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Microwave drying kinetics of olive fruit (*Olea europeae* L.)

*Mahdhaoui, B., Mechlouch, R. F., Mahjoubi, A. and Ben Brahim, A.

Applied Thermodynamic Research Unit (UR11ES80), National School of Engineering of Gabes, Gabes University, Avenue of Omar IbnElkhattab 6029 Gabes–Tunisia

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Abstract

The main objective of this study was to investigate the effects of microwave power density on drying kinetics of olive fruit (variety Zarrazi).The thin layer drying characteristics of olive fruit (variety Zarrazi) was investigated under three microwave power densities; 1, 1.5 and 2 W/g. The experimental data were fitted appropriately to Page model. The effective moisture diffusivity was calculated in the range from 5.96×10^{-9} to 13.00×10^{-9} m^2/s. The values of k and D_{eff} increased with the increase of power density. An Arrhenius relation with an activation energy value of 1.6316 W/g expressed the effect of microwave power density on the diffusivity.

Introduction

The evergreen olive cultivar (*Olea europea* L., *Oleaceae*) is an important Mediterranean tree (Kiple and Ornelas, 2000). Tunisian olei culture constitutes one of the principal economical and agricultural strategic sectors that are known for their richness of varieties (Abaza *et al*., 2001). Now, the olive plantation, occupying about 1.6 million ha, is dominated by three main cultivars (Issaoui *et al*., 2008). The Chétoui cultivar is omnipresent in the north, the Zarrazi is omnipresent in the south, while the Chemlali one is ubiquitous to the rest of the country (Grati-Kamoun *et al*., 2006). The olive-growing areas spread from the northern to the southern regions, where a wide range of edaphic-climatic conditions are prevailing. These three varieties account for 97% of the total olive tree orchards and constitute more than 92% of the national production of olive oil.

Virgin olive oil is a valuable vegetable oil extracted from fresh and healthy olive fruits (*Olea europeae* L.) by mechanical processes and without any preliminary refining (Garcia and Yousfi, 2006). It has an excellent nutritional, functional and sensorial qualities (Matos *et al*., 2007), and is a product of major economic importance in Tunisia. In addition, virgin olive oil owns a high antioxidant capability and reduces the risk of suffering from cardiovascular diseases and contracting breast or colon cancers (Cicerale *et al*., 2010; Gigon and Le Jeune, 2010).

Healthy eating is one of the most important factors in food choice among Tunisian citizens. They are conscious that more frequent consumption of fruit and vegetables should be a part of a healthy diet. One of the most important of these fruits and vegetables is the olive fruit. The olive fruit has an excellent nutritional, functional and sensorial quality, and it owns a high antioxidant capability. Fruits and vegetables are often dried by sunlight or hot air. The two techniques were investigates for some fruit such mulberry (Doymaz, 2004a; Akpinar, 2008). However, there are many problems in sun drying such as the slowness of the process, the exposure to environmental contamination, uncertainty of the weather, and the manual labor requirement (Maskan and Gogus, 1998). On the other hand low-energy efficiency and lengthy time during the falling rate period are major disadvantages of hot air drying of foods, because heat transfer to the inner sections of foods during conventional heating is limited by the low thermal conductivity of food materials in this period (Maskan, 2000). Due to these difficulties, more rapid, safe and controllable drying methods are required. Also, it is necessary to dry the product with minimum cost, energy and time. In microwave drying, drying time is shortened due to a quick absorption of energy by water molecules, which causes rapid evaporation of water, giving high drying rates of the food (Soysal *et al*., 2006; Darvishi *et al*., 2013).

One of the most important aspects of drying technology is the modeling of the drying process. The present research is focused on this issue. Therefore, the aim of this work was to (i) study the effect of power density on the drying kinetic of olive fruit, (ii) compare the measured findings obtained during the drying of olive fruit with the predicted values obtained with Page thin layer drying semi-empirical model, (iii) calculate the effective moisture

*Corresponding author.
Email: *mahdhaouib@gmail.com*
Tel.: +21696059739; Fax: +21675600632

diffusivity and activation energy.

Material and Methods

To determine the initial moisture content, three samples of 10 g were dried in an oven (Memmert UM-400) at 105ºC for 24 h. Drying tests were carried out in the microwave oven (Bosch, type HMT84M651). It is a digital furnace domesticates, its following design features: The microwaves are emitted there at a frequency of 2450 MHZ; it makes it possible to operate on 5 different levels of power, namely, 90 W, 180 W, 360, 600 and 900 W. Its room for drying measures 215 x 337 x 354 mmof volume; it has a glass plate of about 315 mm of diameter which can carry out 5 turns per minute and whose direction of rotation to 360° can be reversed while pressing on the button" On/Stop".The microwave dryer was operated by a control terminal which could control both microwave power level and emission time. Experiments were performed at three initial masses of 45, 60 and 90 g at a microwave power of 90 W (or power densities (microwave power/mass) of 1, 1.5, 2 W/g).The moisture losses of the samples were recorded at 3 min intervals during the drying process by an analytical balance (Sartorius, Model CP2245) with a precision of ± 0.01 g. After the set time, the sample was taken out of the drying chamber, weighed on the analytical balance (accuracy of 0.01 g) and placed back into the chamber within 10 s (Karaaslan and Tuncer, 2008).

Drying was carried out until the final moisture content reached 12.51 ± 0.29 (%). The experimental drying data for determination of diffusivity was interpreted by using Fick's second law:

$$\frac{\partial X}{\partial t} = D_{eff}\left(\frac{\partial^2 X}{\partial r^2} + \frac{2}{r}\frac{\partial X}{\partial r}\right) \quad (1)$$

The initial and boundary conditions for spherical geometry can be written as:

$$X(r,t)\Big|_{t=0} = X_0 \quad (2)$$

$$\left.\frac{\partial X(r,t)}{\partial X}\right|_{r=0} = 0 \quad (3)$$

$$X(R,t)\Big|_{t>0} = X_e \quad (4)$$

The moisture ratio of olive samples during the thin layer drying experiments was calculated using the following equation:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (5)$$

where X_t is the moisture content at any time t (% d.b.); X_0 is the initial moisture content (% d.b.), and X_e is the equilibrium moisture content (% d.b.). The values of X_e are relatively small compared to X_t and X_0, hence the error involved in the simplification by assuming that X_e is equal to zero is negligible.

The solution to Eq. (1) developed by Crank (1975) can be used for various regularly shaped olive fruit such as rectangular, cylindrical and spherical products, and the form of Eq. (6) can be applicable for particles with spherical geometry by assuming uniform initial moisture distribution, constant diffusion coefficient and negligible shrinkage (Darvishi and Hazbavi, 2012).

$$MR = \frac{X_t}{X_0} = \frac{6}{\pi^2}\sum_{n=o}^{\infty}\left(\frac{1}{n^2}exp\left(-\frac{D_{eff}n^2\pi^2 t}{R^2}\right)\right) \quad (6)$$

where D_{eff} is the effective moisture diffusivity, m^2/s. This could be further simplified to a straight-line equation as:

$$ln(MR) = \frac{6}{\pi^2} - \left(\frac{D_{eff}\pi^2}{R^2}\right)t \quad (7)$$

The drying rate is expressed as the amount of the evaporated moisture over time. The drying rate (% d.b./min) of olive were calculated using the following equation (8):

$$DR = \frac{X_{t+\Delta t} - X_t}{\Delta t} \quad (8)$$

where $X_t + \Delta t$ is moisture content at time $\Delta t + t$ (% d.b.), t is the time (min) and DR is the drying rate (% d.b./min).

One of the most useful empirical models is Page's equation (Page, 1949), which is an empirical modification of the simple exponential model. It is written in the form:

$$MR = exp(-kt^n) \quad (9)$$

where k is the drying constant, n is the Page's parameter and t is the process time (s). There are several criteria such as coefficient of determination (R^2) and chi-square (χ^2) are used to determine the quality of the fit.

The model is said to be good if R^2 value is high and χ^2 value is low. These parameters are defined as follows (Akpinar, 2006):

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{pre,i} - \overline{MR}_{exp}\right)^2}\right) \quad (10)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N-z} \quad (11)$$

where $MR_{pre,i}$ is the ith predicted moisture ratio, $MR_{exp,i}$ is the ith experimental moisture ratio, N is the number of observations and z is the number of constants in drying model.

The correlation between the effective diffusion coefficient and ($1/P_d$) is used for calculation of the activation energy (Minaei *et al*., 2012).

$$D_{eff} = D_0 exp\left(-\frac{E_a}{P_d}\right)$$

where E_a is the activation energy (W/g), m is the mass of raw sample (g) and D_0 is the pre-exponential factor (m^2/s).

Results and Discussion

The moisture content versus drying time curves for microwave drying of olive fruit samples as affected by various microwave powers densities are shown in Figure 1. The time required to dry olive fruit samples from initial moisture content of 46 ± 2% (d.b.) to the final moisture content of 12.5 ± 0.3% (d.b.) were 30, 21 and 15 min at 1, 1,5 and 2 W/g respectively. It indicated that increasing the drying power density decreases the drying time.

The drying time is decreased significantly in comparison with infrared drying of olive (Celma *et al*., 2008) which reflects higher drying rates. The instantaneous moisture ratio rapidly decreases as the microwave power density increases which is due to faster moisture diffusion from the centre of olive. This phenomenon indicated that the mass transfer of drying sample was rapid during microwave heating because the microwave penetrated directly into the sample. The heat was generated inside the sample and provided fast and uniform heating throughout the entire product, thus creating a large vapor pressure differential between the centre and the surface of product and allowing rapid transport and evaporation of water. As a result, this phenomenon may be related to the nature of olive fruit, which is mainly composed of free water in the inner flesh. Free water is heated and subsequently removed much easier than bound water. In the present work the drying time is decreased significantly with increase in microwave output power. Similar results were found by Darvishi *et al.* (2012) on the study of energy consumption and mathematical modeling of microwave drying of potato slices.

The estimated parameters and statistical analysis of the models examined for the different drying

Table 1. Statistical results of the thin layer drying model for MW drying of olive fruit at different power densities

S. N°.	Power density (w/g)	k (1/min)	n	R^2	χ^2
1	1	0.00100	2.05373	0.99794	0.00013
2	1.5	0.00105	2.30404	0.99878	0.00010
3	2	0.00111	2.58329	0.99799	0.00020

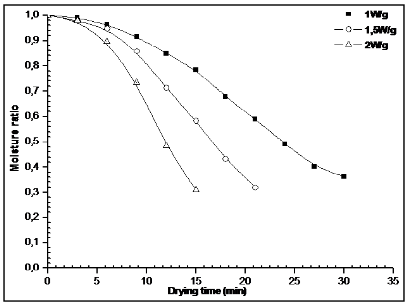

Figure 1. Drying curves of moisture ratio with drying time at different microwave power densities

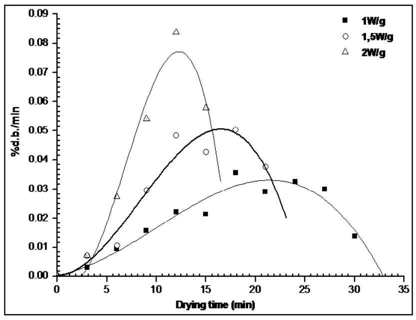

Figure 2. Variations of drying rate at different microwave power densities

conditions were illustrated in Table 1. The statistical parameter estimations showed that R^2 and χ^2 values were ranged from 0.99794 to 0.99878 and 0.0001 to 0.0002, respectively. The high values of R^2 and low values of χ^2 are indicative of good fitness of Page's model to represent the variation in moisture ratio drying time of olive fruit. It is clear that k and n increases as the microwave power density increases, which implies that the drying curve becomes steeper and faster drying is obtained.

Figure 2 compares experimental data with those predicted with the Page model for olive at 1, 1.5, and 2 W/g. There was a very good agreement between the experimental and predicted moisture ratio values, which closely banded around a 45° straight line.The Page model has also been suggested by others to describe the microwave drying of date palm (Darvishi *et al*., 2012), microwave drying of aromatic Pandanusamaryllifolius leaves (Rayaguru *et al*., 2011) and microwave power on the drying characteristics, color and phenolic content of *Spirogyra* sp. (Assawarachan *et al*., 2013).

Based on the multiple regression analysis, the Page's model constants and coefficients were expressed in terms of the drying micowave power density as follows.

Table 2. Effective diffusivities of olive fruit at different power densities

S. N°.	Power density (w/g)	Diffusivity (m²/s)
1	1	5.96×10^{-9}
2	1.5	9.07×10^{-9}
3	2	13.00×10^{-9}

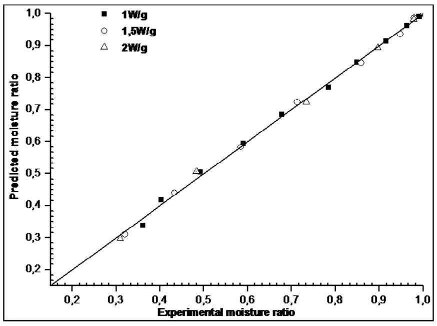

Figure 3. Comparison of experimental and calculated moisture ratio values by the two-term exponential model

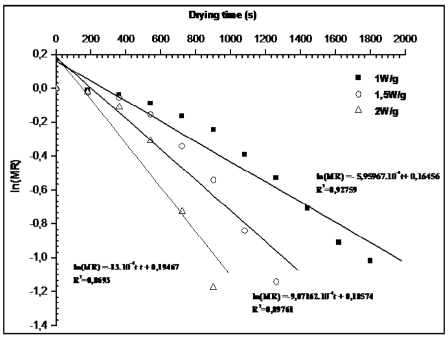

Figure 4. lnMR vs drying time (s)

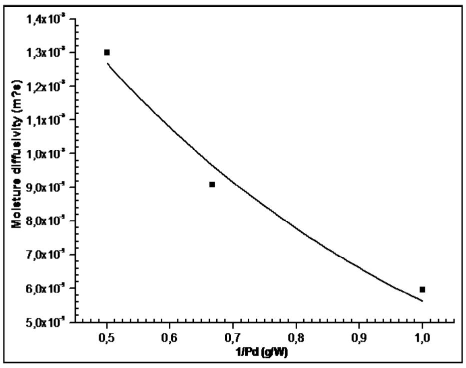

Figure 5. Variation of effective diffusivity as function of power densities

$$MR = exp\left(-kt^n\right)$$

$$n = 0.00436P_d^3 + 0.03827P_d^2 + 0.38425P_d + 1.62685 \qquad R^2 = 0.9929$$

$$k = 0.001P_d^{0.13699} \qquad R^2 = 0.9993$$

These expressions can be used to estimate the moisture ratio of olive fruit at any time during the drying process using microwave with a high accuracy. The consistency of the model and relationship between the coefficients and drying microwave power density is evident. Similar findings were also reported by Darvishi and Hazbavi (2012).

The drying rate, DR, is expressed as the amount of the evaporated moisture over time. Values for DR were calculated as $DR = (M_{t+\Delta t} - M_t)/\Delta t$. The variation of drying rate with drying time is shown in Figure 3. After an initial period of sample heating, the drying rate reached its maximum value, and then it decreases gradually. The necessary instants so that the drying rate reaches its maximum value, are: 21.25, 16.25 and 12 min at 1, 1.5 and 2 W/g, respectively. The values were equal: 0.033, 0.052, and 0.078 (% d.b./min) respectively for 1, 1.5, and 2 W/g. In general, two distinct periods are identifiable, namely a warming-up, and falling rate period. The initial stage was a short warming-up period corresponding to solid heating and consequently to non-isothermal drying conditions. This was followed by falling rate period. As can be seen from Figure 2, after short warming-up stage, only falling rate periods were observed during drying processes under this conditions (1, 1.5, 2 w/g). Similar findings were also reported by several authors for various foods under microwave drying (Wang *et al.*, 2006; Al-Harahsheh *et al.*, 2009; Darvishi and Hazba, 2012).

It was observed that the drying rates were higher at the beginning of the drying operation, when the product moisture content was higher. The moisture content of the material was very high during the initial phase of the drying which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate. The absence of a constant drying rate period may be due to the thin layer of product that did not provide a constant supply of water in the specified period of time. Also, some resistance to water movement may exist due to shrinkage of the product on the surface, which reduces the drying rate considerably.

To calculate the effective diffusivity by using the method of slopes, the logarithm of moisture ratio values, ln(MR), were plotted against drying time (t) according to the experimental data obtained at various microwave power density. The linearity of the relationship between ln(MR) and drying time is illustrated in Figure 4. It was determined that, the effective diffusivity of olive fruit varied from 5.96×10^{-9} to13.00×10^{-9} m²/s over the microwave power density range studied. Values of effective diffusivities of olive fruit determined under the microwave power density range of 1, 1.5, 2 W/g are given in Table 2. As expected, the values of diffusivities increased with the increase of microwave power density due to the increase of temperature and consequently water vapor pressure. The increase in power resulted in rapid heating of the product, thus increasing the vapor pressure inside the product that made the diffusion of moisture towards the surface faster.

The determined values of D_{eff} for different microwave power density are given in Fig. 5 accurately fit to Eq. (19) with coefficient of determination (R^2) of 0.97699. Then, D_0 and E_a values were estimated as 2.87×10^{-8} m²/s and 1.6316 W/g. The dependence of the effective diffusivity of olive samples on the power density can be represented by the following equation:

$$D_{eff} = 2.87\times 10^{-8}\, exp\left(-\frac{1.6316}{P_d}\right) \qquad R^2 = 0.97699$$

The diffusivity values for the runs found 5.96×10^{-9}, 9.07×10^{-9}, 13.00×10^{-9} m^2/s at 1, 1.5 and 2 W/g, respectively. The values lie within the general range from 10^{-11} to 10^{-9} m^2/s for food materials (Madamba *et al*., 1996). It can be seen from Fig. 5 that effective diffusivity for olive fruit increases with microwave power density. Similar results were obtained by Gogus and Maskan (1999) for okra drying, Kaleemullah and Kailappan (2005) for red chillies drying, and Sacilik *et al*. (2006) for tomato drying.

Conclusion

Microwave drying technique can be successfully used to dry olive fruit with maximum gain time. Drying time is decreased significantly with increase in microwave output power. After a short heating period, the process attained very high drying rates followed by the falling rate period during which maximum drying took place. The Page model gave an excellent fit for the drying data of the olive fruit.The effective diffusivities increased with the microwave power density and varied from 5.96×10^{-9} to 13.00×10^{-9} m^2/s. The dependence of the effective moisture diffusivity on the power density is generally described by the Arrhenius equation and the activation energy for the diffusion of moisture was found to be 1.6316 W/g. The results found in this study can be applied to industrial food engineering and operational guide for the microwave drying of olive fruit.

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References

Abaza, L., Daoud, D., Msallem, M.andZarrouk, M. 2001. Evaluation biochimique des huiles de sept variétés d'Olivier cultivées en Tunisie Oléagineux. Corps Gras, Lipides 9: 174-179.

Akpinar, E.K. 2008.Mathematical modelling and experimental investigation on sun and solar drying of white mulberry. Journal of Mechanical Science and Technology 22(8): 1544-1553.

Akpinar, E.K., Bicer, Y. andCetinkaya, F. 2006. Modelling of thin layer drying of parsley leaves in a convective dryer and under open sun. Journal of Food Engineering 75(3): 308-315.

Al-Harahsheh, M., Al-Muhtaseb, A.H. and Magee, T.R.A. 2009. Microwave drying kinetics of tomato pomace: Effect of osmotic dehydration. Chemical Engineering and Processing: Process Intensification. Process 48(1): 524-531.

Assawarachan, R., Nookong, M., Chailungka, N. and Amornlerdpison, D. 2013. Effects of microwave power on the drying characteristics, color and phenolic content of *Spirogyra* sp. Journal of Food, Agriculture and Environment 11(1): 15-18.

Celma, A.R., Rojas, S. andLopez-Rodríguez, F. 2008. Mathematical modelling of thin-layer infrared drying of wet olive husk. Chemical Engineering and Processing: Process Intensification 47(9-10): 1810-1818.

Cicerale, S., Lucas, L. and Keast, R. 2010. Biological activities of phenolic compounds present in virgin olive oil. International Journal of Molecular Sciences 11(2): 458-479.

Crank J. 1975. The mathematics of diffusion. Oxford England: Clarendon Press.

Darvishi, H., Azadbakht, M., Rezaieasl, A. and Farhang, A. 2013. Drying characteristics of sardine fish dried with microwave heating. Journal of the Saudi Society of Agricultural Sciences 12(2): 121-127.

Darvishi, H. and Hazbavi, E. 2012. Mathematical modeling of thin-Layer drying behavior of date palm. Global Journal of Science Frontier Research Mathematics and Decision Sciences 12(10): 247-255.

Doymaz, I. 2004. Drying kinetics of white mulberry. Journal of Food Engineering 61(3): 341-346.

Garcia, J. M. and Yousfi, K. 2006. The postharvest of mill olives. Grasasaceites 57(1): 16-24.

Gigon, F. and Le Jeune, R. 2010. Huile d'olive, *Olea europaea* L. Phytothérapie 8(2): 129-135.

Gogus, F. and Maskan, M. 1999. Water adsorption and drying characteristics of okra (*Hibiscus esculentus* L.)", Drying Technology 17(4-5): 883-894.

Grati-Kamoun, N., Lamy, M. F., Rebaï, A., Gargouri, A., Panaud, O. and Saar, A. 2006. Genetic diversity of Tunisian olive tree (*Olea europea* L.) cultivars assessed by AFLP markers. Genetic Resources and Crop Evolution 53(2): 265-275.

Issaoui, M., Mechri, B., Echbili, A., Dabbou, S., Yangui, A., Belguith, H., Trigui, A. and Hammami, M. 2008. Chemometric characterization of five tunisian varietals of *Olea europaea* L. olive fruit according to different maturation indices. Journal of Food Lipids 15(3): 277–296.

Kaleemullah, S. and Kailappan, R. 2005. Drying kinetics of red chillies in rotary dryer.Biosystems Engineering 92(1): 15-23.

Karaaslan, S.N. andTuncer, I.K. 2008.Development of a drying model for combined microwave-fan-assisted convection drying of spinach.Biosystems Engineering 100(1): 44-52.

Kiple, K.F. and Ornelas, K.C. 2000. Olive Oil, The cambridge world history of food, Cambridge University Press. New York, NY 377–381.

Madamba, P.S., Driscoll, R.H. and Buckle, K.A. 1996. Enthalpy–entropy compensation models for sorption and browning of garlic. Journal of Food Engineering 28(2): 109-119.

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

Maskan, M. and Gogus, F. 1998. Sorption isotherms and drying characteristics of mulberry (*Morus alba*). Journal of Food Engineering 37(4): 437-449.

Matos, L. C., Cunha, S.C., Amaral, J.S., Pereira, J.A., Andrade, P.B., Seabra, R.M. and Oliveira, B.P.P. 2007. Chemometric characterization of three varietal olive oils (Cvs. Cobrancosa, Madural and Verdeal Transmontana) extracted from olives with different maturation indices. Food Chemistry 102: 406-414.

Minaei, S., Motevali, A., Ahmadi, E. and Azizi, M.H. 2012. Mathematical models of drying Pomegranate arils in vacuum and microwave dryers. Journal of Agricultural Science and Technology 14(7): 311-325.

Page, G. E. 1949. Factors influencing the maximum rates of air drying shelled corn in thin layers”, M.S. Thesis, Department of mechanical engineering, Purdue university, Purdue USA.

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.

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

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

Tutuncu, M.A. and Labuza, T.P. 1996. Effect of geometry on the effective moisture transfer diffusion coefficient. Journal of Food Engineering 30(3-4): 433-447.

Wang, J. and Sheng, K. 2006. Far-infrared and microwave drying of peach. LWT- Food Science and Technology 39(3): 247-255.