kg dry matter. Finally, the artichoke hearts were soaked in a 1% citric acid solution and stored at 4°C until the drying experiments.

2.2. Microwave Vacuum Drying System

A complete diagram of the laboratory-scale microwave vacuum dryer is presented in Fig. 1. The primary components of the microwave vacuum dryer consist of a vacuum chamber (7), microwave applicator set (17), heating plates (15), control panel (1-5), condenser (11), vacuum pump (12), pressure metre (13) and solenoidal valve (14). The microwave applicator (drying chamber) has the rectangular shape (30 cm wide, 21 cm high and 25 cm deep) and stainless-steel walls typical of many industrial and microwave multimode cavities. A magnetron emitting at a frequency of 2.45 GHz with a maximum microwave power of 1000 W was placed at the top of the drying chamber. The microwave power was transmitted through a waveguide (WR340), which is characterized by its TE10 mode pattern of field distribution. Heating plates were used to maintain the temperature of the cabinet walls at the targeted drying temperature (±1°C) to prevent condensation within the drying chamber. The MV drying system was completed with a condenser (water cooling system) to prevent water accumulation in the vacuum pump, which could damage the pump. The pressure control was performed using a pressure sensor (Autonics, Korea, model PSA-V01-Rc1/8) and its associated solenoid valve (Parker, USA) through an on-off control with a hysteresis value of±1.33 kPa (Fig. 1).

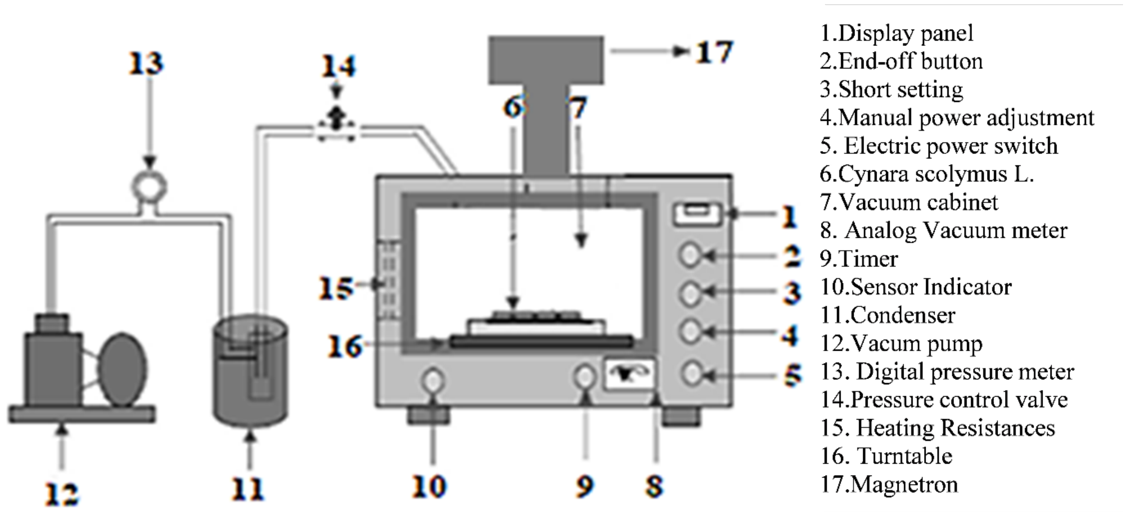

Figure 1. Microwave vacuum drying system.

2.3. Drying experiments

The artichoke hearts were removed from the 1% citric acid solution and drained. They were then gently blotted with filter paper to remove the adhering solution and weighed before being dried. The average moisture content of the artichokes prior to MV drying was found to be 8.9472±0.7152 kg H_2O/kg dry matter. Since the MV drying equipment was operated in batch mode due to the vacuum, new samples were used in each experiment. A single artichoke with an average weight of 52.2312±5.1249 g was used for each drying experiment. The artichokes were vertically positioned 15 cm below the top of the vacuum chamber and horizontally relative to the centre of the base. Microwave energy was supplied to the drying chamber as soon as the desired vacuum was attained. The rotation speed of the turntable was set to 5 rpm to avoid the uneven heating of the product by nonuniform microwave radiations. The artichokes were removed from the drying

chamber at specified sampling times after the vacuum was released. The dried samples were kept in airtight glass jars until the analysis.
MV drying experiments were performed at two levels of microwave power (450 W and 800 W) and two levels of absolute pressure (31.20 kPa and 12.40 kPa) until the final moisture content of the artichokes fell below 0.1 kg H_2O/kg dry matter. The microwave power levels were determined after preliminary trial runs with consideration for the calorimetric effect of the microwave system (4-6 W/g of sample). The drying time of the artichokes was recorded to be approximately 25 min at 450 W and 15 min at 800 W, regardless of the pressure level. Therefore, the quality characteristics (i.e., the shrinkage coefficient, rehydration ratio, and colour values) were determined at 5 min intervals up to 15 min for 800 W and 25 min for 450 W at all pressure levels.
The MV drying experiments were repeated separately at the specified combinations of microwave power and pressure levels to determine the drying kinetics and temperature profiles. The temperature distributions and weight loss of the samples were monitored at 1 min intervals. The weights of the samples were recorded with a digital balance that had an accuracy of 0.001 g (Sartorius, Germany). The surface temperature was measured from the top layer with an infrared camera (Testo 880-3, Germany). All the weight and thermal imaging recordings were completed in 10-15 sec. Two replicates were used for each drying experiment to determine the drying kinetics, temperature profiles and quality control parameters. The average values were used in the following calculations.

2.4. Drying characteristics and modelling the drying curves

2.4.1 Determination of drying kinetics

A graphical representation of the drying rates as a function of the drying time and free moisture content (M_t) was used to describe the drying behaviour of the artichokes during MV drying. The rate of drying (R) is expressed as the amount of water (kg) removed from the artichokes per unit area (h) per unit time (m^2) and is calculated by the following equation:

$$\boldsymbol{R} = -\frac{\boldsymbol{L_s}}{\boldsymbol{A(t)}} * \frac{\boldsymbol{dM}}{\boldsymbol{dt}} \tag{1}$$

where L_s is the dry solid weight (kg), *A(t)* is the surface area (m^2) of an artichoke at any drying time (t), *dM* is the change in moisture content (kg water/kg dry solids) and *dt* is the time (h) between measurements (GEANKOPLIS, 2003). The moisture contents of the samples were determined by drying them in a vacuum oven at 70°C under 57.6 kPa gauge pressure (AOAC, 2005). The moisture content determinations were performed in triplicate and the average values were used in the calculations.

2.4.2 Models for drying curves

The moisture transport during the microwave vacuum drying of the artichokes was characterized by the model based on Fick's second law of diffusion, which is given in Eq. (2).

$$\frac{\partial M}{\partial t} = \nabla(D_{eff} \cdot \nabla M) \tag{2}$$

In this equation, $M(t,x)$ is the moisture content (kg water/kg dry matter.); t is time (s), x is the distance from centre (m), and D_{eff} is the effective diffusion coefficient (m^2/s).

Equation (2) can be solved analytically by using the separation of variables method for an infinite slab using the following initial (IC) and boundary conditions (BC1 and BC2) with the assumptions that the shrinkage, constant temperature and diffusion coefficients would be neglected. Equation (3) is the initial condition stating the uniform distribution of moisture within the samples. Equation (4) is the symmetry condition in the centre of the slab and Eq. (5) is the boundary condition at the surface, and it establishes that at this point, the equilibrium moisture content is reached immediately due to the effect of the vacuum (CRANK,1975).

$$\text{IC: } M(0,x) = M_0 \quad \forall x \tag{3}$$

$$\text{BC 1: } \left.\frac{\partial M}{\partial x}\right|_{x=0} = 0 \quad t > 0 \tag{4}$$

$$\text{BC 2: } M(t, L/2) = M_S = M_e \quad \text{t} > 0 \tag{5}$$

where M_0 is the initial moisture content (kg H_2O/kg dry matter.); M_s is the moisture content at the surface (kg H_2O/kg dry matter); M_e is the equilibrium moisture content (kg H_2O/kg dry matter); and L is the thickness of the slab.

$$\frac{M-M_e}{M_0-M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2} exp\left(-(2n+1)^2\frac{\pi^2 D_{eff}}{L^2}t\right) \tag{6}$$

Equation (6) gives the moisture concentration at a given time and a given location in an infinite slab. Since the experimental data were obtained for the total moisture loss from the entire product, Eq. (6) should be integrated throughout the entire volume to obtain the average moisture content of the sample as a function of time. In taking the average moisture contents and only the first term of the infinite series solution in case Fourier Number ($\tau = D_{eff}t/(L/2)^2$) > 0.2, Eq. (6) can be simplified to Eq. (7) as follows:

$$MR = \frac{\bar{M}-M_e}{M_0-M_e} = \frac{8}{\pi^2} exp\left(-\frac{D_{eff}\pi^2 t}{L^2}\right) \tag{7}$$

where *MR* is the dimensionless moisture ratio based on the average moisture contents.
In addition to the theoretical models, several researchers have proposed simple models to simulate the drying curves of foods that can provide adequate representations of experimental data, although the parameters of these models lack physical sense. Among the semi-empirical drying models, namely, the Lewis or exponential model (Eq. (9)), the Henderson and Pabis model (Eq. (8)) and the Page model (Eq. (10)) are used widely (EREN *et al.*, 2008; SUTAR and PRASAD, 2007)

$$MR = \frac{\bar{M}-M_e}{M_0-M_e} = \text{a exp }(-\text{kt}) \tag{8}$$

$$MR = \frac{\bar{M}-M_e}{M_0-M_e} = \text{exp }(-\text{kt}) \tag{9}$$

$$MR = \frac{\bar{M}-M_e}{M_0-M_e} = exp(-kt^n) \tag{10}$$

where k is the drying rate constant (*1/s*) or (*1/s^n*) and a and n are parameters in the models.

2.4.3 Temperature profiles and heating uniformity calculations

A heating uniformity evaluation of artichoke samples was conducted by using temperature uniformity indices, which are based on the average experimental temperatures (T_{av}) and the target temperature (T_{tg}) of drying. The target temperatures were 50 and 70°C because they correspond to the boiling temperatures of pure water at the applied chamber pressure levels. The indices given in Eq. (11) and Eq. (12) describe the temperature deviation of any point at the surface of the artichoke from the target and average temperatures at certain drying times as follows:

$$HUI_{av} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_i - T_{av})^2} \tag{11}$$

$$HUI_{tg} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_i - T_{tg})^2} \tag{12}$$

where T_i is the local temperature of any point at the surface of the product (°C) and N is the number of data points. If the temperatures deviate from the reference values, the HUI will be higher and represents worse heating uniformity. Image processing software (IRSoft PC v4, Germany) was used to analyse the surface temperature data from the dried artichokes. From each thermal image, at least 8619 individual temperature data points were used for the calculations.

2.4.4 Shrinkage coefficient calculations

The shrinkage is defined as the ratio of the volume (V) of an artichoke sample at any dryness level to that of the fresh sample (V_0). The volumetric shrinkage coefficient (S) is calculated using the following equation:

$$S = \frac{V}{V_0} \tag{13}$$

Volume measurements of the artichoke samples were conducted by volume displacement method as described by (SEGNINI *et al.*, 2004). Rapeseeds (*Brassica napus*) with a typical diameter of (~2 mm) were used as the granular material. At the first stage, a 500 mL beaker was filled with seeds and compressed manually to determine the calibrated amount of seeds. The seeds were then transferred carefully to a larger beaker containing an artichoke sample, and the excess seeds were swept away with a metal slab. The excess seeds were measured with a graduated cylinder (100±1 mL) to determine the apparent volumes of the samples. The volume measurement procedure was repeated three times for each artichoke sample and the average values were evaluated with a shrinkage coefficient calculation.

2.4.5 Rehydration ratio

The rehydration ratio (RR) is defined as the ratio of the weight of the rehydrated sample (WR) to the weight of the dried sample (WD). For this purpose, dried artichoke samples were immersed in 200 mL of distilled water at a temperature of 30±0.5°C. Samples were withdrawn from the solution at 20-min intervals and blotted with tissue paper to remove excess moisture. The weights of the rehydrated samples were then recorded for up to 80 min. The RR was calculated using the following equation:

$$R = \frac{WR}{WD} \quad (14)$$

The rehydration ratio determinations were performed in duplicate, and the average values were evaluated using calculations.

2.4.6 Determination of Colour Changes

The colours of fresh and dried artichoke samples were determined using a colourimeter (Minolta CR-410, USA) based on the CIELAB colour space. L^* represents the lightness of the luminance component (0 for black and 100 for white) and the coordinates a^* and b^* are the two chromatic components that represent the greenness to redness (-60 to +60) and the blueness to yellowness (-60 to +60), respectively. In addition, three derived colour parameters, the total colour differences (ΔE), hue angle ($h°$) and browning index (*BI*), were calculated using the following equations:

$$\Delta E = [(L_{ref} - L^*)^2 + (a_{ref} - a^*)^2 + (b_{ref} - b^*)^2]^{1/2} \quad (15)$$

$$h° = arctan(b^*/a^*) \quad (16)$$

$$BI = \frac{100(x-0.31)}{0.17} \quad (17)$$

$$x = \frac{(a^*+1.75L^*)}{(5.645L^*+a^*-3.012b^*)} \quad (18)$$

The colour parameters were also written in normalized form as $\boldsymbol{\Delta a}$ (a-a_{ref}), $\boldsymbol{\Delta b}$ (b-b_{ref}), $\boldsymbol{\Delta L}$ (L-L_{ref}), $\boldsymbol{\Delta L}$ (L-L_{ref}) and $\boldsymbol{\Delta BI}$ (BI-BI_{ref}). The subscript *"ref"* in calculations of the colour parameters denotes the reference values obtained from pre-treated artichokes prior to MV drying. The larger the ΔE values, the greater the colour change from the fresh sample (DONG *et al.*, 2018). The hue angle (h°) expresses the colour change (an angle of 0 or 360° represents a red hue, while angles of 90, 180, and 270° indicate yellow, green and blue hues, respectively). A decrease in the hue angle values is an indication of more browning colour and a shift away from yellowness (HAWLADER *et al.*, 2006). The browning index represents the purity of the brown colour and is an important parameter in processes in which enzymatic or nonenzymatic browning take place (PALOU *et al.*, 1999). The colour measurements were performed in duplicate, and six measurements were taken over the entire artichoke surface through rotation.

2.5. Statistical analysis

An analysis of variance was used to determine the effects of the microwave power, system pressure and drying time on the heating uniformity indices (HUI_{av} and HUI_{tg}), shrinkage coefficient, rehydration ratio and change in colour parameters of artichokes at the 95% level of significance. The experimental data for dimensionless moisture contents were fitted to the diffusion model, the Lewis model (exponential model), the Henderson-Pabis model and the Page model using a nonlinear regression analysis. All the statistical and regression analyses were performed using a statistical package program (SPSS v22.0, IBM Inc., 2013, USA). The coefficient of determination (R^2) and root mean square error (*RMSE*) were used to evaluate the goodness of the fit for the tested models. The best model

describing the drying behaviour was chosen as the one with the highest R^2 and the lowest *RMSE* (EREN *et al.*, 2008).
The RMSE values were calculated using the following equation:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(Y_{exp_i} - Y_{pre_i})^2\right]^{1/2} \tag{19}$$

where Y_{exp_i} is the experimental dimensionless moisture value, Y_{pre_i} is the predicted dimensionless moisture contents from the model, and N is the number of observations.

3. RESULTS AND DISCUSSION

The drying kinetics of artichokes were studied for average moisture contents ranging from 8.9472±0.7152 to 0.0643±0.0004 kg H_2O/kg dry matter by applying two different microwave powers (450 W and 800 W) and pressure levels (31.20 kPa and 12.40 kPa). The experimental moisture contents on a dry basis over the course of MV drying are given in Fig. 2-a. A non-linear relationship between the moisture contents and the drying times was observed under all the processing conditions. Similar MV drying curves were also obtained by JAYA and DURANCE (2007) for alginate-starch gels and by SONG *et al.* (2009) for potato slices. Microwave power significantly affected the drying curves and decreased the drying time of the samples from 25 to 15 min.
Fig. 2-b shows that the drying rates increased at the initial stages of drying (2-3 min) when the absorbed microwave energy was converted into sensible heat within moist artichokes, and the average temperature of the product increased with time. The average temperatures were increased very sharply with the corresponding boiling temperatures of pure water (Fig. 2-b). The saturation temperature is 50°C at 12.40 kPa and 70°C at 31.20 kPa. However, slight deviations were recorded in the average temperatures during the MV drying of the artichokes from the effects of the process parameters (Fig. 2-b). An increase in microwave power from 450 W to 800 W at 31.20 kPa caused an increase in the maximum average temperatures from 69°C to 75.9°C during MV drying. Similar behaviour in the average temperatures was also observed at lower vacuum levels (12.40 kPa), but the maximum average temperatures were reduced to 56.8°C and 60.4°C for 450 W to 800 W, respectively.
After this initial heating period, the vapour pressure of the product exceeded that of the drying chamber, and the thermal energy converted from microwave energy was used to evaporate moisture. At the low microwave power level (450 W), a constant drying rate region was observed regardless of the applied vacuum intensity. The occurrence of this constant rate period primarily resulted from the wet surface of the artichokes during the initial drying stages. A constant rate of drying was continued as long as water was supplied from the inside of the product to the surface at the rate of surface moisture removal. As the moisture content and the dielectric loss factor decreased, the rate of conversion of the electromagnetic waves to heat slowed and the internal mass transfer resistances became more pronounced. Therefore, a falling drying rate region was observed at moisture contents below 3-4 kg H_2O/kg dry matter at the low microwave power level (Fig. 2-d). CUI *et al.* (2004) reported lower critical moisture content values of 2-3 kg H_2O/kg dry matter after the MV drying of carrots.

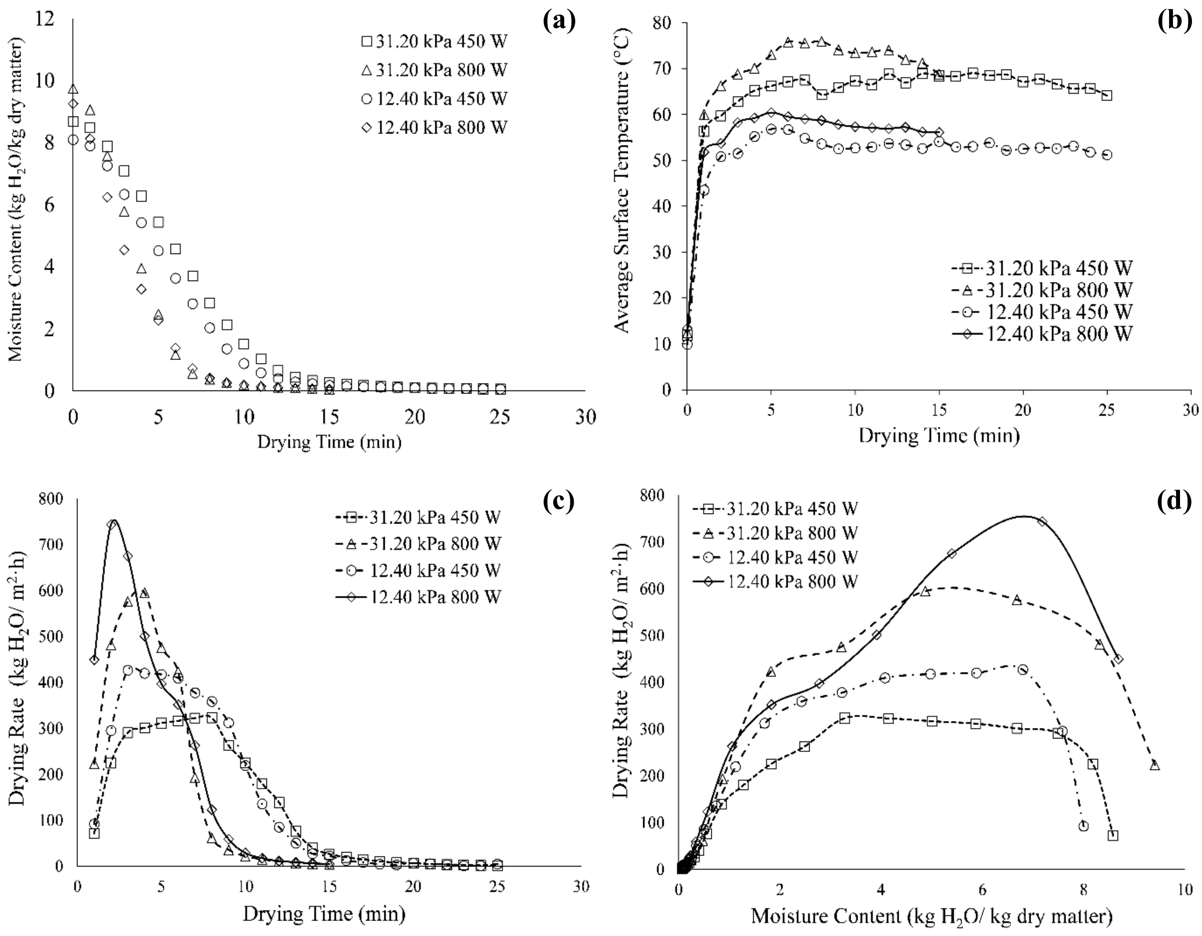

Figure 2. Effects of the process parameters on the drying characteristics and average surface temperatures of artichokes during MVD. (a) Moisture ratio vs. drying time; (b) drying rate vs. drying time; (c) drying rate vs. moisture content; and (d) surface temperature vs. drying time.

However, at the high microwave power level (800 W), the drying rate increased within 2-3 min, and then it decreased exponentially after reaching peak values of 595 and 744 kg $H_2O/m^2\cdot h$ under 31.20 and 12.40 kPa vacuum pressure, respectively (Fig. 2-d). The high microwave power (800 W), which generated higher pressure inside the product, resulted in an additional pressure gradient that was responsible for the higher rates of moisture transport. Thus, the surface moisture was removed very quickly during the initial stage of drying, and drying took place directly during a falling rate period, which is an indication of an internal resistance-controlled drying mechanism. This result was expected because as the surface moisture is removed, the surface layer becomes dry and hard due to tissue shrinkage and creates resistance against the inside moisture moving towards the surface. Compared with microwave power, the effect of system pressure on the drying rates appears to have decreased towards the end while being more pronounced in the initial stages of drying. This result also indicated that the moisture transport during the MV drying of artichokes was primarily controlled by internal resistance mass transport.

The slopes of the drying rate curves in Fig. 2-d show two distinct falling rate periods for all the MV drying conditions. The first and second falling-rate periods were determined by using the locations of the critical moisture contents, which were calculated from the plot of the drying rate gradient vs. the moisture content (LAW *et al.*, 2003). At low microwave power (450 W), the critical moisture contents (x_{c1}) for the first falling-rate period were found to be 3.277 and 4.075 kg H_2O/kg dry matter for 31.20 kPa and 12.40 kPa, respectively. Under high microwave power (800 W), the first critical moisture contents were increased to 4.867 kg H_2O/kg dry matter for 31.20 kPa and 7.184 kg H_2O/kg dry matter for 12.40 kPa. By contrast, as the microwave power increased to 800 W, the second critical moisture contents (x_{c2}) decreased from 0.399 to 0.263 kg H_2O/kg dry matter for 31.20 kPa and from 0.474 to 0.339 kg H_2O/kg dry matter for 12.40 kPa. Under all the MV drying conditions, the most relevant variable that affected the location of the critical points was the microwave power.

3.3. Evaluation of the mathematical models

Since different drying periods were observed during the MV drying of artichokes, the semi-empirical and theoretical models were fitted to the experimental data for both the first falling rate (*1st FRP*) and second falling (*2nd FRP*) rate periods. Table 1 shows the parameters of the models and the goodness of fit criteria for the semi-empirical models; namely, the Lewis model (Eq. (9)), the Henderson and Pabis model (Eq. (8)), the Page model (Eq. (10)) and the model based on Fick's second law of diffusion (Eq. (7)).

From the values for the coefficient of determination (R^2) and the root mean square error (*RMSE*), it is obvious that the Page model and the Henderson and Pabis model gave satisfactorily good fits for predicting the moisture contents of artichokes for all the MV drying periods. The R^2 values for these two semi-empirical models were greater than 0.982 and the *RMSE* values were less than 1.457×10^{-3}. However, the Page model had better R^2 and *RMSE* values for the 2nd *FRP* than the Handerson and Pabis model. Therefore, the Page is the best model for all the processing conditions. The success of the Page model at characterizing MV drying was also reported by other researchers on the drying of bananas, potatoes and carrot slices using microwave vacuum technology (CUI *et al.*, 2004; MOUSA and FARID, 2002; SONG *et al.*, 2009).

The drying rate constants (k) of the semi-empirical models showed an increasing tendency with increased microwave power and vacuum for both falling rate periods (Table 1). This increase resulted from the increase in the drying rates by more thermal energy generation and consequently more internal vapour pressure inside the product. The drying rate constants (k) of the Page model were recorded over ranges of 3.906×10^{-6} - 3.610×10^{-4} (1/s) and 9.325×10^{-3} - 7.078×10^{-2} (1/s) for the 1st FRP and 2nd FRP, respectively. A graphical representation of the predicted moisture ratios by the Page model in comparison with the experimental moisture ratios under all the processing conditions is shown in Fig. 3. It is clear that the Page model gave good predictions at all stages of MV drying in artichokes.

During the MV drying of the artichokes, the shrinkage effects were ignored and the geometry of the disc-shaped artichokes was assumed to be an infinite slab due to the high diameter/height ratio (*10:1*). Therefore, the diffusional model was solved for an infinite slab assuming negligible shrinkage. When external resistance to mass transfer is considered negligible, the effective diffusion coefficient (D_{eff}) can be identified using Eq. (7) by minimizing the differences between the experimental and estimated MR. The low R^2 (<0.82) and high *RMES* (> 6.817×10^{-2}) values indicated that one or more combinations of different moisture transport mechanisms took place and thus reduced the accuracy of the diffusion model in the 1st FRP. The diffusion model simulated the drying curves more accurately (R2 > 0.82 and RMES < 4.327×10^{-3} in the 2nd FRP (Table 1). The effective diffusion coefficients were found to range from 2.279×10^{-6} - 3.454×10^{-6} m^2/s and 3.600×10^{-6}- 6.297×10^{-6} m^2/s for the 1st FRP and 2nd FRP, respectively (Table 1).

Table 1. Parameters of the semi-empirical and diffusion models for the drying kinetics of artichokes.

Model		Model parameters/ goodness of fit	MV Drying Process Condition: 31.20 kPa 450 W	31.20 kPa 800 W	12.40 kPa 450 W	12.40 kPa 800 W
Lewis Model	1^{st} *FRP*	*k*	2.616×10^{-3}	4.087×10^{-3}	2.662×10^{-3}	4.578×10^{-3}
		R^2	0.760	0.778	0.942	0.973
		RMSE	5.919×10^{-2}	8.310×10^{-2}	7.700×10^{-2}	6.559×10^{-2}
	2^{nd} *FRP*	*k*	3.783×10^{-3}	6.605×10^{-3}	4.087×10^{-3}	6.425×10^{-3}
		R^2	0.970	0.958	0.647	0.945
		RMSE	2.335×10^{-3}	3.310×10^{-3}	4.764×10^{-3}	2.776×10^{-3}
Page Model	1^{st} *FRP*	*k*	3.906×10^{-6}	1.736×10^{-5}	9.944×10^{-6}	3.610×10^{-4}
		n	2.034	1.983	1.920	1.456
		R^2	0.999	0.998	0.999	0.999
		RMSE	1.849×10^{-3}	8.377×10^{-3}	5.899×10^{-3}	9.266×10^{-3}
	2^{nd} *FRP*	*k*	9.325×10^{-3}	2.223×10^{-2}	2.135×10^{-2}	7.078×10^{-2}
		n	0.868	0.805	0.810	0.582
		R^2	0.985	0.992	0.968	0.980
		RMSE	1.629×10^{-3}	1.455×10^{-3}	1.457×10^{-3}	1.714×10^{-3}
Henderson and Pabis Model	1^{st} *FRP*	*k*	5.202×10^{-3}	7.663×10^{-3}	5.050×10^{-3}	5.473×10^{-3}
		a	3.880	2.403	2,649	1.254
		R^2	0.993	0.985	0.986	0.990
		RMSE	9.777×10^{-3}	2.167×10^{-2}	2.049×10^{-2}	2.659×10^{-3}
	2^{nd} *FRP*	*k*	3.284×10^{-3}	5.280×10^{-3}	2.267×10^{-3}	5.166×10^{-3}
		a	0.637	0.515	0.192	0.504
		R^2	0.982	0.989	0.955	0.975
		RMSE	1.754×10^{-3}	1.727×10^{-3}	1.695×10^{-3}	1.843×10^{-3}
Diffusion Model	1^{st} *FRP*	D_{eff}	2.279×10^{-6}	3.367×10^{-6}	2.679×10^{-6}	3.454×10^{-6}
		R^2	0.682	0.669	0.727	0.819
		RMSE	6.817×10^{-2}	1.014×10^{-1}	9.224×10^{-2}	1.140×10^{-1}
	2^{nd} *FRP*	D_{eff}	3.600×10^{-6}	6.297×10^{-6}	3.898×10^{-6}	6.120×10^{-6}
		R^2	0.979	0.973	0.942	0.960
		RMSE	1.754×10^{-3}	2.628×10^{-3}	4.327×10^{-3}	2.383×10^{-3}

The increasing trend in the D_{eff} with the microwave power was observed during both falling rate periods since a higher microwave power level would enhance the drying rate by generating more heat energy inside the product. As shown in Table 1, the D_{eff} values increased by 1.10 times for the 1^{st} *FRP* and remained almost constant for the 2^{nd} *FRP* as the system pressure decreased from 31.20 kPa to 12,40 kPa. The internal mass transfer resistance and the dry surface of the samples during the falling rate periods can be understood as the reason for the limited effect of the pressure on the D_{eff}. SUTAR and PRASAD (2007) also reported that the effect of the pressure on the D_{eff} of carrot slices during MV drying was non-significant over a range of 6.66-33.30 kPa at a 5% level of significance. The effect of microwave power on the D_{eff} was much more pronounced in the 2^{nd} *FRP*. This finding could be the result of the increased microwave power intensities in terms of watts per gram of product load due to the lower moisture contents in the 2^{nd} *FRP* of MV drying. Additionally, a higher moisture diffusivity in the 2^{nd} *FRP* during the microwave drying of kiwifruits was associated with an increased moisture permeability caused by structural changes such as surface cracking, the destruction of cell walls and the formation of open-pore structures (MASKAN,2001).

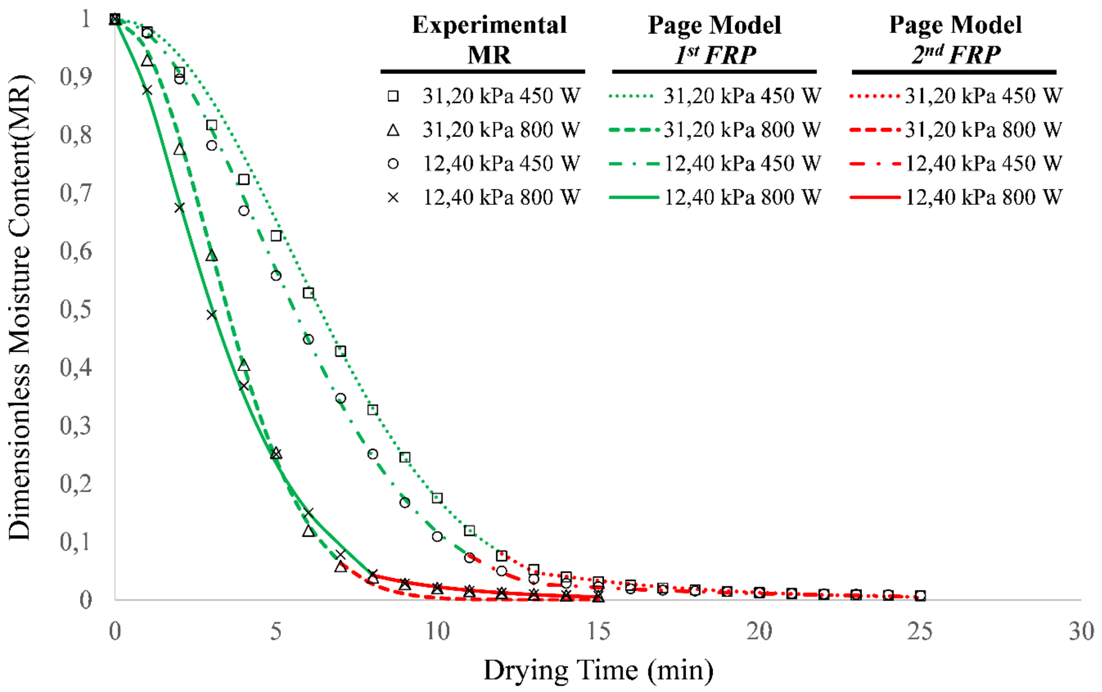

Figure 3. Experimental and predicted drying curves for artichokes using the Page model.

The experimental versus predicted dimensionless moisture ratios (*MR*) obtained by using the Page and the diffusion models at different stages of MV drying are plotted in Fig. 4. While the predicted MR values obtained by the Page model correlates well with the experimental data, clear deviations from the 45° line for the diffusion model can be seen in Fig. 4 for the 1^{st} *FRP*. Inaccurate predictions of the MR values by the diffusion model could have resulted from the fact that internal moisture transport took place in the presence of one or more combinations of different moisture transport mechanisms such as a hydrodynamically driven flow of vapour and liquid, liquid transport with capillary action, and evaporation-condensation. Conversely, the diffusion model eliminated the discrepancies between the experimental and predicted MR values for the 2^{nd} *FRP* (Fig. 4). This finding implied that liquid and vapour diffusion were the primary mechanisms of moisture transport during the MV drying of artichokes.

3.3. Temperature profiles and heating uniformity

The temperature profiles obtained at 5 min intervals with a thermal imager are represented in the form of a colour image (Fig. 5). It is clear that the temperature profiles varied significantly during the MV drying process depending on the process parameters. The formation of an annular hot zone, as represented by red coloured regions, was observed for its drying at high microwave power (800 W). The maximum temperatures reached up to 107°C and 89.2°C at a 31.20 kPa pressure level for 800 W and 450 W between 7 and 12 min of drying for a short time. As the absolute pressure decreased to 12.40 kPa, the maximum temperatures also decreased to 90.1°C and 77.9°C for 800 W and 450 W microwave power levels. High product temperatures (greater than 100°C) were also reported by SUTAR and PRASAD (2007) for a short period during the MV of drying carrot slices.

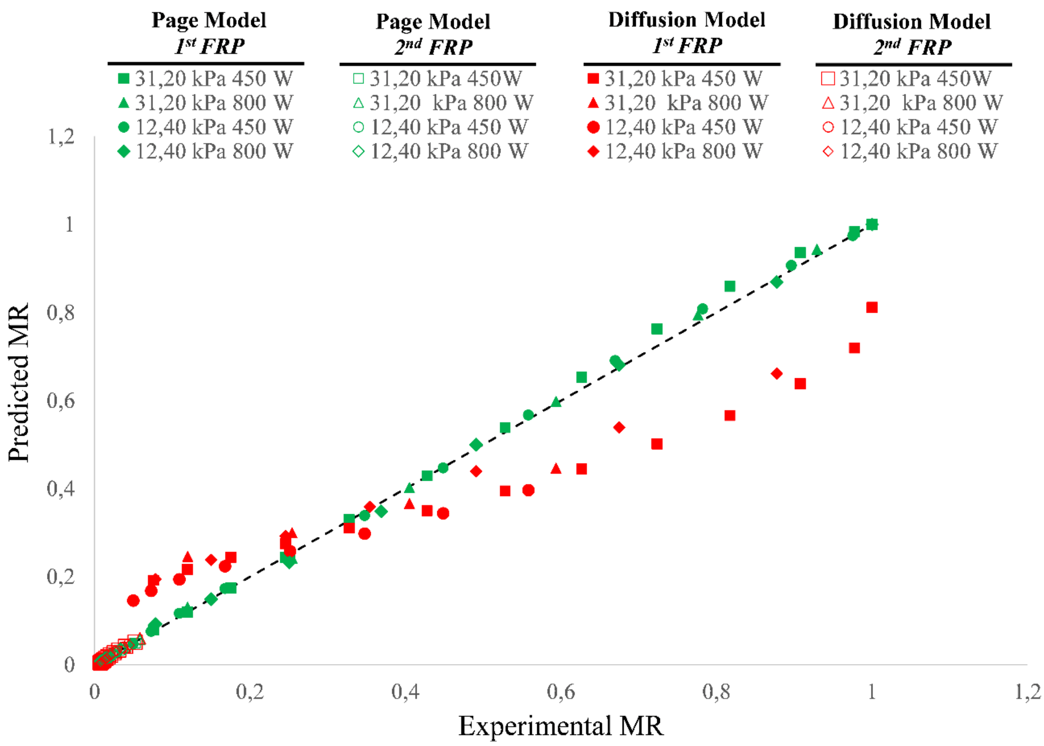

Figure 4. Comparison of the experimental and predicted dimensionless moisture contents simulated using the Page and diffusion models.

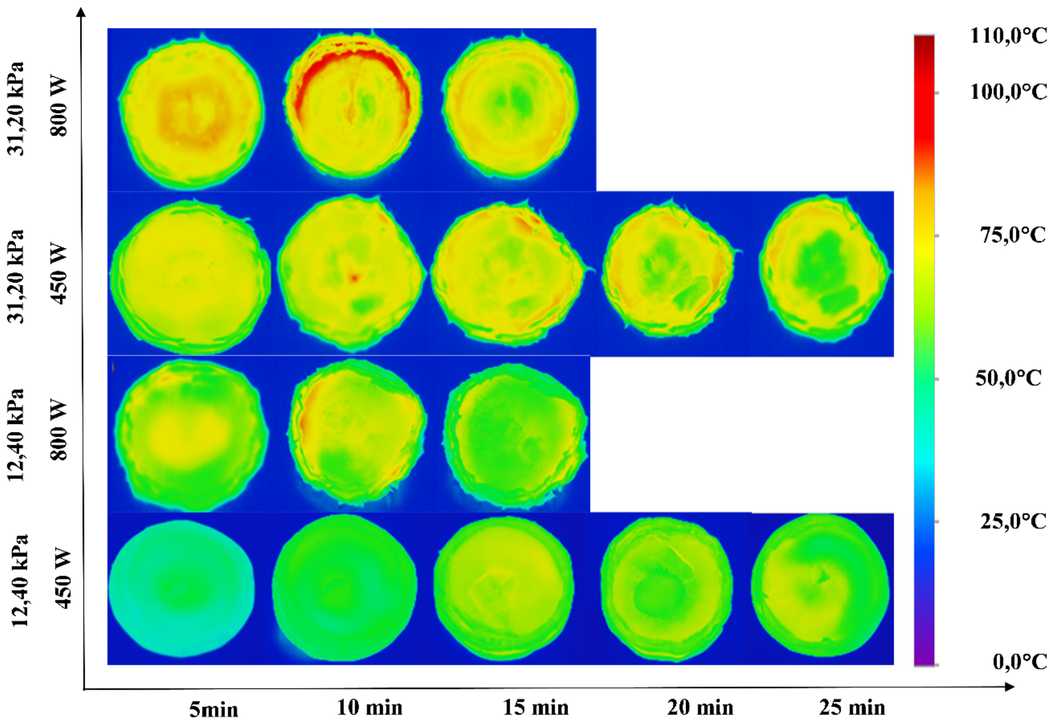

Figure 5. Surface temperature distribution of artichokes during MV drying.

Two different heating uniformity indices based on the average (HUI_{av}) and target (HUI_{tg}) temperatures were calculated to analyse the variation in the temperature distribution as MV drying proceeds (Table 2). The HUI_{av} values were found to range from 2.77±0.40-6.79±0.16. The HUI_{tg} values varied over a wider range between 3.47±0.32 and 15.17±0.07. The effects of process parameters such as the drying time, pressure and microwave power on the heating uniformity indices (HUI_{av} and HUI_{tg}) were statistically evaluated at a 95% confidence level using an analysis of variance (Table 3). The results showed that the variation in both heating uniformity indices could be explained by using the developed general linear models ($p<0.001$) with reasonable high R^2 values of 0.99 and 0.95 for the HUI_{av} and HUI_{tg}, respectively.
Microwave power ($p<0.001$) was the only MV drying parameter that significantly affected the HUI_{tg} values. Although the evaporation rate increase depends on the microwave power, the moisture removal rate has always been lower due to internal resistance because the MV drying takes place primarily during the falling rate period. Therefore, the increase in internal pressure due to vapour accumulation and the superheating of the entrapped vapour resulted in increased product temperatures and hence higher HUI_{tg} values. The effect of the system pressure ($p>0.01$) on the HUI_{tg} values were found to be non-significant at a 95% confidence level even though the average drying temperatures were decreased (Table 3). This result can be explained by the limited effect of the pressure on the MV drying characteristics during falling rate periods.

Table 2. Heating uniformity indices for MV drying of artichokes as a function of the drying time.

Drying Time (min)	MV Drying Process Conditions							
	31.20 kPa 450 W		31.20 kPa 800 W		12.40 kPa 450 W		12.40 kPa 800 W	
	HUI_{av}	HUI_{tg}	HUI_{av}	HUI_{tg}	HUI_{av}	HUI_{tg}	HUI_{av}	HUI_{tg}
5	4.76±0.22	6.19±0.17	5.61±0.20	14.03±0.09	3.53±0.32	9.69±0.11	5.09±0.19	12.58±0.07
10	3.85±0.26	4.91±0.20	6.79±0.16	15.01±0.08	3.47±0.32	3.47±0.32	6.03±0.16	15.17±0.07
15	4.80±0.21	5.08±0.20	5.32±0.19	10.17±0.11	3.55±0.30	11.83±0.09	4.35±0.25	9.12±0.14
20	5.37±0.21	5.46±0.20			2.77±0.40	10.00±0.10		
25	6.67±0.19	8.97±0.14			5.26±0.20	9.69±0.12		

Table 3. ANOVA table showing the effects of the process parameters on the heating uniformity indices.

Source	DF	HUI_{av}			HUI_{tg}		
		Sum of Squares	Mean Square	*p*-value	Sum of Squares	Mean Square	*p*-value
Model	7	389.326 [a]	55.617	<0.001	1554.157 [b]	222.022 [b]	<0.001
Pressure	1	5.221	5.221	.008	8.586	8.586	.354
MW Power	1	7.106	7.106	.003	101.475	101.475	.008
Time	4	6.669	1.667	.048	14.306	3.576	.806
Error	9	4.047	0.450		80.984	8.998	

Notably, the HUI_{av} values were significantly affected by all three process parameters at a 95% confidence level. It was observed that microwave power ($p<0.01$) increased the HUI_{av} values because it supported the formation of hot spots. The continuous supply of electromagnetic energy and the sinusoidal propagation characteristics of microwaves were the primary reasons for the occurrence of annular hot zones during MV drying, especially at the 15th min for 450 W and the 10th min for 800 W. The effect of the pressure ($p<0.01$) seemed to be more effective due to evaporative cooling in the regions where the temperature was high, rather than lowering the average temperature. Table 3 also shows that the effect of the drying time ($p<0.05$) on the HUIav values is not as pronounced as the microwave power and pressure. A slight increase in the HUI_{av} values was observed through the end of the MV drying due to selective heating with a decrease in moisture content.

3.4. Shrinkage coefficient

The shrinkage coefficients of artichokes as a function of the moisture content under different microwave power and vacuum intensity conditions are given in Fig. 6. As the moisture contents decreased up to 60% (w/w), the shrinkage coefficients decreased sharply due to the high moisture removal rates during the initial stages of MV drying. The reduced volume of the artichoke samples for all the MV drying conditions were found to range from 63% to 78%, with the lowest shrinkage effect occurring when high microwave power (800 W) and low pressure (12.40 kPa) were applied. The standard deviations for each experimental shrinkage coefficient ranged between 0.01 and 0.33, which corresponds to experimental uncertainty limits between ±1.37% and ±9.21%.

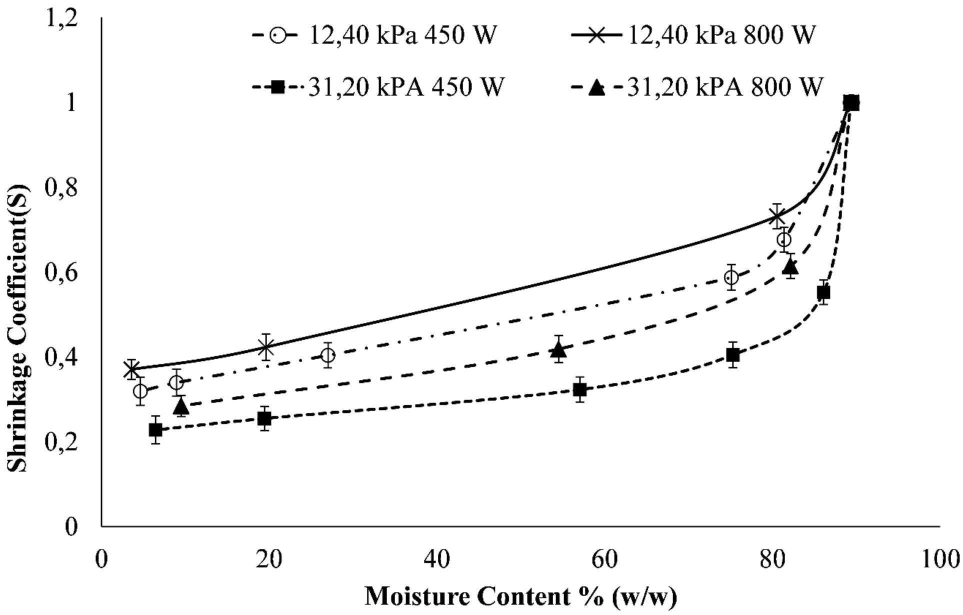

Figure 6. Shrinkage coefficient of artichokes as a function of moisture.

A statistical analysis using an ANOVA showed that the moisture content ($p<0.001$) and system pressure ($p<0.001$) have more pronounced effects on the shrinkage coefficients than microwave power ($p<0.05$). Removing water from plant structures reduces the turgor pressure created by intracellular fluids and a pressure imbalance between the inner and outer parts of the tissue occurs (MAHIUDDIN *et al.*,2018). Therefore, decreasing the system pressure from 31.20 kPa to 12.40 kPa minimized the pressure imbalances and resulted in higher shrinkage coefficients for a given microwave power level. The volumetric heating effect of the microwaves caused an additional increase in internal pressure due to vaporization, and the shrinkage-reducing effect of microwave power was also found to be statistically significant. However, the decrease in the heat generation rate due to the reduced moisture contents at the falling rate period of drying caused this effect to be more limited. Similar results have also been reported by GIRI and PRASAD (2006) for the MV drying of button mushrooms.

3.5. Rehydration ratio

The rehydration ratios of artichoke samples that were dried at different system pressures and microwave power levels are depicted in Fig. 7. Initially high rates of moisture uptake were followed by a slower absorption rate in the final stages of rehydration. This typical rehydration behaviour has also been observed for MV-dried button mushrooms, potato cubes and green beans (GIRI and PRASAD, 2007; MARKOWSKI *et al.*, 2009; ZIELINSKA *et al.*, 2013). The equilibrium conditions for the rehydration process were reached within 80 min at 30°C. At that point, the rehydration ratio of the artichokes was determined to be within a range from 1,7326±0,1673 to 3,82±0,091 for various drying conditions. Similar to that of the shrinkage coefficients, the system pressure ($p<0.001$) and microwave power level ($p<0.05$) were found to be the statistically significant MV drying factors that affected the rehydration ratio at a 95% confidence level.

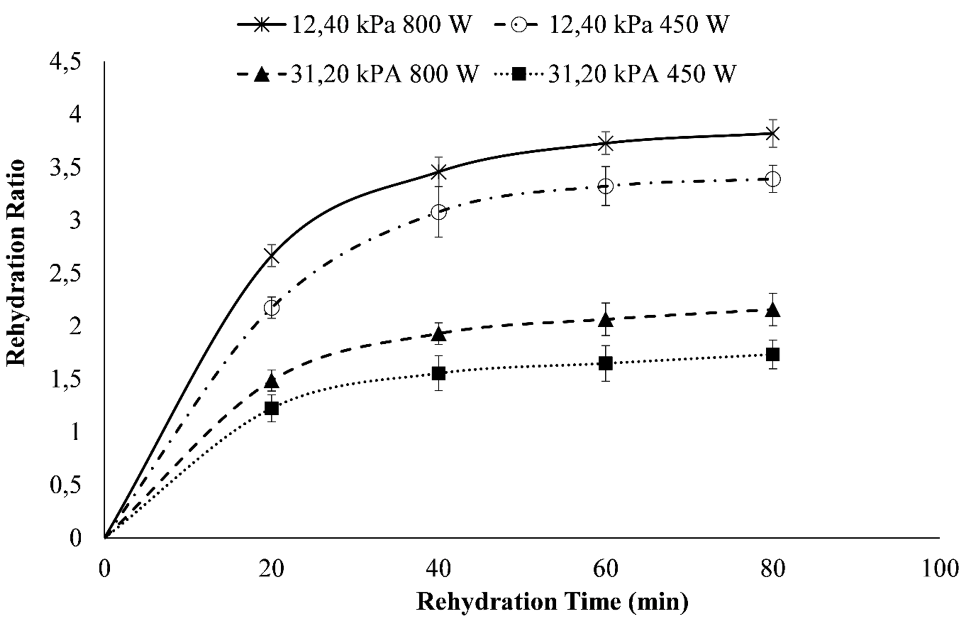

Figure 7. Rehydration Ratio of MV-dried artichokes as a function of rehydration time.

As indicated by the higher shrinkage coefficients, drying at a lower system pressure and higher microwave power enhanced the porous structure of the dried artichokes. Therefore, the capillaries and cavities with a larger volume absorbed much more water, leading higher rehydration ratios by decreasing the system pressure and increasing the microwave power.

3.6. Colour changes during MV drying of artichokes

Artichokes have been known to be very prone to enzymatic and non-enzymatic browning during storage and post-harvest processes due to their high enzymatic activity and phenolic contents, in combination with temperature-dependent phase changes in the cellular membrane (DOĞAN *et al.*, 2005; LATTANZIO and LINSALATA, 1989). The mean values of the L^*, a^* and b^* for the artichoke samples prior to MV drying were found to be 73.32±6.97, -4.31±1.22 and 27.31±2.46, respectively. These values indicate that the artichoke hearts used in the experiments were light, yellowish and greenish, but there was considerable variability among the samples. It was observed that the changes in the L^*, a^* and b^* values of the samples during MV drying were lower than the variation in the initial colour values. A statistical analysis also showed that the MV drying parameters did not affect the L^*, a^* and b^* values of the dried artichokes significantly at the 95% confidence level. Therefore, the deviations in the colour values of the artichokes prior to MV drying were eliminated by normalizing (Δ) the dry product colour values relative to the colour values of the artichokes used in the experiments (Table 4).

Table 4. Normalized colour parameters for MV-dried artichoke hearts.

Drying Conditions	Drying Time (min)	ΔL	Δa	Δb	Δh°	ΔE	ΔBI
31.20 kPA 450 W	5	2.06	-1.05	6.59	-0.20	6.99	9.74
	10	2.64	-0.90	6.00	-0.38	6.62	11.17
	15	3.74	0.69	6.09	-2.75	7.18	11.28
	20	3.21	0.82	7.29	-2.70	8.01	16.08
	25	2.30	0.90	7.98	-3.01	8.35	16.56
31.20 kPa 800 W	5	3.17	1.06	7.43	-3.71	8.14	15.37
	10	3.51	1.00	7.18	-2.89	8.05	15.57
	15	3.45	1.11	8.58	-2.96	8.99	23.53
12.40 kPA 450 W	5	3.15	-1.36	5.32	0.86	7.52	5.25
	10	3.90	-1.07	5.44	0.28	6.78	6.32
	15	2.51	0.87	7.54	-4.14	7.99	16.41
	20	2.47	1.68	8.12	-5.26	8.65	19.22
	25	3.17	1.00	10.94	-4.09	10.99	24.14
12.40 kPa 800 W	5	3.46	-1.09	10.76	-1.84	11.36	17.50
	10	2.94	-0.06	9.56	-1.60	10.00	18.02
	15	1.88	0.67	12.97	-3.12	13.12	29.76

The ANOVA results revealed that the normalized colour parameters except for *ΔL* were affected by at least one MV drying parameter, i.e., the microwave power, system pressure and drying time at a 95% confidence level. The ***ΔBI***, ***ΔE*** and ***Δh°*** were found to be more explanatory at describing the colour changes during the Mv drying of the artichokes. The microwave power ($p<0.01$) and drying time ($p<0.01$) were the most influential MV drying parameters, since they affected all the normalized colour parameters for all the drying conditions. As the microwave power and drying time increased, the ***ΔE*** and ***ΔBI*** values increased and the ***Δh°*** values decreased. The negative correlation of the ***Δh°*** values to both ***ΔE*** and ***ΔBI*** were found to be statistically significant ($p<0.05$) with high Pearson's correlation coefficients ($r>0.71$) under all the drying conditions. The lower ***Δh°*** values revealed that the redness of the dried artichokes increased more than the yellowness, indicating more browning. HAWLADER *et al*. (2006) also stated that decreases in the hue angle values could be interpreted as an indication of a more browning colour and a shift away from yellowness.

Another important point regarding the colour changes during the MV drying of artichokes is that the effect of the system pressure on the ***Δh°*** and ***ΔBI*** values was statistically insignificant (p >0,1). This finding may be because the Maillard reactions remained at a limited level and enzymes such as polyphenol oxidase (PPO) largely retained their activity at the studied temperature ranges (56.8-60.4°C at 12.40 kPa and 69-75.9°C at 31.20 kPa). A residual PPO activity of 32% was also reported by (JAISWAL *et al.*,2010) for the hot air drying of pomegranate arils in which the temperature was gradually reduced from 90°C to 50°C. Therefore, enzymatic browning reactions are thought to be more determinant of discolouration in artichoke samples. The highest ***ΔE*** and ***ΔBI*** values were recorded at the lowest system pressure (12.40 kPa) and the highest microwave power (800 W) as 13.12 and 29.76, respectively. PARIN (2004) reported higher ***ΔBI*** (38.35) and ***ΔE*** (42.80) values for artichokes dried with hot air at 60°C despite the pretreatments, such as blanching for 15 min followed by immersion in 1% (w/v) citric acid solution for 30 min.

4. CONCLUSIONS

Microwave power was found to be the most influential parameter on the drying characteristics of artichokes compared to system pressure. Both the constant and falling rate periods of drying were observed under low microwave power levels, whereas drying took place primarily during the falling rate period at high microwave power. Two distinct falling rate periods were evident from the drying characteristic curves. The low accuracy of the diffusion model in the *1st FRP* indicated that one or more combinations of different moisture transport mechanisms took place. The diffusion model simulated the drying curves more accurately in the *2nd FRP*. The effective diffusion coefficients were found to range from 2.279×10^{-6}- 3.454×10^{-6} m^2/s and 3.600×10^{-6} - 6.297×10^{-6} m^2/s for the *1st FRP* and *2nd FRP*, respectively. An increasing trend in the D_{eff} with microwave power was observed during both falling rate periods since higher microwave power levels would enhance the drying rate by generating more heat energy inside the product. In addition, empirical models accurately simulated the drying curves during the MV drying of artichokes, even though the estimated parameters do not provide mechanistic information and lack physical meaning. Reducing the microwave power and system pressure resulted in lower HUI_{av} values, indicating a higher uniformity in the temperature distribution. However, the average temperatures deviated slightly from the targeted drying temperature at high microwave power and the HUI_{tg} values increased. An intermittent (pulsed) supply of electromagnetic energy would be an effective approach not for only eliminating the deviations from target temperatures but also for increasing the energy efficiency. The MV drying at lower system pressure and higher microwave power resulted in increased shrinkage coefficients and rehydration ratio values. High ***ΔBI*** and low ***Δh°*** values indicated slight discolouration in the samples due to browning reactions induced by microwave power. Enzymatic browning is thought to be the primary discolouration mechanism during the MV drying of artichokes due to the relatively low average drying temperatures, but further investigations on the enzymatic activity are necessary for confirmation. It can be concluded that MV technology has great potential for drying artichokes in terms of drying times and dried product characteristics.

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