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KINETIC MODELING OF REHYDRATION IN AIR-DRIED QUINCES PRETREATED WITH OSMOTIC DEHYDRATION AND ULTRASONIC

MOHAMMAD NOSHAD[1], MOHEBBAT MOHEBBI, FAKHRI SHAHIDI and SEYED ALI MORTAZAVI

Department of Food Science and Technology, Ferdowsi University of Mashhad, PO Box 91775-1163, Mashhad, Iran

[1]Corresponding author. TEL: +98511-7627238; FAX: +98511-8787430; EMAIL: mo.noshad@gmail.com

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ABSTRACT

The effect of pretreatment, osmotic–ultrasonic dehydration, on the rehydration kinetic of quince at three temperatures (25, 45 and 70C) was examined. The values of the effective moisture diffusivity of quinces were in the range 8.114×10^{-11} to 2.020×10^{-10} for untreated samples and 6.085×10^{-11} to 1.308×10^{-10} for pretreated samples, respectively. The temperature dependence of the diffusivity coefficient was also described by the Arrhenius-type relationship. The activation energy was found to be 14.48 and 17.27 kJ/mol, for pretreated and untreated samples quince, respectively. Five different models, Fick's second law of diffusion, Peleg, Weibull, first-order and exponential association, were evaluated based on coefficient of determination (R^2), reduced chi-square (χ^2) and root means error (RMSE). The Weibull model gives the highest values of R^2 and the lowest values of χ^2, SSE and RMSE for untreated and pretreated quince samples.

PRACTICAL APPLICATIONS

Rehydration is a complex process aimed at the restoration of raw-material properties when dried material comes in contact with water and can be considered as a measure of the injury to the material caused by drying. The capacity of the dry material to be rehydrated depends on certain intrinsic properties of the vegetal tissue and also on how the rehydration process is carried out (process conditions) and on the previous pretreatments applied to the product. These pretreatments are usually used to obtain a better quality of the final product (i.e., better preserved from undesirable changes) and in this sense applying an osmotic–ultrasonic dehydration step prior to the rehydration process could be interesting. The objective of rehydration study is to attain as many products in their original characteristics as fast as possible. An improved knowledge of rehydration kinetics would significantly enhance the feasibility of this process.

INTRODUCTION

Drying is one of the possibilities of processing the vegetables and fruits. Using dehydrated products in many processed or ready-to-eat foods as replacement of fresh foods has several vantages such as convenience in transportation, storage and preparation (Mazza and LeMaguer 1980; Lewicki *et al.* 1998). Dehydrated products before consumption or further processing need to be rehydrated (Oliveira and Ilincanu 1999). By rehydration, the product will show similar characteristics to the fresh product and leads to restoration of the final product properties (Krokida *et al.* 1999; Bilbao-Sáinz *et al.* 2005). Rehydration of dried vegetal tissues is composed of three simultaneous processes: the absorptions of water into dried material, the swelling of the rehydrated products and the leaching of soluble solids to rehydration medium (Krokida and Maroulis 2001; Krokida and Marinos-Kouris 2003; Lee *et al.* 2006; Vega-Gálvez *et al.* 2009). Several factors affect rehydration, grouped as intrinsic factors (product chemical composition, predrying treatment, product formulation, drying techniques and conditions, post-drying procedure, etc.) and extrinsic factors such as composition of immersion media, temperature and hydrodynamic conditions (Oliveira and Ilincanu 1999). Impairment in the reconstitution properties, result changes in the structure and composition of the plant tissue by some of these factors (Taiwo *et al.* 2002). A pretreatment can be used to minimize shrinkage and improve rehydration of dried vegetables and therefore optimize product quality. Osmotic dehydration is the most reported pretreatment used prior to air-drying (Antonio *et al.* 2008; Fernandes *et al.* 2008; Lombard *et al.* 2008; Pani *et al.* 2008; Azoubel *et al.* 2009, Corrêa *et al.* 2010). On the other hand, among emergent new technologies, ultrasonic dehydration is very promising because the process can be carried out at low temperatures, which reduces the probability of food degradation (Povey and Mason 1998) and permits the removal of moisture content from solids without producing a liquid phase change. Ultrasonic pretreatment involves the immersion of the fruit in water or in a hypertonic aqueous solution to which ultrasound is applied. Ultrasonic waves can cause rapid series of alternative compressions and expansions, in a similar way to a sponge when it is squeezed and released repeatedly (sponge effect). In addition, ultrasound produces cavitations, which may be helpful to remove strongly attached moisture. The sponge effect caused by ultrasound application may be responsible for the creation of microscopic channels in porous materials, such as fruits, that reduce the diffusion boundary layer and increase the convective mass transfer in the fruit (Tarleton 1992; Tarleton and Wakeman 1998). If distilled water is used as the liquid medium, the ultrasonic treatment will not incorporate soluble solids into the fruit, changing its natural taste (Fernandes *et al.* 2008). Recently, several researchers studied the rehydration kinetics of foods after drying. Several empirical and theoretical equations for the modeling of mass transfer kinetics during the rehydration process have been applied. The results will be useful for the optimization of the process itself. The food products studied included broccoli (Sanjuán *et al.* 1999), soybean (Hsu *et al.* 1983), green pea (Krokida and Philippopoulos 2005), carrot (Kompany *et al.* 1993; Marabi and Saguy 2004; Krokida and Philippopoulos 2005), corn and pumpkin (Krokida and Philippopoulos 2005), apple (Krokida and Philippopoulos 2005), mushroom (Garcia-Pascual *et al.* 2005; Krokida and Philippopoulos 2005), blueberry products(Chen *et al.* 2001), celery (Madamba and Liboon 2001), sword bean (Min *et al.* 2005), shrimp (Namsanguan *et al.* 2004), parsley (Bobi *et al.* 2002), potato (Bobi *et al.* 2002), green and red pepper (Kaymak-Ertekin 2002; Krokida and Philippopoulos 2005), rough rice(Basunia and Abe 2005), avocado (Lee *et al.* 2006) and onion (Krokida and Philippopoulos 2005; Sharma *et al.* 2005).

Dried quinces are used to make jam, marmalade and jelly, as well as quince pudding. Additionally, dried quinces can be used as ingredients of traditional Iranian food such as quince khoresh, chowder and other food. It is notable that no published data are present in literature on rehydration of quince. Therefore, the objective of this work was to investigate the effect of combination of osmotic dehydration and ultrasonic as pretreatment and rehydration temperature on the rehydration process and kinetic modeling of the process.

MATERIAL AND METHODS

Preparation of Samples

Fresh quinces were bought from a local market in Mashhad, Iran. Quince samples were cut to obtain slabs of the same dimensions (0.009 m average in thickness and 0.026 m average diameter) and then immersed in 1% sodium Meta bisulphate (Merck, Berlin, Germany) solution for 5 min in order to prevent enzymatic browning reactions. The moisture content was determined by heating in a drying oven at 105C for 48 h according to AOAC method 931.04 (AOAC 1990).

Ultrasonic Pretreatment

An experimental set of four quince samples was immersed in distilled water and submitted to ultrasonic waves for 0–30 min. The experiments with ultrasonic treatment were carried out in separate 250-mL Erlenmeyer flasks to avoid interference between the samples and runs. The experiments were carried out under ambient temperature (30C) in an ultrasonic bath (Schaper model Unique USC 25 kHz, Berlin, Germany) without mechanical agitation. The ultrasonic frequency was 25 kHz, and the intensity was 500 W. The temperature increase during the experiments was measured using a thermometer and was lower than 2C after 30 min of ultrasonic treatment. To determine the effect of ultrasonic, the same experimental procedure was carried out without applying ultrasonic. After removal from the distilled water, the samples from each group were drained, blotted with absorbent paper to remove the excess water. Weight and moisture content were measured individually. At the end, samples were transferred to osmotic solution.

Osmotic Dehydration

Each experimental group consisting of three quince slabs was immersed in the osmotic solution for 1, 1.5 or 2 h. The osmotic solution used in each experiment was prepared by mixing food-grade sucrose with distilled water to give a concentration of 40–60 Brix. The osmotic solution to fruit ratio was maintained at 20:1 (weight basis). Experiments were performed with the same constant magnetic agitation. The temperature was monitored by thermocouple was set at 50C. After removal from the solution, the dehydrated samples from each group were drained, blotted with absorbent paper to remove the excess solution. Weight and moisture content were measured individually.

Response surface methodology (RSM) was applied to optimize the osmotic–ultrasonic conditions considered in this research. As a consideration of the osmotic–ultrasonic predrying treatment, it was appropriate to maximize water loss (WL) and weight reduction and minimize solid gain (SG). The results of the optimum conditions for quinces were found to be 27.25 min for ultrasonic time, 120 min for osmotic dehydration and 50.52% for sucrose concentration. Details have been published in another paper (Noshad *et al.* 2011).

Air-Drying

Hot air-drying was performed in a laboratory drier (Soroush Medical Company, Mashhad, Iran) operating with an air velocity of 1.5 m/s. Before each drying experiment, the drier was run without sample for about 0.5 h to set desired conditions. The quince samples, fresh and pretreated with optimized osmotic–ultrasonic dehydration condition, were subjected to air-drying at 80C. The drying process was stopped when the moisture content decreased to 14 ± 0.3% (wet basis [w.b.]) from an initial value of 83.13 ± 0.5% (w.b.). Finally, the moisture content of dried quince was determined at 105C for 48 h according to AOAC method 931.04 (AOAC 1990). The experiments were conducted with three replications.

Rehydration Experiments

Rehydration experiments were carried out in a distilled water bath at constant temperatures of 25, 45 and 70C (±0.2C). Sample of dehydrated quince was placed inside a flask. For all experiments, the solid–liquid relation was kept at 1:50. The sample weight was measured every 15 min for the first hour of rehydration, then every 20 min for the next until 180 min (final stage of the process). Finally, the moisture content of dried quince was determined at 105C for 8–10 h according to AOAC method (AOAC 1980). The experiments were conducted with three replications.

Light Microscopic Analysis

After the end of ultrasonic pretreatment, the samples were carefully cut into cubes of 5 mm average side. The sample cubes were fixed with 4% solution of paraformaldehyde in 0.1 M phosphate buffer, pH 7.2 and 1% glutaraldehyde for 24 h at ambient temperature. The material was then dehydrated in a graded ethanol series and embedded in Historesin embedding kit (Jung). The tissue blocks were sectioned at 8 μm. The Periodic Acid-Schiff reagent (PAS) cytochemical reaction was employed for polysaccharide detection (Fernandes *et al.* 2008). Photomicrographs of the cell structure were taken using an Olympus BX41 (Olympus, Tokyo, Japan) light microscope with digital image capture system.

MATHEMATICAL MODELING OF REHYDRATION PROCESS

It was assumed that water transport from the surface to the center of the solid mainly takes place by diffusion. Therefore, an effective diffusion coefficient could be computed from the combination of the second Fick's law with the microscopic mass balance. The integrated equation for long periods and infinite slab geometry was applied (Eq. 1), representing the first term of the development of the series in Eq. (2) (Crank 1979; Garcia-Pascual *et al.* 2006). In order to solve this equation, the following was assumed: (1) uniform initial moisture content; (2) negligible external resistance to heat and mass transfer; (3) a constant effective diffusion coefficient; (4) no shrinkage (Sanjuán *et al.* 2001; Garcia-Pascual *et al.* 2006; Cunningham *et al.* 2008).

$$X_w = X_e + (X_0 - X_e)\sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}\exp\left(\frac{-D_{ew}(2n+1)^2\pi^2 t}{4L^2}\right) \tag{1}$$

$$X_w = X_e + (X_0 - X_e)\frac{8}{\pi^2}\exp\left[\frac{-D_{we}\pi^2 t}{4L^2}\right] \tag{2}$$

where D_{ew} is the effective diffusivity (m^2/s); X_{W} is the moisture content of the sample at time t (kg water/kg dm), X_0 is the initial moisture content (kg water/kg dm), X_{e} is the equilibrium moisture content (kg water/kg dm), t is the time (s) and L is the half-thickness of the slab (m).

The temperature affinity of the effective diffusivity may be portrayed by an Arrhenius-type relationship (Akgun and Doymaz 2005) as follows:

$$D_{eff} = D_0\exp\left(-\frac{E_{\mathrm{a}}}{RT}\right) \tag{3}$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_{a} is the activation energy (kJ/mol), R is the universal gas constant (kJ/mol K) and T is the absolute temperature (K). From the slope of the straight line of lnD_{eff} versus reciprocal of T, described by the Arrhenius equation, the activation energy, E_{a}, could be calculated.

Among the various models thus far proposed, empirical models are the most commonly employed because of their mathematical simplicity and utility (Moreira *et al.* 2008). Peleg's model (Eq. 4), Weibull equation (Eq. 6), first-order kinetic model (Eq. 7) and exponential association equation (Eq. 8) were used (Hsu *et al.* 1983; Peleg 1988; Sopade and Obekpa 1990; Sopade *et al.* 1992; LU *et al.* 1994; Machado *et al.* 1999; Garcia-Pascual *et al.* 2005; Krokida and Philippopoulos 2005; Gowen *et al.* 2006; Kaptso *et al.* 2008; Apar *et al.* 2009; Demirhan and Zbek 2010).

$$X_w = X_0 + \left[\frac{t}{A + B.t}\right] \tag{4}$$

where X_w is the moisture content at any time (kg/kg dry basis [d.b.]), X_0 is the moisture content at $t = 0$ (kg/kg d.b.), t is the rehydration time (s), A is a kinetic constant of the model (s. [kg d.b.]/kg) and B is a characteristic constant of the model (kg d.b./kg). If the time of rehydration is long enough, the equilibrium moisture content (X_e) (kg/kg d.b.) is given by:

$$X_e = X_0 + \frac{1}{B} \tag{5}$$

To establish when equilibrium is achieved during rehydration is difficult, because many changes happen at long soaking times. Therefore, unlike drying, in this process, the equilibrium moisture content (M_e) cannot be measured separately. Hence, the equilibrium moisture content M_e is considered as an additional parameter to be identified in the Weibull model (Eq. 6).

$$X_w = X_e + (X_0 - X_e)\exp\left[-\left(\frac{t}{B}\right)^A\right] \tag{6}$$

where B (s) and A (dimensionless) are the scale and the shape parameters, respectively.

$$X_w = X_e + (X_0 - X_e)\exp(-kt) \tag{7}$$

where k is the rehydration kinetic constant (s^{-1}).

$$X_w = X_e[1 - \exp(-Ht)] \tag{8}$$

where H is the kinetic constant (s^{-1}).

STATISTICAL ANALYSIS

The software package, MATLAB R2008a (Math Works, Inc., Natick, MA) was used in the numerical calculations. Fitting quality of the models used on the experimental data was evaluated by means of statistical tests: The correlation coefficient (r) was one of the primary criterions for selecting the best equation to define the drying curves of quinces. In addition to r, various statistical parameters such as reduced chi-square (χ^2), sum of square error (SSE) and root mean square error ($RMSE$) were used to determine the quality of the fit. These parameters can be calculated as following:

$$\chi^2 = \frac{\sum_{i=1}^{N}(X_{ei} - X_{ci})^2}{N - Z} \tag{9}$$

$$SSE = \frac{1}{N}\sum_{i-1}^{N}(X_{ei} - X_{ci})^2 \tag{10}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(X_{ci} - X_{ei})\right]^2 \tag{11}$$

where, X_{ei} experimental moisture content (kg water/kg dm), X_{ci} calculated moisture content (kg water/kg dm), N is number of experimental data points and z is number of constants in model. The higher values of R^2 and the lower values of χ^2 and $RMSE$ are chosen as the criteria for goodness of fit.

RESULTS AND DISCUSSION

Effect of Temperature on Rehydration Kinetics

The untreated quince samples were rehydrated at various rehydration temperatures, 25, 45 and 70C, in order to evaluate the effect of rehydration temperature on moisture content uptake during rehydration. Figure 1 shows the data of moisture content uptake during rehydration versus rehydration time of quince. As can be seen from this figure, increasing the rehydration temperature causes increased the moisture content uptake of dried quince. Also, substantially, all curves showed typical rehydration behavior with a high water absorption rate at the beginning of the process then absorption rate decreases until equilibrium moisture. The rapid

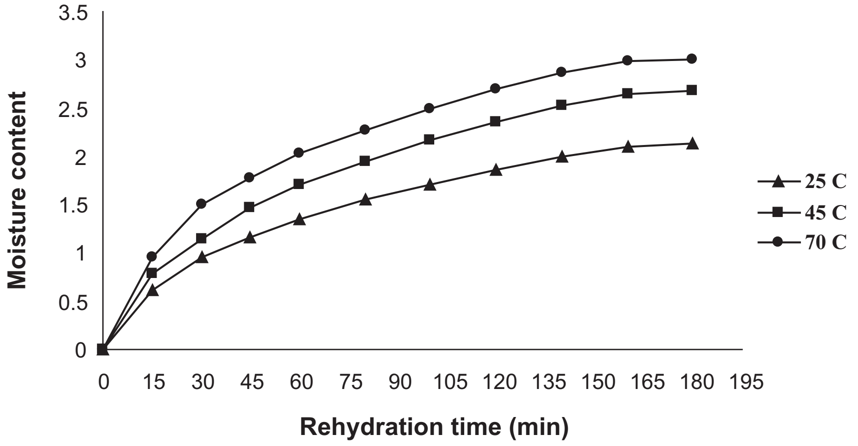

FIG. 1. REHYDRATION RATE CURVES OF QUINCE AT DIFFERENTTEMPERATURES

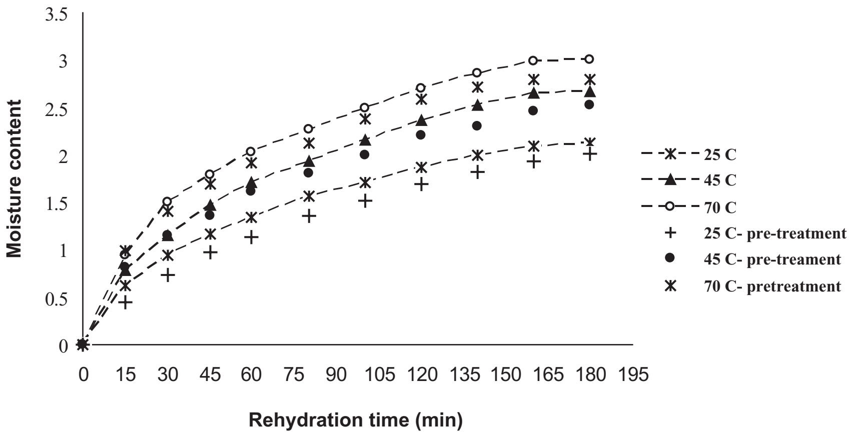

FIG. 2. REHYDRATION RATE CURVES OF QUINCE AT DIFFERENT TEMPERATURES OF PRETREATED AND UNTREATED

initial water uptake was likely due to the filling of capillaries on the surface of the sample. As water absorption proceeds, the soaking rate starts to decline due to the filling of free capillaries and intercellular spaces with water. It is found that water temperate affects rehydration rates and equilibrium moisture content, positively (Sanjuán *et al.* 1999; Cunningham *et al.* 2008). Similar results have been reported by other authors working with different food products: (Kaymak-Ertekin 2002) with green and red peppers,(Krokida and Marinos-Kouris 2003) with apple, potato, carrot, banana, pepper, garlic, mushroom, onion, leek, pea, corn, pumpkin and tomato (Bilbao-Sáinz *et al.* 2005); with apple (Resio *et al.* 2006); with amaranth grain (Garcia-Pascual *et al.* 2006); with mushroom,(Moreira *et al.* 2008); and with chestnuts.

Effect of Osmotic–Ultrasonic Pretreatment on Rehydration Kinetics

The effect of osmotic–ultrasonic pretreatment on moisture content uptake during rehydration is depicted in Fig. 2. During rehydration, the moisture content of osmotic-ultrasonic pretreated samples was lower, at any time during rehydration, as compared with that of the untreated samples.

The microscopic image analysis of the fresh fruit showed typical thin-walled cells with normal morphology and no visible intercellular spaces (Fig. 3a). After ultrasonic treatment, the cells became more distorted, and microscopic channels began to form (Fig. 3b). Although the fruit presented microchannels that might ease water diffusion during rehydration process, the water diffusivity of the pretreated samples decreased. The decrease can be explained by a high sugar gain. Sugar may have entered into the microchannel, saturating the channel, reduced the pore size and creating an extra resistance for water diffusion during rehydration and therefore the rate of moisture absorption decreased significantly (Bakalis and Karathanos 2005). Also, osmotic dewatering affects the rehydration properties of dried material, because of cell permeability due to osmotic stress and hence, upon rehydration these cells cannot absorb as much as water as the

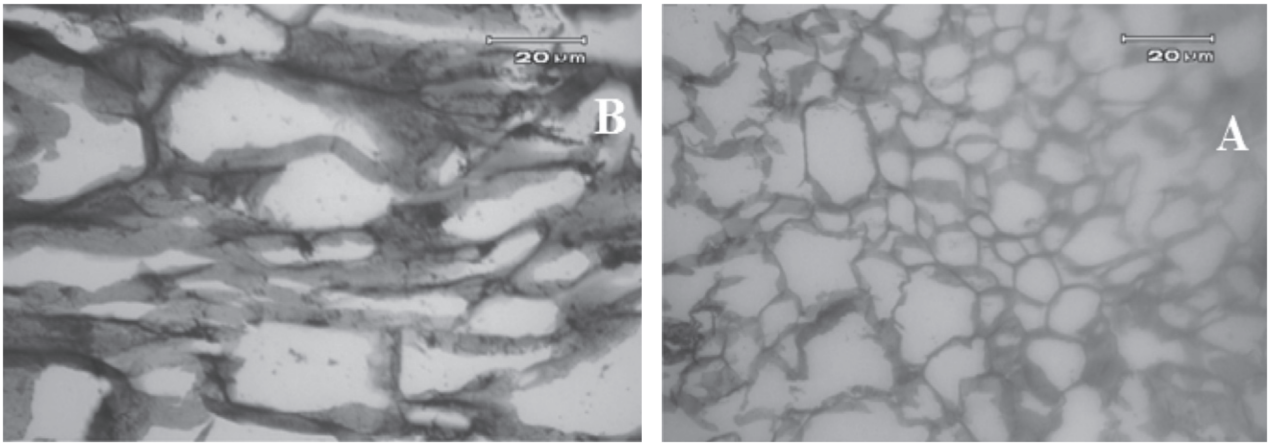

FIG. 3. PHOTOMICROGRAPHS OF QUINCE CUBES BEFORE PROCESSING, RAW FRUIT (A), AFTER OF ULTRASONIC PRETREATMENT (B)

un-treatment (Lewicki 1998). The reduced water absorption during rehydration of samples pretreated with osmotic solution was reported by (Lewicki *et al.* 1998) and (Rastogi *et al.* 2004).

Modeling of Rehydration Curves

Diffusion Model. Table 1 shows the values of D_{we} at each term. The results showed that D_{we} values increased as water rehydration temperature increased. As expected, water absorption rate was higher as temperature increased. Similar results have been reported in other researches: 1.78–3.32 and $1.87–4.99 \times 10^{-10}$ m²/s for broccoli stems rehydrated between 25C and 80C (Sanjuán *et al.* 1999), $0.22–99.63 \times 10^{-11}$ m²/s for broccoli florets rehydrated between 25C and 80C (Sanjuán *et al.* 2001), 5.69–9.90 and $4.20–8.02 \times 10^{-11}$ m²/s for pasta rehydrated between 20C and 80C (Cunningham *et al.* 2007), $2.16–59.50 \times 10^{-10}$ m²/s for cowpea and groundnuts seeds rehydrated between 25C and 45C (Kaptso *et al.* 2008) and $1.52–9.32 \times 10^{-10}$ m²/s for potato rehydrated between 20C and 80C (Cunningham *et al.* 2008). The samples pretreated have lower water diffusion coefficients during rehydration as compared with the control sample. Similar results have been reported in other researcher (Rastogi *et al.* 2004) for osmotic pretreatments on rehydration characteristics of carrots.

Plotting the $\ln D_{eff}$ versus, the reciprocal of the temperature is presented in Fig. 4. The activation energy values were found to be 14.48 and 17.27 kJ/mol, for pretreated and untreated samples, respectively. The value of activation energy of untreated samples is higher than that of pretreated samples. Eqs. (12) and (13) show the effect of temperature on D_{eff} of pretreated and untreated quinces:

$$\text{Pretreated: } D_{eff} = 2.06\times10^{-8}\exp\left(\frac{14.48}{T+273.15}\right) \qquad (12)$$

$$\text{Untreated: } D_{eff} = 8.36\times10^{-8}\exp\left(\frac{17.27}{T+273.15}\right) \qquad (13)$$

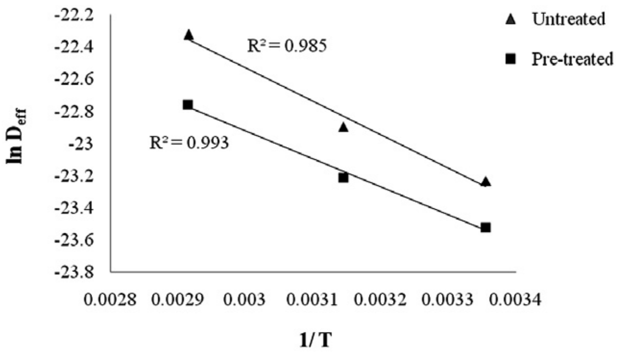

FIG. 4. INFLUENCE OF TEMPERATURE ON THE EFFECTIVE DIFFUSIVITY FOR PRETREATED AND UNTREATED QUINCES

TABLE 1. EFFECTIVE DIFFUSION COEFFICIENTS OF QUINCE AT DIFFERENT TEMPERATURES OF PRETREATED AND UNTREATED

	Effective diffusivity (m²/s)	
Temperature (C)	Untreated	Pretreated
25	8.114×10^{-11}	6.085×10^{-11}
45	1.02×10^{-10}	8.316×10^{-11}
70	2.02×10^{-10}	1.308×10^{-10}

Empirical Rehydration Models. Tables 2 and 3 show the mean values for the parameters of the models used at three work temperatures. Parameter *A* values for the Peleg model decreased as temperature increased. This shows a higher water absorption rate at higher temperature. As (Solomon 2007) suggested, this parameter may be representative of water absorption rate in the early phase of rehydration process. The high *B* values observed for pretreated samples indicate the decreased water absorption rate of samples compared with untreated samples. This result is similar to the observations of other authors, such as Moreira *et al.* (2008) with chestnuts and Solomon (2007) with lupin. Parameter *B* for the Peleg model decreases as temperature increases. Solomon (2007) suggested that this parameter is inversely related to the absorption ability of foods or to equilibrium moisture content. Higher water absorption capacity is correlated to lower value of *B* and vice versa. By increasing rehydration water temperature, the water absorption capacity increases. The high *B* values observed for pretreated samples indicate the decreased absorption ability and equilibrium moisture content (water gain) of samples compared with untreated samples.

Tables 2 and 3 also show the values of parameters *A* and *B* for the Weibull model, obtained for the experimental rehydration data at each temperature for untreated and pretreated samples, respectively. The Weibull shape parameter *A*, which measures the velocity of water absorption at the beginning of the process, ranged between 0.65 and 0.785 for untreated samples and between 0.66 and 0.915 for pretreated samples; its values are within the reported values for foodstuffs, which vary between 0.2 and 1.0 (Magee and Richardson 2007; Goula and Adamopoulos 2009). The lower the value of *A* indicated the faster the rate of water absorption (Garcia-Pascual *et al.* 2006). Thus, the kinetics for untreated samples at the beginning of the rehydration are faster than pretreated samples. Also at the beginning of the rehydration, the kinetics at 70C are faster than at lower temperatures. A similar trend was observed by (Garcia-Pascual *et al.* 2006). The parameter *B* decreases as temperature increases. A similar behavior has

TABLE 2. VALUE OF THE PARAMETERS OF ALL MODELS USED AT DIFFERENT TEMPERATURES FOR UNTREATED QUINCE

Temperature (C)	Peleg			Weibull		First-order rehydration kinetic model	Exponential association model
	Untreated			Untreated		Untreated	Untreated
	A	*B*	X_e*	*D*	*C* (s)	*K*	*H*
25	1,787.787	0.344	3.07	0.785	9,901.864	0.000108	0.000117
45	1,289.128	0.282	3.71	0.69	6,914.751	0.000178	0.000192
70	996.468	0.261	3.994	0.653	4,950.947	0.000201	0.000218

* Equilibrium moisture content (X_e).

been reported by Machado *et al*. (1999) with 97.6–8.4 min in puffed breakfast cereals, by Garcia-Pascual *et al*. (2006) with 8.5–2.5 min in mushroom and by Cunningham *et al*. (2007) with 1,193–60 min in pasta. Machado *et al*. (1999), Marabi and Saguy (2004) and Cunningham *et al*. (2007) suggested that parameter *B* represents the time needed to accomplish approximately 63% of the process. In addition, Tables 2 and 3 show the kinetic constants of first-order and exponential association models (*K* and *H*) increased with the increase of temperature. Also the kinetic constants of first-order and exponential association models for untreated samples are higher than pretreated samples.

Statistical Analysis of the Models

Mean values of statistical analyses applied to the equations proposed to model rehydration kinetics of dried quinces are shown in Figs. 5 and 6. In general, all proposed models showed a good fit with values close to zero for SSE, RMSE and χ^2. Therefore, and according to the results obtained, the models that best fitted experimental data were as follows:

Untreated samples: Model of Weibull ($SSE = 3.07 \times 10^{-4}$; $RMSE = 1.753 \times 10^{-4}$; $\chi^2 = 3.84 \times 10^{-4}$; $R^2 = 0.99$) followed by the Fick model ($SSE = 3.73 \times 10^{-4}$; $RMSE = 1.932 \times 10^{-4}$; $\chi^2 = 4.15 \times 10^{-4}$; $R^2 = 0.98$) and first-order rehydration

TABLE 3. VALUE OF THE PARAMETERS OF ALL MODELS USED AT DIFFERENT TEMPERATURES FOR PRETREATED QUINCE

Temperature (C)	Peleg			Weibull		First-order rehydration kinetic model	Exponential association model
	Pretreated			Pretreated		Pretreated	Pre-treated
	A	*B*	X_e*	*D*	*C* (s)	*K*	H
25	2,308.13	0.364	2.91	0.915	16,945.03	0.000077	0.000084
45	1,583.9	0.321	3.278	0.725	9,714.713	0.000134	0.000145
70	1,141.67	0.319	3.297	0.665	5,401	0.000192	0.000205

* Equilibrium moisture content (X_e).

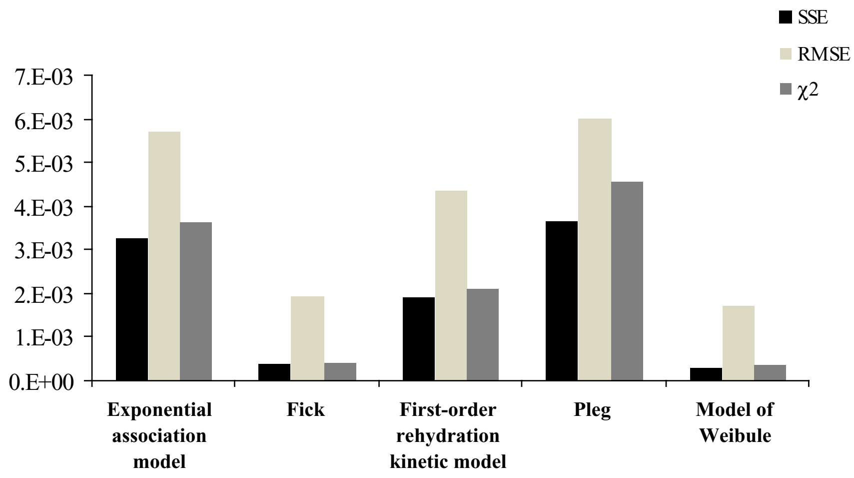

FIG. 5. STATISTICAL TESTS FOR EACH REHYDRATION MODEL FOR UNTREATED QUINCE SAMPLES (RMSE $\times 10^{-1}$)

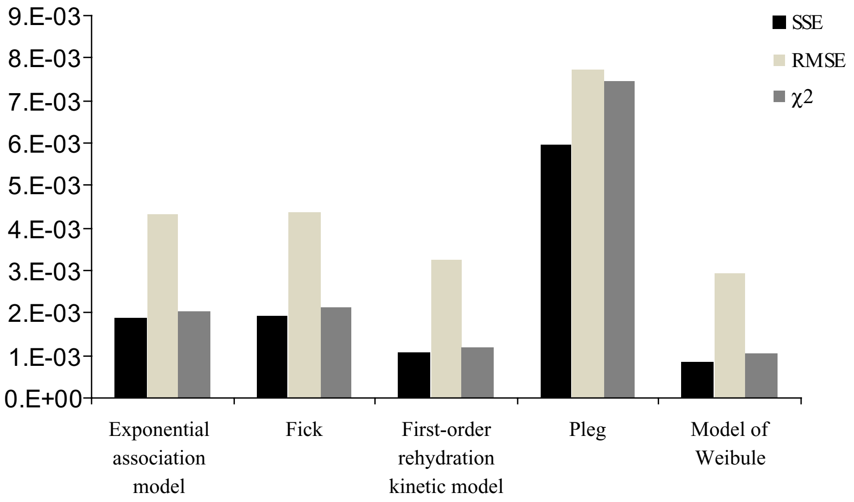

FIG. 6. STATISTICAL TESTS FOR EACH REHYDRATION MODEL FOR PRETREATED QUINCE SAMPLES (RMSE $\times 10^{-1}$)

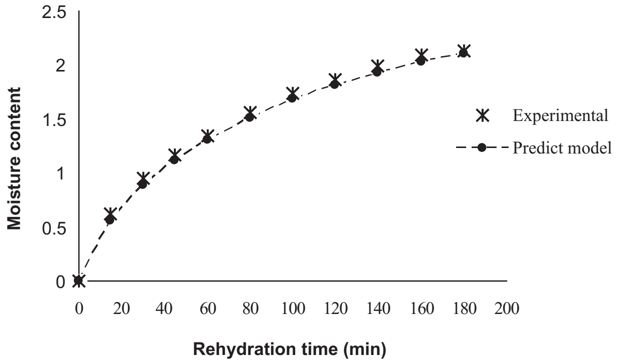

FIG. 7. EXPERIMENTAL AND CALCULATED MOISTURE CONTENT BY WEIBULL MODEL OF UNTREATED QUINCE 45C

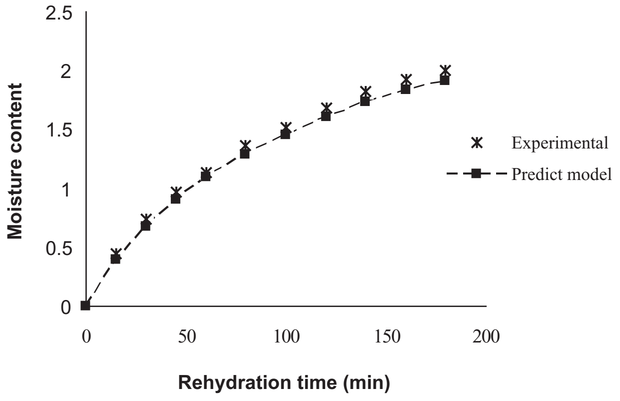

FIG. 8. EXPERIMENTAL AND CALCULATED MOISTURE CONTENT BY WEIBULL MODEL OF PRETREATED QUINCE AT 45C

kinetic model ($SSE = 1.905 \times 10^{-3}$; $RMSE = 4.364 \times 10^{-3}$; $\chi^2 = 2.116 \times 10^{-3}$; $R^2 = 0.94$) and exponential association model ($SSE = 3.283 \times 10^{-3}$; $RMSE = 5.73 \times 10^{-3}$; $\chi^2 = 3.648 \times 10^{-3}$; $R^2 = 0.93$) and Peleg model ($SSE = 3.651 \times 10^{-3}$; $RMSE = 6.042 \times 10^{-3}$; $\chi^2 = 4.564 \times 10^{-3}$; $R^2 = 0.97$).

Pretreated samples: Model of Weibull ($SSE = 8.62 \times 10^{-4}$; $RMSE = 2.935 \times 10^{-4}$; $\chi^2 = 1.077 \times 10^{-3}$; $R^2 = 0.98$) followed by first-order rehydration kinetic model ($SSE = 1.083 \times 10^{-3}$; $RMSE = 3.29 \times 10^{-3}$; $\chi^2 = 1.203 \times 10^{-3}$; $R^2 = 0.95$), exponential association model ($SSE = 1.87 \times 10^{-3}$; $RMSE = 4.324 \times 10^{-3}$; $\chi^2 = 2.078 \times 10^{-3}$; $R^2 = 0.94$) and Fick model ($SSE = 1.923 \times 10^{-3}$; $RMSE = 4.385 \times 10^{-3}$; $\chi^2 = 2.137 \times 10^{-3}$; $R^2 = 0.96$) and Peleg model ($SSE = 5.974 \times 10^{-3}$; $RMSE = 7.73 \times 10^{-3}$; $\chi^2 = 7.467 \times 10^{-3}$; $R^2 = 0.98$).

The model of Weibull gives the highest values of R^2 and the lowest values of χ^2, *RMSE* and *SSE* for untreated and pretreated quince samples. Several authors studying rehydration kinetics for different foods reported the good fit quality obtained by the model of Weibull: Marabi and Saguy (2004) in carrot, Garcia-Pascual *et al.* (2006) in mushroom and Cunningham *et al.* (2007) in pasta.

Figures 7 and 8 depict the experimental and calculated moisture content at 45C temperature, predicted by the Weibull model. It is apparent from these figures that the predicted data closely banding around the straight line, which indicated the sufficiency of the model, proposed in describing the rehydration behavior of quince.

CONCLUSION

The results of this study indicate that osmotic–ultrasonic dehydration pretreatment caused samples with lower water absorption ability in comparison with the untreated samples because of cell permeabilization, due to osmotic–ultrasonic dehydration stress. Several models were tested to model the rehydration kinetic and the model of Weibull, which gave higher coefficient of determination and lower chi-square sum of square error and root mean square error, was considered as the best for elucidating the rehydration characteristics of quince. The effective diffusivity of pretreated and untreated varied between 8.114×10^{-11} and 2.02×10^{-10} for untreated samples and 6.085×10^{-11} to 1.308×10^{-10} for pretreated samples, respectively. This difference can be related to structural changes induced by osmotic–ultrasonic dehydration pretreatment. The temperature affinity of the effective diffusivity was also portrayed by the Arrhenius-type relationship. The activation energy for moisture diffusion was 14.48 and 17.27 kJ/mol for pretreated and untreated samples, respectively.

REFERENCES

AKGUN, N. and DOYMAZ, I. 2005. Modelling of olive cake thin-layer drying process. J. Food Eng. *68*, 455–461.

ANTONIO, G., ALVES, D., AZOUBEL, P., MURR, F. and PARK, K. 2008. Influence of osmotic dehydration and high temperature short time processes on dried sweet potato (Ipomoea batatas Lam.). J. Food Eng. *84*, 375–382.

AOAC. 1980. Official methods of analysis of the Association of Official Analytical Chemists. *Washington, DC*, 298.

AOAC. 1990. Official methods of analysis. Association of Official Analytical Chemists Washington.

APAR, D., DEMIRHAN, E., OEZBEK, B. and DADALI, G. 2009. Rehydration Kinetics of microwave-dried okras as affected by drying conditions. J. Food Process. Preserv. *33*, 618–634.

AZOUBEL, P., EL-AOUAR, Â., TONON, R., KUROZAWA, L., ANTONIO, G., MURR, F. and PARK, K. 2009. Effect of osmotic dehydration on the drying kinetics and quality of cashew apple. Int. J. Food Sci. Technol. *44*, 980–986.

BAKALIS, S. and KARATHANOS, V. 2005. Study of rehydration of osmotically pretreated dried fruit samples. Dry. Technol. *23*, 533–549.

BASUNIA, M. and ABE, T. 2005. Thin-layer re-wetting of rough rice at low and high temperatures. J. Stored Prod. Res. *41*, 163–173.

BILBAO-SÁINZ, C., ANDRES, A. and FITO, P. 2005. Hydration kinetics of dried apple as affected by drying conditions. J. Food Eng. *68*, 369–376.

BOBI, Z., BAUMAN, I. and URI, D. 2002. Rehydration ratio of fluid bed-dried vegetables. Sadhana *27*, 365–374.

CHEN, C., RAMASWAMY, H. and ALLI, I. 2001. Prediction of quality changes during osmo-convective drying of blueberries using neural network models for process optimization. Dry. Technol. *19*, 507–523.

CORRÊA, J.L.G., PEREIRA, L.M., VIEIRA, G.S. and HUBINGER, M.D. 2010. Mass transfer kinetics of pulsed vacuum osmotic dehydration of guavas. J. Food Eng. *96*, 498–504.

CRANK, J. 1979. *The Mathematics of Diffusion*, pp. 205–209, Oxford University Press, Oxford, U.K.

CUNNINGHAM, S., MCMINN, W., MAGEE, T. and RICHARDSON, P. 2007. Modelling water absorption of pasta during soaking. J. Food Eng. *82*, 600–607.

CUNNINGHAM, S., MCMINN, W., MAGEE, T. and RICHARDSON, P. 2008. Experimental study of rehydration kinetics of potato cylinders. Food Bioprod. Process. *86*, 15–24.

DEMIRHAN, E. and ZBEK, B. 2010. Rehydration kinetics of microwave dried basil. J. Food Process. Preserv. *34*, 664–680.

FERNANDES, F., GALLÃO, M. and RODRIGUES, S. 2008. Effect of osmotic dehydration and ultrasound pre-treatment on cell structure: Melon dehydration. LWT – Food Sci. Technol. *41*, 604–610.

GARCIA-PASCUAL, P., SANJUÁN, N., BON, J., CARRERES, J. and MULET, A. 2005. Rehydration process of Boletus edulis mushroom: Characteristics and modelling. J. Sci. Food Agric. *85*, 1397–1404.

GARCIA-PASCUAL, P., SANJUÁN, N., MELIS, R. and MULET, A. 2006. Morchella esculenta (morel) rehydration process modelling. J. Food Eng. *72*, 346–353.

GOULA, A. and ADAMOPOULOS, K. 2009. Modeling the rehydration process of dried tomato. Dry. Technol. *27*, 1078–1088.

GOWEN, A., ABU-GHANNAM, N., FRIAS, J., BARAT, J., ANDRES, A. and OLIVEIRA, J. 2006. Comparative study of quality changes occurring on dehydration and rehydration of cooked chickpeas (Cicer Arietinum L.) subjected to combined microwave–convective and convective hot air dehydration. J. Food Sci. *71*, E282–E289.

HSU, K., KIM, C. and WILSON, L. 1983. Factors affecting water uptake of soybeans during soaking. Cereal Chem. (USA) *60*, 208–211.

KAPTSO, K., NJINTANG, Y., KOMNEK, A., HOUNHOUIGAN, J., SCHER, J. and MBOFUNG, C. 2008. Physical properties and rehydration kinetics of two varieties of cowpea (Vigna unguiculata) and bambara groundnuts (Voandzeia subterranea) seeds. J. Food Eng. *86*, 91–99.

KAYMAK-ERTEKIN, F. 2002. Drying and rehydrating kinetics of green and red peppers. J. Food Sci. *67*, 168–175.

KOMPANY, E., BENCHIMOL, J., ALLAF, K., AINSEBA, B. and BOUVIER, J. 1993. Dehydration kinetics and modelling. Dry. Technol. *11*, 451–470.

KROKIDA, M. and MARINOS-KOURIS, D. 2003. Rehydration kinetics of dehydrated products. J. Food Eng. *57*, 1–7.

KROKIDA, M. and MAROULIS, Z. 2001. Structural properties of dehydrated products during rehydration. Int. J.Food Sci. Technol. *36*, 529–538.

KROKIDA, M. and PHILIPPOPOULOS, C. 2005. Rehydration of dehydrated foods. Dry. Technol. *23*, 799–830.

KROKIDA, M., KIRANOUDIS, C. and MAROULIS, Z. 1999. Viscoelastic behaviour of dehydrated products during rehydration. J. Food Eng. *40*, 269–277.

LEE, K., FARID, M. and NGUANG, S. 2006. The mathematical modelling of the rehydration characteristics of fruits. J. Food Eng. *72*, 16–23.

LEWICKI, P. 1998. Effect of pre-drying treatment, drying and rehydration on plant tissue properties: A review. Int. J.Food Prop. *1*, 1–22.

LEWICKI, P., WITROWA-RAJCHERT, D., POMARANSKA-LAZUKA, W. and NOWAK, D. 1998. Rehydration properties of dried onion. Int. J.Food Prop. *1*, 275–290.

LOMBARD, G., OLIVEIRA, J., FITO, P. and ANDRES, A. 2008. Osmotic dehydration of pineapple as a pre-treatment for further drying. J. Food Eng. *85*, 277–284.

LU, R., SIEBENMORGEN, T. and ARCHER, T. 1994. Absorption of water in long-grain rough rice during soaking. J. Food Process Eng. *17*, 141–154.

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.

MADAMBA, P. and LIBOON, F. 2001. Optimization of the vacuum dehydration of celery (Apium graveolens) using the response surface methodology. Dry. Technol. *19*, 611–626.

MAGEE, S. and RICHARDSON, P. 2007. Modelling water absorption of pasta during soaking. J. Food Eng. *82*, 600–607.

MARABI, A. and SAGUY, I. 2004. Effect of porosity on rehydration of dry food particulates. J. Sci. Food Agric. *84*, 1105–1110.

MAZZA, G. and LEMAGUER, M. 1980. Dehydration of onion: Some theoretical and practical considerations. Int. J. Food Sci. Technol. *15*, 181–194.

MIN, Z., CHUNLI, L., GONGNIAN, X., LIANG, S., CAO, C. and LE-QUN, Z. 2005. Dehydrated sword beans: The squeezing process and accelerated rehydration characteristics. Dry. Technol. *23*, 1581–1589.

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.

NAMSANGUAN, Y., TIA, W., DEVAHASTIN, S. and SOPONRONNARIT, S. 2004. Drying kinetics and quality of shrimp undergoing different two-stage drying processes. Dry. Technol. *22*, 759–778.

NOSHAD, M., MOHEBBI, M., SHAHIDI, F. and ALI MORTAZAVI, S. 2011. Multi-objective optimization of osmotic–ultrasonic pretreatments and hot-air drying of quince using response surface methodology. Food Bioprocess Technol. DOI: 10.1007/s11947-011-0577-8 [Epub ahead of print].

OLIVEIRA, F. and ILINCANU, L. 1999. Rehydration of dried plant tissues: Basic concepts and mathematical modeling. In *Processing foods* (F.A.R Oliveira and J.C. Oliveira, eds) pp. 201–227, CRC Press, Boca Raton, FL.

PANI, P., LEVA, A., RIVA, M., MAESTRELLI, A. and TORREGGIANI, D. 2008. Influence of an osmotic pre-treatment on structure-property relationships of air-dehydrated tomato slices. J. Food Eng. *86*, 105–112.

PELEG, M. 1988. An empirical model for the description of moisture sorption curves. J. Food Sci. *53*, 1216–1217.

POVEY, M. and MASON, T. 1998. *Ultrasound in Food Processing*, Blackie Academic and Professional, Netherlands.

RASTOGI, N., NAYAK, C. and RAGHAVARAO, K. 2004. Influence of osmotic pre-treatments on rehydration characteristics of carrots. J. Food Eng. *65*, 287–292.

RESIO, A., AGUERRE, R. and SUAREZ, C. 2006. Hydration kinetics of amaranth grain. J. Food Eng. *72*, 247–253.

SANJUÁN, N., CARCEL, J., CLEMENTE, G. and MULET, A. 2001. Modelling of the rehydration process of brocolli florets. Eur. Food Res. Technol. *212*, 449–453.

SANJUÁN, N., SIMAL, S., BON, J. and MULET, A. 1999. Modelling of broccoli stems rehydration process. J. Food Eng. *42*, 27–31.

SHARMA, G., VERMA, R. and PATHARE, P. 2005. Thin-layer infrared radiation drying of onion slices. J. Food Eng. *67*, 361–366.

SOLOMON, W. 2007. Hydration kinetics of lupin (lupinus albus) seeds. J. Food Process Eng. *30*, 119–130.

SOPADE, P. and OBEKPA, J. 1990. Modelling water absorption in soybean, cowpea and peanuts at three temperatures using Peleg's equation. J. Food Sci. *55*, 1084–1087.

SOPADE, P., AJISEGIRI, E. and BADAU, M. 1992. The use of Peleg's equation to model water absorption in some cereal grains during soaking. J. Food Eng. *15*, 269–283.

TAIWO, K., ANGERSBACH, A. and KNORR, D. 2002. Influence of high intensity electric field pulses and osmotic dehydration on the rehydration characteristics of apple slices at different temperatures. J. Food Eng. *52*, 185–192.

TARLETON, E. 1992. The role of field-assisted techniques in solid/liquid separation. Filtr. Sep. *29*, 246–252.

TARLETON, E. and WAKEMAN, R. 1998. Ultrasonically assisted separation process. *Ultrasounds in Food Processing, Blackie Academic and Professional, London*.

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.