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Modulus of elasticity (E) and total soluble solids (TSS) effects on drying characteristics of two apricot varieties

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ABSTRACT

The moisture diffusion coefficient and energy activation of two Iranian apricot varieties was determined at five drying air temperatures and at a constant air velocity of 1.5 m/s. The initial moisture content (d.b.), modulus of elasticity, surface area, half of pomace thickness of halved apricot, and total soluble solids of both varieties were determined. The results showed that there were significant differences ($p<0.01$) in the modulus of elasticity and total soluble solids between two varieties, but no significant differences ($p>0.01$) were observed for other parameters. The water effective diffusion coefficient ranged from 1.34×10^{-10} to 4.15×10^{-10} m^2/s, and from 2.03×10^{-10} to 5.95×10^{-10} m^2/s, for *Ghavami* and *Nasiry*, respectively. Energy activation was 27.1 and 25.34 kJ/mol for *Ghavami* and *Nasiry* varieties, respectively. The results showed that modulus of elasticity and total soluble solids play a major role in moisture diffusion by limiting water movement within the material subjected to drying.

Introduction

Apricot (*prunus armeniaca* L.) is a cultivated type of zerdali (wild apricot) which is produced by domestication (Ozbek 1978). Apricot is mainly produced in Turkey, Iran, Italy, Pakistan, Spain and France. Apricot fruits can be used as fresh, dried or processed fruit (Doymaz 2004). Fresh apricot is perishable product due to its high moisture content. Drying of apricot is an alternative process to preserve it by reducing the moisture content to a level that allows safe storage over extended period. Historically, the sun drying is used for preservation of agricultural products. There are many problems associated with sun drying method, such as lack of sufficient control during drying, being extremely weather dependent, contamination with dust, soil and insects and undesirable changes in the quality of product. These problems could be overcome if new techniques of drying are used. Several researchers have investigated the drying kinetics of various agricultural products in order to determine the best mathematical models (Lahsasni *et al.* 2004; Bakri and Hobani 2000; Aghbashlo *et al*. 2009). Also, the drying kinetics of apricot under various drying techniques has been thoroughly investigated by many researchers.

Vagenes and Marinos-Kouris (1991) examined the kinetics of apricot dehydration using a factorial experimental design in order to evaluate the effect of air temperature, air velocity and pretreatment of the sample on the drying time and the transport coefficients of apricots. They concluded that the moisture transfer is entirely controlled by the external resistance to mass transfer for the air velocities examined. They also proposed a new method for the evaluation of the relative significance of the external and the internal mass transfer.

Togrul and Ispir (2007) studied diffusion coefficient and the variation of density and shrinkage of apricots during osmotic dehydration. They proposed a mathematical model for apricot shrinkage during osmotic dehydration. Togrul and Pehlivan (2003) studied drying kinetics of single apricot at different values of air temperatures and air flow rates. They applied mathematical models to simulate drying kinetics of single apricot drying.

Doymaz (2004) studied the effect of pre-treatments such as Potassium Metabisulphide ($K_2S_2O_5$) and Alkaline Ethyl Oleate (EO) on the drying kinetics of apricots and concluded that the plus treated apricots have shorter drying times (hence higher drying rates) compared to that of $K_2S_2O_5$ and EO treated alone or untreated. Bon *et al.* (2007) investigated the drying kinetics of halved and deseeded apricots during convective drying at different temperatures (from 50 to 90°C). They proposed and solved a diffusion model using the finite element method.

Khoyi and Hesari (2007) studied osmotic dehydration of apricot using sucrose solution. They proposed temperature of 50°C and concentration of 60% as the best treatment for apricot osmotic dehydration. Ispir and Togrul (2009) investigated the effect of osmotic dehydration parameters such as concentration of solution, temperature, the ratio of sample/solution, time, and geometry of the sample. They concluded that the rate of water loss and solid gain in the osmotic dehydration of apricot was directly related to the concentration and temperature of solution, the ratio of sample to solution and the geometry of sample.

Agricultural crops and food products have several unique characteristics which set them apart from engineering materials. Rizvi (1986) stated that effective diffusivities depend on the drying air temperature in addition to variety and composition of material. Initial moisture content, modulus of elasticity (E), surface area (S), pomace thickness of fruit (2Z) and total soluble solids (TSS) are the main parameters affecting the drying characteristics of fruits. Modulus of elasticity is a measure of the stiffness of material and could be used as an index of internal resistance of drying material to moisture movement. High value of modulus of elasticity causes high value of internal resistance to moisture movement, increases drying time and decreases

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moisture diffusion during drying. Whereas, reverse results may be obtained for material with low value of modulus of elasticity.

The drying characteristics of agricultural products differ from industrial products. Case hardening occurs with increasing in soluble solids content of material. The total soluble solids of material is an important factor affecting case hardening. Case hardening encloses the moisture within the bulk of the solid so that the interior moisture cannot be easily removed. Case hardening causes the undesirable changes in chemical properties and quality, decreases the water diffusion coefficient and increases energy utilization during drying process. High value of initial moisture content increases both diffusion coefficient and required drying time. Increasing the surface area of material increases the corresponding contact area with drying air and is associated with high heat and mass transfer values. Therefore, the majority of moisture within material begins to evaporate. Pomace thickness of fruits affects heat and mass transfer. Increasing the pomace thickness decreases heat and mass transfer coefficients. This can be explained by the fact that the internal moisture travels a large distance to reach the surface and discharges to the drying media. Thus, it is vital for researchers to investigate the effect of variety properties on drying characteristics.

No research work has been found in the literature on the effect of variety properties on moisture diffusion and drying time of apricot. Therefore, the objective of this study was to investigate the effect of variety properties especially the total soluble solids and modulus of elasticity, on the drying time, effective moisture diffusivity and energy activation of apricot during hot air drying.

Materials and Methods

Sample Preparation

Two Iranian apricot cultivars *Ghavami* and *Nasiry* were obtained from orchard located in Shahroud, Iran (170 km far from Semnan Province) in July 2009 and stored in a refrigerator at about 4ºC. The initial moisture content of apricots was determined at 78ºC for 48 h using the oven method (AOAC 1984) in three replications.

Determination of surface area and pomace thickness

To determine the average size of the fresh fruits, three linear dimensions namely as length (*L*), width (*W*) and thickness (*T*) were measured by using a digital caliber with 0.01 mm sensitivity. The 100 fruits of each variety were tested in the "Agricultural Engineering and Technology Laboratory", University of Tehran, Karaj, Iran. Surface area of fresh fruit was calculated using Eq. (1) (Mohsenin 1986):

$$S = \pi (LWT)^{2/3} \qquad (1)$$

in which S is the surface area (mm^2).

Before starting the drying experiment, pomace thickness of halved apricots was measured.

Determination of modulus of elasticity

The calculation of modulus of elasticity is based on the following assumptions:

(a) The apricots are long elliptic in shape,

(b) Very small expansion in the longitudinal plane is occurred with compression in vertical plane,

(c) Each side of the apricot in contact with the flat plates has an equal deformation (O′Brien 1965).

A Universal Testing Machine (Santam, SMT–5) were used for conducting the experiment This machine has four main components, which are a stationary clamp, a moving platform, a driving unit (AC electric motor and reduction unit) and a data acquisition system (a load cell, a PC card and the software) (Fig. 1). The load cell capacity was 500 N at a compression rate of 30 mm/min.

Fig. 1. Universal Testing Machine (Santam, SMT–5) used to determine modulus of elasticity

Failure force and deformations of samples are expressed in terms of the peak force-deformation curve. The modulus of elasticity was calculated by Eq. (2):

$$E = \frac{F}{\pi \delta^2} \qquad (2)$$

where *E* is modulus of elasticity of fruits (MPa), δ is deformation of one side of fruit (mm) and *F* is compression force (N) (Fig. 2).

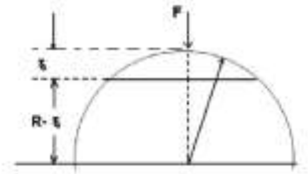

Fig. 2. Deformation occurred in measuring modulus of elasticity, δ: deformation of one side, R: half of thickness, and F: compression force

Determination of total soluble solids (TSS)

TSS is an index of soluble solids concentration in a fruit. Apricot juice was extracted and after stirring to make the juice homogenized, the total soluble solids were determined by a digital refractometer ECLIPSE 45-02 (eclipse, 003320, UK). Results were expressed as %.

Drying experiments

A laboratory scale hot–air dryer was used (Fig. 3). The dryer consists of a fan, heaters, a straightener, a PC, a microcontroller, a digital balance, a tray, sensors for temperature and humidity (Omid *et al*. 2007).

>Fig. 3

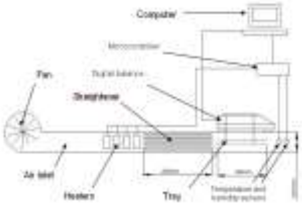

Fig. 3. Schematic view of the drying equipment

Before commencing the drying process, apricots were washed in clean running tap water and samples were selected based on uniformity of ripeness and their cores were separated. 200 g of halved apricots were placed on the tray and enclosed in the dryer to dry. The drying experiment was carried out at 40, 50, 60, 70 and 80 ºC and with constant air velocity of 1.5 m/s.

Samples were weighed using a digital balance with 0.01 g sensitivity (GF3000, A&D, Japan) every 5 s during the drying process.

Theoretical considerations

Drying curve

The moisture content of the samples was found during the drying process at different drying time using Eq. (3):

$$M_t = \frac{W_t - W_d}{W_d} \qquad (3)$$

where M_t is the moisture content at time (t); W_t is the weight at time (t) and W_d is the dry weight.

The moisture ratio of the halved apricots was determined using Eq. (4):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (4)$$

where MR is the moisture ratio (dimensionless), M_e is the equilibrium moisture content (kg water/kg dry solid), and M_o is the initial moisture content (kg water/kg dry solid)

The values of M_e are relatively small compared to M_t or M_0; hence, the error involved in the simplification is negligible. Thus, the moisture ratio was simplified to (Doymaz 2004):

$$MR = \frac{M_t}{M_0} \qquad (5)$$

Calculation of moisture diffusivity and activation energy

Fick's second law of diffusion can be used to model the drying behavior of fruits and vegetables. The following analytical solution for diffusion in an infinite planar slab for long drying time is given by (Doymaz 2009):

$$MR = \frac{M_t}{M_0} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}\, t}{4Z^2}\right) \qquad (6)$$

where n = 1, 2, 3, . . . the number of terms, t is the time of drying in s, D_{eff} is effective moisture diffusivity in m^2/s and Z is the half of pomace thickness of halved apricot (m). The Eq. (6) can be simplified further by taking the first term of series solution (Doymaz 2009):

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\, t}{4Z^2}\right) \qquad (7)$$

The effective diffusivity is usually calculated by using the slope of Eq. (7). A straight line with a slope of K_1 is obtained when $ln(MR)$ is plotted versus (t):

$$K_1 = \frac{\pi^2 D_{eff}}{4Z^2} \qquad (8)$$

The energy of activation is calculated by using an Arrhenius type equation (Kashaninejad *et al.* 2007):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{\Re\theta_{abs}}\right) \qquad (9)$$

where E_a is the energy activation (kJ/mol), $\Re$ is the universal gas constant (8.314 J/mol K), θ_{abs} absolute drying temperature (K) and D_0 is the initial diffusivity (m^2/s). A plot of $ln(D_{eff})$ versus $1/\theta_{abs}$ from the Eq. (9) gives a straight slope of K_2:

$$K_2 = \frac{E_a}{\Re} \qquad (10)$$

Consequently, the energy of activation (E_a) is obtained using Eq. (10).

Statistical analysis

Means of initial moisture content (d.b), surface area, pomace thickness, modulus of elasticity and total soluble solids of two varieties were compared using Duncan's multiple range tests. All drying experiments in this study were conducted by three replications at five levels of air temperatures (40, 50, 60, 70 and 80°C) and two apricot varieties. The individual and combined effects of the variables (variety and air temperature) were analysed on drying time and moisture diffusion coefficient of apricot drying based on the factorial experiments (two factor completely randomised design (5×2)) using SPSS 15 software.

Results and Discussion

Initial moisture content (d.b.), surface area (S), pomace thickness (2Z), total soluble solids (TSS) and modulus of elasticity (E) for each variety are shown in Table 1.

>Table 1.

The *Ghavami* variety had the high value of the modulus of elasticity and total soluble solids (p<0.01) as compared to that of the *Nasiry* variety. There were no significant differences (p>0.01) in initial moisture content, surface area and pomace thickness between two varieties.

The moisture content at different drying conditions was converted to the dimensionless moisture ratio expression (*MR*) using Eq. (5). The influence of air temperature on moisture ratio on two varieties of apricot during air drying is shown in Fig. 4.

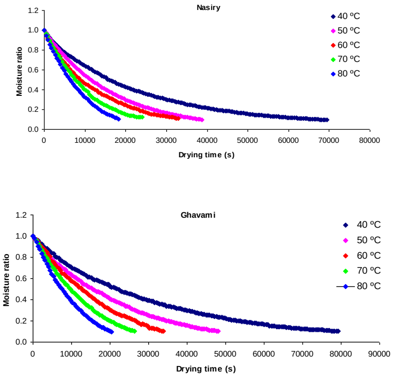

Fig. 4. Effect of air temperature on moisture ratio of two apricot varieties

It is clear that the apricot drying occurred in the falling rate period. It is also obvious from the figure that with increase in the drying air temperature the moisture ratio at any given time is decreased, due to the fact that higher air temperature causes a higher reduction of moisture content. On the other hand, at high temperatures the rate of heat and mass transfer is high and water loss is excessive. Similar findings are reported by several authors for drying of food product (Bon *et al*. 2003; Togrul and Pehlivan 2004; Kashaninejad and Tabil 2004; Kashaninejad *et al*. 2007; Orikasa *et al*. 2008; Doymaz 2008; Omid *et al*. 2009 ; Aghbashlo *et al*. 2009).

>Fig. 4

Fig. 5 shows the effect of variety on moisture ratio of apricot at air temperatures of 40 and 50°C. Similar trend of moisture ratio variation was observed for other drying temperatures. It is clear from the figure that the variety had a significant effect on drying curves. Values of moisture ratio for the *Ghavami* variety are higher than that of the *Nasiry* at each given level of time. It could be related to physical properties of *Ghavami* variety (the high values of TSS and E). The high value of these parameters lead to surface hardness or case hardened layers from which restriction of moisture movement and retardation of drying rate are resulted. It is also mentioned that the case hardening is caused due to the formation of tough leather–like outer skin sometimes leading to virtual halt of drying (Fernando *et al*. 2008).

>Fig. 5

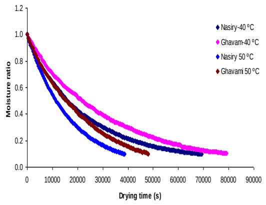

Fig. 5. Effect of variety on moisture ratio at air temperatures of 40 and 50°C

Fig. 6 shows the drying time to reach to the moisture ratio of 0.1 versus temperature for both varieties. It is clear that at higher temperatures, the difference between the required times is negligible whereas at low temperatures, the difference between the required times is significant. Case hardening may contribute to increasing drying time of *Ghavami* variety at low temperatures due to its high value of total soluble solids. It also might be due to longer drying time at low drying air temperatures that gives enough time to forming the hardened curst and decreasing drying rate of *Ghavami* variety. Thus, the difference between drying time of two varieties of apricot increased with decreasing in drying air temperature.

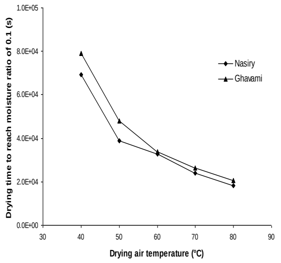

Fig. 6. Drying time versus drying air temperature for two apricot varieties

The total drying time required to reach moisture ratio of 0.1 for *Ghavami* variety is increased by a factor of 1–1.25 compared to that of *Nasiry* for all drying temperatures. At air temperature of 40°C, the total drying time is increased by a factor of 3.75–4 compared to that achieved at 80°C for both varieties. The *Nasiry* variety had low drying time at the same value of air temperature than the *Ghavami*, due to low value of modulus of elasticity and total soluble solids resulting in reduced resistance to moisture movement. Therefore, a lower drying time is required to achieve the specific water content in *Nasiry* variety than that of *Ghavami*.

>Fig. 6

The results of analysis of variance (ANOVA) showed that drying air temperature and variety had a significant effect on the drying time (Table 2) whereas, the interactions of temperature and variety were not significant.

Similar findings are reported by several researchers, based on studies in which drying air temperature is considered as the main factor affecting drying rate (Madamba *et al*. 1996; Kashaninejad and Tabil 2004; Doymaz 2004; Kashaninejad *et al*. 2007; Corzo *et al*. 2008).

>Table 2.

Using Eq. (8), the effective moisture diffusivity values for all of experiments were calculated and reported in Table 3. Minimum value of moisture diffusivity was found to be 1.34×10^{-10} m^2/s for the *Ghavami* variety when air temperature is at 40°C. Maximum value of moisture diffusivity is 5.95×10^{-10} for *Nasiry* variety when air temperature is 80°C. These values lies within the normally expected range of D_{eff} (10^{-12} to 10^{-8} m^2/s) for dehydrated foods (Zogzas *et al*. 1996; Doymaz 2004; Kashaninejad and Tabil 2004; Kashaninejad *et al*. 2007).

This variability depends on the types and conditions of experimental procedures used for determining the moisture diffusivity, data treatment methods (Zogzas and Maroulis 1996) as well as the product properties composition, physiological state and heterogeneity of the structure (Corzo *et al*. 2008). Generally, the values of water diffusion coefficient for *Ghavami* variety are lower than that of *Nasiry*. Therefore, higher drying time and energy is required to achieve specific water content in *Ghavami* variety than that of *Nasiry*.

High modulus of elasticity of *Ghavami* variety was associated with stiffer tissue of sample, resulting in increased resistance to moisture movement. It also might be due to detrimental effect of high value of total soluble solids that causes the crystallization of solids, and thus leading to clogging of pores on the surface. It is also mentioned that the resistance to moisture movement from the surface to the drying medium is negligible if compared to that of internal resistance. This leads to lower diffusion of water from the surface during drying.

>Table 3.

The results of analysis of variance (ANOVA) showed that drying air temperature and variety had a significant effect ($p<0.01$) on effective moisture diffusivity (Table 4) whereas, the interactions of temperature and variety were not significant. A similar effect of air temperature has been found in the air drying of various fruits such as mango (Corzo *et al*. 2008), apricot (Togrul and Pehlivan 2003), pistachio (Kashaninejad *et al*. 2007), purslane (Kashaninejad and Tabil 2004) and carrot (Doymaz 2004).

>Table 4.

ln (D_{eff}) was plotted versus $1/\theta_{abs}$ and energy activation, was calculated using Eq. (10). The energy activation during drying of apricot, for *Ghavami* and *Nasiry* varieties were 27.10 and 25.34 kJ/mol, respectively. Energy activation generally lies in the range of 12.7–110 kJ/mol for most food materials (Zogzas *et al*. 1996). A higher energy activation value indicated a greater temperature sensitivity of diffusion coefficient. It can be seen that the diffusion coefficient for *Ghavami* variety is more temperature sensitive. On the other hand, the activation energy is an indication of the required energy to remove moisture from a solid matrix. The higher activation energy obtained for the *Ghavami* variety ($p<0.01$) as compared to that of *Nasiry* may be attributed to the high value of total soluble solids and modulus of elasticity. Thus, the *Ghavami* variety needs much more energy than that of *Nasiry* to lose its water in the drying process. The activation energy is a characteristics quantity that elucidates the fundamental diffusion mechanism during the drying process. Corzo *et al*. (2008) reported that a diffusion–controlled process will have an activation energy less than 34 kJ/mol. Therefore, the values found in activation energy for air drying of apricot fruit suggest that the limiting mechanism is the diffusion.

Effect of other physical and chemical properties of fruits varieties on their drying characteristics requires further investigations.

Conclusion

The drying characteristics during hot air drying of two varieties of apricot were measured at five temperature levels.

Moreover, the effect of variety and temperature on drying curve, drying time, effective moisture diffusivity and activation energy during hot air drying were examined. The results of the analysis of variance test showed significant effects of air temperature and variety on the water effective diffusion coefficient and drying time. Values of water diffusion coefficient for *Ghavami* variety are lower than that of *Nasiry*. The temperature dependence of the water effective diffusion coefficient was obtained using Arrhenius relationship. Value of energy activation for *Ghavami* variety was found to be higher than that of *Nasiry*. It could be related to high value of modulus of elasticity and total soluble solids of *Ghavami* variety. Also, it was found that the modulus of elasticity and total soluble solids had significant effect on moisture diffusion and energy activation during drying.

Nomenclature

L	Length (mm)
W	Width (mm)
T	Thickness (mm)
S	Surface area (mm^2)
E	Modulus of elasticity (MPa)
δ	Side deformation (mm)
F	Compression force (N)
M_t	Moisture content at time t (kg water/kg dry matter)
W_t	Sample weight at time t (kg)
T	Drying time (s)
M_e	Equilibrium moisture content
W_d	Sample dry weight (kg)
MR	Moisture ratio (dimensionless)
$n = 1, 2, 3, \ldots$	Number of terms
D_{eff}	Effective moisture diffusivity (m^2/s)
K_1 and K_2	Straight line slope
θ_{abs}	Absolute temperature (K)
E_a	Activation energy (kJ/mol)
$\Re$	Universal gas constant (8.314 J/mol K)
D_0	Initial diffusivity (m^2/s)
Z	Half of pomace thickness of halved apricot (m)
TSS	Total soluble solids

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Table 1. Some physical properties of fresh apricots

variety	Initial moisture content (d.b)	Surface area (mm^2)	Pomace thickness of halved apricot (mm)	Modulus of elasticity (MPa)	Total soluble solids (%TSS)
Ghavami	3.57^{a}	3947.22^{a}	4.25^{a}	0.51^{a}	22.00^{a}
Nasiry	3.73^{a}	3954.94^{a}	4.25^{a}	0.33^{b}	18.50^{b}

Same letter indicates no significant difference at p<0.01 within the same column

Table 2. Analysis of variance (ANOVA) for the effect of variety and air temperature on drying time

Moisture ratio	Source	d.f.	SS	MSE	F	p>F
Moisture ratio of 0.5	Variety	1	21173.63	21173.63	37.43**	0.0001
	Temperature	4	146130.5	36532.62	64.59**	0.0001
	Variety×Temperature	4	2526.867	631.7167	1.12$^{n.s.}$	0.3793
	Error	18	10181.53	565.6407		
	Total	27	29	190475		
Moisture ratio of 0.1	Variety	1	18056.53	18056.53	5.87*	0.00261
	Temperature	4	2795250	698812.4	227.36**	0.0001
	Variety×Temperature	4	13839.8	3459.95	1.13$^{n.s.}$	0.3755
	Error	18	55325.8	3073.656		
	Total	27	29	2967449		

d.f.–degree of freedom, SS–Sum of square MSE–mean square error, F–statistical distribution, P–test statistic probability, n.s.–not significant, * significant at p<0.05, ** significant at p<0.01.

Table 3. Effective moisture diffusion for each experiment

Temperature (°C)	D_{eff} of *Ghavami*	D_{eff} of *Nasiry*
40	1.34E-10	2.03E-10
50	1.98E-10	2.66E-10
60	2.63E-10	3.79E-10
70	3.34E-10	4.84E-10
80	4.50E-10	5.95E-10

Table 4. Analysis of variance (ANOVA) for the effect of variety and air temperature on moisture diffusion

Source	d.f.	SS	MSE	F	p>F
Variety	1	9.01E-20	9.01E-20	75**	0.0001
Temperature	4	4.75E-19	1.19E-19	98.9**	0.0001
Variety×Temperature	4	9.54E-21	2.38E-21	1.99$^{n.s.}$	0.14
Error	18	2.16E-20	1.20E-21		
Total	27	29	6.53E-19		