Korean J. Chem. Eng., **27**(5), 1377-1383 (2010)
DOI: 10.1007/s11814-010-0251-2

Drying kinetics and effective moisture diffusivity of purslane undergoing microwave heat treatment

Elçin Demirhan and Belma Özbek†

Yıldız Technical University, Department of Chemical Engineering, Davutpaşa Campus, 34210, Esenler/Istanbul, Turkey
(*Received 21 December 2009 • accepted 16 January 2010*)

Abstract−The effects of microwave drying on moisture content, moisture ratio, drying time and effective moisture diffusivity of purslane leaves (*Portulaca oleracea L.*) were investigated. By increasing the microwave output power (180-900 W) and the sample amounts (25-100 g), the drying time decreased from 43 to 12.5 minutes and increased from 27 to 54 minutes, respectively. To determine the kinetic parameters, the drying data were fitted to various models based on the ratios of the differences between the initial and final moisture contents and equilibrium moisture content versus drying time. Among the models proposed, the semi-empirical Midilli et al. model gave a better fit for all drying conditions applied. By increasing the microwave output power and decreasing the sample amount, the effective moisture diffusivity values ranged from 5.913×10^{-11} to 1.872×10^{-10} m^2/s and from 9.889×10^{-11} to 3.292×10^{-11} m^2/s, respectively. The activation energy was calculated using an exponential expression based on the Arrhenius equation.

Key words: Microwave Drying, Purslane Leaves, Drying Kinetic, Activation Energy, Effective Moisture Diffusivity

INTRODUCTION

Purslane (*Portulaca oleracea L.*), which is a member of *Portulacaceae*, is widespread as a weed and has been ranked the eight most common plant in the world [1]. It is listed by the World Health Organization as one of the most used medicinal plants and it has been given the term 'Global Panacea' [2]. The leaves are sappy, rich in different salts, proteins and carbohydrates. The maximum concentrations of proteins and carbohydrates were noted during the period of seed maturity. The leaves are also rich in carotenes, ascorbic acid, nicotinic acid, tocopherols and glutathione [3]. The tender stems and leaves can be eaten raw, cooked or pickled in vinegar or sugar. The leaves of purslane can be frozen or dried and stored in jars for several years. Purslane is one of the vegetable crops that is eaten extensively in soups and salads in Greece, Turkey and other Mediterranean countries, where the incidence of both heart disease and cancer is low [4,5].

Drying, in general, means removal of water from a material. The purpose of drying food products is to allow longer periods of storage with minimal packaging requirements, reduce shipping weights, and preserve seasonal plants and make them available to consumers during the whole year. Drying not only affects the water content of the product but also alters other physical, biological, and chemical properties, such as enzymatic activity, microbial spoilage, viscosity, hardness, aroma, flavour, and palatability of foods [6,7].

The most common methods widely used for drying are sun drying and hot air drying. But their disadvantages include inability to handle the large quantities and to achieve consistent quality standards, contamination problems, long drying times, low energy efficiency and high costs, which is not desirable for the food industry. Microwave drying is an alternative method because of its uniform energy and high thermal conductivity to the inner sides of the material, space utilization, sanitation, energy savings, precise process control, and fast start-up and shutdown conditions. It also reduces the drying time and prevents food from decomposing [8-12].

The study of the drying kinetic of foods during microwave heat treatment has recently been a subject of interest for various investigators: for example, garlic [12-14], apple [15-17], wheat [18], yellow pea [19], carrot [20-24], peach [25], parsley [26], black tea [27, 28], mushroom [29,30], lactose [31-33], potato [34,35], cabbage [36], paper plant [37], millet [38], tobacco [39], okra [40], spinach [41], and basil [42].

The aim of this study was to investigate the effect of microwave output power and sample amount on the drying kinetic of purslane leaves, to compare the experimental data found during drying with the predicted values obtained by using some drying models, to calculate the activation energy, to calculate the effective moisture diffusivity and to derive a relationship between the drying rate constant and the effective moisture diffusivity.

MATERIALS AND METHODS

1. Material

Plants of fresh purslane leaves samples were purchased from a local supplier in Istanbul. They were washed and stored at 4±0.5 °C in a refrigerator for about one day for equilibration of moisture. Before the drying experiments, the samples were taken out of the refrigerator and leaves from stems were separated, and then weighed. To determine the initial moisture content, four 50 g of samples were dried in an oven (Memmert UM-400) at 105 °C for 12 h. The initial moisture content of purslane leaves was calculated as 9.51 g water/g dry base as an average of the results obtained. The reproducibility of the measurement was within the range of ±5%. On the other hand, for calculation of the effective moisture diffusivity values of purslane leaves, the thickness of the samples was measured by a

†To whom correspondence should be addressed.
E-mail: bozbek@yildiz.edu.tr

micrometer (Leica ICM 1000, Germany) on 20 samples of leaves and found as 0.67 (±0.03) mm.

2. Microwave Drying Technique

Microwave heating is dielectric heating but refers to the heating that takes place in a non-conductor due to polarization effects at frequencies between 300 MHz and 300 GHz (wavelengths between 1 m and 1 mm). While a microwave is processing, microwaves radiate from a source in all directions. These waves carry energy, and during the drying process, material absorbs this energy and converts it to heat by polar molecules. Water is a common polar molecule and a component of foods. So, during this process, water molecules convert microwave energy to heat. Then, the water molecules start to evaporate as a result of this heat, and so on the material starts to dry [11].

3. Drying Equipment and Drying Procedure

Drying treatment was performed in a domestic digital microwave oven (Arcelik MD 594, Turkey) with technical features of ~230 V, 50 Hz and 2,650 W, a frequency of 2,450 MHz (a wavelength of 12.24 cm). The microwave oven has the capability of operating at five different microwave output powers: 180, 360, 540, 720 and 900 W. The area on which microwave drying was carried out was 530·500·322 mm, and consisted of a rotating glass plate with 300 mm diameter at the base of the oven. The microwave output power and processing time were adjusted with a digital control facility located on the microwave oven.

During drying experiments, each sample was put on the rotating glass of the microwave and placed at the center of the oven. Moisture loss was periodically measured by taking out the rotating glass and weighing on the digital balance with a precision of 0.01 g. Three replications of each experiment were performed according to a preset microwave output power and time schedule, and the data given was an average of these results. The reproducibility of the experiments was within the range of ±5%. The microwave power was applied until the weight of the sample was reduced to a level corresponding to moisture content of about 0.1 g water/g dry base. All weighing processes were completed in less than 10 s during the drying process.

4. Mathematical Modelling of Drying Data

To determine the moisture ratio as a function of drying time, six different thin-layer drying models, namely, Page model [8,26], Henderson & Pabis model [43], Lewis model [44], Midilli et al. model [45], Wang & Singh model [44,46] and Logarithmic model [13,47], were used (Table 1). The moisture ratio and drying rate of purslane leaves were calculated using the following equations:

$$MR=\frac{M_t-M_e}{M_o-M_e} \quad (1); \qquad \text{Drying rate}=\frac{M_{t+dt}-M_t}{dt} \quad (2)$$

where, MR is the moisture ratio, M_t is the moisture content at a specific time (g water/g dry base), M_0 is the initial moisture content (g water/g dry base), M_e is the equilibrium moisture content (g water·g dry base^{-1}), M_{t+dt} is the moisture content at t+dt (g water/g dry base) and t is drying time (min). The equilibrium moisture content (M_e) was assumed to be zero for microwave drying [41,42,48].

5. Effective Moisture Diffusivity

The effective moisture diffusivity of a food material characterizes its intrinsic mass transfer property of moisture. During drying, it can be assumed that diffusivity, explained with Fick's second law, is the only physical mechanism to transfer the water to the surface. Effective moisture diffusivity, which is affected by composition, moisture content, temperature and porosity of the material, is used due to the limited information on the mechanism of moisture movement during drying and complexity of the process [49]. Because the thickness of the sample (0.67±0.03 mm) was much less than its diameter (about 30 mm), the purslane leaves were assumed as a slab. The following assumptions were made for the slab shaped body of purslane leaves [50]:

1. Moisture is initially uniformly distributed throughout the mass of the sample.
2. Mass transfer is symmetric with respect to the center.
3. Surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air.
4. Resistance to mass transfer at the surface is negligible compared to internal resistance of the sample.
5. Mass transfer is represented by a diffusional mechanism.
6. Diffusion coefficient is constant, and shrinkage is negligible.

The effective moisture diffusivity was therefore calculated by the following equation:

$$MR=\frac{M_t-M_e}{M_0-M_e}=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\cdot\pi^2\cdot D_{eff}}{4L^2}\cdot t\right) \quad (3)$$

where, D_{eff} is the effective moisture diffusivity (m^2/s), L is the half thickness (drying from both sides) of purslane leaves (L=0.34 mm) and t is drying time (s).

For long drying times; n=1, then Eq. (3) can be written as:

$$MR=\frac{M_t-M_e}{M_0-M_e}=\frac{8}{\pi^2}\exp\left(-\frac{\pi^2\cdot D_{eff}}{4L^2}\cdot t\right) \quad (4)$$

Several researchers demonstrated that Eq. (4) could be further simplified to a straight-line equation as Eq. (5) [51,52]:

$$\ln(MR)=\ln\left(\frac{8}{\pi^2}\right)-\left(\frac{D_{eff}\cdot\pi^2}{4L^2}\cdot t\right) \quad (5)$$

The effective moisture diffusivities are typically determined by plot-

Table 1. The thin-layer drying models used

Models	Equations	References
Page	$MR=\exp(-k\cdot t^n)$	Soysal (2004), Maskan (2000)
Henderson & Pabis	$MR=A_0\cdot\exp(-k\cdot t)$	Pehlivan & Toğrul (2004)
Lewis	$MR=\exp(-k\cdot t)$	Ozdemir & Devres (1999)
Midilli et al.	$MR=a\cdot\exp(-k\cdot t^n)+b\cdot t$	Midilli, Kucuk & Yapar (2002)
Wang & Singh	$MR=1+a\cdot t+b\cdot t^2$	Ozdemir & Devres (1999), Chen & Wu (2001)
Logarithmic	$MR=a\cdot\exp(-k\cdot t)+b$	Ertekin & Yaldiz (2004), Madamba, Driscoll & Buckle (1996)

ting experimental drying data in terms of ln(MR) versus time.

6. Computational Work

The software package MATLAB 5.0 was used in the numerical calculations. The parameters were evaluated by the nonlinear least squares method of Marquardt-Levenberg until minimal error was achieved between experimental and calculated values. The residual (SSR) is defined as the sum of the squares of the differences between experimental and calculated data and is given by:

$$SSR = \sum_{m=1}^{N_d} (C_m^{obs} - C_m^{cal})^2 \tag{6}$$

where, m is observation number and N_d is total number of observations. The estimated variance of the error (population variance) is calculated by the SSR at its minimum divided by its degrees of freedom:

$$\sigma^2 \approx s^2 = \frac{(SSR)_{min}}{(m-p)} \tag{7}$$

where, p is the number of parameters and s^2 is the variance. The standard error, σ (the estimated standard deviation), is calculated by taking the square root of the estimated variance of the error. The best model describing the thin layer drying characteristics of purslane leaves was chosen as the one with the lowest reduced standard error (σ^2) and the highest R^2.

RESULTS AND DISCUSSION

1. Effect of Microwave Output Power on the Drying Kinetic of Purslane Leaves

To investigate the effect of microwave output power on moisture content, moisture ratio, drying rate, drying time, five microwave output powers (180, 360, 540, 720 and 900 W) were used for drying of 25 g purslane leaves. The values of moisture ratio versus drying time of purslane as affected by microwave output power are shown in Fig. 1. As can be seen from this figure, the drying time of samples was significantly decreased as the microwave output power was increased, expectedly. The microwave drying process which reduced the moisture content of purslane leaves from 9.51 to 0.1 g water/g dry base took 43-12.5 minutes, depending on microwave output power applied. By working at 900 W instead of 180 W, the drying time was shortened by 71%.

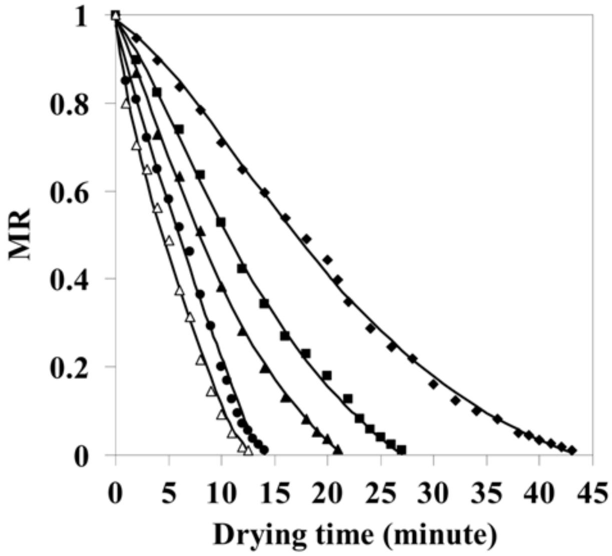

Fig. 1. Moisture ratios versus time at various microwave output powers for sample amount of 25 g, comparing experimental curve with the most predicted one semi-empirical Midilli et al. model; ◆ 180 W, ■ 360 W, ▲ 540 W, ● 720 W, △ 900 W, — Kinetic models.

The drying times obtained in this present study were extremely low compared to the results obtained in the previous studies given in literature. Kashaninejad and Tabil [53] concluded that during air drying of purslane leaves, a weight of approximately 100 g and drying time of 7 h at 70 °C would be most suitable for the air drying of purslane leaves. The results obtained in this present work showed that as compared to air drying, the drying time can be shortened by 33-fold by working at microwave output power of 900 W.

The experimental results illustrated that during microwave drying of purslane, there is no constant rate period observed and drying takes place only in the falling period in which internal liquid diffusion controls throughout. It was also determined that the critical moisture content is equal to the initial moisture content (9.51 g water/g dry base) and the drying process was entirely controlled by internal mass transfer resistance [54]. These results were in agreement with the results for black tea [27], apple pomace [51] and spinach [41].

To describe the effect of microwave output power on drying kinetic of purslane leaves, six different semi empirical thin-layer drying models as mentioned in Section 2.4 were used. Among those models examined, the semi-empirical Midilli et al. model (Eq. (8)) was observed to be the most appropriate for all the experimental data with higher value for the coefficient of determination (R^2) and lower standard error (σ) compared with the statistical values obtained for other models.

$$MR = a \cdot \exp(-kt^n) + bt \tag{8}$$

The estimated parameters and statistical analysis of this model for a given drying condition are presented in Table 2. It was determined that the value of the drying rate constant (k) increased with the increase in microwave output power. This implies that with an increase in microwave output power the drying curve becomes steeper, indicating an increase in drying rate.

2. Effect of Sample Amount on the Drying Kinetic of Purslane Leaves

To investigate the effect of sample amount on moisture content, moisture ratio, drying rate, drying time, four sample amounts (25, 50, 75 and 100 g) were dried at a constant microwave output power

Table 2. The estimated coefficients and statistical analysis of Midilli et al. model at various microwave output powers

Power (W)	a	k (min^{-1})	n	b (min^{-1})	s	R^2
180	0.9806	0.0162	1.4877	−0.0019	0.0137	0.9992
360	0.9903	0.0281	1.3259	−0.0043	0.0139	0.9993
540	0.9913	0.0337	1.2598	−0.0055	0.0126	0.9994
720	0.9769	0.0391	1.0137	−0.0331	0.0252	0.9974
900	0.9873	0.0441	0.8247	−0.0289	0.0277	0.9971

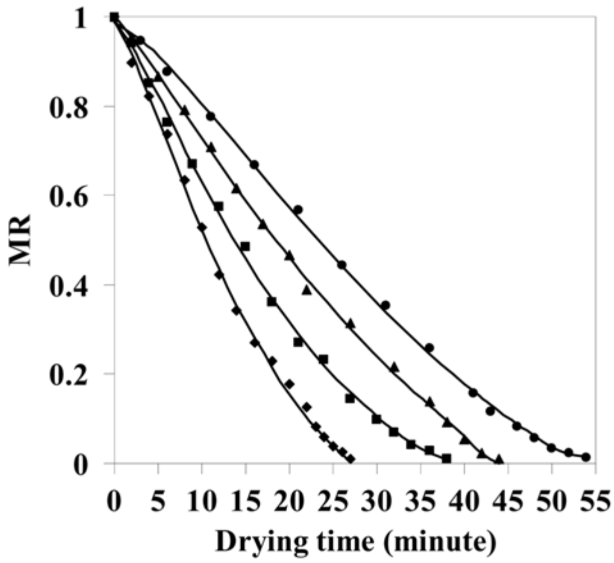

Fig. 2. Moisture ratios versus time at various sample amounts for microwave output power of 360 W, comparing experimental curve with the most predicted one semi-empirical Midilli et al. model; ◆ 25 g, ■ 50 g, ▲ 75 g, ● 100 g, — Kinetic models.

of 360 W. The values of moisture ratio versus drying time of purslane as affected by microwave output power are shown in Fig. 2. As can be seen, the drying time was increased as the sample amount was increased. The microwave drying process which reduced the moisture content of purslane from 9.51 to 0.1 g water/g dry base took 27-54 minutes as the sample amount increased from 25 to 100 g, respectively. By working at 25 g instead of 100 g, the drying time up to the moisture content of 0.1 g water/g dry base was shortened by 50%.

The experimental results illustrated that during microwave drying of purslane, again there is no constant rate period observed and drying takes place only in the falling period in which internal liquid diffusion controls throughout for the sample amounts dried from 25 to 100 g at a constant microwave output power of 360 W.

To describe the effect of various amounts of purslane on its drying kinetic, six different semi-empirical thin-layer drying models were used. Among these models, the semi-empirical Midilli et al. model, Eq. (8), was again found the most suitable one for all the experimental data with higher value for the coefficient of determination (R^2) and lower standard error (σ) compared with the statistical values obtained for other models. The estimated parameters and statistical analysis of this model for a given drying condition are presented in Table 3. It was determined that the value of the drying rate constant (k) increased with the decrease in the sample amount.

Table 3. The estimated coefficients and statistical analysis of Midilli et al. model at various sample amounts

Sample (g)	a	k (min^{-1})	n	b (min^{-1})	s	R^2
25	0.9903	0.0281	1.3259	−0.0043	0.0139	0.9993
50	0.9927	0.0156	1.2603	−0.0029	0.0146	0.9993
75	1.0008	0.0116	1.1849	−0.0054	0.0108	0.9996
100	0.9870	0.0064	1.4065	−0.0038	0.0134	0.9994

3. Hot Air Drying of Purslane Leaves

In addition to the above studies, an experiment was performed by hot air drying in order to compare with conventional method and microwave method. Purslane leaves were dried at 40 °C by using only the fan feature of the oven (Arçelik MD 594). 25 g of purslane leaves were dried by weighing in certain time intervals until the moisture content was 0.1 g water/g dry base. The drying of purslane leaves with hot air drying method from the initial moisture content of M_0= 9.51 g water/g dry base to 0.1 g water/g dry base was completed approximately 330 minutes at 40 °C. The drying time obtained for 25 g purslane leaves dried with hot air was quite higher than the drying time obtained from microwave drying (43 minutes at 180 W microwave output power and 12.5 minutes at 900 W microwave output power). This result indicates that the microwave technique can be successfully used to dry purslane leaves as compared to hot air drying.

4. Calculation of the Effective Moisture Diffusivity

To calculate the effective moisture diffusivity by using the method of slopes, the logarithm of moisture ratio values, ln(MR), was plotted against drying time (t) according to the experimental data obtained at various microwave output powers and sample amounts. The linearity of the relationship between ln(MR) and drying time (t) was also illustrated in Fig. 3 and Fig. 4 for various microwave output powers and sample amounts, respectively. The effective moisture diffusivity values (D_{eff}), the corresponding values of coefficients of determination (R^2) and the standard error (σ) of Eq. (5) are presented in Table 4 for various microwave output powers and in Table 5 for various sample amounts.

In literature, no documentation was found about investigation of the effective moisture diffusivity for purslane leaves undergoing microwave treatment. In this study, the range of effective moisture diffusivity of purslane leaves undergoing microwave drying varied from 5.913×10^{-11} to 1.872×10^{-10} m^2/s, because of the lower drying times obtained under microwave treatment.

On the other hand, the effective moisture diffusivity of purslane

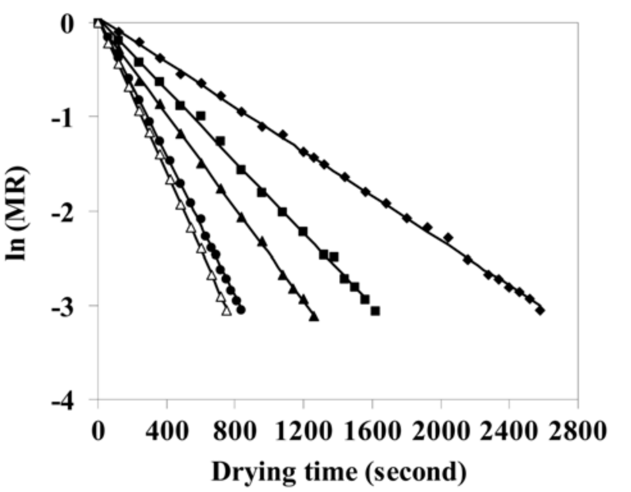

Fig. 3. Linear relationship between ln(MR) and drying time at various microwave output powers of 25 g purslane leaves; ◆ 180 W, ■ 360 W, ▲ 540 W, ● 720 W, △ 900 W, — Kinetic models.

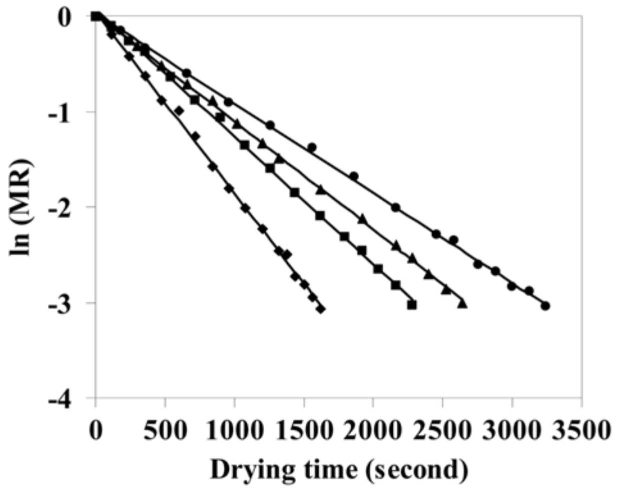

Fig. 4. Linear relationship between ln(MR) and drying time at various sample amounts for microwave output power of 360 W; ◆ 25 g, ■ 50 g, ▲ 75 g, ● 100 g, — Kinetic models.

Table 4. The estimated effective moisture diffusivity and statistical analysis of linear model at various microwave output powers for sample amount of 25 g

Power (W)	Slope	$D_{eff}\cdot 10^{10}$ (m^2/s)	σ	R^2
180	0.0012	0.5913	0.0269	0.9996
360	0.0019	0.9889	0.0427	0.9992
540	0.0025	1.2690	0.0213	0.9988
720	0.0037	1.6888	0.0249	0.9987
900	0.0041	1.8723	0.0205	0.9988

Table 5. The estimated effective moisture diffusivity and statistical analysis of linear model at various sample amounts for microwave output power of 360 W

Sample (g)	Slope	$D_{eff}\cdot 10^{10}$ (m^2/s)	σ	R^2
25	0.0019	0.9889	0.0427	0.9992
50	0.0013	0.6104	0.0333	0.9991
75	0.0011	0.4689	0.0231	0.9996
100	0.0009	0.3292	0.0304	0.9996

leaves for microwave drying at various sample amounts decreased from 9.889×10^{-11} to 3.292×10^{-11} m^2/s, as the sample amount increased from 25 to 100 g. For comparing the results obtained, no documentation was found in the literature that considers the effect of sample amount on effective moisture diffusivity for microwave drying of purslane leaves.

5. Estimation of Activation Energy

In this study, as the temperature is not a measurable variable in the standard microwave oven used for the drying process, the Arrhenius equation was used in a modified form to illustrate the relationship between the kinetic rate constant and the ratio of the microwave output power to sample amount instead of the temperature for calculation of the activation energy. After evaluation of the data, the dependence of the kinetic rate constant on the ratio of microwave output power to sample amount was represented with an exponential equation Eq. (9) derived by Dadali et al. [40]:

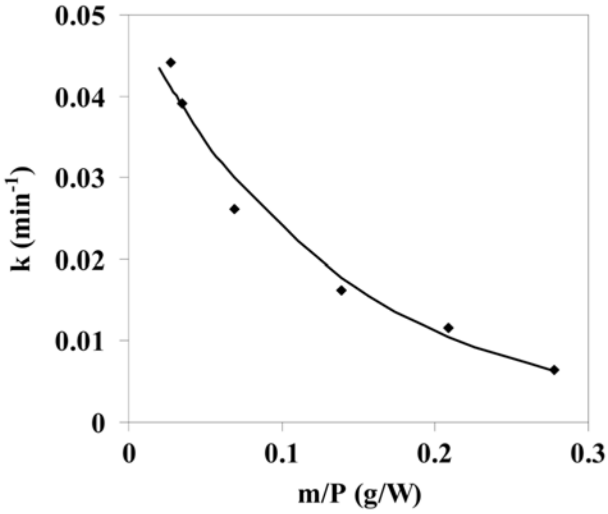

Fig. 5. The relationship between the values of drying rate constant (k) versus Sample amount/Power (m/P), ■ Experimental Data, — Model.

$$k=k_0\exp\left(\frac{-E_a\cdot m}{P}\right) \tag{9}$$

where, k is the drying rate constant obtained by using Midilli et al. model (min^{-1}), k_0 is the pre-exponential constant (min^{-1}), E_a is the activation energy (W/g), P is microwave output power (W) and m is the mass of raw sample (g). The values of k versus m/P shown in Fig. 5 accurately fit to Eq. (9) with the statistic values of standard error (σ) and coefficient of determination (R^2) of 0.1046 and 0.9917, respectively. Then, k_0 and E_a values were estimated as 0.0506 min^{-1} and 7.531 W/g.

6. Effect of Ratio of Microwave Output Power to Sample Amount on Effective Moisture Diffusivity

The aim of this study was to predict a relationship between the effective moisture diffusivity and the ratio of microwave output power to sample amount by following the procedure as mentioned in the previous section. After evaluation of the data, to determine the dependence of the effective moisture diffusivity on the ratio of microwave output power to sample amount, an Arrhenius type exponential model, Eq. (10), which was derived by Dadali et al. [41] were used with the standard error (σ) of 1.5905×10^{-11} and coefficient of determination of (R^2) statistical value of 0.9708. The fitness of the data with the model is illustrated in Fig. 6.

$$D_{eff}=D_o\exp\left(\frac{-E_a\cdot m}{P}\right) \tag{10}$$

where, P is the microwave output power (W), m is the weight of raw sample (g), D_{eff} is the effective moisture diffusivity (m^2/s); D_0 is pre-exponential factor (m^2/s) and E_a is the activation energy (W/g). The values of D_0 and E_a were estimated as 2.195×10^{-10} m^2/s and 8.306 W/g. As a conclusion, the value of E_a found from this study is quite similar to the value (7.531 W/g) obtained from the previous section by using Eq. (9).

7. The Relationship between Drying Rate Constant and Effective Moisture Diffusivity

For prediction of the relationship between drying rate constant and effective moisture diffusivity, Eq. (11) was derived by using

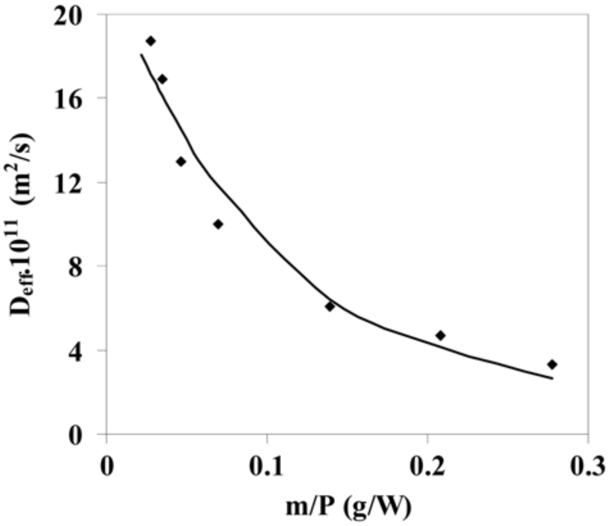

Fig. 6. The relationship between the values of effective moisture diffusivity (D_{eff}) versus Sample Amount/Power (m/P), ■ Experimental Data, — Model.

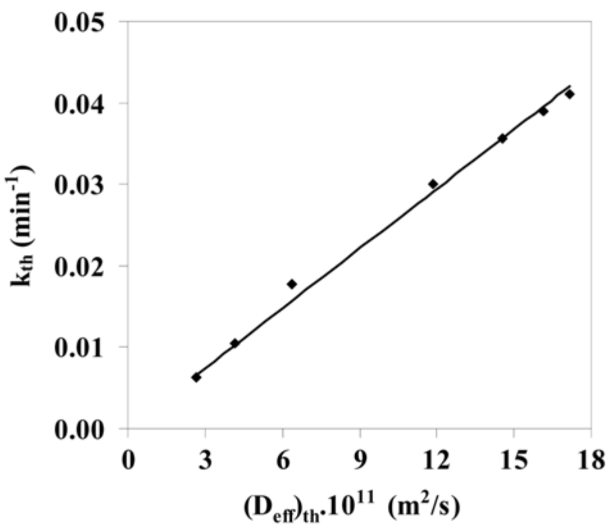

Fig. 7. The relationship between the theoretical values of drying rate constant (k_{th}) and the theoretical values of effective moisture diffusivity $(D_{eff})_{th}$; ■ Theoretical Data, — Model.

Eqs. (9) and (10) with the assumption of E_a values being quite similar to each other, as mentioned in the previous section. The theoretical values of drying rate constant, k_{th}, obtained from Eq. (9) and the theoretical values of effective moisture diffusivity $(D_{eff})_{th}$ obtained from Eq. (10) for this study were fitted sufficiently to Eq. (11) with the standard error (σ) of 0.0018 and the coefficient of determination of (R^2) statistical value of 0.9971. The value of constant (A) was obtained as 2.46×10^8 s/min·m^2. The fitness of the data with Eq. (11) is illustrated in Fig. 7.

$$k_{th}=A\cdot(D_{eff})_{th} \qquad (11)$$

CONCLUSIONS

Drying kinetic of purslane leaves was investigated in a microwave oven at various microwave output powers and sample amounts. Drying time decreased considerably with increase in microwave output power and with decrease in sample amount of purslane leaves as well as by using the microwave drying technique. This study showed that microwaves enhance the drying process significantly in comparison to purely convective conditions (hot air drying).

Evaluation was made by means of a number of different empirical models as well as by the diffusion model. Among six models proposed to describe the drying kinetic of purslane leaves used in the study, the semi-empirical Midilli et al. model provided a good agreement between experimental and predicted moisture ratio values with higher coefficient of determination and lower standard error of estimates. The value of the drying rate constant, k, increased with the increase in microwave output power, but on the other hand, decreased with the increase in sample amount.

The effective moisture diffusivity was also calculated to understand the mass transfer mechanism of purslane leaves at various microwave output powers and sample amounts. A linear relationship was obtained between the data of ln(MR) and drying time (t). For constant amount of 25 g sample, the effective moisture diffusivities increased from 5.913×10^{-11} to 1.872×10^{-10} m^2/s with the increase in microwave output power. On the other hand, the values of the effective moisture diffusivities decreased from 9.889×10^{-11} to 3.292×10^{-11} m^2/s, as the sample amount increased from 25 to 100 g.

The activation energy of purslane leaves was calculated by using the exponential expression based on the Arrhenius equation (derived by Dadali et al. [40,52]) and found similar as 7.53 and 8.31 W/g, respectively. The benefit of this study, by using the exponential equation based on the Arrhenius equation, is that the k_{th} values for drying kinetic of purslane leaves can be calculated by choosing the microwave output power and sample amount as well as for calculation of $(D_{eff})_{th}$ value. The evaluation of the data of effective moisture diffusivity $(D_{eff})_{th}$ and drying rate constant k_{th} showed that a linear model perfectly fitted to data.

It should be noted that the results obtained are limited to the microwave oven used in this study, because any microwave oven exhibits an individual power distribution. However, the study performed demonstrates the methodology and guidance for use of a microwave oven as a gentle tool for drying of heat-sensitive substances.

ACKNOWLEDGEMENTS

Elçin Demirhan gratefully acknowledges TUBITAK (The Scientific and Technological Research Council of Turkey) for a scholarship.

REFERENCES

1. I. Yazıcı, I. Türkan, A. H. Sekmen and T. Demiral, *Environ. Exp. Bot.*, **61**, 49 (2007).
2. Y. Y. Lim and E. P. L. Quah, *Food Chem.*, **103**(3), 734 (2007).
3. N. Garti, Y. Slavin and A. Aserin, *Food Hydrocolloid*, **13**(2), 145 (1999).
4. E. Fontana, J. Hoeberechts, S. Nicola, V. Cros, G. B. Palmegiano and P. G. Peiretti, *J. Sci. Food Agric.*, **86**, 2417 (2006).
5. C. C. Kilic, Y. S. Kukul and D. Anac, *Agr. Water Manage.*, **95**(7), 854 (2008).
6. G. V. Barbosa-Canovas and H. Vega-Mercado, *Dehydration of*

Foods, 1st Ed., Chapman & Hall, New York (1996).
7. K. J. Park, Z. Vohnikova and F. P. R. Brod, *J. Food Eng.*, **51**(3), 193 (2002).
8. M. Maskan, *J. Food Eng.*, **44**(2), 71 (2000).
9. Y. Soysal and S. Oztekin, *J. Agric. Eng. Res.*, **78**(1), 57 (2000).
10. R. V. Decareau, Microwaves *in the Food Processing Industry*, 1st Ed., Academic Press, Orlando, FL (1985).
11. R. V. Decareau, Encyclopaedia of Food Science and Technology, 3, John Wiley & Sons, USA (1992).
12. G. P. Sharma and S. Prasad, *J. Food Eng.*, **75**(4), 441 (2005).
13. P. S. Madamba, R. H. Driscoll and K. A. Buckle, *J. Food Eng.*, **29**(1), 75 (1996).
14. G. Vázquez, F. Chenlo, R. Moreira and A. Castoyas, *Drying Technol.*, **17**(6), 1095 (1999).
15. A. Bilbao-Sáinz, C. Andrés, A. Chiralt and P. Fito, *J. Food Eng.*, **74**(1), 160 (2006).
16. M. K. Krokida, Z. B. Maroulis and G. D. Saravacos, *Int. J. Food Sci. Tech.*, **36**(1), 53 (2001).
17. H. Feng, J. Tang and R. P. Cavalieri, *Drying Technol.*, **17**, 1981 (1999).
18. S. G. Walde, K. Balaswamy, V. Velu and D. G. Rao, *J. Food Eng.*, **55**(3), 271 (2002).
19. P. Kadlec, A. Rubecova, A.Hinkova, J. Kaasova, Z. Bubnik and V. Pour, *Innov. Food Sci. Emerg.*, **2**(2), 133 (2001).
20. G. Sumnu, E. Turabi and M. Oztop, *LWT*, **38**(5), 549 (2005).
21. J. Wang and Y. S. Xi, *J. Food Eng.*, **68**(4), 505 (2005).
22. W. Wang, B. H. Thorat, G. Chen and A. S. Mujumdar, *Drying Technol.*, **20**(9), 1855 (2002).
23. J. Stanisławski, *Drying Technol.*, **23**(8), 1711 (2005).
24. C. Zheng-Wei, X. Shi-Ying, S. Da-Wen and W. Chen, *Drying Technol.*, **23**(5), 1057 (2005).
25. J. Wang and K. Sheng, *LWT*, **39**(3), 247 (2006).
26. Y. Soysal, *Biosyst. Eng.*, **89**(2), 167 (2004).
27. P. C. Panchariya, D. Popovic and A. L. Sharma, *J. Food Eng.*, **52**(4), 349 (2002).
28. S. J. Temple and A. J. B. Van Boxtel, *J. Agric. Eng. Res.*, **74**(2), 203 (1999).
29. T. Funebo and T. Ohlsson, *J. Food Eng.*, **38**(3), 353 (1998).
30. R. Rodríguez, J. I. Lombrana, M. Kamel and C. Elvira, *Drying Technol.*, **23**(9-11), 2197 (2005).
31. W. A. M. McMinn, *Food Res. Int.*, **37**, 1041 (2004).
32. W. A. M. McMinn, *J. Food Eng.*, **72**(2), 113 (2006).
33. W. Wang and G. Chen, *Drying Technol.*, **23**(9-11), 2147 (2005).
34. W. A. M. McMinn, M. A. M. Khraisheh and T. R. A. Magee, *Food Res. Int.*, **36**, 977 (2003).
35. W. A. M. McMinn, M. A. M. Khraisheh and T. R. A. Magee, *Food Res. Int.*, **37**, 497 (2004).
36. Y. Xu, Z. Min, A. S. Mujumdar, Z. Le-Qun and S. Jin-Cai, *Drying Technol.*, **22**(9), 2201 (2004).
37. Y. K. Yeo, K. S. Hwang, S. C. Yi and H. Kang, *Korean J. Chem. Eng.*, **21**(4), 761 (2004).
38. K. B. Choi, S. I. Park, Y. S. Park, S. W. Sung and D. H. Lee, *Korean J. Chem. Eng.*, **19**(6), 1106 (2002).
39. S. C. Yi and S. K. Moon, *Korean J. Chem. Eng.*, 14(2), 141 (1997).
40. G. Dadali, D. K. Apar and B. Ozbek, *Drying Technol.*, **25**(5), 917 (2007).
41. G. Dadali, E. Demirhan and B. Ozbek, *Drying Technol.*, **25**(10), 1703 (2007).
42. E. Demirhan and B. Ozbek, *J. Food Process. Pres.*, **34**, 476 (2010).
43. D. Pehlivan and I. T. Toğrul, *J. Food Eng.*, **65**(3), 413 (2004).
44. M. Ozdemir and Y. O. Devres, *J. Food Eng.*, **42**(4), 225 (1999).
45. A. Midilli, H. Küçük and Z. Yapar, *Drying Technol.*, **20**, 1503 (2002).
46. C. Chen and P. C. Wu, *J. Agric. Eng. Res.*, **80**, 45 (2001).
47. C. Ertekin and E. Yaldız, *J. Food Eng.*, **63**, 349 (2004).
48. E. K. Akpınar, *J. Food Eng.*, **77**, 864 (2006).
49. T. Abe and T. M. Afzal, *J. Agric. Eng. Res.*, **67**, 289 (1997).
50. J. Crank, *The mathematics of diffusion* (2nd ed.), Oxford, UK, Clarendon Press (1975).
51. Z. Wang, J. Sun, F. Chen, X. Liao and X. Hu, *J. Food Eng.*, **80**(2), 536 (2007).
52. G. Dadali, D. K. Apar and B. Ozbek, *Drying Technol.*, **25**(9), 1445 (2007).
53. M. Kashaninejad and L. G. Tabil, *Drying Technol.*, **22**(9), 2183 (2004).
54. F. Gogus and M. Maskan, *Drying Technol.*, **17**(4-5), 883 (1999).