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Modeling Rehydration Behavior of Dried Figs

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ABSTRACT

In this research, rehydration behavior of dried figs was studied at different temperatures (25, 60, 70, 80, and 90°C). The rehydration kinetic was examined using the four most frequently used empirical models, namely, Weibull, Peleg, first-order, and exponential association models. The Weibull model gave the highest coefficient of determination (R^2) and the lowest values of root mean square error (RMSE), sum of squared error (SEE), and chi-square (χ^2) was considered the best. In all models examined, the equilibrium moisture content showed statistically significant differences as compared to the rehydration temperature. The temperature dependence of kinetic constants was described in terms of Arrhenius relationship. The average activation energy for the four models was 24.362 kJ mol^{-1}. During the rehydration process hardness of dried figs decreased, which was further confirmed by microscopic evaluation. Scanning electron microscopy (SEM) images of rehydrated figs indicated porous structure proposing the presence of free water.

Keywords: Kinetic model, Moisture content, Texture, Water absorption.

INTRODUCTION

Fig (Ficus carica L.), which belongs to the Moraceae family, is one of the oldest cultivated fruits. It is commonly grown in warm and dry climates; so the Middle Eastern and Mediterranean areas are especially suitable for this plant (Mujic *et al*., 2012; Slavin, 2006; Vinson, 1999). Fig has been used for human consumption for centuries, and recently its nutritive and pharmacological values have been investigated. This nutritive fruit contains high amounts of carbohydrates, minerals, vitamins, and dietary fibers. It is fat and cholesterol-free and an excellent source of phenolic compounds, which have been proven to have positive effects on human health (Doymaz, 2005; Veberic *et al*., 2008). According to FAO statistics, the world production of fig in 2010 was 1,184,884 tons in which Iran ranked third after Turkey and Egypt (FAOSTAT, 2010). About 85% of Iran's total fig production is for dry consumption. Estahban (Fars province, southern Iran), with an annual production of 30,000 t, is the largest dried-fig producing region in Iran. Fig, due to its high moisture and sugar content, is one of the most perishable fruits even in refrigerated conditions, and, therefore, preservation methods are necessary to keep them fresh over long periods of time (Farahnaky *et al*., 2009). The most widely employed method for preservation of this product is drying, which results in physicochemical and microbiological stability in addition to some undesirable alterations such as textural and color changes (Krokida and Marinos-Kouris, 2003; Doymaz, 2005; Sharifian *et al*., 2012; Xanthopoulos *et al*., 2010). These changes are thought to reduce consumer acceptability and have a negative

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impact on the marketability of this valuable agricultural commodity (Farahnaky *et al*., 2010).

Most dried food materials must be rehydrated before direct consumption or in combination with other products. In the rehydration process, the dried products come into contact with water or other liquids such as fruit juices, sucrose, glucose or glycerol solutions (Maldonado *et al*., 2010; Krokida and Marinos-Kouris, 2003). This process is complex and is aimed at restoring the properties of the fresh products. Three main steps which occur simultaneously during rehydration are: absorption of water into the dry material, swelling, and loss of soluble materials (Lee *et al*., 2006). During the initial stages of rehydration, a higher rate of water absorption occurs. Several factors affect the rehydration process, grouped as intrinsic factors (product chemical composition, drying pre-treatments, product formulation, drying techniques, etc.) and extrinsic factors (composition of immersion media, temperature and hydrodynamic conditions), with immersion temperature being the most important factor influencing rehydration. More rapid rehydration is obtained at higher water temperatures (Garcia-Segovia *et al*., 2011). It is more desirable for the rehydration process to be as fast as possible in order to retain suitable structural and chemical characteristics and acquire better quality-reconstituted products (flavor, texture, and nutritional quality) (Sanjuan *et al*., 2001). Mathematical models are important tools in the design and optimization of dehydration and rehydration processes. Among the various models proposed to describe the rehydration kinetic of foods, the empirical equations are most frequently used due to their mathematical simplicity and utility (Krokida and Marinos-Kouris, 2003; Peleg, 1988; Cox *et al*., 2012).

The aim of this work was to study the effect of temperature on the rehydration kinetic of dried figs and to evaluate different mathematical models for the analysis and proper description of the process.

MATERIALS AND METHODS

Raw Material

Dried figs (Sabz-cultivar) were purchased from Estahban Fig Research Station (Fars Province, southern Iran). They were packed in polyethylene bags and stored at 4°C until analysis. Initial moisture content of dried figs was 6.15% (dry basis).

Rehydration Experiments

Dried fig samples, with a fig to water ratio of 1:3 (w/w), were rehydrated in distilled water using a thermostatically controlled stirred water bath. Five rehydration temperatures were considered: 25, 60, 70, 80, and 90°C (±0.1°C). The samples were weighed after different time intervals ranging from 2 to 70 minutes depending on the rehydration temperature. Then, they were packed and stored at room temperature until moisture conditioning. The moisture content of samples was measured by vacuum oven drying at 65°C (AOAC, 1990).

Rehydration Kinetic Modeling

In order to describe the water absorption kinetics, four of the most frequently used empirical models from the literatures were applied including Peleg [Equation (1)], Weibull [Equation (3)], First-order [Equation (4)] and Exponential association [Equation (5)] models. The model proposed by Peleg is a two parameter, non-exponential equation mostly used to describe moisture absorption due to its calculation simplicity (capability to transform into a linear relationship). This model has been applied to rehydration for different kinds of foods such as some edible mushrooms (García-Pascual *et al*., 2006; Garcia-Segovia *et al*., 2011), chestnuts (Moreira *et al*., 2008); broccoli florets (Sanjuán *et al*., 2001) and aloe vera (Vega-Gálvez *et al*., 2009):

$$X_t = X_0 + \left(\frac{t}{A + B \times t}\right) \qquad (1)$$

Where, Xt is the moisture at time t (kg water kg^{-1} db), X_0 is the initial moisture content (kg water kg^{-1} db), t is the rehydration time (min), A (min kg db kg^{-1} water) and B (kg db kg^{-1} water) are constants. For a long enough time of rehydration, the equilibrium moisture content X_{eq} (kg water kg^{-1} db) is given by Equation (2):

$$X_{eq} = X_0 + \left(\frac{1}{B}\right)$$

As attaining equilibrium during rehydration is difficult (in spite of drying), the equilibrium moisture content (X_{eq}) cannot be determined separately. In Weibull model [Equation (3)], the X_{eq} is considered as an additional parameter to be calculated. This model has been widely applied in food processing, due to its simplicity and flexibility in the estimation of kinetic parameters, and has been suggested for rehydration of edible mushroom (García-Pascual *et al*., 2006; Garcia-Segovia *et al*., 2011), food particulates (Marabi *et al*., 2003) and aloe vera (Vega-Gálvez *et al*., 2009).

$$X_t = X_{eq} + \left(X_0 - X_{eq}\right)\exp[-(t \, {}^{t}\!/_{b})^{a}] \qquad (3)$$

Where, b and a are model constants.

The first-order kinetic model is based on the diffusion model of Fick's second law for different geometrics and is expressed in Equation (4): (Krokida and Marinos-Kouris, 2003)

$$X_t = X_{eq} - \left(X_{eq} - X_0\right)\exp(-k_{r1} \times t) \qquad (4)$$

Where, k_{r1} is the rehydration rate (min^{-1}).

The exponential association model is represented by Equation (5) in which k_{r2} is the model constant (Cox *et al*., 2012):

$$X = X_{eq}[1 - \exp(-k_{r2} \times t)] \qquad (5)$$

The parameters of the models were estimated by non-linear least squares using the ''Solver" in Excel program (Microsoft Office, 2007). The goodness of fit of the tested mathematical models to the experimental data was evaluated from the coefficient of determination (R^2), sum of squared errors [SSE; Equation (6)], root mean square error [RMSE; Equation (7)] and the chi-square [χ^2; Equation (8)] between the predicted and experimental values.

$$SSE = \frac{1}{N}\sum_{i=1}^{n}(X_{i,\exp} - X_{i,pre})^2 \qquad (6)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(X_{i,\exp} - X_{i,pre})^2\right]^{1/2} \qquad (7)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(X_{i,\exp} - X_{i,pre})^2}{N - Z} \qquad (8)$$

Where, $X_{i^{th},exp}$ is the i^{th} experimental moisture content, $X_{i^{th},pre}$ is the i^{th} predicted moisture content, N is the number of observations and z is the number of constants. The equation giving the smallest $RMSE/SSE/\chi^2$ and the highest R^2 value was considered to be the best fitted equation (Ansari *et al*., 2011; Mortezapour *et al*., 2014).

In order to prove the temperature dependence of rate constants, the Arrhenius equation was applied as follows:

$$A = A_0 \times exp(-E_a/RT) \qquad (9)$$

Where, A is the kinetic parameter of each model, E_a is the activation energy ($kJ\,mol^{-1}$), T is the absolute temperature (K) and R is the universal gas constant ($8.314 \times 10^{-3} kJ\,K^{-1}mol^{-1}$). From the slope of the straight line of *ln A versus* reciprocal of T, described by the Arrhenius equation, the activation energy (Ea), could be calculated (Machado *et al*., 1999; Sanjuan *et al*., 2001).

Texture Analysis

Texture profile analysis (TPA) tests were carried out using a texture analyzer (Texture Analyzer, TA Plus, Stable Microsystems, Surrey, England) with a load cell of 30 kg. Each sample corresponding to a rehydration time after moisture conditioning was subjected to a compression force test using a cylindrical probe having dimensions greater than those of the sample. Samples were compressed to 20% of their original height using a cylindrical probe of 100 mm diameter at a speed of 1 mm s^{-1}. The compression force versus time was used to calculate texture hardness. Using the Texture Exponent Lite supplied by the manufacturer, hardness was calculated as the maximum force of the compression cycle. All textural measurements were performed at room temperature (22±2°C) with three replications of each sample.

Scanning Electron Microscopy (SEM)

Microscopic structure of the dried and rehydrated figs with different moisture contents prepared at 60 and 90°C were obtained using scanning electron microscopy (SEM) (Cambridge, UK) under high-vacuum condition at an accelerating voltage of 20.0 kV and a working distance of 7.5–9.5 mm (i.e. the distance between the surface of the sample and the microscope lens). Samples were dried using a freeze dryer; thin layer of samples were fixed on the aluminum sample holder and then sputtered with gold in a sputter coater (Polaron SC7640, UK).

Statistical Analysis

Analysis of variance (One-way ANOVA) of model parameters for rehydration and texture of samples rehydrated at different temperatures was performed to determine the presence of significant differences among the means. Duncan multiple range test was used to compare the means using IBM SPSS Statistics software, version 19.

RESULTS AND DISCUSSION

Rehydration Kinetics

Rehydration kinetic of food products can be described using changes in moisture content (calculated as grams of water/grams of solids) versus time of rehydration (Markowski and Zielinska, 2011). Figure 1 shows changes in moisture content as a function of time for the five rehydration

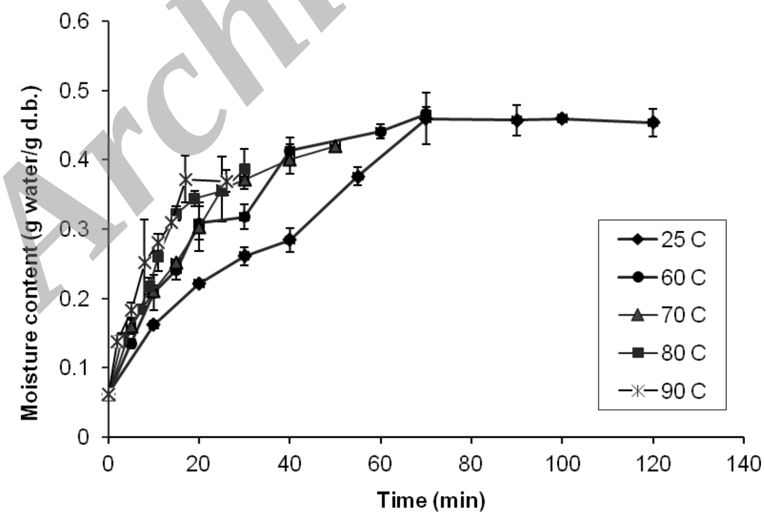


Figure 1. Rehydration rate curve for dried figs at different temperatures (25-90°C). Bars are ±standard deviation.

temperatures. The moisture content at each rehydration time represents the mean value of three replicates. All rehydration curves demonstrate an exponential trend with high water absorption rates mainly at the beginning of the process. However, as rehydration time progressed, the driving force for water movement decreased and the system slowly attained equilibrium moisture. Increasing the rehydration temperature from 25 to 90°C increased both the rehydration rate and amount of water absorbed. This behavior has been also reported by other authors for different rehydrated products such as apples, potatoes, bananas, peppers, garlic, mushrooms, onions, leeks, peas, corn, pumpkin, tomato (Krokida and Marinos-Kouris, 2003), amaranth grains (Resio *et al*., 2006) and chestnut (Moreira *et al*., 2008).

In order to describe the rehydration kinetic of dried fig, four experimental models [Equations (1) to (5)] were applied. The parameters obtained from the models applied as well as the equilibrium moisture contents derived for dried figs during soaking are shown in Table 1. The *A* value of Peleg's model decreased significantly as temperature increased. This shows a higher water absorption rate at higher temperatures. According to Solomon (2007), this parameter may be representative of water absorption rate in the early phase of the rehydration process. Similar behavior was found by other authors regarding the rehydration of other products (Garcia-Pascual *et al*., 2006; Moreira *et al*., 2008). Parameter *B* for Peleg's model increased slightly as temperature increased from 25 to 90°C. As Solomon (2007) suggested, this parameter is related to the maximum capacity of water absorption or to equilibrium moisture content, so that the lowest values of *B* show a higher water absorption capacity. Indeed, according to the results of other authors, *B* may change with temperature if there is a change in the material, as it was reported for lupine (Solomon, 2007) and chickpeas ((Turhan *et al*., 2002) as increasing trend and hazelnut (Lopez *et al*., 1995) amaranth (Resio *et al*., 2006) and wheat products (Maskan, 2002) as decreasing trend.

These results do not agree with those reported by some authors, considering *B* a characteristic parameter for each material that is independent of temperature. Table 1 also shows the values of parameters *a* and *b* for Weibull's model, where temperature has

Table1.Results of fitting of rehydration kinetics to the four models at different temperatures.[a]

Models	Parameters	Temperature (°C) 25	60	70	80	90	*F*-value
Peleg	X_0	$0.07^a \pm 0.003$	$0.06^a \pm 0.000$	$0.06^a \pm 0.010$	$0.06^a \pm 0.003$	$0.06^a \pm 0.004$	1.02 ns
	X_{eq}	$0.80^a \pm 0.06$	$0.65^b \pm 0.02$	$0.62b^c \pm 0.05$	$0.61^{bc} \pm 0.01$	$0.54^c \pm 0.04$	15.54**
	A	$105.19^a \pm 5.09$	$53.22^b \pm 5.03$	$45.62^b \pm 6.23$	$35.81^c \pm 2.93$	$26.11^d \pm 2.11$	138.07**
	B	$1.37^c \pm 0.03$	$1.70^b \pm 0.13$	$1.80^{ab} \pm 0.13$	$1.82^{ab} \pm 0.23$	$2.09^a \pm 0.18$	8.64**
Weibull	X_0	$0.07^a \pm 0.003$	$0.06^a \pm 0.003$	$0.06^a \pm 0.004$	$0.07^a \pm 0.004$	$0.07^a \pm 0.003$	1.86 ns
	X_{eq}	$0.56^a \pm 0.01$	$0.51^a \pm 0.00$	$0.45^b \pm 0.04$	$0.40^c \pm 0.04$	$0.40^c \pm 0.02$	21.89**
	b	$56.11^a \pm 2.45$	$29.60^b \pm 0.46$	$20.28^c \pm 5.12$	$12.47^d \pm 1.71$	$10.12^d \pm 2.74$	121.21**
	a	$1.01^a \pm 0.02$	$0.91^a \pm 0.03$	$1.03^a \pm 0.22$	$1.02^a \pm 0.20$	$1.05^a \pm 0.07$	0.46 ns
1th-order	X_0	$0.07^a \pm 0.002$	$0.06^a \pm 0.002$	$0.06^{ab} \pm 0.007$	$0.06^{ab} \pm 0.003$	$0.06^b \pm 0.001$	3.04**
	X_{eq}	$0.56^a \pm 0.01$	$0.40^b \pm 0.02$	$0.46^{bc} \pm 0.03$	$0.44^c \pm 0.03$	$0.36^d \pm 0.03$	25.27*
	k_{r1}	$0.018^d \pm 0.000$	$0.04^c \pm 0.003$	$0.05^c \pm 0.010$	$0.07^b \pm 0.000$	$0.14^a \pm 0.009$	157.96**
Exponential	X_{eq}	$0.50^a \pm 0.002$	$0.46^b \pm 0.010$	$0.42^c \pm 0.020$	$0.40^d \pm 0.030$	$0.38^e \pm 0.003$	29.01**
	k_{r2}	$0.03^e \pm 0.001$	$0.05^d \pm 0.010$	$0.07^c \pm 0.002$	$0.10^b \pm 0.010$	$0.14^a \pm 0.008$	192.01**

[a] Data are reported as the mean (±SD) of three replicates. Means of model parameters in the same row with different letters are significantly different (a< 0.05) as estimated with Duncan's test. (**: Highly significant at a< 0.01 ; *: Significant at a< 0.05, ns: Not significant as estimated with ANOVA test).

no linear influence on parameter a. However, parameter *b* decreases significantly as temperature increases. The Weibull shaped parameter a measures the velocity of the water absorption at the beginning of the process; the lower its value the faster the water absorption rate at the beginning. Its value ranged between 0.914 and 1.052, which was within the reported value for food stuffs (0.2-1.0) (Magee and Richardson, 2007; Goula and Adamopoulos, 2009). Parameter b, which represents the time needed to accomplish approximately 63% of the process, (Machado *et al*., 1999, Marabi and Saguy, 2004), ranged between 10.12 and 56.11 minutes at 25-90°C for dried figs. Similar behavior has been reported by Machado *et al*. (1999) in puffed breakfast cereals, Garcia-Pascual *et al*. (2006) in mushrooms, Cunningham *et al*. (2007) in pasta and Noshad *et al*. (2011) in air-dried quinces. In addition, Table 1 shows the parameters of the first order kinetic and exponential association models, which can also describe water uptake during rehydration of dried figs. As can be seen, the kinetic constants of first-order (K_{r1}) and exponential association models (K_{r2}) increased significantly with increased rehydration temperatures, which implies a faster rehydration velocity at higher temperatures.

Regarding the effect of rehydration temperature on X_{eq}, literatures showed different results depending on the product. Some researchers such as Abu-Ghannem and McKenna (1997), Sopade *et al*. (1992) and Sopade and Obckpa (1990) reported that X_{eq} decreased as the rehydration temperature increased while Lin *et al*. (1998) found the opposite results. In some cases, no significant differences were observed at the end of the process (Abu-Ghannem and McKenna, 1997). In this study, the values of X_{eq} identified from all the four models decreased with increasing temperature, and the Peleg model gave higher values (0.54-0.80) compared with Weibull (0.40-0.56), first-order kinetic (0.36-0.56), and exponential association model (0.38-0.50).

Table 2 and Figure 2 show the results of fitting experimental data to the different

Table 2. Statistical indices upon modeling the rehydration of dried figs at a range of temperatures.

Model	Parameter	Temperature (°C) 25	60	70	80	90
Peleg	SSE	4.68×10^{-4}	2.24×10^{-4}	1.11×10^{-4}	1.92×10^{-4}	2.29×10^{-4}
	RMSE	0.0204	0.0150	0.0100	0.0138	0.0151
	R^2	0.977	0.987	0.991	0.982	0.979
	χ^2	6.24×10^{-4}	2.88×10^{-4}	1.43×10^{-4}	2.46×10^{-4}	3.05×10^{-4}
Weibull	SSE	3.92×10^{-4}	2.25×10^{-4}	0.83×10^{-4}	1.46×10^{-4}	1.93×10^{-4}
	RMSE	0.0198	0.0150	0.0091	0.0121	0.0139
	R^2	0.977	0.987	0.994	0.982	0.982
	χ^2	5.04×10^{-4}	0.32×10^{-4}	1.06×10^{-4}	1.88×10^{-4}	2.58×10^{-4}
1th-order	SSE	4.41×10^{-4}	2.32×10^{-4}	0.83×10^{-4}	1.64×10^{-4}	3.69×10^{-4}
	RMSE	0.0198	0.0152	0.0091	0.0128	0.0192
	R^2	0.979	0.986	0.994	0.985	0.967
	χ^2	5.04×10^{-4}	2.61×10^{-4}	0.94×10^{-4}	1.84×10^{-4}	4.21×10^{-4}
Exponential	SSE	10.70×10^{-4}	8.78×10^{-4}	6.57×10^{-4}	7.03×10^{-4}	9.09×10^{-4}
	RMSE	0.0254	0.0297	0.0152	0.0166	0.0207
	R^2	0.949	0.965	0.974	0.961	0.944
	χ^2	12.04×10^{-4}	9.88×10^{-4}	7.39×10^{-4}	7.91×10^{-4}	10.38×10^{-4}

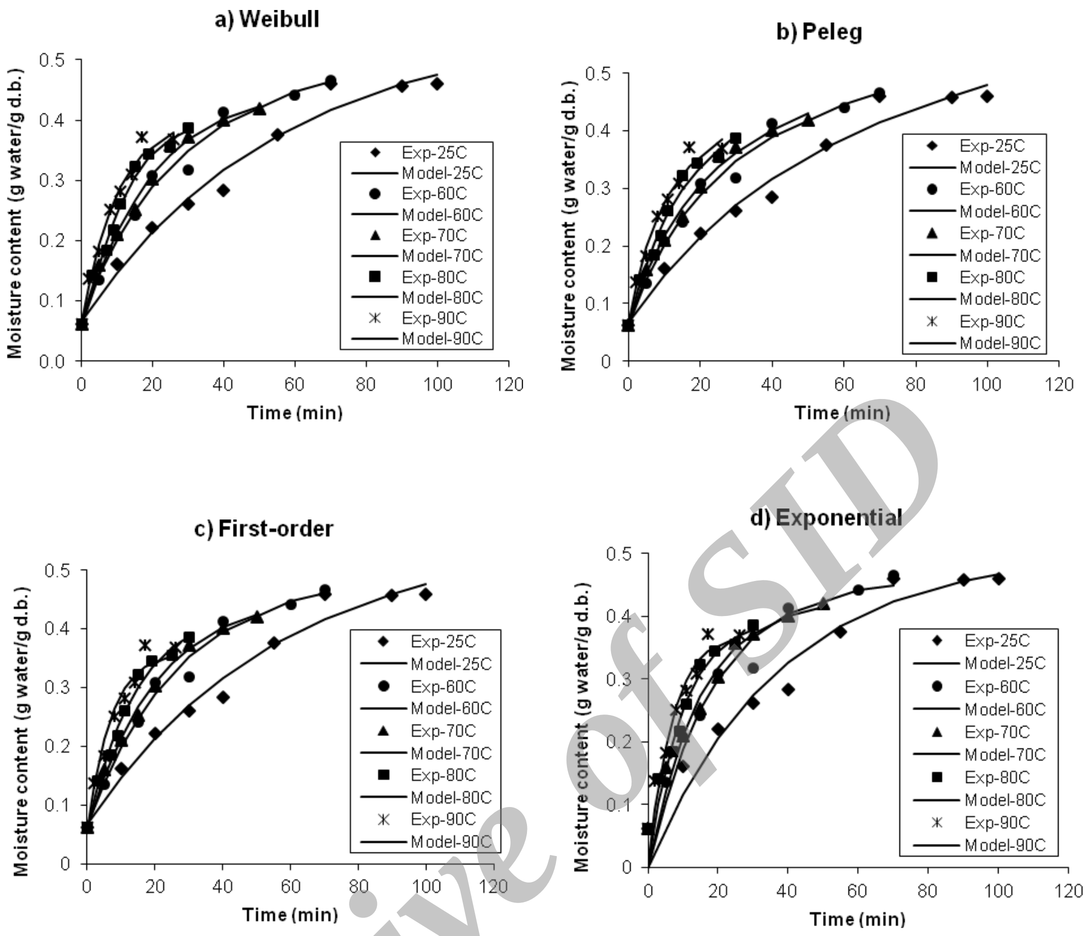


Figure 2. Experimental and predicted rehydration curves for (a) Weibull; (b) Peleg's; (c) First-order, and (d) Exponential models for the five temperatures.

kinetic equations (R^2, RMSE, SSE and χ^2). It can be observed that all proposed models showed a good fit with low values of *SEE*, *RMSE*, and χ^2 close to zero. The R^2 values ranged from 0.944 to 0.994 for different models with the exponential association model having the lowest R^2. Overall, the Weibull model, which yielded the highest values of R^2 and the lowest values of χ^2, *RMSE*, and *SSE*, was considered the best, followed by the Peleg, first order and Exponential models, respectively. Several authors such as Marabi and Saguy (2004), Garcia-Pascual *et al*. (2006), Cunningham *et al*. (2007) and Noshad *et al*. (2011), studying rehydration kinetic of carrots, mushrooms, pasta and quince respectively also reported the good fit quality obtained by the Weibull model.

In order to verify the dependence of kinetic constants on rehydration temperature, the Arrhenius equation [Equation (9)] was applied graphically represented by *Ln k versus 1/T*. The activation energy with coefficient of determination (R^2) obtained for each model is shown in Table 3, confirming the dependence of rehydration on temperature. The activation energy for b (Weibull model) and A (Peleg model) are 23.7 (kJ mol^{-1}) and 18.33 (kJ mol^{-1}), respectively, which is similar to those obtained in other studies such as 16.47 kJ mol^{-1} in mushroom (Garcia-Pascual *et al*., 2006) and 20.23 kJ mol^{-1} in Aloe vera (Vega-Galvez *et al*., 2009) for *b*

Table 3. Arrhenius equation parameters for different rehydration kinetic constants in rehydrated dried figs.

Kinetic model	Parameter	Ea (Kj mol^{-1})	R^2
Peleg	A	18.335	0.975
Weibul	b	23.710	0.936
First-order	k_{r1}	33.150	0.892
Exponential	k_{r2}	22.254	0.947
Average		24.362	

(Weibull model); 19.16 kJ mol^{-1} in mushroom (García-Pascual *et al*., 2006) and 18.32 kJ mol^{-1} in Aloe vera (Vega-Galvez *et al*., 2009) for *A* (Peleg model).

Texture Analysis during Rehydration

In order to study the textural changes during rehydration of the samples, the maximum compression force in the force *vs.* time curves of TPA was taken as the sample hardness. Hardness changes of dried figs as a function of moisture content at different rehydration temperatures is presented in Figure 3. As expected, the hardness of samples decreased with moisture content. In the beginning a dramatic decrease in texture hardness was observed followed by a progressive decrease. This loss of hardness could be attributed to the effect of water plasticization as the moisture content of the samples increased. Similar behavior has been reported by other authors on the soaking process of cereal grains in water (Sopade *et al*., 1992) and breakfast cereals in semi-skimmed milk (Sacchetti *et al*., 2003). Moreover, the hardness values as obtained revealed no significant differences between rehydration temperatures. However, when this data was analyzed according to the rehydration time (and so the moisture content), a significant difference was observed between samples containing 0.062 and 0.162 (unit of moisture content) with other samples at 25°C as well as at

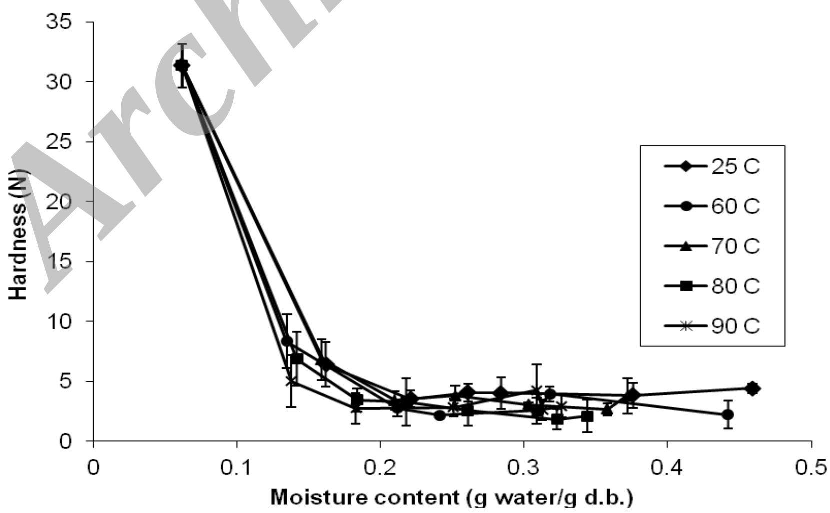


Figure 3. Hardness of dried figs after rehydration at different temperatures (25-90°C). Bars are ±standard deviation.

temperatures of 60, 70, 80, and 90°C.

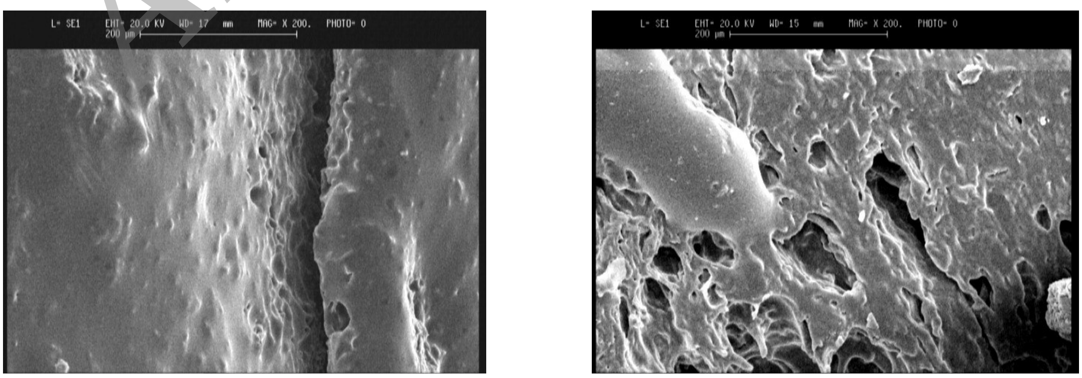
Scanning Electron Microscopy (SEM) Images

For better understanding of changes in the product quality, especially the changes in texture during rehydration, microscopic evaluation of dried figs compared to rehydrated ones was performed. From Figure 4, it can be concluded that the dried samples had nonporous structures; while upon rehydration, the number of open structures and pores increased considerably. In the samples with 22 and 34% moisture contents, relatively large pores with diameters of up to 20 and 70 micrometer can be seen, respectively. Indeed, in the rehydrated figs with moisture content more than 22%, the porous structure was the consequence of sublimation of the free water during freeze drying, therefore, these voids (or pores) observed on SEM images clearly indicate the presence of water molecules with high mobility. It can be assumed that at the beginning of the rehydration process capillaries near the surface absorbed water quickly based on concentration gradient; but after they were filled, the concentration of surface moisture raised to the limit of saturation and, thereafter, the rate of water absorption slowed down. This may have greater importance at elevated temperatures since the initial absorption rate increases at higher temperatures.

Microstructure of dried figs rehydrated at 60 and 90°C for two different time intervals with the same moisture content is shown in Figure 5. As can be seen, rehydration time strongly affected the microstructure of the dried figs and the size of pores. At a constant rehydration temperature, the number of pore sizes increased with increasing rehydration time, which significantly influenced the product texture in terms of hardness. The hardness of samples rehydrated at longer times was lower but was not significantly different between rehydration temperatures. This can be attributed to higher water absorption; therefore, swelling of the samples rehydrated at longer time intervals may be reflected in larger porosity after freeze drying, resulting in decrease of hardness.

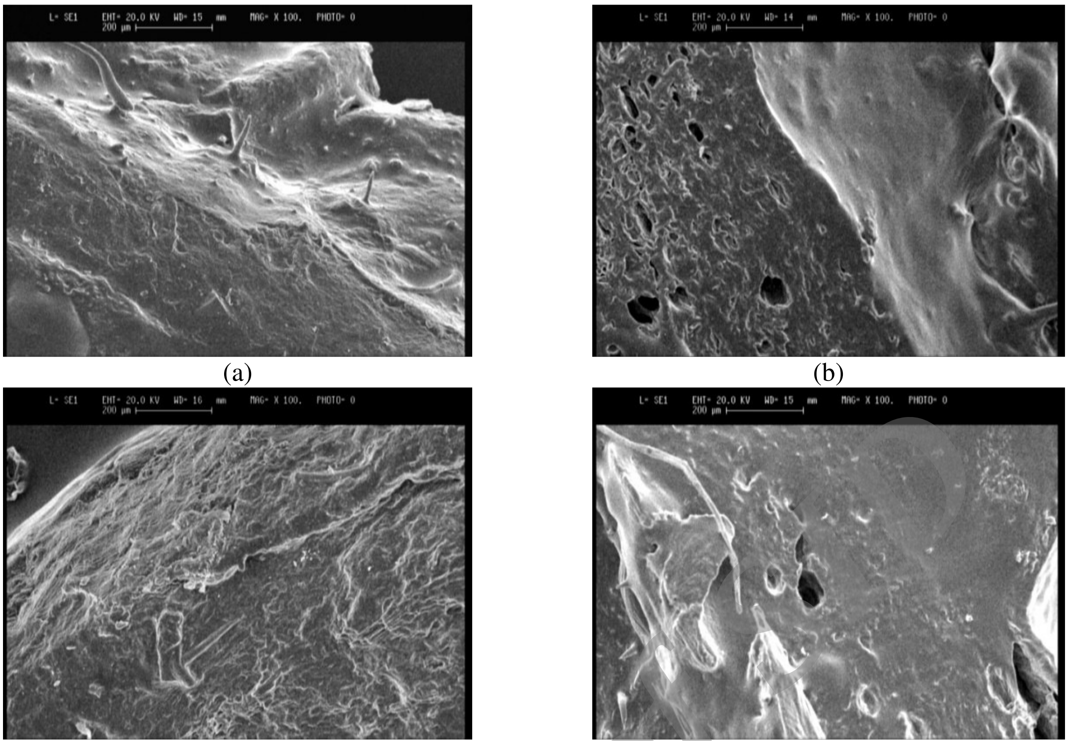
CONCLUSIONS

The results of this study indicated that using higher temperatures for rehydration of figs led to increase both in water absorption rates and in the amount of water absorbed. Moreover, in each temperature examined, the rate of water absorption was high in the initial stages followed by a decrease in rehydration rate. This may be attributed to the filling (or saturation) of the free capillaries near the surface with water as rehydration proceeds. Several empirical



(a) (b)

Figure 4. SEM micrographs of: (a) Dried and (b) Rehydrated figs at 60°C for 29.5 minutes.



(a) (b) (c) (d)

Figure 5. SEM micrographs of dried figs rehydrated at (a) 60°C for 10 minutes (MC: 22%); (b) 60°C for 29.5 minutes (MC: 34%); (c) 90°C for 7 minutes (MC: 22%), and (d) 90°C for 15 minutes (MC: 34%).

models were used to predict the rehydration kinetic of dried figs, where the Weibull model was found to be the best. With respect to texture results, it was seen that hardness of samples decreased after rehydration, which was found to be highly dependent on moisture content and rehydration temperature. The higher the temperature of rehydration, the greater the rate of change in textural properties. For instance, after rehydration for 11 minutes at 25°C, hardness decreased by 83%; while at 90°C this change occurred after 2 minutes. Overall, in order to increase the consumer acceptability of dried figs, it is more desirable to rehydrate samples at 50-60°C instead of using high temperatures (90°C). Rehydration process at intermediate temperatures can have some advantages including energy savings, decrease in heat damage to fig components, higher nutritional quality, and so on. Further research is required to examine the effect of rehydration kinetic on the phytochemical properties of dried figs.

REFERENCES

1. Abu-Ghannam, N. and McKenna, B. 1997. The Application of Peleg's Equation to Model Water Absorption during the Soaking of Red Kidney Beans (*Phaseolus vulgaris* L.). *J. Food Eng.,* **32:** 391-401.
2. Ansari, S., Farahnaky, A. and Majzoobi, M. 2011. Modelling the Effect of Glucose Syrup on the Moisture Sorption Isotherm of Figs. *Food Biophys.,* **6(3):** 377-389.
3. AOAC. 1990. *Official Methods of Analysis*. 15th Edition. Association of Official Analytical Chemist, Washington, DC, USA.
4. Cox, S., Gupta, S. and Abu-Ghannam, N. 2012. Effect of Different Rehydration Temperatures on the Moisture, Content of Phenolic Compounds, Antioxidant Capacity and Textural Properties of Edible Irish Brown Seaweed. *LWT - Food Sci. Technol.,* **47:** 300-307.

5. Cunningham, S. E., McMinn, W. A. M., Magee, T. R. A. and Richardson, P. S. 2007. Modelling Water Absorption of Pasta during Soaking. *J. Food Eng.,* **82:** 600-607.
6. FAOSTAT. 2010. *Food and Agriculture Organization (FAO), Statistical Data*. FAO. http://faostat.fao.org/site/339/default.aspx accessed on 21/04/2013.
7. Doymaz, I. 2005. Sun Drying of Figs: an Experimental Study. *J. Food Eng.,* **71:** 403–407.
8. Farahnaky, A., Ansari, S. and Majzoobi, M. 2009. Effect of Glycerol on the Moisture Sorption Isotherms of Figs. *J. Food Eng.,* **93:** 468-473.
9. Farahnaky, A., Ansari, S. and Majzoobi, M. 2010. Effects of Glucose Syrup and Glycerol on some Physichochemical Properties of Figs. *J. Texture Stud.,* **41(5):** 633-650.
10. Garcia-Pascual, P., Sanjuan, N., Melis, R. and Mulet, A. 2006. *Morchella esculenta* (Morel) Rehydration Process Modelling. *J. Food Eng.,* **72:** 346-353.
11. Garcia-Segovia, P., Andres-Bello, A. and Martinez-Monzo, J. 2011. Rehydration of Air-dried Shiitake Mushroom (*Lentinus edodes*) Caps: Comparison of Conventional and Vacuum Water Immersion Processes. *LWT - Food Sci. Technol.,* **44:** 480-488.
12. Goula, A. and Adamopoulos, K. 2009. Modeling the Rehydration Process of Dried Tomato. *Dry. Technol.,* **27:** 1078-1088.
13. Krokida, M. K. and Marinos-Kouris, D. 2003. Rehydration Kinetics of Dehydrated Products. *J. Food Eng.,* **57:** 1-7.
14. Lee, K. T., Farid, M. and Nguang, S.K. 2006. The Mathematical Modelling of the Rehydration Characteristics of Fruits. *J. Food Eng.,* **72:** 16-23.
15. Lin, T. M., Durance, T. and Scaman, C. H. 1998. Characterization of Vacuum Microwave, Air and Freeze Dried Carrot Slices. *Food Res. Int.,* **31:** 111-117.
16. Lopez, A., Pique, M., Clop, M., Tasias, J., Romero, A., Boatella, J. and Garcia, J. 1995. The Hygroscopic Behaviour of the Hazelnut. *J. Food Eng.,* **25:** 197–208.
17. Machado, M., Oliveira, F. and Cunha, L. 1999. Effect of Milk Fat and Total Solids Concentration on the Kinetics of Moisture Uptake by Ready-to-eat Breakfast Cereal. *Int. J. Food Sci. Technol.,* **34:** 47–57.
18. Magee, S. and Richardson, P. 2007. Modelling Water Absorption of Pasta during Soaking. *J. Food Eng.,* **82:** 600–607.
19. Maldonado, S., Arnau, E. and Bertuzzi, M. A. 2010. Effect of Temperature and Pretreatment on Water Diffusion during Rehydration of Dehydrated Mangoes. *J. Food Eng.,* **96:** 333-341.
20. Marabi, A., Livings, S., Jacobson, M. and Saguy, I. S. 2003. Normalized Weibull Distribution for Modeling Rehydration of Food Particulates. *Eur. Food Res. Technol.,* **217:** 311-318.
21. Marabi, A. and Saguy, I.S. 2004. Effect of Porosity on Rehydration of Dry Food Particulates. *J. Sci. Food Agr.,* **84:** 1105-1110.
22. Markowski, M. and Zielińska, M. 2011. Kinetics of Water Absorption and Soluble-Solid Loss of Hot-air-dried Carrots during Rehydration. *Int. J. Food Sci. Tech.,* **46:** 1122-1128.
23. Maskan, M. 2002. Effect of Processing on Hydration Kinetics of Three Wheat Products of the Same Variety. *J. Food Eng.,* **52:** 337–341.
24. Moreira, R., Chenlo, F., Chaguri, L. and Fernandes, C. 2008. Water Absorption, Texture, and Color Kinetics of Air-dried Chestnuts during Rehydration. *J. Food Eng.,* **86:** 584-594.
25. Mortezapour, H., Ghobadian, B., Khoshtaghaza, M. H. and Minaei, S. 2014. Drying Kinetics and Quality Characteristics of Saffron Dried with a Heat Pump Assisted Hybrid Photovoltaic-thermal Solar Dryer. *J. Agr. Sci. Tech.,* **16(1):** 33-45.
26. Mujic, I., Bavcon Kralj, M., Jokic, S., Jarni, K., Jug, T. and Prgomet, Z. 2012. Changes in Aromatic Profile of Fresh and Dried Fig: The Role of Pre-treatments in Drying Process. *Int. J. Food Sci. Tech.,* **47:** 2282-2288.
27. Noshad, M., Mohebbi, M., Shahidi, F. and Mortazavi, S. A. 2011. Kinetic Modeling of Rehydration in Air-dried Quinces Pretreated with Osmotic Dehydration and Ultrasonic. *J. Food Process Pres.,* **36:** 383-392.
28. Peleg, M. 1988. An Empirical Model for the Description of Moisture Sorption Curves. *J. Food Sci.,* **53:** 1216-1217.
29. Resio, A. C., Aguerre, R. J. and Suarez, C. 2006. Hydration Kinetics of Amaranth Grain. *J. Food Eng.,* **72:** 247-253.
30. Sacchetti, G., Pittia, P., Biserni, M., Pinnavaia, G. G. and Rosa, M. D. 2003. Kinetic Modelling of Textural Changes in Ready-to-eat Breakfast Cereals during

Soaking in Semi-skimmed Milk. *Int. J. Food Sci. Tech.,* **38:** 135–143.
31. Sanjuan, N., Carcel, J. A., Clemente, G. and Mulet, A. 2001. Modelling of the Rehydration Process of Brocolli Florets. *Eur. Food Res. Technol.,* **212:** 449–453.
32. Sharifian, F., Modarres Motlagh, A. and Nikbakht, A.M. 2012. Pulsed Microwave Drying Kinetics of Fig Fruit (*Ficus carica* L.). *Aust. J. Crop Sci.,* **6(10):** 1441-1447.
33. Slavin, J. L. 2006. Figs: Past, Present and Future. *Nutr. Today,* **41:** 180–184.
45. Solomon, W. K. 2007. Hydration Kinetics of Lupin (*Lupinus albus*) Seeds. *J. Food Process Eng.,* **30:** 119-130.
46. Sopade, P. A., Ajisegiri, E. S. and Badau, M. H. 1992. The Use of Peleg's Equation to Model Water Absorption in Some Cereal Grains during Soaking. *J. Food Eng.,* **15:** 269-283.
47. Sopade, P. A. and Obekpa, J. A. 1990. Modelling Water Absorption in Soybean, Cowpea and Peanuts at Three Temperatures Using Peleg's Equation. *J. Food Sci.,* **55:** 1084-1087.
48. Turhan, M., Sayar, S. and Gunasekaran, S. 2002. Application of Peleg Model to Study Water Absorption in Chickpea during Soaking. *J. Food Eng.,* **53:** 153–159.
49. Veberic, R., Colaric, M. and Stampar, F. 2008. Phenolic Acids and Flavonoids of Fig Fruit (*Ficus carica* L.) in the Northern Mediterranean Region. *Food Chem.,* **106:** 153-157.
50. Vega-Gálvez, A., Notte-Cuello, E., Lemus-Mondaca, R., Zura, L. and Miranda, M. 2009. Mathematical Modelling of Mass Transfer during Rehydration Process of Aloe vera (*Aloe barbadensis* Miller). *Food Bioprod. Process.,* **87:** 254-260.
51. Vinson, J. A. 1999. The Functional Food Properties of Figs. *Cereal Foods World,* **44:** 82-87.
52. Xanthopoulos, G., Yanniotis, S. and Lambrinos, G. R. 2010. Study of the Drying Behaviour in Peeled and Unpeeled Whole Fig. *J. Food Eng.,* **97:** 419-424.

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چکیده

در این تحقیق رفتار رهیدراسیون انجیر خشک در دماهای مختلف (۲۵، ۶۰، ۷۰، ۸۰ و ۹۰ درجه سانتی گراد) بررسی گردید. سنتیک رهیدراسیون با استفاده از چهار مدل تجربی وایبول، پلگ، درجه یک و ارتباط نمایی که غالباً در این زمینه کاربرد زیادی دارند مورد بررسی قرار گرفت. مدل وایبول که دارای بالاترین ضریب تعیین و کمترین ریشه میانگین مربعات خطا، مجموع مربعات خطا و مجذور کای است به عنوان بهترین مدل شناخته شد. در تمامی مدل های مورد بررسی محتوای رطوبت تعادلی اختلاف معنی داری را از نظر آماری با دماهای رهیدراسیون نشان می دهد. وابستگی دمایی ثابت های سینتیکی از طریق رابطه آرنیوس توضیح داده شد که مقدار متوسط انرژی فعالسازی برای هر چهار مدل حدود ۲۴/۳۶۲ کیلوژول بر مول بود. طی فرایند رهیدراسیون سفتی انجیر خشک کاهش می یابد که تصاویر میکروسکوپ الکترونی انجیرهای رهیدره نیز که نشان دهنده ساختار متخلخل در این محصول و وجود آب آزاد است این مساله را تایید می کند.