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EFFECT OF TEMPERATURE ON REHYDRATION KINETICS, FUNCTIONAL PROPERTIES, TEXTURE AND ANTIOXIDANT ACTIVITY OF RED PEPPER VAR. HUNGARIAN (*CAPSICUM ANNUUM L.*)

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ABSTRACT

Dehydrated peppers at 60C were rehydrated at three temperatures (20, 40 and 60C) to analyze the effect of processing temperature on rehydration kinetics and quality attributes of final products. Several empirical and diffusive models were applied to simulate rehydration kinetics. Based on statistical results (sum of square error, root mean square error and chi-square), Weibull and exponential models obtained the best fit quality for the experimental data. Water holding capacity and rehydration ratio presented a maximum and minimum value at 40C, respectively, indicating structural modifications of pepper due to thermal processing. Based on the glass transition temperature of the dried samples, it could be inferred that peppers are susceptible to structural disruption during rehydration at the three working temperatures. Increasing rehydration temperatures lead to a reduction in the pepper firmness. The radical scavenging activity showed higher antioxidant activity at high temperatures (e.g., 60C) rather than at low temperatures (e.g., 20 and 40C).

PRACTICAL APPLICATIONS

The main utility of this study is the appliance of diffusional, statistical and empirical models in food rehydration, which can be considered a basis for a very accurate estimation of rehydration time and the optimization of the rehydration process. The physicochemical analyses on food products can confirm that thermal processes modify the cell structure of food, reducing the rehydration ability due to cellular and structural disruption that takes place during dehydration. Also, families of most peppers are rich in antioxidants due to the presence of bioactive compounds, which are associated to reduction of biological complications such as aging, cardiovascular disease and carcinogenesis. In addition, dried red pepper var. Hungarian and other dried pepper exports from Chile have become especially important, because these products are consumed both dry and rehydrated. Major markets for these products include the U.S.A., the European community and Japan.

INTRODUCTION

Modern lifestyle is leading to a continuous rise in the demand for convenient foods which include dehydrated products (Marabi and Saguy 2009). Red pepper (var. Hungarian) is highly appreciated for its flavor, color as well as its content of antioxidant compounds (Krajayklang *et al.* 2000; Materska and Perucka 2005; Guil-Guerrero *et al.* 2006; Chuah *et al.* 2008; Di Scala and Crapiste 2008; Vega-Gálvez *et al.* 2009b). Its antioxidant components have shown important action against certain cancers and stimulate the immune system, prevent cardiovascular diseases and delay the aging process (Deepa *et al.* 2007; Podsedek 2007; Chuah *et al.* 2008). Dehydrated peppers are used extensively in instant dry soups, ready-to-eat meals, snack foods and seasoning blends, to name only a few. The most common drying method used is the removal of water by means of forced-air drying convection due to its reduced cost and the relatively simple equipment required (Marabi and Saguy 2009). However, it is well known that during forced-air heat convection, vegetables undergo physical, structural, chemical and nutritional changes due to its quality degradation (Di Scala and Crapiste 2008; Vega-Gálvez *et al.* 2009b). Moreover, dehydration provokes concentration of food solids due to water removal resulting in an almost anhydrous state of food components (Roos 2009). These changes in food state have been related to food quality through the glass transition temperature concept (Telis and Sobral 2002; Katekawa and Silva 2007; Roos 2009).

Dried foods often need to be rehydrated before they are consumed (Weerts *et al.* 2005). During the rehydration process, the dry material, which is submerged in water or some other aqueous medium, undergoes several simultaneous physicochemical changes (e.g., moisture and solid content, porosity, volume, temperature, state transitions and texture) (Krokida and Philippopoulus 2005; Marabi and Saguy 2009; Maldonado *et al.* 2010). Some rehydration indices were proposed in order to estimate the functional properties of the dried material which measures the ability of the dried product to rehydrate and shows the tissue damage caused by drying and rehydration processes (Bilbao-Sáinz *et al.* 2005; García-Pascual *et al.* 2006; Moreira *et al.* 2008; Vega-Gálvez *et al.* 2009a). When considering dried foods that need to be reconstituted, it is essential to bear in mind that the utmost requirement is to meet consumers' expectations with respect to the sensory aspects of the final product. Thus, optimizing the rehydration conditions for each specific product is necessary, because predrying treatment, drying and rehydration processes induce many changes in the structure and composition of dried foods (Marabi and Saguy 2009). In this sense, the use of different mathematical models facilitates the understanding of some of the process characteristics (e.g., rehydration kinetics), and provides insight into the governing mechanisms that take place. Two main approaches can be identified. One approach uses the empirical and semiempirical models, e.g., the Peleg and the Weibull equations (Peleg 1988; Marabi *et al.* 2003; Marfil *et al.* 2008; Vega-Gálvez *et al.* 2009a). The other approach employs diffusive models based on Fick's second law of diffusion (Marabi and Saguy 2009; Maldonado *et al.* 2010).

Therefore, the aim of this research was to mathematically model the rehydration kinetics of dehydrated red pepper and to study the effect of process temperature on rehydration rates and quality attributes, namely, rehydration indices, antioxidant activity, firmness and glass transition during rehydration process.

MATERIALS AND METHODS

Raw Material and Drying Experiment

Red peppers were grown and harvested in Salamanca, Chile, and stored at 4.5 ± 0.2C and 92.3 ± 1.5% before processing for a maximum time period of 5 days. The samples were selected visually by color, size and freshness, with no signal of mechanical damage. Then, they were cut into slabs of 4.0 ± 0.2 mm in thickness. Hot air drying process was carried out in a pilot-scale convective tray dryer (Vega-Gálvez *et al.* 2009a,b). Drying air temperature and flow rate were kept constant at 60.0 ± 0.4C and 2.0 ± 0.2 m/s, respectively. By the end of the drying process, when the dehydrated samples reached a constant weight (equilibrium condition), they were removed and packed in polyethylene bags and stored until further use (4.5 ± 0.2C and 91.9 ± 1.3%). All measurements were done in triplicate.

Rehydration Experiments

The characteristics of selected rehydration temperatures are based on studies by Kaymak-Ertekin (2002) for green and red peppers, García-Pascual *et al.* (2006) for *Morchella esculenta*, Falade and Abbo (2007) for palm fruits, Cunningham *et al.* (2008) for potatoes, Femenia *et al.* (2000) for broccoli, Moreira *et al.* (2008) for chestnuts and Maldonado *et al.* (2010) for mangoes. In addition, most of the dried products rehydrated, principally in typical hand-processed and industrial applications, are usually rehydrated at temperatures below 80C (Krokida and Marinos-Kouris 2003). Thus, rehydration experiences were carried out at 20, 40 and 60C (±0.2C) for 600 min (final stage of the process), in order to avoid damaging the product tissue. For all assays, dried peppers (100.0 ± 2.0 g) were placed inside a flask, which contained distilled water as rehydration medium with a solid-liquid relation of 1:50. Sample moisture content was determined according to methodology AOAC No. 934.06 (AOAC 1990) using a vacuum oven (OVL570, Gallenkamp, Leicester, U.K.) and an analytic balance (Jex120, CHYO, Kyoto, Japan) of accuracy 0.0001 g. Each experiment was carried out in triplicate.

Estimation of D_{we} and Mathematical Modeling

Fick's second law was used for estimation of the diffusion coefficient (D_{we}) during rehydration process. When internal mass transfer is the controlling mechanism and one-dimensional transport in an infinite slab with constant effective diffusivity can be assumed, the solution of the Fick's second law is given by Eq. (1) according to Crank (1975). For sufficiently long process times, the first term ($n = 0$) in the series expansion of Eq. (2) gives a good estimation of the solution and can be applied to determine the water diffusion coefficients for each working temperature (Sanjuán *et al.* 2001; García-Pascual *et al.* 2006; Cunningham *et al.* 2008).

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

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

where X_w is the moisture content and D_{we} is the moisture diffusion coefficient (m^2/s), t is the drying time (s) and L is the half thickness of the slab (m). In practice, the moisture diffusion coefficient for each temperature was calculated by plotting experimental rehydration data in terms of ln X_w versus rehydration time and the D_{we} value obtained from the straight line's slope.

Regarding the empirical models that are the most widely employed because of their mathematical simplicity and utility, the following equations were used: Peleg (Peleg 1988; Sanjuán *et al.* 2001; García-Pascual *et al.* 2006; Resio *et al.* 2006; Solomon 2007; Moreira *et al.* 2008; Sobukola and Abayomi 2011), Weibull (Machado *et al.* 1998; Marabi *et al.* 2003; García-Pascual *et al.* 2006; Cunningham *et al.* 2007; Vega-Gálvez *et al.* 2009a), first-order kinetics (Chhinnan 1984; Machado *et al.* 1998; Pappas *et al.* 1999; Maskan 2001; Krokida and Marinos-Kouris 2003), exponential (Misra and Brooker 1980) and Vega-Gálvez *et al.* (2009a) model.

$$X_w = X_o + \left[\frac{t}{A + B\cdot t}\right] \quad \text{Peleg} \tag{3}$$

$$X_w = X_e + (X_o - X_e)\exp\left[-\left(\frac{t}{B}\right)^A\right] \quad \text{Weibull} \tag{4}$$

$$X = X_e + (X_o - X_e)\exp(-A\cdot t) \quad \text{First-order kinetics} \tag{5}$$

$$X_w = X_e + (X_o - X_e)\exp(-A\cdot t^B) \quad \text{Exponential model} \tag{6}$$

$$X_w = A\exp\left[\frac{-B}{(1+t)^\alpha}\right] \quad \text{Vega-Gálvez } et\ al. \text{ (2009a)} \tag{7}$$

where A, B, $\alpha > 0$

In order to determine the influence of the rehydration temperature on moisture diffusion coefficient as well as on the kinetic parameters, an Arrhenius-type equation was applied, Eq. (8) From this equation, the activation energy, E_a (kJ/mol) can be estimated by plotting ln ψ against 1/T, where ψ is the parameter to be studied (D_{we}, A and B) and ψ_o is the Arrhenius factor (García-Pascual *et al.* 2006; Kaptson *et al.* 2008; Moreira *et al.* 2008; Sobukola and Abayomi 2011).

$$\psi = \psi_o\cdot\exp\left[\frac{-E_a}{RT}\right] \tag{8}$$

Functional Properties: Rehydration Ratio and Water Holding Capacity

To study the temperature effect on the rehydration phenomenon, two typical rehydration indices were evaluated (García-Pascual *et al.* 2006; Moreira *et al.* 2008; Vega-Gálvez *et al.* 2009a). The rehydration ratio (*RR*) was calculated according to Eq. (9) and it is expressed as g absorbed water/g d.m. Water holding capacity (*WHC*) was determined by centrifuging the rehydrated samples at 4,000 rpm for 10 min at 5C in tubes provided with a centrally placed metallic mesh which allowed water to drain freely from the sample during centrifugation. *WHC* was calculated from the amount of water removed according to Eq. (10) and it is expressed as g retained water/100 g water. All measures were performed in triplicate and means were calculated for each sample.

$$RR = \frac{W_{reh}\cdot X_{reh} - W_{dried}\cdot X_{dried}}{W_{dried}\cdot(1 - X_{dried})} \tag{9}$$

$$WHC = \frac{W_{reh}\cdot X_{reh} - W_l}{W_{reh}\cdot X_{reh}}\times 100 \tag{10}$$

Determination of Firmness

The property firmness, e.g., the maximum force applied to puncture the red pepper tissue, was measured as an indicator of texture. Firmness of samples was measured using a Texture Analyzer (TA, XT2, Texture Technologies Corp., Scardale, NY). The puncture diameter was 3 mm, with a travel distance of 10 and 1.7 mm/s test speed. The maximum force was measured by making one puncture in each rehydrated pepper sample, using 20 slabs per treatment. The mean value of maximum firmness for each treatment was then calculated and the results were expressed as N/mm.

Glass Transition Measurements

The glass transition temperature (*Tg*) of rehydrated peppers was determined by using a differential scanning calorimetry (DSC) (Model DSC823e, Mettler-Toledo, Schwerzenbach, Switzerland) equipped with DSC sensor HSS7. The instrument was calibrated by using indium standard. A 10–15 mg rehydrated sample minced was placed into a Mettler-Toledo DSC pan (ME-00026763), and hermetically sealed. An empty pan was used as reference (air). The sample was first cooled to –50C at 10 K/min, and then scanned from –50 to 80C at a rate of 10 K/min to determine its thermal behavior. Before scanning the samples, a scan of two empty pans under the same test conditions was conducted to obtain baseline subtraction. *Tg* was recorded as the middle temperature in the curves of the heat flow versus temperature as reported in the previous study for low moisture foods (Slade and Levine 1995). STARe software version 9.01 was used to determine onset and midpoint temperatures for DSC glass transition.

Determination of 2,2-Diphenyl-2-picryl-hydrazyl Radical-Scavenging Activity

Free radical scavenging activity of the samples was determined using the 2,2-diphenyl-2-picryl-hydrazyl (DPPH) method (Turkmen *et al.* 2005) with some modifications. Different dilutions of the extracts were prepared in triplicate. An aliquot of 2 mL of 0.15 mM DPPH radical in ethanol was added to a test tube with 1 mL of the sample extract. The reaction mixture was vortex-mixed for 30 s and left to stand at room temperature in the dark for 20 min. The absorbance was measured at 517 nm, using a spectrophotometer (Spectronic 20 Genesys, IL). An 80% (v/v) solution of ethanol was used to calibrate the spectrophotometer. Control sample was prepared without adding extract. All solvents and reagents were purchased from Sigma (Sigma Chemical CO., St. Louis, MO). The total antioxidant activity was expressed as the percentage inhibition of the DPPH radical and was determined by Eq. (11):

$$(\%)\,TAA = \left(1 - \frac{Abs_{sample}}{Abs_{control}}\right) \times 100 \tag{11}$$

IC_{50} is defined as the concentration of substrate that brings about 50% loss of the DPPH (Locatelli *et al.* 2009). IC_{50} was expressed as μg/mL sample and *Abs* is absorbance.

Determination of Total Phenolic Content

Total phenolic content (TPC) was estimated as gallic acid equivalents as described by Folin–Ciocalteau's (FC) with modifications (Chuah *et al.* 2008). 0.5 mL aliquot of the pepper extract solution is transferred to a glass tube; 0.5 mL of reactive FC is added after 5 min.; 2 mL of Na_2CO_3 (200 g/L) is added and shaken. After 15 min of incubation at ambient temperature, 10 mL of ultrapure water was added and the formed precipitate was removed by centrifugation during 5 min at 4,000 rmp. Finally, the absorbance was measured in a spectrophotometer (Spectronic 20 Genesys) at 725 nm and compared with a gallic acid (GA) calibration curve. Results were expressed as mg GA/100 g dry matter. All reagents were purchased from Merck (Merck KGaA, Darmstadt, Germany), and all measurements were done in triplicate.

Statistical Analysis

For statistical analysis of experimental data, the software StatGraphics Plus 5.1 (Statistical Graphics Corp., Herndon, VA) was used, applying an analysis of variance to estimate any statistically significant differences at a confidence level of 95% ($P < 0.05$). In addition, the multiple range test included in the statistical program was used to prove the existence of homogeneous groups within each of the parameters analyzed. Fitting quality of the models used on the experimental data was evaluated by means of statistical tests: linear regression coefficient (R^2), sum of square error (*SSE*) Eq. (12), root mean square error (*RMSE*) Eq. (13) and chi-square (χ^2) Eq. (14).

$$SSE = \frac{1}{n}\sum_{i=1}^{n}(X_{ei} - X_{ci})^2 \tag{12}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(X_{ci} - X_{ei})^2\right]^{1/2} \tag{13}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(X_{ei} - X_{ci})^2}{n - z} \tag{14}$$

RESULTS AND DISCUSSION

Drying Process

Initial moisture content of fresh red pepper slabs was 4.88 ± 0.20 g water/g d.m. Figure 1A shows the pepper moisture content as a function of drying time at 60C. Final moisture content at the end of drying process was 0.23 ± 0.11 g water/g d.m. This moisture content represents the initial moisture content for rehydration processes.

Rehydration Kinetics

Experimental rehydration curves of red pepper slabs at the three working temperatures are shown in Fig. 1B. It is observed that the rehydration temperature has an important effect on water absorption of red pepper. During rehydration, water absorption is quick during the first 2 h for each working temperature, then the rate gradually decreases as moisture content approaches equilibrium; near equilibrium water has practically filled available pores (Bilbao-Sáinz *et al.* 2005; Maldonado *et al.* 2010). Previous reports have shown that water temperature enhanced rehydration rates (Sanjuán *et al.* 1999; Cunningham *et al.* 2008). Similar results have been reported by other authors working with green and red peppers (Kaymak-Ertekin 2002), apple, potato, carrot, banana, pepper, garlic, mushroom, onion, leek, pea, corn, pumpkin and tomato (Krokida and Marinos-Kouris 2003), apple (Bilbao-Sáinz *et al.* 2005), amaranth grain (Resio *et al.* 2006), mushroom (García-Pascual *et al.* 2006) and chestnuts (Moreira *et al.* 2008).

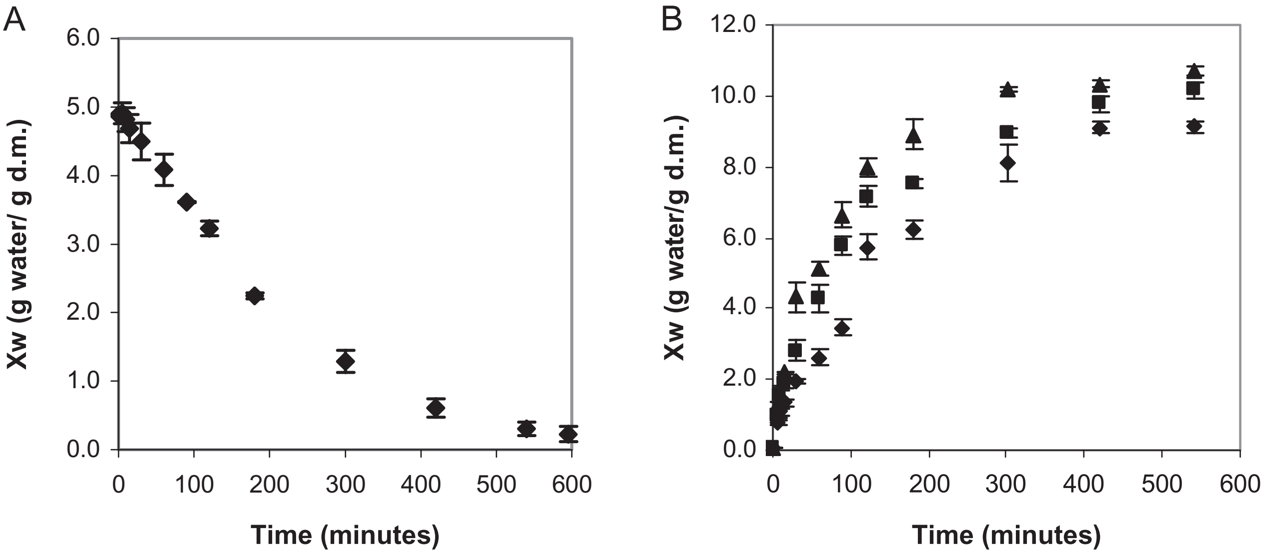

FIG. 1. (A) DRYING CURVE OF RED PEPPER SAMPLES AT 60C, (B) REHYDRATION CURVES OF RED PEPPER SAMPLES AT DIFFERENT TEMPERATURES. EXPERIMENTAL: ◆ 20C, ■ 40C, ▲ 60C

Equilibrium moisture contents of rehydration processes were 9.14 ± 0.16 g water/g d.m., 10.16 ± 0.24 g water/g d.m and 10.71 ± 0.12 g water/g d.m. at 20, 40 and 60C, respectively ($P > 0.05$). Higher rehydration temperatures resulted in higher water content of samples mainly caused by previous drying process and posterior rehydration process (Krokida and Philippopoulus 2005; Chang *et al.* 2006; Lemus-Mondaca *et al.* 2009). This behavior shows that dehydration procedure causes irreversible modifications in food structure such as reduction pores and cell partial destruction resulting in a loss of the *WHC* and increased rehydration capacity (Krokida and Maroulis 2001; Krokida and Marinos-Kouris 2003).

Estimation of D_{we} and Mathematical Modeling

Table 1 shows the mean values and the deviations of the parameters of the mathematical models applied to simulate

TABLE 1. PARAMETERS OF THE SELECTED MODELS FOR REHYDRATION SIMULATION AS A FUNCTION OF PROCESS TEMPERATURES

		Rehydration temperature (C)		
Model	Parameters	20	40	60
Fick	D_{we} (10^{-10})*	6.84 ± 0.21^{a}	7.81 ± 0.19^{b}	11.96 ± 0.56^{c}
Peleg	$A \times 10^{2}$†	6.42 ± 0.12^{a}	3.77 ± 0.14^{b}	2.73 ± 0.13^{c}
	$B \times 10^{-2}$‡	9.12 ± 0.15^{a}	8.94 ± 0.05^{a}	8.62 ± 0.11^{b}
Weibull	$A \times 10^{-1}$§	7.58 ± 0.14^{a}	7.81 ± 0.05^{b}	8.10 ± 0.14^{c}
	$B \times 10^{3}$¶	10.39 ± 1.00^{a}	6.87 ± 0.35^{b}	4.81 ± 0.21^{c}
Vega-Gálvez *et al.* (2009b)	A**	19.62 ± 0.78^{a}	26.27 ± 1.16^{b}	31.05 ± 1.66^{c}
	B††	5.83 ± 0.16^{a}	5.96 ± 0.14^{a}	6.01 ± 0.15^{a}
First-order kinetics	A (10^{-4})‡‡	1.05 ± 0.03^{a}	1.21 ± 0.03^{b}	1.85 ± 0.09^{c}
Exponential model	A x10^{-2}§	2.02 ± 0.08^{a}	2.47 ± 0.05^{b}	0.19 ± 0.02^{c}
	$B \times 10^{-1}$§	7.58 ± 0.14^{a}	7.81 ± 0.05^{b}	7.79 ± 0.10^{ab}

* m^2/s.
† min g d.m./g water.
‡ g d.m./g water.
§ dimensionless.
¶ min.
** g water/g d.m.
†† min g water/g d.m.
‡‡ min^{-1}.
Similar letters in the exponential in the same line show there are no significant differences ($P < 0.05$).

the rehydration kinetics of peppers at different rehydration temperatures. The diffusion coefficients of rehydrated sample varied within a range of 6.84–11.96 × 10^{-10} m^2/s at 20–60C. The results showed that D_{we} values increased as water rehydration temperature increased. Several works reported similar results when working with broccoli florets (0.22–99.63 × 10^{-11} m^2/s) and potato (1.52–9.32 × 10^{-10} m^2/s) (Sanjuán *et al.* 2001; Cunningham *et al.* 2008). In addition, other authors showed similar results working with food of different shapes, components and/or physical properties such as pasta (5.69–9.90 × 10^{-11} m^2/s and 4.20–8.02 × 10^{-11} m^2/s), and cowpea and groundnut seeds (2.16–59.50 × 10^{-10} m^2/s) (Cunningham *et al.* 2007; Kaptson *et al.* 2008).

The parameters *A* and *B* of Peleg model had the same trends and decreased as temperature increased from 20 to 60C. Solomon (2007) suggested that this parameter may represent water absorption rate in the early phases of rehydration process. Similar trends of this parameter have been reported by several authors working with different products: 50.8–21.3 min g d.m./g water and 47.6–18.0 and 46.7–16.2 min g d.m./g water for amaranth grain soaking in plain water and SO_2 solutions, respectively (Resio *et al.* 2006); 2.54–0.24 min g d.m./g water for lupin (Solomon 2007) and 45.55–10.58 min g d.m./g water for chestnuts (Moreira *et al.* 2008). With respect to the parameter *B*, Solomon (2007) suggested that this parameter is related to maximum capacity of water absorption or to equilibrium moisture content, in such a way that lowest values of *B* show a higher water absorption capacity. Similar behavior has been observed in amaranth grain soaking in plain water and SO_2 solutions with 1.87–1.17 g d.m./g water and 1.56–1.22 and 1.54–1.24 g d.m./g water, respectively (Resio *et al.* 2006), and in chestnuts with 1.57–0.54 g d.m./g water (Moreira *et al.* 2008).

When analyzing the *A* and *B* Weibull parameters, Table 1 shows that temperature has no influence on the parameter *A*. However, the parameter *B* shows a decreasing trend as the rehydration temperature increases. Similar behavior has been reported by other authors working with puffed breakfast cereals (Machado *et al.* 1998), mushroom (García-Pascual *et al.* 2006) and pasta (Cunningham *et al.* 2007). Some authors reported that parameter *B* represents the time needed to accomplish approximately 63% of the process, and when *B* tends to unity the Weibull distribution function reduces to first-order kinetics (Marabi *et al.* 2003; Cunningham *et al.* 2007). Meda and Ratti (2005) interpreted the rehydration results of Marabi *et al.* (2003) research using the Weibull distribution model, and they concluded that for products with high porosity (e.g., freeze-dried), capillarity controls the mass transfer, while for products with low porosity (e.g., air-dried) diffusion phenomena are predominant.

Regarding the model proposed by Vega-Gálvez *et al.* (2009a) with $\alpha = 0.3$, it was observed that the parameter *A* increases as temperature increases as well as the parameter *B* increases gradually. From the mathematical point of view, when $t = 0$, rehydration kinetics $X_w = A \exp[-B]$ approaches very accurately to initial condition X_o in all temperature ranges. On the other hand, when time (t) tends to infinite (equilibrium condition), the parameter *A* approaches to equilibrium moisture content (Vega-Gálvez *et al.* 2009a). Finally, the parameter *A* of the first-order model increased as rehydration temperature increased.

Effect on Kinetic Parameters

Influence of temperature on the kinetic parameters of the selected models was performed applying an Arrhenius-type equation ($P < 0.05$). Table 2 shows the values obtained for activation energy and Arrhenius factor for each parameter in the temperature range from 20 to 60C. These results are similar to those corresponding to activation energy of D_{we} of previous investigations working with broccoli stems (Sanjuán *et al.* 1999), mushroom (García-Pascual *et al.* 2006), pasta (Cunningham *et al.* 2007), potato (Cunningham *et al.* 2008), and cowpea and groundnut seeds (Kaptson *et al.* 2008). Regarding the activation energy related to the parameters *A* and *B*, similar results were reported by several authors working with peanut butter cereal and corn cereal (Machado *et al.* 1998); mushroom (García-Pascual *et al.* 2006); wheat, dövme and firik (Maskan 2002); and mushroom (García-Pascual *et al.* 2006).

Statistical Analysis of the Rehydration Models

Table 3 shows the statistical analyses applied to the mathematical models proposed to simulate the rehydration kinetics of dried red pepper slabs. In general, all proposed models showed a good fit with values close to zero for *SSE*, *RMSE* and χ^2. This good fit by the rehydration models may be due to the possession of empirical parameters, which is coupled to each exponential function. Thus, and according to these results,

TABLE 2. PARAMETERS OF THE ARRHENIUS RELATIONSHIP

Model	Parameter	Arrhenius factor (m^2/s)	E_a (kJ/mol)
Fick	D_{we}	1.53×10^{-7}	13.28
Peleg	*A*	4.90×10^{-1}	17.44
	B	5.74×10^{-2}	1.13
Weibull	*A*	1.90×10^{0}	2.24
	B	8.99×10^{0}	17.16
Vega-Gálvez *et al.* (2009b)	*A*	9.28×10^{2}	9.36
	B	7.60×10^{0}	0.64
First-order kinetics	*A*	1.12×10^{1}	0.01
Exponential model	*A*	2.49×10^{-10}	46.42
	B	5.82×10^{-1}	0.98

TABLE 3. STATISTICAL ANALYSIS OF THE SELECTED MODEL FOR REHYDRATION SIMULATION AS A FUNCTION OF PROCESS TEMPERATURES

Model	Statistical	Rehydration temperature (C) 20	40	60
Fick	R^2	9.58×10^{-1}	9.81×10^{-1}	9.96×10^{-1}
	SSE	2.10×10^{-1}	2.03×10^{-1}	1.62×10^{-1}
	RMSE	4.58×10^{-1}	4.50×10^{-1}	4.03×10^{-1}
	χ^2	2.52×10^{-1}	2.43×10^{-1}	1.95×10^{-1}
Peleg	R^2	9.15×10^{-1}	9.78×10^{-1}	9.87×10^{-1}
	SSE	1.70×10^{-4}	1.72×10^{-5}	1.35×10^{-5}
	RMSE	1.31×10^{-2}	4.17×10^{-3}	3.68×10^{-3}
	χ^2	2.05×10^{-4}	2.07×10^{-5}	1.62×10^{-5}
Weibull	R^2	9.57×10^{-1}	9.91×10^{-1}	9.89×10^{-1}
	SSE	2.38×10^{-5}	2.75×10^{-6}	7.45×10^{-6}
	RMSE	4.88×10^{-3}	1.66×10^{-3}	2.73×10^{-3}
	χ^2	2.86×10^{-5}	3.31×10^{-6}	8.94×10^{-6}
Vega-Gálvez *et al.* (2009b)	R^2	9.83×10^{-1}	9.97×10^{-1}	9.91×10^{-1}
	SSE	1.12×10^{-3}	1.94×10^{-4}	1.90×10^{-3}
	RMSE	3.35×10^{-2}	1.39×10^{-2}	4.36×10^{-2}
	χ^2	1.12×10^{-3}	1.94×10^{-4}	1.90×10^{-3}
First-order kinetics	R^2	9.85×10^{-1}	9.81×10^{-1}	9.81×10^{-1}
	SSE	7.24×10^{-5}	1.50×10^{-3}	3.80×10^{-4}
	RMSE	8.51×10^{-3}	3.88×10^{-2}	1.95×10^{-2}
	χ^2	8.69×10^{-5}	1.80×10^{-3}	4.56×10^{-4}
Exponential model	R^2	9.57×10^{-1}	9.91×10^{-1}	9.72×10^{-1}
	SSE	2.62×10^{-5}	4.64×10^{-6}	8.94×10^{-6}
	RMSE	5.11×10^{-3}	2.15×10^{-3}	2.99×10^{-3}
	χ^2	3.14×10^{-5}	5.56×10^{-6}	1.07×10^{-5}

the models that best fitted experimental data were Weibull followed by the exponential, Peleg and first-order kinetics. Figure 2A–F shows the experimental and the simulated rehydration kinetics at the three process temperatures. Figure 2A,D confirms that Fick and Vega-Gálvez *et al.* (2009a) models do not provide a good fit to experimental data during all rehydration, although Fick's model predicted the final moisture content (X_e) as accurately as Weibull model. In Fig. 2C,F, it is observed that the models that best fit the experimental data for the rehydration process were Weibull and exponential models, which agrees with the results of the statistical tests applied. Several authors reported similar results when studying rehydration kinetics of different foods like puffed breakfast cereals (Machado *et al.* 1998), carrot (Marabi *et al.* 2003), mushroom (García-Pascual *et al.* 2006) and pasta (Cunningham *et al.* 2007). Marabi *et al.* (2003) suggest that the utilization of Weibull distribution showed an excellent fit for the description of rehydration of a variety of dried foods, and adequately described rehydration processes controlled by different mechanisms which included internal diffusion, external convection and relaxation.

RR and *WHC*

It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption (Kaymak-Ertekin 2002; Krokida and Philippopoulus 2005). Figure 3 presents the behavior of the *RR* as well as the *WHC* for each rehydration temperature. The *WHC* decreased as the air temperature increased ($P < 0.05$). The maximum *WHC* was 38.6 ± 0.2 g retained water/100 g water at 40C which implies that this drying temperature causes tissue structure damage; thus, the pepper dehydrated at this temperature retained a great amount of water. On the other hand, samples dried at 60C have reduced their *WHC*, thereby preventing the complete rehydration of the dried product. Similar investigations reported that drying temperature is the main factor affecting *WHC* (Vega-Galvez *et al.* 2009a,b). In the same figure, *RR* was affected by the rehydration temperatures, because absorbed water decreased with temperature from 20 to 40C and increased the water absorbed at 60C. However, *RR* showed significant differences ($P > 0.05$). The lowest *RR* value was 4.53 ± 0.12 g absorbed water/g d.m. at 40C. This could be explained due to cellular structure damage resulting in modifications of osmotic properties of the cell as well as lower diffusion of water through the surface during rehydration (Kaymak-Ertekin 2002).

Effect on Firmness and Glass Transition Temperature

Firmness is one of the most desirable attributes in fresh as well as in rehydrated peppers (Castro *et al.* 2008). The behavior of this physical property as affected by drying temperature is

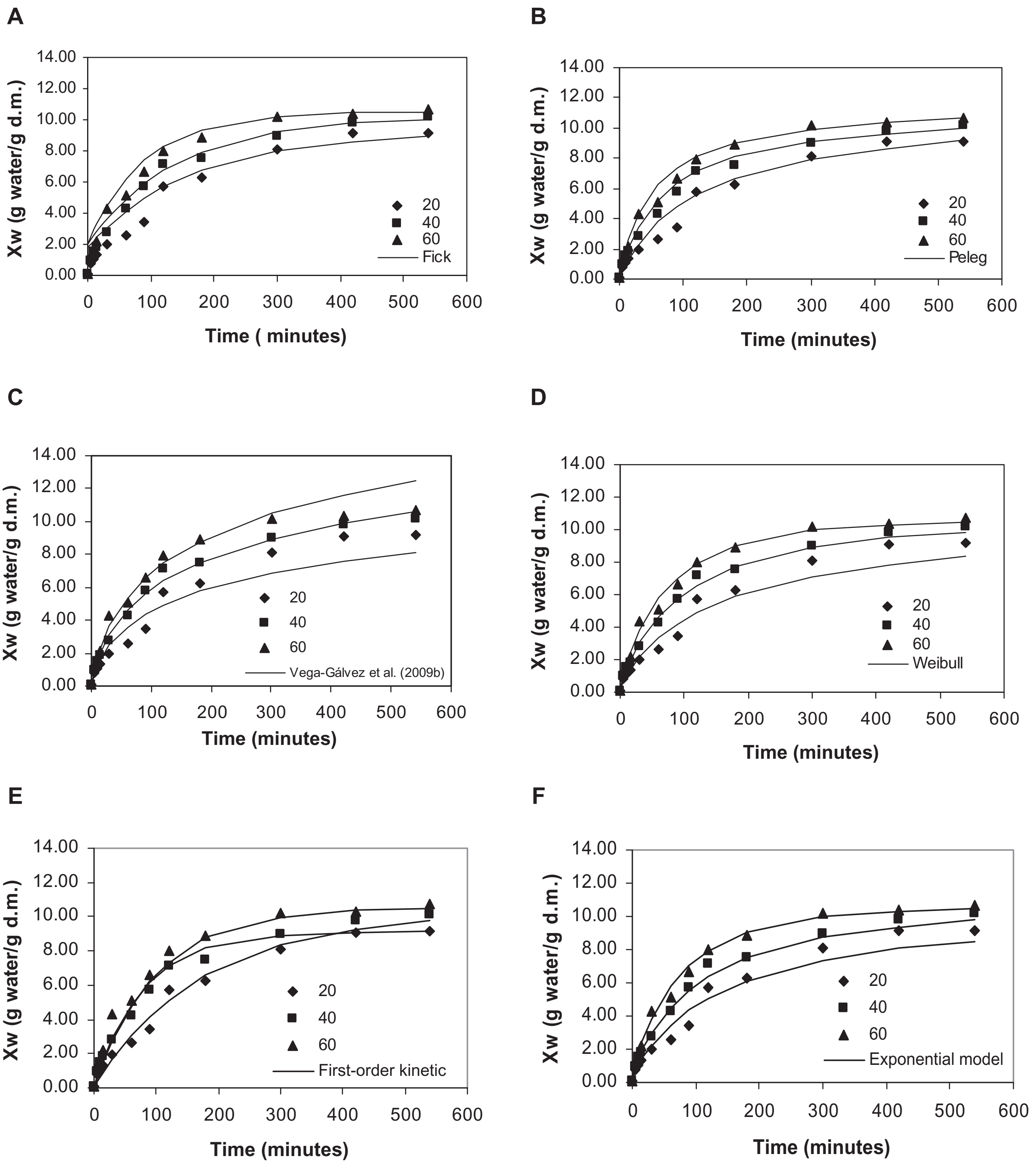

FIG. 2. EXPERIMENTAL AND ESTIMATED MOISTURE CONTENT FOR (A) FICK, (B) PELEG, (C) WEIBULL MODELS, AND (D) NEW PROPOSED MODEL, (E) FIRST-ORDER KINETIC, (F) EXPONENTIAL MODEL

illustrated in Fig. 4. It can be observed that rehydration temperature influences this textural property presenting a maximum decrease at 60C compared with the fresh sample ($P < 0.05$). Every process is detrimental to integrity of plant tissue, particularly cellular membranes. Accordingly, increasing rehydration temperature causes a deterioration of texture promoting a significant loss of mechanical resistance in the samples. This excessive softening of tissues alters the mass

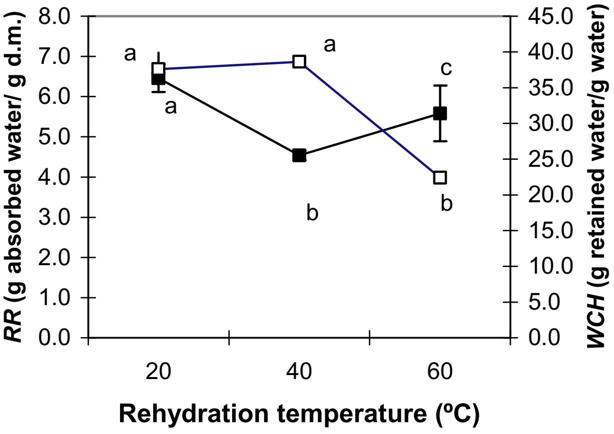

FIG. 3 EFFECT OF REHYDRATION TEMPERATURE ON REHYDRATION RATIO (*RR*) AND WATER HOLDING CAPACITY (*WHC*) FOR RED PEPPER SAMPLES. EXPERIMENTAL: ■, *RR*, □, *WHC*
Identical letters above the bars indicate no significant difference.

transfer ability of the system (Maldonado *et al.* 2010). Several authors have postulated that the physicochemical basis for the structural deformation was the loss of selective semipermeability of the cytoplasmic membranes and the resultant loss of turgor pressure in the cell during thermal processing (Papageorge *et al.* 2003; Krokida and Philippoulos 2005; Castro *et al.* 2008).

In order to corroborate that the observed water uptake behavior is related to structural collapse of dried peppers during rehydration, the glass transition concept was employed, because it is necessary to better understand physical deterioration during thermal processing (Roos 2009). According to this concept, a significant structural disruption can be noticed only if the water bath temperature is higher than the glass transition temperature (*Tg*) of the material at that particular moisture content (Marques *et al.* 2009). *Tg* value for dried pepper at moisture content of 0.23 g water/ g d.m. was −33.3C. On application of the principle relating the value of *Tg* to the collapse of the product, it could be inferred that peppers having a *Tg* value lower than the water bath temperatures (20, 40 and 60C) are susceptible to structural disruption during rehydration, i.e., a reduction in its porosity (Marques *et al.* 2009). Moreover, dried peppers were rehydrated until saturation according to Fig. 1B and the changes in the values of the *Tg* can be observed in Fig. 4. In all rehydration process, the degree of amorphous fractions in the powder is influenced by pretreatment conditions, compositions and properties of the individual ingredients (Bhandari and Adhikari 2009). Although values of *Tg* increased in rehydrated samples, the state of pepper samples corresponds to rubber conditions rather than glass, leading to softening of the final product which is observed in Fig. 4 (Kasapis 2005). Quantifying the mobility changes induced by glass transition may be the route for the elucidation of the link between process and product quality (Telis and Sobral 2002).

Effect on Antioxidant Activity

Foods of plant origin supply our diet with antioxidants in large amounts such as phenolic compounds which act as primary antioxidants or free radical terminators (Chang *et al.* 2006; Tabart *et al.* 2009). Peppers contain numerous phenolic compounds, and not all of the genotypes may contain a similar profile or relative proportions of these compounds within the profile. Differences in these profiles may subse-

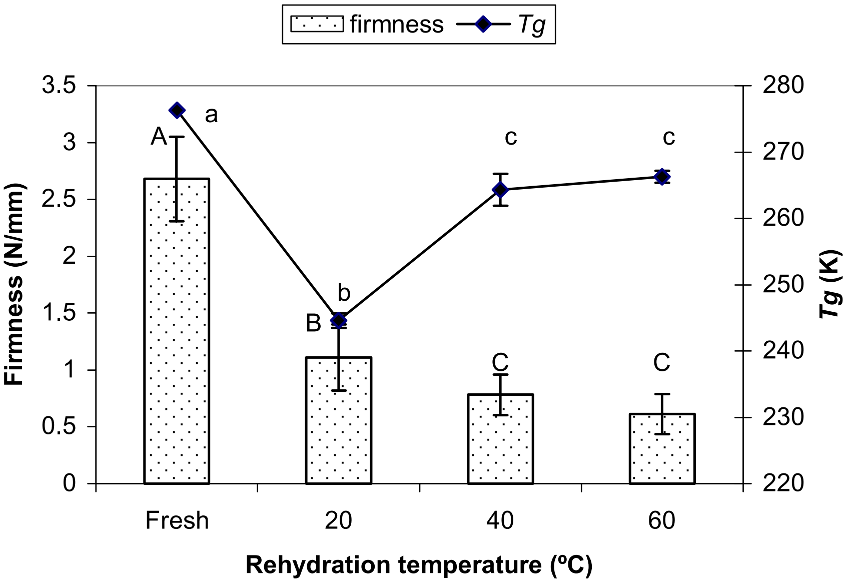

FIG. 4. EFFECT OF REHYDRATION TEMPERATURE ON FIRMNESS AND GLASS TRANSITION TEMPERATURE OF FRESH AND REHYDRATED RED PEPPER SAMPLES. EXPERIMENTAL: BAR, FIRMNESS; ◆, *TG*
Identical letters above the bars indicate no significant difference.

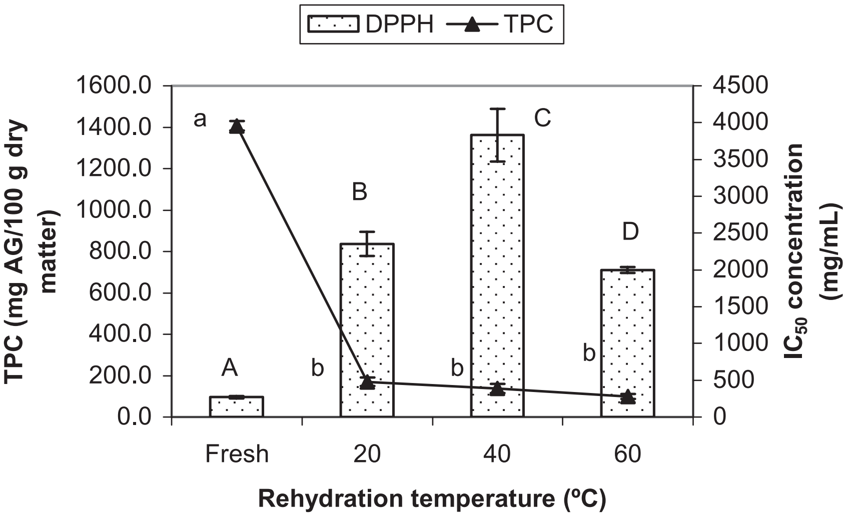

FIG. 5. EFFECT OF REHYDRATION TEMPERATURE ON FREE RADICAL SCAVENGING ACTIVITY [2,2-diphenyl-2-picryl-hydrazyl (DPPH)] AND TOTAL PHENOLIC COMPOUNDS (TPC) OF FRESH AND REHYDRATED RED PEPPER SAMPLES. EXPERIMENTAL: BAR, FIRMNESS; ▲, TPC
Identical letters above the bars indicate no significant difference.

quently result in complex changes in antioxidant activity or other bioactivities (Deepa *et al.* 2007). It can be observed (Fig. 5) that an increase in rehydration temperature has an important effect on the TPC ($P < 0.05$). Reductions in TPC during process may be ascribed to the binding of polyphenols with other compounds (proteins) or the alterations in the chemical structure of polyphenols which cannot be extracted and determined by available methods (Chan *et al.* 2009; Qu *et al.* 2010).

The DPPH radical scavenging activity was investigated based on rehydration temperature ($P < 0.05$) as also observed in Fig. 5, where rehydration at high temperatures (e.g., 60C) shows higher antioxidant activity rather than at low temperatures (e.g., 20 and 40C). This enhancement at high rehydration temperature could be explained due to generation and accumulation of Maillard-derived melanoidins having a varying degree of antioxidant activity (Vega-Gálvez *et al.* 2009b). Thus, the higher temperature promotes the water penetration and immediately more antioxidants are released, resulting in a high DPPH activity (Podsedek 2007). Other related studies on thermally processed fruits have shown that heating caused an increase in their overall antioxidant potential due to production of nonnutrient antioxidants and it is concluded that although natural antioxidants are lost during heating, the overall antioxidant properties of foods could be maintained or enhanced by the development of new antioxidants (Lopez *et al.* 2010).

CONCLUSIONS

Effects of rehydration temperatures (20, 40 and 60C) on rehydration kinetics as well as quality attributes of dried peppers were investigated in this work. The rehydration temperature was found to influence the rehydration rates and the equilibrium moisture content in a positive way. Based on simulation results and statistical tests, Weibull model and followed by the exponential model were the equations that best fit the experimental rehydration data. D_{we} increased with process temperature from 6.84 to 11.96×10^{-10} m^2/s, for the range of temperatures studied. Activation energy of 13.28 kJ/mol was obtained for D_{we} by means of an Arrhenius-type equation. The *RR* decreased with temperature showing a lower *RR* of 4.53 ± 0.12 g absorbed water/g d.m. at 40C. The maximum *WHC* was 38.6 ± 0.2 g retained water/100 g water at 40C. Although rehydrated samples increased the *Tg* values, the state of pepper samples corresponds to rubber conditions rather than glass, leading to softening of the final product. TPC decreased as rehydration temperature increased. However, the radical scavenging activity was higher at temperatures (e.g., 60C) rather than at low temperatures (e.g., 20 and 40C). These results clearly highlight the impact of drying and rehydration temperature on rehydration kinetics and quality of final product. Thus, combining the drying and rehydration processes and the resulting quality attributes to meet consumer expectations is not only recommended but also probably the only way to truly optimize the rehydration process.

NOMENCLATURE

A, B, α	parameters of rehydration models
a_w	water activity (dimensionless)
D_{we}	effective diffusivity (m^2/s)
E_a	activation energy (kJ/mol)
L	half thickness (m)
n	number of data
R	universal gas constant (8.314 J/mol K)
t	process time (min)
T	absolute temperature(K)
z	number of constants

W_l	drained liquid weight after centrifugation (g)
W_{reh}	sample weight after rehydration (g)
W_{dried}	sample weight after drying (g)
X_{ci}	calculated moisture content (g water/g d.m.)
X_{dried}	sample moisture content after drying (g water/g d.m.)
X_e	equilibrium moisture content (g water/g d.m.)
X_{ei}	experimental moisture content (g water/g d.m.)
X_o	initial moisture content (g water/g d.m.)
X_{reh}	sample moisture content after rehydration (g water/g d.m.)
X_w	moisture content (g water/g d.m.)

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