Modeling Rehydration Behavior of Dried Figs

S. Ansari¹∗, N. Maftoon-Azad², E. Hosseini¹, A. Farahnaky³, and Gh. Asadi¹

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 ($\chi^2$) 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 (García-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; García-Segovia et al., 2011), chestnuts (Moreira et al., 2008); broccoli florets (Sanjuán et al., 2001) and aloe vera (Vega-Gálvez et al., 2009):
Rehydration Behavior of Dried Figs

\[ X_i = X_0 + \left( \frac{t}{A + B \times t} \right) \]  (1)

Where, \( X_t \) 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):

\[ X_{eq} = X_0 + \left( \frac{1}{B} \right) \]  (2)

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).

\[ X_i = X_{eq} + (X_0 - X_{eq}) \exp\left[-\left(\frac{t}{B}\right)^a\right] \]  (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)

\[ X_i = X_{eq} - (X_{eq} - X_0) \exp(-k_{r1} \times t) \]  (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):

\[ X = X_{eq} [1 - \exp(-k_{r2} \times t)] \]  (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 \([SSE; \text{Equation (6)}]\), root mean square error \([\text{RMSE; Equation (7)}]\) and the chi-square \([\chi^2; \text{Equation (8)}]\) between the predicted and experimental values.

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

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

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

Where, \( X_{i,exp} \) is the \( i \)th experimental moisture content, \( X_{i,pre} \) 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 \( \text{RMSE}/\text{SSE}/\chi^2 \) 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:

\[ A = A_0 \exp\left(-\frac{E_a}{RT}\right) \]  (9)

Where, \( A \) is the kinetic parameter of each model, \( E_a \) is the activation energy \( (\text{kJ mol}^{-1}) \), \( T \) is the absolute temperature (K) and \( R \) is the universal gas constant \( (8.314 \times 10^{-5} \text{kJ K}^{-1}\text{mol}^{-1}) \). From the slope of the straight line of \( \ln A \) versus reciprocal of \( T \), described by the Arrhenius equation, the activation energy \( (E_a) \), 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.](image)

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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(170,233) 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 Marinoss-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

<table>
<thead>
<tr>
<th>Models</th>
<th>Parameters</th>
<th>Temperature (°C)</th>
<th>F-value</th>
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</thead>
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<td></td>
<td></td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>Peleg</td>
<td>X₀</td>
<td>0.07±0.003</td>
<td>0.06±0.000</td>
</tr>
<tr>
<td></td>
<td>Xₑ</td>
<td>0.80±0.06</td>
<td>0.65±0.02</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>105.19±5.09</td>
<td>53.22±5.03</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.37±0.03</td>
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</tr>
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<td>Weibull</td>
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</tr>
<tr>
<td></td>
<td>Xₑ</td>
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<td>0.51±0.00</td>
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<td>b</td>
<td>56.11±2.45</td>
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<tr>
<td></td>
<td>a</td>
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<tr>
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<td>k₂</td>
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</table>

* 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 (K1) and exponential association models (K2) increased significantly with increased rehydration temperatures, which implies a faster rehydration velocity at higher temperatures.

Regarding the effect of rehydration temperature on Xeq, 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 Xeq 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 Xeq 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>
<thead>
<tr>
<th>Model</th>
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<td>1.92×10⁻⁴</td>
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<td>0.991</td>
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<td>1th-order</td>
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<td>Exponential</td>
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Figure 2. Experimental and predicted rehydration curves for (a) Weibull; (b) Peleg’s; (c) First-order, and (d) Exponential models for the five temperatures.

It can be observed that all proposed models showed a good fit with low values of $SEE$, $RMSE$, and $\chi^2$ 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 $\chi^2$, $RMSE$, 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

<table>
<thead>
<tr>
<th>Model</th>
<th>$R^2$ (kJ mol$^{-1}$)</th>
<th>$\chi^2$</th>
<th>$RMSE$ (kJ mol$^{-1}$)</th>
<th>$SSE$ (kJ mol$^{-1}$)</th>
</tr>
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<tr>
<td>Peleg</td>
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<td>0.003</td>
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<tr>
<td>First-order</td>
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<td>0.965</td>
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Table 3. Arrhenius equation parameters for different rehydration kinetic constants in rehydrated dried figs.

<table>
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<tr>
<th>Kinetic model</th>
<th>Parameter</th>
<th>$E_a$ (Kj mol$^{-1}$)</th>
<th>$R^2$</th>
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<td>Weibul</td>
<td>b</td>
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<tr>
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<td>$k_{r1}$</td>
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<td>0.892</td>
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</tbody>
</table>

Textural changes in 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.](image-url)
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
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


