International Food Research Journal 22(2): 494-501 (2015)

Journal homepage: *http://www.ifrj.upm.edu.my*

Mathematical modelling, moisture diffusion and specific energy consumption of thin layer microwave drying of olive pomace

Sadi, T. and *Meziane, S.

Laboratory of Applied Chemistry and Chemical Engineering, Faculty of Sciences, University Mouloud Mammeri, B.P N°17 RP, 15000 Tizi-Ouzou, Algeria

Article history

Received: 2 March 2014
Received in revised form:
28 January 2015
Accepted: 7 February 2015

Keywords

Olive pomace
Microwave drying
Modeling
Effective moisture diffusivity
Specific energy consumption

Abstract

In this study, the effects of microwave drying power on drying kinetics, effective moisture diffusivity, and specific energy consumption of olive pomace were studied at three different microwave power levels of 170, 360 and 510 W. Increasing microwave power resulted in a considerable decrease in drying time. The experimental data for moisture loss was converted to moisture ratios and fitted to eleven thin layer drying mathematical models to describe the drying process. Among the models tested, the Midilli *et al.* and Diffusion Approch models were found to be the most appropriate in describing microwave drying kinetics of olive pomace. The effective moisture diffusivity values varied from 3.55 x 10^{-9} to 20.47 x 10^{-9} m^2/s and increased with increase in microwave power. The activation energy was calculated using an exponential expression based on Arrhenius equation and was found to be 20.98 W/g. The specific energy consumption values were in the range of 52.56 to 25.32 MJ/kg [H_2O], under applied drying conditions.

Introduction

Agricultural products are characterized with high initial moisture content. Drying is one of the oldest and most widely used methods of food preservation. It is based on removal of moisture contained in the product by means a complicated process involving simultaneous heat and mass transfer (Krokida *et al.*, 2003; Yilbas *et al.*, 2003). Drying of agricultural products can be performed using different drying methods (solar drying, hot air drying, microwave drying, infrared drying, etc.). In particular, the conventional hot air drying processes was the most common method used. However, this drying technique has a number of disadvantages such as poor quality of dried products, low energy efficiency and a long drying time (Maskan, 2000; Soysal and Oztekin, 2001).

The microwave technology is widely applied to treat various kinds of raw materials and products including food, fruits, vegetables, wood, etc. In drying agricultural products, microwave drying has gained much popularity as an alternative drying method in the last few years, due to high potential in improving process efficiency and quality of dried products. Some of the recent studies focus on fruits, vegetables, and the by-products of agricultural industry such as parsely (Soysal, 2004; Soysal *et al.*, 2006), garlic cloves (Sharma, 2006), nettles leave (Alibas, 2007), okra (Dadali *et al.*, 2007), mint leaves (Ozbek and Dadali, 2007; Therdthai and Zhou, 2009), spinach (Ozkan *et al.* 2007), apple pomace (Wang *et al.*, 2007), red pepper (Soysal *et al.*, 2009), whole fruit Chinese jujube (Wang *et al.*, 2009), purslane (Demirhan and Ozbek, 2010), rosehips (Evin, 2011a), white mulberry (Evin, 2011b), Pandanus leaves (Rayaguru and Routray, 2011), coriander leaves (Sarimeseli, 2011), liquorice root (Balbay and Sahin, 2012), *Gundelia tournefortii* L. (Evin, 2012), mango ginger (Krishna Murthy and Manohar, 2012) and potato slices (Darvishi *et al.*, 2013). This alternative method of drying presents several advantages including shortening drying time, high energy efficiency, high quality finished products, and uniform heating due to the penetration of microwaves into the body of the product (Yongsawatdigul and Gunasekaran, 1996; Soysal, 2004; Vadivambal and Jayas, 2007; Wang *et al.*, 2007; Soysal *et al.*, 2009; Therdthai and Zhou, 2009). On the other hand, microwave drying is known to lead low quality product when it's not appropriately applied (Yongsawatdigul and Gunasekaran, 1996; Soysal *et al.*, 2009).

Microwave drying differs fundamentally from the conventional hot-air drying. Microwaves are a form of electromagnetic energy with frequencies that lie between 300 MHz and 300 GHz, generated by magnetrons under the combined force of an electric and a magnetic field perpendicular to each other. During microwave drying, the water molecules of the product to be dried readily absorb this energy, which

---

*Corresponding author.
Email: *smmeziane@yahoo.fr*

is converted to heat. Thus, the water vaporizes and diffuses through the product to the surface where it's led away.

Olive production is a significant agriculture activity in the countries of the Mediterranean basin with important environmental, social and economic implications. Olive pomace is an important biomass by-product of olive oil industry, which can be used in very large amounts at very low cost. It is composed of a mixture of olive pulp and olive stones and it has been widely used as an animal feed supplement (Molina-Alcaide and Yáñez-Ruiz, 2008), energy source (Skoulou *et al*., 2009), fertilizer (Altieri and Esposito, 2010) and in many industrial purposes. However, this seasonal product is quite perishable due to its high moisture content, which can reach 65% depending on the olive oil extraction process used. It's then essential to dry this abundant agricultural waste quickly up to certain level, at which microbial spoilage and deterioration chemical reactions are greatly minimized. Therefore, the study on drying olive pomace is of great significance for recycling resource and environmental protection. Most of the previous studies on drying of olive pomace have focused on convective hot-air drying (Doymaz *et al*., 2004; Akgun and Doymaz, 2005; Jumah *et al*., 2011; Meziane, 2011; Vega-Galvez *et al*., 2011). In all these studies, the mathematical modeling of drying curves and the effects of drying on drying kinetics, effective moisture diffusivity were investigated. Other methods such as the drying using microwave and infrared energy (Gogus and Maskan, 2001, Celma *et al*., 2008) were also used. In their study, Gogus and Maskan (2001) studied the effects of microwave power, thickness and temperature on the drying kinetics of olive pomace in a combined microwave-fan assisted convection oven. However, to our knowledge, there is no available report regarding the effect of microwave power on effective moisture diffusivity and energy consumption during microwave drying of olive pomace.

In this study, attention is focused on the microwave drying kinetics of olive pomace over a microwave power range of 170 to 510 W. Several thin layer-drying models were fitted to the experimental data of moisture ratio versus drying time in order to evaluate a suitable form of the drying kinetics curves for olive pomace. The influence of microwave power on the drying kinetics, moisture diffusivity and energy consumption was studied.

Materials and Methods

Raw material

Fresh olive pomace was obtained from local continuous three-phase centrifugal system. The initial moisture content of the sample was approximately 45.02% (wb) and average particle diameter of 1.2 mm. The sample was kept in air tight plastic bottles and stored at a temperature of 4°C until the drying process.

Drying equipment and experimental procedure

The drying experiments were performed in a domestic digital microwave oven (whirlpool; MWO 611) presented in Figure 1.

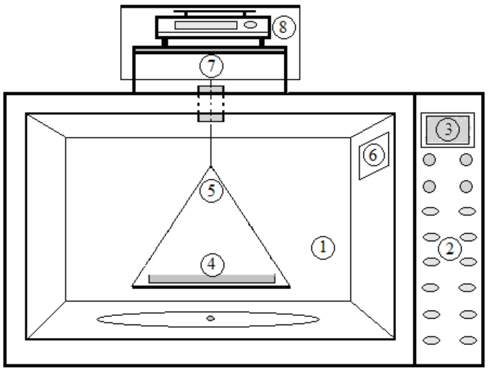


Figure 1. Schematic diagram of microwave dryer
1: microwave drying chamber; 2: control panel of the microwave; 3: time and power display; 4: sample; 5: glass stem; 6: aeration; 7: bracket; 8: digital balance

It consists of a microwave generator with maximum output of 850 W at a frequency of 2450 MHz. The oven is fitted with a controller to set the microwave output power and the time of processing. The dimensions of the microwave inner cavity were 220 x 354 x 358 mm. An electronic balance (JA5003, Shanghai Balance Instrument Factory, China) with accuracy of ±0.01 g was positioned on a bracket on the top of the microwave oven for mass determination. Drying experiments were carried out at three microwave powers of 170, 340 and 510 W.

Before each run, the microwave oven was set to operating drying power by heating 500 ml of water in a glass beaker for few min. The Petri-dish in glass (6 mm depth and 95 mm diameter) containing the sample with initial load of about 20.00 g and thickness of 6 mm was then placed on the tray, which was suspended on the balance with a glass stem out through a hole in the center of chamber ceiling. Moisture loss in the sample was continuously measured by using an electronic balance and recorded at 2 min intervals for drying experiments with the microwave powers of 170 and 350 W, and at 1 min intervals for experiments with 510 W. Drying process continued till the moisture content of olive pomace was reduced to about 7.0% (wb). After, the glass Petri-dish containing the dried sample was placed in an oven set at 105°C for 24 hours in order to determine its dry matter. Each drying run was carried out in triplicate and average value was reported.

Modelling of drying curves

In this study, the microwave experimental drying data of olive pomace at three power levels were fitted to the eleven commonly used thin layer drying mathematical models (Ertekin and Yaldiz, 2004; Sacilik *et al*., 2006; Akpinar and Bicer, 2008), listed in Table 1. In these models, MR represents the dimensionless moisture ratio expressed as follow:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where, M_t is the moisture content of the sample at any time (kg water/kg dry matter), M_e is the equilibrium moisture content of the sample (kg water/kg dry matter) and M_0 is its initial moisture content (kg water/kg dry matter). The values of M_e are relatively small compared with M_t or M_t/M_0 for long drying time (Akgun and Doymaz, 2005). Thus, moisture ratio can be simplified to $MR = M_t/M_0$.

The non-linear regression analysis was performed using Statistica 5.0 software (Statsoft, USA) to fit the experimental data to the eleven selected mathematical models available in literature. The coefficient of determination (R^2) is one of the primary criteria in order to evaluate the fit quality of selected models. In addition to R^2, reduced chi-square (χ^2) and root mean square error (RMSE) are used to determine suitability of the fit. The reduced chi-square and the root mean square error can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{ei} - MR_{pi}\right)^2}{N - z} \quad (2)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{ei} - MR_{pi}\right)^2\right]^{1/2} \quad (3)$$

where MR_{ei} is the *i*th experimental moisture ratio, MR_{pi} is the *i*th predicted moisture ratio, N is the number of observations and z is the number of constants in a model. The higher the R^2 values and the lower the χ^2 and RMSE values, the better is the goodness of fit (Ertekin and Yaldiz, 2004; Doymaz and Ismail, 2011).

The drying rate (DR) is expressed as the amount of the evaporated moisture over time. The drying rate (kg moisture/kg dry solid min) of olive pomace was computed using the following equation:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (4)$$

where $M_{t+\Delta t}$ is the moisture ratio at t+Δt.

Effective moisture diffusivity and activation energy

The effective moisture diffusivity can be defined from Fick's second law of diffusion (Eq. 5), which describes the movement of moisture within the solid.

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M \quad (5)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), M is the material moisture content (kg/kg of dry solid), and t is the time (s). An analytical solution of this law in the case of drying an infinite slab of thin layer, assuming moisture migration being by diffusion, one-dimensional moisture movement, uniform initial moisture distribution, negligible shrinkage, constant moisture diffusivity, and negligible external resistance to heat and mass transfer can be developed in the form of the following equation (Crank, 1975):

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2}{4L^2}D_{eff}\,t\right] \quad (6)$$

where D_{eff} is the effective moisture diffusivity ($m^2\ s^{-1}$), L is the half-thickness of the product being dried (m) and t is the time (s).

For long drying periods, Eq. (6) can be further simplified to only the first term of the series (n=0). Thus, simplified Eq. (6) is written in a logarithmic form as follows (Chen, 2007; Doymaz and Ismail, 2011):

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - D_{eff}\left(\frac{\pi}{2L}\right)^2 t \quad (7)$$

The effective moisture diffusivity was calculated by using the method of slopes. From Eq. (7), a plot of ln (MR) versus time gives a straight line with a slope of:

$$Slope = -D_{eff}\left(\frac{\pi}{2L}\right)^2 \quad (8)$$

The energy of activation in the microwave dryer was calculated using the Arrhenius exponential model (Dadali *et al*., 2007; Ozbek and Dadali, 2007; Darvishi *et al*., 2013).

$$D_{eff} = D_{eff0}\exp\left(-E_a \times \frac{m}{P}\right) \quad (9)$$

where D_{eff0} is the pre-exponential factor (m^2/s); P is the microwave output power (W), m is the average mass of raw sample (g), and E_a is the activation energy (W/g). The linear form of Eq.(10) can be obtained by applying the logarithms as:

$$\ln(D_{eff}) = \ln(D_{eff0}) - E_a\left(\frac{m}{P}\right) \quad (10)$$

Both Arrhenius parameters (E_a and D_{eff0}) can be estimated from the slope ($-E_a$) and intercept $\ln(D_{eff0})$ of the plot $\ln D_{eff}$ versus (m/P).

Specific energy consumption

Effect of microwave drying power on the energy efficiency of microwave drying was evaluated by the specific energy consumption (SEC). This energy, expressed in (MJ/kg[H_2O]), was calculated as the energy needed to evaporate a unit mass of water (Yongsawatdigul and Gunasekaran, 1996; Soysal *et al*., 2006).

$$SEC = \frac{P \times \Delta t}{m_w} \times 10^{-6} \quad (11)$$

where m_w is the mass of evaporated water (kg) and Δt is the time interval (s).

Results and Discussion

Analysis of drying curves

The experimental data for moisture loss were converted to dimensionless moisture ratio and plotted against time. Figure 2 presents the drying curves [MR=f(t)] for microwave drying of olive pomace at different microwave powers.

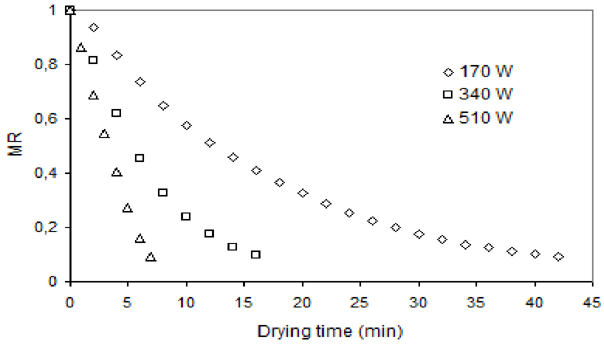


Figure 2. Microwave drying kinetics of olive pomace at different microwave powers

As show this figure, the drying process is characterized by a progressive decrease in moisture ratio with drying time depending on the microwave output power. As expected, the total drying time showed a substantial reduction as microwave drying power was increased. Indeed, the total drying times to reach the final moisture ratio of the pomace were 42, 16 and 7 min at 170, 340, 510 W, respectively. The required drying time for microwave drying at 170 W was 6 times longer than that at 510 W. This indicates that an increasing microwave power strongly accelerates the drying process, thus greatly shortening the drying time. Similar finding was reported for microwave drying of many biological products by many researchers. Thus, the drying time was found to be shortened by 64% with the increase of microwave power from 360 W to 900 W for microwave drying of parsley (Soysal, 2004). This time was reduced by 76% in the power range from 180 to 900 W for microwave drying of mint leaves (Ozbeck and Dadali, 2007) and by 88% working at 800 W instead of 90 W for rosehips (Evin, 2011a). By working at 900W instead of 180 W, Dadali *et al*. (2007) showed that the drying time was shortened by 72% for microwave drying of okra. Alibas (2007) reported that the required time for microwave drying of nettle leaves at 500 W was 1.5 times longer than that at 850 W. Ozkan *et al*. (2007) studied microwave drying of spinach. The authors were observed that the drying time at 90 W microwave power level was 13.81 times longer than that for 1000 W.

Furthermore, the results obtained in this present study showed that as compared to convective hot air drying of olive pomace performed in a tunnel dryer at 90 °C (Meziane and Mesbahi, 2012), the drying time to achieve the required final moisture content of about 7% can be reduced by 8-fold by working at microwave output power of 510 W.

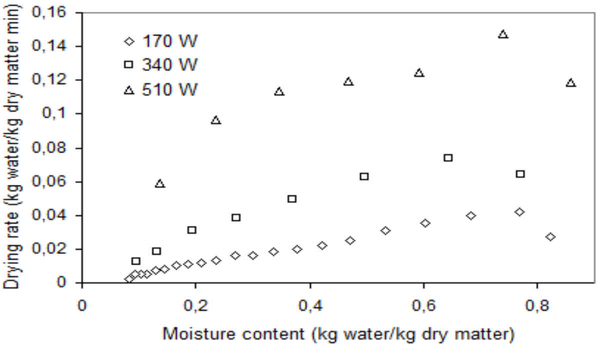


Figure 3. Drying rate versus moisture ratio of olive pomace at different microwave powers

Drying rate curves [DR=f(MR)] for olive pomace at different microwave power are shown in Figure 3. The drying rate decreased continuously with decreasing moisture ratio, indicating that microwave drying of olive pomace took place only during the falling rate period. This observation is in agreement with previous reports on thin layer microwave drying of bioproducts (Wang *et al*., 2007; Evin, 2011a, 2011b; Balbay and Şahin, 2012; Evin, 2012; Darvishi *et al*., 2013). In this drying period, the drying process was controlled by diffusion of moisture from the interior of solid to the surface. Drying rate increased also with microwave power level. This can be explained by rapid heating of the product, thus accelerating moisture migration toward the surface of the product where it's carried away.

Table 1. Statistical analysis of the eleven models fitted to the drying data for thin layer microwave drying of olive pomace

Model name	Model	P(W)	R^2	χ^2	RMSE
Lewis	$\exp(-kt)$	170	0.99783	0.0001747	0.012927
		340	0.98815	0.0012745	0.033868
		510	0.96037	0.0043125	0.061552
Henderson and Pabis	$a\exp(-kt)$	170	0.99907	0.0000784	0.008459
		340	0.99152	0.0010259	0.028648
		510	0.96855	0.0039931	0.054725
Logarithmic	$a\exp(-kt) + c$	170	0.99912	0.0000783	0.008249
		340	0.99631	0.0005105	0.018905
		510	0.99821	0.0002722	0.013044
Page	$\exp(-k(t)^n)$	170	0.99916	0.0000707	0.008036
		340	0.99975	0.0000304	0.004932
		510	0.99723	0.0003514	0.016235
Wang and Sing	$1 + at + bt^2$	170	0.99610	0.0003290	0.017333
		340	0.99889	0.0001340	0.010370
		510	0.99816	0.0002333	0.013229
Two-term exponentiel	$a\exp(-kt) + (1-a)\exp(-kat)$	170	0.99783	0.0001830	0.012926
		340	0.98815	0.0014338	0.033868
		510	0.96037	0.0050312	0.006143
Diffusion approch	$a\exp(-kt) + (1-a)\exp(-kbt)$	170	0.99985	0.0000136	0.003443
		340	0.99989	0.0000145	0.003189
		510	0.99570	0.0006551	0.020235
Verma *et al.*	$a\exp(-k_1t) + (1-a)\exp(-k_2t)$	170	0.99783	0.0001922	0.012926
		340	0.98815	0.0016387	0.033868
		510	0.96037	0.0060374	0.061428
Two-term	$a\exp(-k_1t) + b\exp(-k_2t)$	170	0.99907	0.0000866	0.008459
		340	0.99152	0.001368	0.028648
		510	0.96855	0.0059896	0.054725
Midilli *et al.*	$a\exp(-k(t)^n) + bt$	170	0.99955	0.0000417	0.005872
		340	0.99995	0.0000074	0.002114
		510	0.99958	0.0000794	0.006300
Modified Henderson and Pabis	$a\exp(-k_1t) + b\exp(-k_2t) + c\exp(-k_3t)$	170	0.99907	0.0000968	0.008459
		340	0.99152	0.0020518	0.028649
		510	0.96855	0.0119793	0.054725

Mathematical modelling of drying curves

The experimental data for moisture loss were converted to dimensionless moisture ratios and fitted to eleven thin layer drying mathematical models to describe the microwave drying behaviour of olive pomace. The values of the determination coefficient (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE) for different microwave powers determined by nonlinear regression analysis are presented in Table 1.

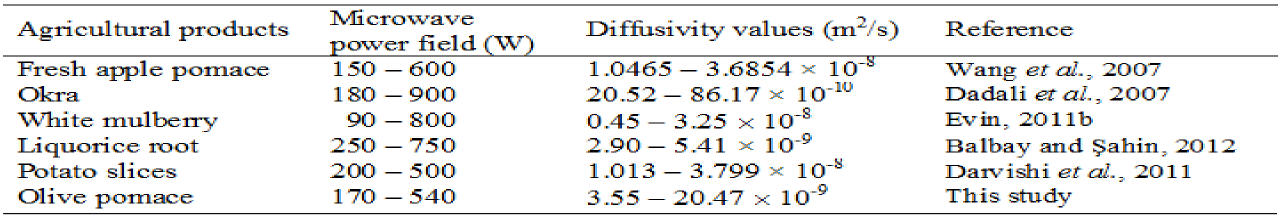
For all the models, the statistical parameter estimations showed that R^2, χ^2 and RMSE values were ranged from 0.96037 to 0.99995, 0.0000074 to 0.0119793, and 0.002114 to 0.061552, respectively, within the experimental range of study. Based on higher value of R^2, and lower values of χ^2 and RMSE the Page, Wang and Singh, Diffusion approach, Logarithmic and Midilli et al. models gave a good fit to the experimental data with R^2 values greater than 0.995 in all cases. However, the Midilli *et al.* model (2003) gave comparatively the highest R^2 value (0.99995) and the lowest χ^2 (0.0000074) and RMSE (0.002114) values at microwave power levels of 340 and 510 W. For the low power level of 170 W, the highest R^2 value (0.99985) and the lowest RMSE (0.0000136) and χ^2 (0.003443) values were found for the Diffusion approach model. Note that for this power, seven models (Page, Diffusion approach, Logarithmic, Two-term, Henderson and Pabis, Modified Henderson and Pabis and Midilli *et al*. models) gave an excellent fit to the experimental results with determination coefficients greater than 0.999. In their study Gogus and Maskan (2001) tested two models, i.e. the empirical Page's model and the diffusion model (Lewis) to describe the drying process of olive pomace in a combined microwave-fan assisted convection oven. They found that Lewis model provides a good fit to the experimental data.

The Midilli *et al*. model has also been suggested by many researchers to describe the drying behavior kinetics of biological materials dried using different drying methods such as microwave drying (Soysal *et al*., 2006; Ozbek and Dadali, 2007; Demirhan and Ozbek, 2010; Sarimeseli, 2011; Evin, 2012; Darvishi *et al*., 2013), infrared drying (Celma *et al*., 2009), hot air drying (Ertekin and Yaldiz, 2004; Akpinar, 2006; Wang *et al*., 2009; Amiri Chayjan *et al*., 2011; Meziane, 2011; Mihindukulasuriya and Jayasuriya, 2013) and natural sun drying (Akpinar and Bicer, 2008).

Calculation of effective moisture diffusivity and activation energy

In the literature, no report was found relating

Table 2. Effective moisture diffusivity values of some agricultural products



Agricultural products	Microwave power field (W)	Diffusivity values (m^2/s)	Reference
Fresh apple pomace	150 – 600	$1.0465 – 3.6854 \times 10^{-8}$	Wang *et al.*, 2007
Okra	180 – 900	$20.52 – 86.17 \times 10^{-10}$	Dadali *et al.*, 2007
White mulberry	90 – 800	$0.45 – 3.25 \times 10^{-8}$	Evin, 2011b
Liquorice root	250 – 750	$2.90 – 5.41 \times 10^{-9}$	Balbay and Şahin, 2012
Potato slices	200 – 500	$1.013 – 3.799 \times 10^{-8}$	Darvishi *et al.*, 2011
Olive pomace	170 – 540	$3.55 – 20.47 \times 10^{-9}$	This study

to investigation of the effective moisture diffusivity (D_{eff}) for olive pomace under microwave drying conditions. In this study, the effective moisture diffusivity values of the pomace for different levels of microwave power were calculated using the slope derived from the linear regression ln(MR) versus drying time (Eq.8). The plots gave straight lines with high determination coefficients ranging between 0.9535 and 0.9994. The Deff values obtained, presented in Table 2, ranged from 3.55 x 10^{-9} to 20.47 x 10^{-9} m^2 s^{-1}. These values are comparable with diffusivities obtained for the microwave drying of agricultural products, which are reported in Table 2.

As expected, microwave drying power had an appreciable effect on the diffusivity of olive pomace, which increased vigorously with increases in drying power from 170 to 510 W. Indeed, the value of Deff at 540 W is about 2.6 times higher than at 340 W and 5.8 times higher than at 170 W. Thus, the drying rate can be hastened and drying time can be shortened by using higher microwave powers, which increase effective moisture diffusivity. Same trend was observed for microwave drying of white mulberry (Evin, 2011b), fresh apple pomace (Wang *et al*., 2007) and potato slices (Darvishi *et al*., 2013). Moreover, the Deff values are substantially higher that those obtained during drying of the pomace using a tunnel-type dryer at drying air temperatures of 50, 60, 70, 90 °C (Meziane and Mesbahi, 2012). Indeed, the diffusivity value at microwave drying power level of 510 W was about 8-fold higher than in the drying by means of hot air steam at 90 °C. The relationship between effective moisture diffusivity and microwave power can be expressed as follow:

$$D = 6 \text{ x} 10^{-14} P^2 + 8 \text{ x } 10^{-13} P + 2 \text{ x } 10^{-9} \qquad R^2 = 1 \qquad (12)$$

The activation energy (E_a) of drying process of olive pomace calculated from the slope of the linearized Arrhenius relationship was found to be 20.98 W/g, with a determination coefficient of 0.9473. This value is similar to the reported value for microwave drying of mango ginger (21.6 kW kg^{-1}) (Krishna Murthy and Manohar, 2012), but it's higher than the value obtained in the microwave drying of okra (5.54 W/g) (Dadali *et al.*, 2007), mint leaves (12.2839 W g^{-1}) (Ozbek and Dadali, 2007), *Pandanus amaryllifolius* leaves (13.6 W/g) (Rayaguru and Routray, 2011) and potato slices (14.945 W/g) (Darvishi *et al*., 2013).

Calculation of specific energy consumption

The specific energy consumption values for the drying of olive pomace at different microwave powers of 170, 340 and 510 W were 52.56, 42.21 and 25.32 MJ/kg evaporated water, respectively. The SEC decreased by approximately 51.8% when the microwave power increased from 170 to 510 W. Similar trends were reported for microwave drying of parseley (5.10 to 4.18 MJ kg^{-1} [H_2O]), with microwave power ranging from 297 to 489 W (Soysal *et al.*, 2006) and slices potato slices (5.882 to 4.645 MJ/kg water), in the microwave power range of 300-500 W (Darvishi *et al*., 2013). Wang *et al*. (2009) studied the microwave drying of whole fruit Chinese jujube. It was shown that energy consumption decreased from 2.07 to 1.35 kWh as microwave power increased from 45 to 135 W. On the other hand, the specific energy consumption in microwave drying of garlic cloves at 40 W of microwave power output was 26.32 MJ/kg of water removed, resulting in about a 70% energy saving as compared to convective drying processes (Sharma and Prasad, 2006).

Conclusions

Microwave drying of olive pomace was investigated at microwave powers of 170, 340 and 510 W. It was observed that microwave drying took place in the falling rate period. Drying time up to the moisture content of about 7.0% (wb) can be reduced 7-fold by working at 510 W instead of 170 W. The Midilli et al. drying model was considered to be the best model for describing the drying behavior of olive pomace for the high drying powers considered here, whereas for the low power level of 170 W, the Diffusion approach model seems to be the most adequate. The effective moisture diffusivity value, which ranged between 3.55 x 10^{-9} and 20.47 x10^{-9} m^2 s^{-1}, increased with the increase in microwave power. The activation energy was found to be 20.98 W/g. The specific energy consumption decreased from

52.56 to 25.32 MJ/kg [H_2O] as the microwave power increased from 170 to 510 W.

References

Akgun, N. A. and Doymaz, I. 2005. Modeling of olive cake thin-layer drying process. Journal of Food Engineering 68(4): 455–461.

Akpinar, E. K. 2006. Determination of suitable thin layer drying curve model for some vegetables and fruits. Journal of Food Engineering 73(1): 75–84.

Akpinar, E. K. and Bicer, Y. 2008. Mathematical modelling of thin layer drying process of long green pepper in solar dryer and under open sun. Energy Conversion and Management 49(6): 1367–1375.

Alibas, I. 2007. Energy consumption and colour characteristics of nettle leaves during microwave, vacuum and convective drying. Biosystems Engineering 96(4): 495–502.

Altieri, R. and Esposito, A. 2010. Evaluation of the fertilizing effect of olive mill waste compost in short-term crops. International Biodeterioration and Biodegradation 64(2): 124-128.

Amiri Chayjan, R., Amiri Parian, J. and Esna-Ashari, M. 2011. Modeling of moisture diffusivity, activation energy and specific energy consumption of high moisture corn in a fixed and fluidized bed convective dryer. Spanish Journal of Agricultural Research 9(1): 28-40.

Balbay, A. and Şahin, O. 2012. Microwave drying kinetics of a thin-layer liquorice root. Drying Technology 30(8): 859–864.

Chen, X. D. 2007. Moisture Diffusivity in Food and Biological Materials. Drying Technology 25(7-8): 1203–1213.

Crank, J. 1975. The mathematics of diffusion. 2nd ed. Oxford (UK): Clarendon Press.

Dadali, G., Dilek Kilic, A. and Ozbek, B. 2007. Estimatioin of effective moisture diffusivity of okra for microwave drying. Drying Technology 25(9): 1445-1450.

Darvishi, H., Asl, A. R., Asghar, A., Najafi, G. and Gazori, H. A. 2013. Mathematical modeling, moisture diffusion, energy consumption and efficiency of thin layer drying of potato slices. Journal of Food Processing and Technology 4(3): 215.

Demirhan, E. and Özbek, B. 2010. Drying kinetics and effective moisture diffusivity of purslane undergoing microwave heat treatment. Korean Journal of Chemical Engineering 27(5): 1377-1383.

Doymaz, I., Gorel, O. and Akgun, N. A. 2004. Drying characteristics of the solid by-product of olive oil extraction. Biosystems Engineering 88(2): 213–219.

Doymaz, I. and Ismail, O. 2011. Drying characteristics of sweet cherry. Food and bioproducts processing 89(1): 31–38.

Evin, D. 2011a. Investigation on the drying kinetics of sliced and whole rosehips at different moisture contents under microwave treatment. Scientific Research and Essays 6(11): 2337-2347.

Evin, D. 2011b. Microwave drying and moisture diffusivity of white mulberry: experimental and mathematical modeling. Journal of mechanical science and technology 25(10): 2711-2718.

Evin, D. 2012. Thin layer drying kinetics of *Gundelia tournefortii* L. Food and bioproducts processing 90(2): 323–332.

Ertekin, C. and Yaldiz, O. 2004. Drying of eggplant and selection of a suitable thin layer drying model. Journal of Food Engineering 63(3): 349–359.

Gogus, F. and Maskan, M. 2001. Drying of olive pomace by a combined microwave-fan assisted convection oven. Nahrung/Food 45(2): 129– 132.

Jumah, R., Al-Kteimat, E., Al-Hamad, A. and Telfah, E. 2007. Constant and intermittent drying characteristics of olive cake. Drying Technology 25(9): 1421-1426.

Krishna Murthy, T. P. and Manohar, B. 2012. Microwave drying of mango ginger (*Curcuma amada* Roxb) prediction of drying kinetics by mathematical modelling and artificial neural network. International Journal of Food Science and Technology 47(6): 1229–1236.

Krokida, M. K., Karathanos, V. T., Maroulis, Z. B. and Marinos-Kouris, D. 2003. Drying kinetics of some vegetables. Journal of Food Engineering 59(4): 391–403.

Maskan, M. 2000. Microwave/air and microwave finish drying of banana. Journal of Food Engineering 44(2): 71–78.

Midilli, A., Kucuk, H. and Yapar, Z. 2002. A new model for single layer drying. Drying Technology 20(7): 1503–1513.

Mihindukulasuriya, S. D. F. and Jayasuriya, H. P. W. 2013. Mathematical modeling of drying characteristics of chilli in hot air oven and fluidized bed dryers. Agricultural Engineering International: CIGR Journal 15(1): 154-166

Meziane, S. 2011. Drying kinetics of olive pomace in a fluidized bed dryer. Energy Conversion and Management 52(3): 1644–1649.

Meziane, S. and Mesbahi, N. 2012. Determination of moisture diffusivity and activation energy in thin layer drying of olive pomace. International Journal of Food Engineering, 8, Article 34.

Molina-Alcaide, E. and Yáñez-Ruiz, D. R. 2008. Potential use of olive by-products in ruminant feeding: A review. Animal Feed Science and Technology 147(1-3): 247-264.

Ozbek, B. and Dadali, G. 2007. Thin-layer drying characteristics and modelling of mint leaves undergoing microwave treatment. Journal of Food Engineering 83(4): 541-549.

Ozkan, I. A., Akbudak, B. and Akbudak, N. 2007. Microwave drying characteristics of spinach. Journal of Food Engineering 78(2): 577–583.

Rayaguru, K. and Routray, W. 2011. Microwave drying kinetics and quality characteristics of aromatic *Pandanus amaryllifolius* leaves. International Food Research Journal 18(3): 1035-1042.

Ruiz Celma, A., Rojas, S. and Lopez-Rodrıguez, F.

2008. Mathematical modelling of thin-layer infrared drying of wet olive husk. Chemical Engineering and Processing 47(9-10): 1810–1818.

Sacilik, K., Keskin, R. and Elicin, A. K. 2006. Mathematical modeling of solar tunnel drying of thin layer organic tomato. Journal of Food Engineering 73(3): 231–238.

Sarimeseli, A. 2011. Microwave drying characteristics of coriander (*Coriandrum sativum* L.) leaves. Energy Conversion and Management 52(2): 1449–1453.

Sharma, G. P. and Prasad, S. 2006. Specific energy consumption in microwave drying of garlic cloves. Energy 31(12): 1921-1926.

Skoulou, V., Swiderski, A., Yang, W. and Zabaniotou, A. 2009. Process characteristics and products of olive kernel high temperature steam gasification (HTSG). Bioresource Technology 100(8): 2444- 2451.

Soysal, Y. and Oztekin, S. 2001. PH—Postharvest Technology: Comparison of seven equilibrium moisture content equations for some medicinal and aromatic plants. Journal of Agricultural Engineering Research 78(1): 57–63.

Soysal, Y. 2004. Microwave drying characteristics of parsley. Biosystems Engineering 89(2): 167–173.

Soysal, Y., Oztekin, S. and Eren, O. 2006. Microwave drying of parsley: Modelling, Kinetics, and Energy aspects. Biosystems Engineering 93(4): 403-413.

Soysal, Y., Ayhan, Z., Esturk, O. and Arıkan, M. F. 2009. Intermittent microwave–convective drying of red pepper: Drying kinetics, physical (colour and texture) and sensory quality. Biosystems engineering 103(4): 455 – 463.

Therdthai, N. and Zhou, W. 2009. Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia* Opiz ex Fresen). Journal of Food Engineering 91(3): 482–489.

Vadivambal, R. and Jayas, D. S. 2007. Changes in quality of microwave-treated agricultural products - a review. Biosystems Engineering 98(1): 1 – 16.

Vega-Galvez, A., Miranda, M., Diaz, L. P., Lopez, L., Rodriguez, K. and Di Scala, K. 2010. Effective moisture diffusivity determination and mathematical modelling of the drying curves of the olive-waste cake. Bioresource Technology 101(19): 7265–7270.

Wang, Z., Sun, J., Chen, F., Liao, X. and Hu, X. 2007. Mathematical modelling on thin layer microwave drying of apple pomace with and without hot air pre-drying. Journal of Food Engineering 80(2): 536-544.

Wang, Z. F., Fang, S. Z. and Hu, X. S. 2009. Effective diffusivities and energy consumption of whole fruit Chinese jujube (*Zizyphus jujuba Miller*) in Microwave Drying. Drying technology 27(10): 1097-1104.

Yilbas, B., Hussain, M. and Dincer, I. 2003. Heat and moisture diffusion in slab products due to convective boundary condition. Heat and Mass Transfer 39(5-6): 471–476.

Yongsawatdigul, J. and Gunasekaran, S. 1996. Microwave-vacuum drying of cranberries, Part II: Quality evaluation. Journal of Food Processing and Preservation 20(2): 145–156.