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Influence of drying methods on activation energy, effective moisture diffusion and drying rate of pomegranate arils (*Punica Granatum*)

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Abstract

In this investigation, thin layer drying behavior of sour pomegranate arils using microwave, vacuum, and infrared methods as well as convection drying (three treatments including control and microwave pretreatments at 100 and 200 W) was studied. Effect of these drying methods on drying rate, effective moisture diffusion and activation energy was analyzed. It was observed that microwave pretreatment increases drying rate and effective moisture diffusion while it decreases activation energy. The highest values of drying rate and effective moisture diffusion were 0.965 g/min and 7.709×10^{-10} m^2/s obtained with pretreatment power of 200 W at air temperature and velocity of 70 °C and 1.5 m/s. while the lowest values were 0.082 g/min and 0.856×10^{-10} m^2/s for the control samples at 45 °C temperature and 0.5 m/s air velocity. Effective diffusion coefficient of pomegranate arils was in the range of 6.77×10^{-10} to 52.5×10^{-10} m^2/s, 3.43×10^{-10} to 29.19×10^{-10} and 4×10^{-10} to 32×10^{-10} m^2/s for vacuum, microwave and IR dryers, respectively. Activation energy for pomegranates in the vacuum dryer was 52.83 kJ, while in the microwave dryer it was 23.563(W/g). Activation energy in the microwave dryer was calculated using the Arrhenius exponential model. A comprehensive comparison of the various dryers revealed that microwave pretreatment combined with convective drying performed best for the drying of pomegranate arils taking into consideration the drying rate, effective moisture diffusion and activation energy.

Keywords: Effective Moisture Diffusion, Activation Energy, Drying Rate, Pomegranate arils.

Abbreviations: M_{t+dt} : Moisture content at time (t+dt) (kg water/kg dry solid), M_t : Moisture content at time t (kg water/kg dry matter), t : Drying time (min), r_e: Radius of pomegranate arils (m), V: Volume of pomegranate arils (m^3), D_{eff}: Effective moisture diffusion (m^2s^{-1}), M_o: Initial moisture content (kg water/kg dry solid), M_e: Equilibrium moisture content of the sample (kg water/kg dry solid), MR: Moisture ratio (dimensionless), n: Number of terms (1,2,3,…), k_1 , k_2: Slope of straight line, E_a: Energy of activation (kJ/mol) and (W/g).

Introduction

Pomegranate (*Punica granatum*) is a fruit-bearing deciduous tree growing between five and eight meters tall. It is mostly native to the Iranian Plateau and the Himalayas in north Pakistan and north India (Shahrestani, 1998). Drying process is one of the best methods to preserve fruits including pomegranate. During drying, water leaves the foodstuff and as a result there is less probability of microorganism growth and unfavorable chemical reactions (Sahin and Dincer, 2002). Due to the importance of drying in food maintanance and post harvest operations, various drying methods have been developed. Convection drying using hot air systems is the basic drying method commonly used (Das et al., 2004). Foodstuff drying using microwave can be a good substitute for convection drying. Microwave drying is a relatively inexpensive method which uses electromagnetic spectrum between 300 MHz and 300 GHz. Unlike conventional warming systems, microwaves penetrate food and expand heat throughout the material (Schiffman, 1992). Drying with infrared radiation is suitable especially for thin product slices exposed to radiation. In this method, heating the material is accomplished without changing its structure, so the structural quality of the material is preserved, its biological function is increased and processing costs are kept low (Chakraverty and Singh, 1998). Minimization of losses resulting from drying is another advantage of using infrared radiation. Also, in some cases, infrared heat can be concentrated on the object faster than convection dryers. In convection dryers part of the heat is absorbed by the milieu and is wasted. Infrared radiation provides for high drying speed without the risk of burning the material (Nonhebel, 1973). The use of vacuum in drying can be a good approach to improve the quality of the product by facilitating moisture extraction. Vacuum application can reduce drying temperature and therefore improve the qualitative features of the food (Kompany et al., 1993; Jaya and Das, 2003). A considerable amount of data has been reported in the literature regarding microwave drying of various agricultural products (fruits, agronomic crops and vegetables), the effect of constant power and constant temperature microwave drying on the diffusion characteristics of moisture in thin layer samples of white beans was studied by Adu and Otten (1996). Investigation of Microwave drying and grinding characteristics of wheat indicated that microwave drying of grain samples before grinding helps to reduce power consumption in due course in wheat milling industries (Walde et al., 2002). Dehydration of carrots by a combination of freeze drying, microwave heating and air or vacuum drying proved that drying at lower temperatures is preferable (Litvin et al., 1998). Vaccum-microwave drying of carrot slices was compared to air drying and freeze drying on the basis of rehydration potential (Lin et al., 1998). Characteristics of chard leaves during microwave, convective, and combined microwave-convective drying were determinad (Alibas, 2006). Microwave drying of grapes was investigated and different models were assessed (Tulasidas et al., 1997). Microwave-assisted hot-air dehydration of apple and mushroom was conducted using low-power microwave energy (Funebo and Ohlsson, 1998). Numerous reports are found based on thin layer drying processes such as pomegranate arils (Motevali et al., 2010, 2011), carrot pieces (Yan et al., 2010), apple (Kaleta and Górnicki, 2010) and bioproducts (Chua and Chou, 2005). However, there is little information on the comparsion of different drying methods in terms of moisture diffusivity, activation energy and drying dynamics. Therefore, the objective of this study was the determination of drying rate, effective moisture diffusion, and activation energy in thin layer drying of pomegranate arils using 5 different drying methods.

Results and Discussion

Drying Rate

In the initial phase of the drying process, aril moisture content and the rate of moisture loss are high. As drying progresses, moisture content decreases. A major portion of the product moisture is lost during the initial drying process, and much time is needed to extract the remaining moisture. As it is clear from Fig. 1, it can be seen that drying rate during the initial stages rapidly increases to a maximum associated with the highest drying rate, after which evaporation decreases gradually. According to the diagrams in Figure 1(a), rate of moisture loss in the control sample is erratic. However, the severity of this problem decreases with increasing temperature. In the 100 W microwave pretreatment, the maximum drying rate is 0.511 (g/min) occurring after the pretreatment and during convective drying (Fig1b). However, in the 200 W microwave pretreatment maximum evaporation rate of 0.965 (g/min) occurs in the microwave dryer (Fig1c). Using microwave pretreatment causes the loss of moisture to be more orderly and less erratic than the control treatment. Moisture loss increases with increasing air velocity at constant temperature in the three different treatments. Increasing temperature causes increased thermal gradients inside the material and as a result increased product drying rate. Also, with the increase in air velocity, drying rate of the product is incresed. The cause of this phenomenon is that vapor pressure decreases with increasing air velocity thus, product moisture faces less resistance to evaporation. In hot air drying of pomegranate arils, the time needed for conductive heating of the bulk of arils to the evaporation temperature is long. This may be due to low aril thermal conductivity and formation of a hardened layer on the surface. Microwave pretreatment results in fine pores on the skin of pomegranate arils and as a consequence, the case hardening problem never occurs. Thus, microwave pretreatment facilitates easy removal of moisture and results in lower drying time. In other words, when the pomegranate arils were subjected to microwave pretreatment, a large amount of moisture was removed in a short time. Similar results have been reported for drying of various agricultural products (Motevali et al., 2012; Babalis and Belessiotis, 2004; Wang et al., 2007; Celma et al., 2007; Ertekin and Yaldiz, 2004). Drying curves shown in figure 2 follow the general expected pattern, however, drying rate in the microwave dryer is somewhat more irregular than those in the vacuum and IR dryers. It can be seen that drying rate increases with increasing microwave power. The highest drying rate occurred at the 200 W microwave pretreatment (Fig 2a). Therefore, microwave output power has a pronounced effect on the drying rate of pomegranate arils similar to what has been reported for other agricultural materials (Gowen et al., 2008; Karaaslan and Tuncer, 2008). Figures 2 b and c illustrate drying rate versus drying time in the vacuum dryer and IR dryer at constant air velocity (0.3 m/s), respectively.

Effective moisture diffusivity

It has been shown that effective moisture diffusivity depends on temperature and the type of material being dried (in terms of tissue and structure) (Rizvi, 1986). Product moisture decreases with increasing air temperature and velocity of the air passing through the drying chamber. ith increasing temperature, the drying time is reduced due to increased thermal gradients inside the material and as a result, drying rate increases. Also, increasing the hot air velocity, reduces product drying time. The cause of this phenomenon is that vapor pressure decreases with increasing air velocity and thus moisture faces less resistance to evaporation. D_{eff} is calculated using Eq. 7 and values for each level of air velocity and temperature are reported in Table 1. Results show that increasing temperature (at constant air velocity) increases the effective moisture diffusivity. Fig 3 shows plots of In (D_{eff}) versus 1/T for various treatments. All plots show that drying of pomegranate arils occurred in the falling rate period. In other words, the moisture diffusion is by the dry air force controlling the drying process and therefore the curves are straight lines. The maximum value of moisture diffusivity was found to be 7.709×10^{-10} (m^2/s) at air velocity of 1.5 m/s and temperature of 70 °C. The minimum value of moisture diffusivity was 0.856×10^{-10} (m^2/s) obtained at air velocity of 0.5 m/s and temperature of 45°C. It was observed that microwave pretreatment increased effective moisture diffusion. Pretreatment with microwave power of 200 W had a more pronounced effect on the diffusion coefficient in comparison with that of the control and the 100 W microwave pretreatment. Microwave pretreatment increases rate of moisture transfer in thin layers of pomegranate and these phenomenon causes increases drying rate and effective moisture diffusivity. Effective moisture diffusion values for three treatments including control and microwave pretreatments at 100 W (for 20 min) and 200 W (for 10 min) are given in Table 1 for various air temperatures and velocities.Other researchers have reported similar results. Effective moisture diffusivity for different foods and vegetables including Apple, Carrot, Potato, Cassava, Grape, Mango and Fish have been compiled by Mendles et al. (2002) which shows that moisture diffusivity varies from 2.2×10^{-10} to 9.4×10^{-10} m^2/s. Doymaz (2004) reported that D_{eff} values for carrot varied in the range of 0.776×10^{-9}-1.371×10^{-9} m^2/s when temperature varied from 50 to70 °C. The value of D_{eff} falls in the general range of 10^{-9}-10^{-11} m^2/s for food materials (Babalis and Belessiotis, 2004; Madamba et al., 1996). Value of D_{eff} Is calculated from equation 7 and is reported for sour pomegranates in tables 2 and 3. The lowest moisture diffusion value for pomegranate arils in vacuum drying at 50 ºC is 6.77×10^{-10} m^2/s while the highest value is obtained at 90 ºC to be 50.08×10^{-10} m^2/s. In microwave drying at 100W, the lowest and highest moisture diffusion values for sour pomegrante were obtained to be 3.43×10^{-10} (m^2/s) and 29.19×10^{-10} (m^2/s), respectively. According to Rizvi (1986),

Table 1. Effective moisture diffusivity (D_{eff}×10^{-10}) and correlation coefficient for the performed experiment.

Temperature (°C)	Control treatment						Microwave pretreatment at 100 W					
	R^2	V_1=0.5m/s	R^2	V_2=1m/s	R^2	V_3=1.5m/s	R^2	V_1=0.5m/s	R^2	V_2=1m/s	R^2	V_3=1.5m/s
45	0.99	0.856	0.99	1.027	0.97	1.370	0.96	1.370	0.98	1.5419	0.98	1.713
50	0.99	1.199	0.97	1.541	0.98	1.713	0.96	1.713	0.96	1.713	0.92	3.597
55	0.98	1.541	0.99	1.713	0.97	2.055	0.98	2.055	0.95	3.426	0.93	4.111
60	0.99	1.884	0.99	2.055	0.99	3.940	0.96	3.426	0.99	3.769	0.95	4.625
65	0.98	3.426	0.98	3.940	0.97	5.482	0.97	4.111	0.97	5.139	0.98	5.311
70	0.98	4.111	0.99	5.139	0.99	5.996	0.99	5.139	0.99	5.653	0.98	6.853
	Microwave pretreatment at 200 W											
	R^2	V_1=0.5m/s	R^2	V_2=1m/s	R^2	V_3=1.5m/s						
45	0.98	1.713	0.97	3.426	0.88	3.597						
50	0.97	3.426	0.97	3.597	0.98	3.769						
55	0.99	4.111	0.99	4.111	0.99	4.454						
60	0.99	4.797	0.99	5.311	0.98	5.311						
65	0.98	5.653	0.95	5.825	0.95	6.339						
70	0.94	6.853	0.98	7.024	0.95	7.709						

Table 2. D_{eff} estimation and statistical analysis from linear model for different temperatures in vacuum drying of sour pomegranate.

Temperature	$D_{eff}\times 10^{-10}$(m^2/ s)	R^2
50	6.77	0.98
60	13.5	0.98
70	16.9	0.99
80	50.08	0.98
90	50.08	0.99

moisture diffusion is dependent upon drying temperature as well as product composition. Due to the difference in drying temperatures in the vacuum and microwave dryers, it can be concluded that the only factor accounting for the difference in moisture diffusion values is drying temperature. Effective moisture diffusion coefficients under various conditions of air flow rate and intensity of infrared radiation for drying of pomegranate arils are given in table 4. With increasing intensity of IR radiation and decreasing air flow, the drying rate increases due to an increase in the temperature of arils and consequently diffusivity increases. The highest value of effective diffusion coefficient for pomegranate is 32.1× 10^{-10} (m^2/s) at the highest temperature of 60 °C (49 W/cm^2) and the lowest air velocity (0.3 m/s), while the lowest effective diffusion coefficient is 4×10^{-10} (m^2/s) obtained at the lowest temperature of 40°C (22 W/cm^2) and the highest air velocity (1 m/s) (table 4).

Temperature in IR drying is dependent on the intensity of infrared radiation and airflow rate thus different effective moisture diffusion values were obtained by different combination of these two factors. Increasing radiation intensity and decreasing air velocity results in the temperature of pomegranate arils to increase. The intensity of cooling the surface of pomegranate arils is decreased with increasing air velocity and therefore the highest amount of diffusion coefficient occurs at the highest radiation intensity and the lowest air velocity. These results are similar to the findings of researchers for other crops (Shin Kim and Bhowmik, 1995; Sharma and Prasad, 2004).

Activation Energy in convection drying

The energy of activation was calculated using the Arrhenius equation (Eq.7) (Yamashita et al., 1999; Yaldiz and Ertekin, 2001). In Fig. 3 the value of ln D_{eff} versus $1/T_{abs}$ is plotted and E_a is obtained using Eq. 9. Table 5 contains the value of E_a for different levels of air velocity, E_a lies in the 12.7-110 (kJ/mol) range for food materials (Aghbashlo et al., 2008). Higher air temperature and velocity levels increase the effective moisture diffusion due to increasing mass and heat transfer. For this reason, microwave pretreatment decreases the activation energy compared with the control treatment (Fig. 3). The maximum value of activation energy (59.68 kJ/mol) was obtained at 200 W microwave pretreatment while the minimum value (27.35 kJ/mol) was associated with the control treatment. In Table 5 values of E_a versus air velocity are reported along with the R^2 value for the fitted equations. Results of this study are in agreement with those of previous studies. For instance, activation energy for corn as has a minimum of 27.61 kJ/mol (Tolaba and Suarez, 1988) while (Kaymak-Ertekin, 2002) reported a maximum activation energy of 51.4 kJ/mol for apple. Water adsorption and drying characteristics of okra *Hibiscus Esculentus L.* indicated that its maximum activation energy was 51.26 kJ/mol (Gogus and Maskan, 1999). Activation energy for sour pomegranate arils in vacuum drying was 52.859 kJ/mol (Fig 4), which is quite close to those reported for agricultural products such as okra 51.26 kJ/mol, (Gogus and Maskan, 1999) and green peppers 51.4 kJ/mol, (Kaymak-Ertekin, 2002).

Activation Energy in microwave drying

Activation energy and D_0 can be calculated from the (k-m/p) curve (Fig 5) and equation 13. Based on statistical analysis and Page model coefficients, it is seen that constant drying rate (k) increases with increasing microwave power. Activation energy for sour pomegranate arils was calculated to be 24.22 (W/g). Another method for calculation of activation energy, is to obtain the coefficients of equation 14

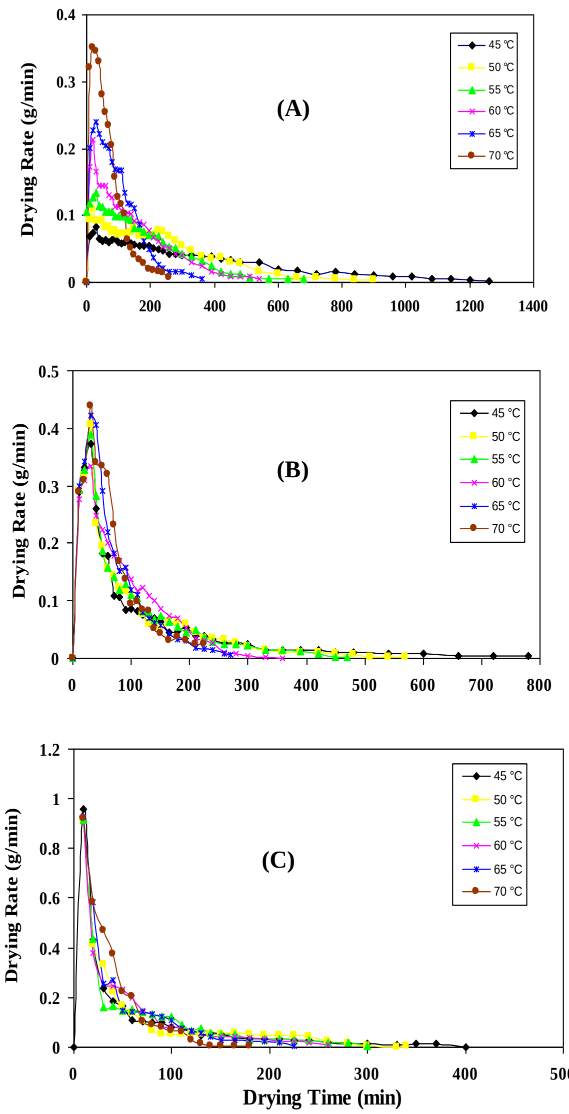

Fig1. Effect of temperatures on drying rate of pomegranate arils at air velocity of 0.5 m/s for (A) control, (B) microwave pretreatment at 100 W and (C) microwave pretreatment at 100 W.

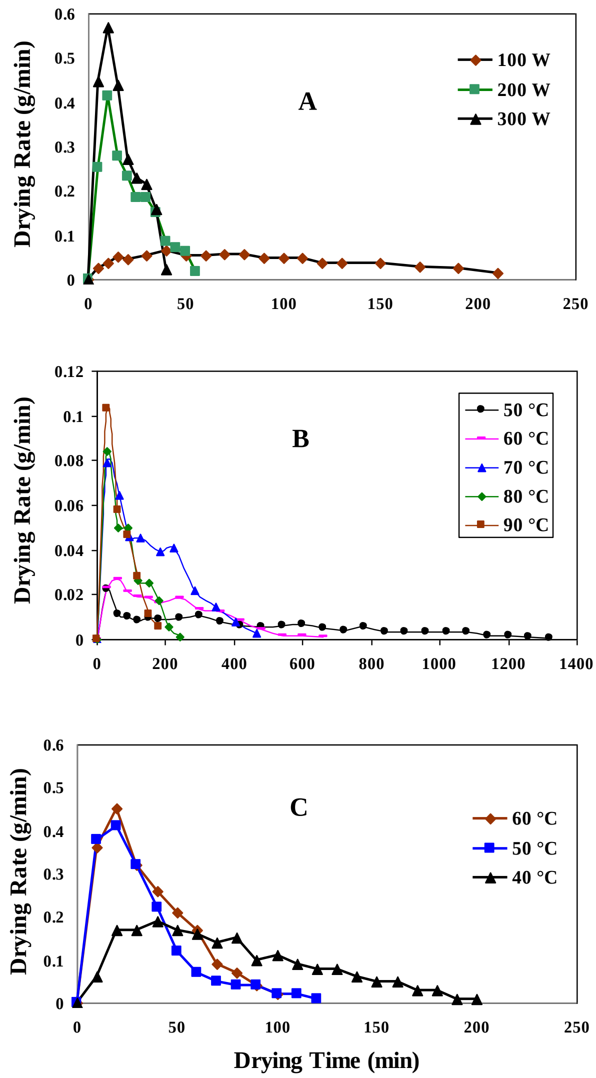

Fig 2. Drying rate curves for *sour* pomegranate arils in A) Microwave B) vacuum C) IR dryers.

from the (D_{eff}) versus (m/p) curve (Fig 6), which would yield an activation energy value of 23.56 (W/g) for sour pomegranates.

Infrared method

In the IR method of drying, effective diffusion coefficient of moisture showed an increasing trend with increasing radiation intensity and decreasing airflow rate. Increasing the intensity of radiation, elevates the temperature gradient of the surface and underlying layers of the product, thus increasing the moisture flow rate inside the product. Also, decreasing the air velocity by reducing the cooling effect of air flow in this method increases the diffusion coefficient inside the product. Activation energy (E_a) that represents the amount of energy required to remove moisture from the material, was obtained between 25.49 and 43.80 kJ/mol for pomegranate arils.

Materials and methods

Sample preparation

Freshly harvested pomegranate fruits were purchased from a local farm in Jouybar city of Mazandaran province and samples were stored in refrigerator at +5 °C. Unripe and broken fruits were separated manually and discarded. Initial moisture content of fruits was obtained using the gravimetric method. A twenty-gram sample of pomegrenate arils was dried in an oven at 105±1°C until the mass did not change between two consequtive weighings. This process was repeated 5 times (Doymaz, 2005) and the initial moisture content was determined to be 331% (d.b.).

Experimental apparatus and levels of independent variables

Experiments were performed at 6 air temperature levels (45, 50, 55, 60, 65 and 70 °C) and three air velocity levels (0.5, 1 and 1.5 m/s). Three pretreatments including control and

Table 3. D_{eff} estimation and statistical analysis from linear model for different output powers in *microwave* drying of *sour* pomegranate.

R^2	$D_{eff} \times 10^{-10}$ (m^2/s)	Microwave power (W)
0.91	3.43	100
0.89	25.76	200
0.90	29.19	300

Table 4. Values of effective moisture diffusion coefficient and determination coefficient for the linear model at various air temperatures and velocities in IR drying pomegranate arils.

60		50		40		Temperature (°C)
$D_{eff}\times10^{-9}$	R^2	$D_{eff}\times10^{-9}$	R^2	$D_{eff}\times10^{-9}$	R^2	Air velocity (m/s)
3.21	0.98	2.41	0.92	1.61	0.92	0.3
1.61	0.99	1.31	0.95	0.72	0.90	0.5
0.80	0.95	0.8	0.88	0.48	0.86	0.7
0.72	0.87	0.56	0.95	0.40	0.88	1

Table 5. Energy of activation (E_a) and related correlation coefficients for different air velocities and pretreatments.

R^2	V_3=1.5m/s	R^2	V_2=1m/s	R^2	V_1=0.5m/s	Type of treatments
0.9552	59.6867	0.9455	57.0668	0.9745	57.9273	Control treatment
0.8698	42.8336	0.9351	51.3906	0.9776	50.4919	Microwave pretreatment at 100 W
0.9726	28.6519	0.9672	27.3548	0.8997	44.7675	Microwave pretreatment at 200 W

microwave pretreatments at 100 W (for 20 min) and 200 W (for 10 min) were implemented so as to obtain similar final moisture contents using the same amount of energy. In this study, various measurements were performed as follows: 1- temperature using a Lutron thermometer, TM-925, (Taiwan) 2- air velocity adjustment using Lutron-YK,80AM anemometer, (Taiwan) 3- humidity using Testo 650, 05366501 humidity meter, (Germany), 4- microwave pretreatment using a Samsung model M945 microwave oven (Korea), 5) sample weight using a 0.0001 g electronic balance (Sarturius, TE214S, AG Germany). In the microwave drying method, three power levels of (100 , 200 , 300 watts) were used for drying pomegrante arils. The drying process was conducted in a vs-1202 v5, vacuum dryer (Korea) using a Serno: 26431801, diaphragm vacuum pump (Germany). A fixed vacuum level (250 kPa) and five temperature levels of 50, 60, 70, 80 and 90°C were used to dry pomegrante arils. Experiments were performed in the IR dryer at three temperature levels (40, 50 and 60 °C) and four air velocities (0.3, 0.5, 0.7 and 1 m/s). Ambient temperature and relative humidity during the experiments were measured to be in range of the 20 to 26 °C and 22-27%, respectively.

Drying Rate

Drying rate of pomegranate arils was calculated using eq.1 (Akpinar et al., 2003)

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \quad (1)$$

Effective moisture Diffusion

Volume (V) of a single pomegranate aril was determined using toluene displacement method for 50 pomegranate arils. This procedure was repeated three times. The equivalent radius of the pomegranate aril was found to be 4.11 mm by equating the volume of a single aril with the equivalent volume of a sphere having radius r_e (Eq. 1) (Mohsenin, 1996).

$$v = \frac{4}{3}\pi r_e^{\,3} \quad (2)$$

The basic equation of Fick's unsteady state law of effective moisture diffusion is of the form given in Eq. 3.

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \quad (3)$$

The analytical solution of Fick's second law of unsteady state diffusion in a spherical body can describe the transport of moisture during the process occurring in the falling rate period, by assuming that effective moisture diffusivity is constant and radial during the drying process and is calculated using the following equation (Crank, 1975):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-n^2\pi^2\frac{D_{eff}t}{r_0^{\,2}}) \quad (4)$$

For solution of Fick’s law of diffusion, with assumptions of moisture migrating only by diffusion, negligible shrinkage, constant temperature and diffusion coefficients in long drying times, are given in equation 5 (Velic et al., 2003). As time increases, terms other than the first one approach zero. Neglecting higher terms, the following equation will be derived (Chayjan et al., 2011):

$$MR = \frac{6}{\pi^2}\exp(-\pi^2\frac{D_{eff}t}{r_0^{\,2}}) \quad (5)$$

Eq. (5) can be simplified to a straight-line equation as follows:

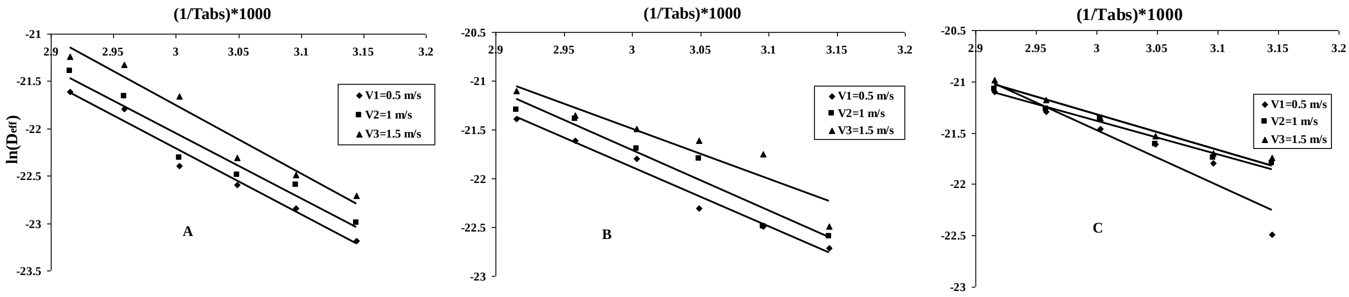

Fig 3. Ln (D_{eff}) versus 1/Tabs at different air velocities for a) control treatment, b) microwave pretreatment at 100 W and c) microwave pretreatment at 200 W.

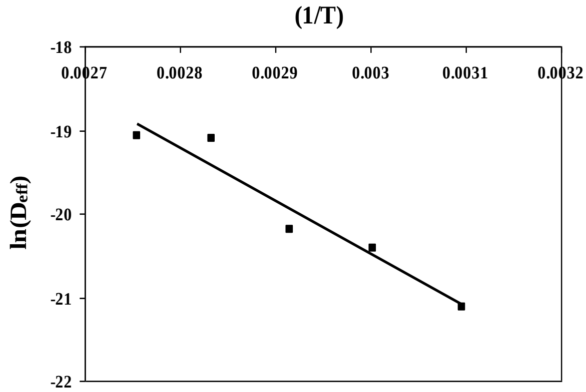

Fig 4. Plot of ln (D_{eff}) versus $1/T_{abs}$ for vacuum drying of pomegranate arils.

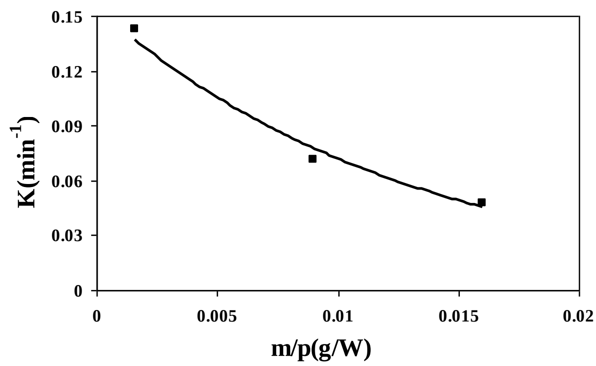

Fig 5. Variation of drying constant rate with [sample weight/microwave output power] for *sour* pomegranate arils.

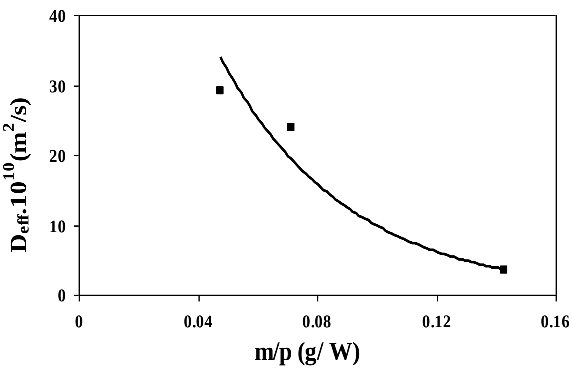

Fig 6. Relationship between D_{eff} versus [sample weight/microwave output power] for *sour* pomegranates.

$$\ln(MR) = \ln(\frac{6}{\pi^2}) - (\pi^2 \frac{D_{eff} t}{r_0^2}) \quad (6)$$

The diffusion coefficient is obtained by plotting the experimental drying data in terms of ln(MR) versus time (s). From Eq. 6, such a plot of ln(MR) versus time gives a straight line with a slope of k_1 in the form of Eq (7):

$$k_1 = \frac{\pi^2 D_{eff}}{r_0^2} \quad (7)$$

Energy of activation in convection, vacuum and IR drying

The energy of activation was calculated using Arrhenius type equation (Aghbashlo et al., 2008).

Eq. (8) can be linearized by taking natural logarithm of both sides.

$$D_{eff} = D_0 \exp(-\frac{E_a}{R_g.T_{abs}}) \quad (8)$$

$$LnD_{eff} = LnD_0 - \frac{E_a}{R_g}.\frac{1}{T_{abs}} \quad (9)$$

A plot of ($\ln D_{eff}$) versus ($1/T_{abs}$) gives a straight line having slope k_2. Activation energy can thus be calculated from Eq. (10):

$$k_2 = \frac{E_a}{R_g} \quad (10)$$

Activation energy in the microwave dryer

Inasmuch as temperature is not precisely measurable inside the microwave drier, the activation energy is found as modified from the revised Arehnious equation. In a first method it is assumed as related to drying kinetic constant rate (k) and the ratio of microwave output power to sample weight (m/p) instead of to air temperature. Then Equation (15) can be effectively used (Dadali, 2007) as follows:

$$K = K_0 \exp(\frac{-E_a.m}{p}) \quad (11)$$

In the second method, the correlation between the effective diffusion coefficient and *(m/p)* is used for calculation of the activation energy.

$$D_{eff} = D_0 \exp(-\frac{E_a.m}{p}) \quad (12)$$

E_a can then be determined, by means of curves, the Dadali model and multiple regression analysis using *MATLAB* software.

Conclusions

Thin layer drying of sour pomegranate arils in vacuum, convection, microwave, microwave plus convective and infrared dryers was examined. The highest drying rate occurred in microwave pretreatment with 200 W power at 70 °C and air velocity of 1.5 m/s, while the lowest rate was obtained in the control treatment at 50 °C and air velocity of 0.5 m/s. Minimum effective diffusion was observed in the control treatment at 45 °C temperature and air velocity of 0.5 m/s while its maximum was associated with the 200 W microwave pretreatment at 70 °C and air velocity of 1.5 m/s. By increasing the vacuum dryer temperature from 50 ºC to 90 ºC and microwave power from 100 to 300 W, moisture diffusion in pomegranate arils increased. In the infrared dryer, effective moisture diffusion increased with increasing infrared radiation and decreasing air velocity. Activation energy values for drying of sour pomegranate arils ranged from 27.35 to 59.69 kJ/mol in convection drying and from 25.49 to 43.48 (kJ/mol) in IR drying.

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