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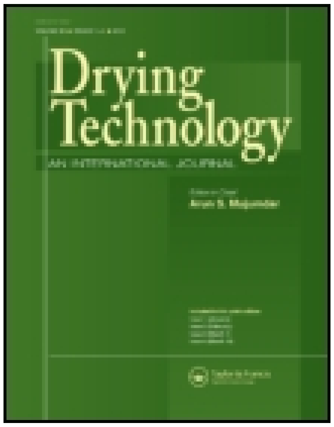

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Rehydration of *Rosa rubiginosa* Fruits Dried with Hot Air

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The effect of perforation, drying temperature, and rehydration temperature on the rehydration kinetics of *Rosa rubiginosa* fruits was investigated. Before drying, half of the fruit sample was perforated three times at equidistant points along the equatorial plane of the fruit, in order to speed up the drying process. Samples were dried at various air temperatures (60, 70, and 80°C), with an air velocity of 5 m/s and 5% relative humidity. Then, dried samples were rehydrated at different temperatures (20, 40, 60, and 80°C). The rehydration kinetics was fitted by two empirical models, Peleg and Weibull, and both represented the phenomenon well, in perforated and nonperforated fruits. Regardless of the drying temperature, the higher the rehydration temperature of rose hip fruits, perforated or not, the higher the water absorption capacity. Temperature dependence of the kinetic parameters was $E_a = 47.5$ kJ/mol (Peleg) and 55.9 kJ/mol (Weibull) for nonperforated fruits and $E_a = 40.1$ kJ/mol (Peleg) and 45.5 kJ/mol (Weibull) for perforated fruits; thus, perforated fruits were influenced more by rehydration temperature than nonperforated fruits. Perforated fruits rehydrated 30% faster than nonperforated fruits.

Keywords Modeling; Pretreatment; Rehydration; *Rosa rubiginosa* fruits

INTRODUCTION

Rehydration is a complex process whose objective is the restoration of the properties of fresh material when a dry product is in contact with water.[1–3] Many researchers have studied the factors that affect the speed and capacity of rehydration. Some studies suggest that the ability of the material to rehydrate depends on the rehydration conditions,[4] such as temperature, time, and amount of water present. However, there is no consistency in the procedure or nomenclature used. The ratio of dry material to mass of water varies from 1:5 to 1:50, the temperature used varies from ambient temperature to 80°C, and the time varies from 2 min to 24 h.

Temperature affects the rate of water absorption, because the speed increases with the temperature, but very high temperatures cause rapid destruction of the cell membrane.

When evaluating the physical properties and the quality of fresh and processed food materials, it is important to analyze the changes in microstructure.[5] In the rehydration of beans, Ogwal and Davis[6] observed that the time required to reach the maximum capacity of absorption decreased at high temperatures. Garcia-Pascual et al.[7] also noted that the rate of water absorption in edible mushrooms increased with temperature. However, Sopade et al.[8] observed no significant effect of temperature on the maximum capacity of water absorption during rehydration in products such as maize, millet, and sorghum, which shows that each product behaves in a different way due to the characteristics of its structural matrix and the condition in which it is.

The drying conditions also affect the rehydration capacity of various products to a large extent. Research relating the duration and severity of treatment during convective drying to the degree and speed of rehydration obtained a greater speed of rehydration and greater absorption capacity by reducing the drying time.[9]

Previous studies have shown the influence of the structure and composition of the feedstock on rehydration. Damage that occurs at the structural level during drying is critical in subsequent rehydration.[3,10] Histological studies indicate selective loss of semipermeability of the cytoplasmic membranes to cause deformation and structural collapse. Moreover, the functionality of the various components will influence different heights and in turn is affected by other factors such as temperature.[3] The degree of hydration depends on the degree of disruption of the cellular structure. Krokida and Marinos-Kouris[11] and Lewicki et al.[12] found that during drying the irreversible disruption of the cellular structure is produced, the integrity is lost, and a dense structure of capillaries and shrunken and destroyed vessels is formed due to the reduction in hydrophilic properties, resulting in a failure in the water retention of the rehydrated product. The volumetric shrinkage of the product during drying due to evaporation of the water alters the surface structure, and gaps are produced while

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the inside is better preserved. It is expected that both the microstructure and the porosity of pores itself play an important role in the mechanism of rehydration (capillarity, absorption, distribution).[3]

Many fruits (blueberries, cranberries, tomatoes, rosehips, grapes, etc.) have a waxy cuticle on the skin that protects them from external factors (e.g., parasites). This cuticle controls the diffusion of water from the interior to the surface of the fruit during the drying process. The drying of *Rosa rubiginosa* fruits is very slow because it has a very hard and impermeable cuticle due to its composition and the waxy coating. With air at 70°C, drying time usually varies between 10 and 15 h, which limits the productivity of the equipment as well as the processable amount during this fruit season, and energy use is inefficient.[13] To accelerate the drying process and minimize changes in product quality, the fruit may be pretreated chemically or mechanically.[14] The chemical and mechanical pretreatments applied before drying remove or modify the waxy cuticle, reducing its impermeability to water, thereby increasing the drying rate at the surface of the waxy fruit.[15,16] Mabellini et al.[13] and Ohaco Domínguez[17] studied different chemical and physical pretreatments of these fruits and concluded that mechanical perforation is optimum, because it reduces the drying time by 58% while preserving the quality of the final product.

The main objectives of this work were to (1) determine rehydration curves experimentally as a function of temperature of drying air and temperature of rehydration and (2) propose rehydration kinetics of rosehip fruits, both nonperforated and perforated, using empirical models.

MATERIALS AND METHODS

Raw Material

Fruits of wild rosehip (*Rosa rubiginosa* L.) used in this work were harvested in El Bolsón, Province of Río Negro, Argentina. The fruits had an average water content of 53.9 ± 3.3% on a wet basis and were kept refrigerated at 2°C and 90% relative humidity until use. Fruits were selected by color and size.

Perforation

Before drying, fruits were perforated in order to speed up the drying process. This consisted of three slightly deep perforations at equidistant points along the equatorial plane of the fruit, manually made with a 0.00111-m-diameter metallic punch.[17]

Drying Equipment

Experiments were carried out in a purpose-built pilot-scale dryer, consisting basically of a closed system with forced air circulation and appropriate control of drying variables. Weight loss was controlled with a digital balance (0.01 g). Air temperature was automatically controlled with an LM35 microcontroller and data logger (Ing. Valgoi, Villa Regina, Río Negro, Argentina), with accuracy ±0.1°C in the range 0–150°C. Velocity of the drying air was measured using a digital thermo-anemometer (CFM Thermo Anemometer EXTECH Instruments, Waltham, MA, USA) and relative humidity was measured using a Hygro Palm hygrometer (Rotronic Instruments, West Sussex, UK). All variables were measured at the drying chamber inlet. Fruits were placed in a single layer on a 0.22-m-diameter and 0.10-m-high perforated shelf.

To evaluate the drying kinetics of fruits, perforated or not, they were dried at three oven temperatures of 60, 70, and 80°C, at relative humidity of 5% and air speed in the dryer of 5 m/s.[18] Weight in grams was measured using an Ohaus Electronic Balance (Ohaus Scale, Ontario, Canada). Samples were dried until constant weight in an oven at 102°C to determine dry mass.[19]

Rehydration Procedures

Both and nonperforated fruits (approximately 4 g) were rehydrated in a water bath at constant temperature. The samples were removed from the bath to different periods of immersion and were weighed in the balance mentioned above, after excess surface water was drained and the fruits were dried with tissue paper. The performance of the samples was evaluated as a function of temperature of the rehydration water (20, 40, 60, and 80°C).

Modeling of Rehydration Kinetics

Peleg's Model

Peleg's model[20] is presented in Eq. (1):

$$X = X_0 + \frac{t}{k_1 + k_2 t}, \tag{1}$$

where t is the drying time (h), X is the moisture content (kg water/kg dry matter) at time t, X_0 is the initial moisture content (kg water/kg dry matter), k_1 is a kinetic constant (h kg dry solids/kg water) and represents the rate of absorption of water in the early stages of the rehydration process, and k_2 is a second parameter of this model (kg dry solids/kg water), which is related to the maximum capacity of water absorption.[4,21] When the rehydration time was longer than 5 h the equilibrium moisture content (X_e) was calculated as given in Eq. (2)[20]:

$$X_e = X_0 + \frac{1}{k_2}. \tag{2}$$

In the rehydration process, unlike the drying process, the equilibrium moisture content cannot be measured independently, because many changes can occur with long steeping times. These changes make it difficult to establish when equilibrium is reached. A more suitable approach is to incorporate the equilibrium moisture content as an aditional parameter in the model proposed by Weibull.[19] The parameters of this model were obtained by nonlinear regression with Systat 5.0 software.

Weibull's Model

The other model analyzed was proposed by Weibull and is presented in Eq. (3):

$$X = X_e + (X_0 - X_e) \cdot e^{-\left(\frac{t}{\beta}\right)^{\alpha}}, \tag{3}$$

where α and β are the kinetic parameters of this model. The α parameter is an index of product behavior during rehydration; when the α value increases, the initial speed of the rehydration process decreases. The β parameter is related to the process kinetics and presents an inverse relation with the rehydration speed.[4,23] The parameters of this model were obtained by nonlinear regression with Systat 5.0 software.

Determination of Goodness of the Settings

Several methods of statistical analysis were used to select the best model to describe the experimental rehydration curves, including the correlation coefficient (r^2; Eq. (4)), the reduction of the sum of the square (SSE; Eq. (5)), the root mean square error (RMSE; Eq. (6)), the function χ^2 (Eq. (7)), and the standard error (SE$_{\bar{X}}$; Eq. (8)). The approach taken as an optimal method for assessing the quality of the fit to the model proposed was to have the lowest values of SSE, SE$_{\bar{X}}$, RMSE, and χ^2 and the highest values of r^2.[13,16,23–26]

$$r^2 = \sum_{i=1}^{N} \left(x^*_{ci} - \overline{x^*_{ei}}\right)^2 \Big/ \sum_{i=1}^{N} \left(x^*_{ei} - \overline{x^*_{ei}}\right)^2 \tag{4}$$

$$SSE = \frac{1}{N} \sum_{i=1}^{N} \left(x^*_{ei} - x^*_{ci}\right)^2 \tag{5}$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(x^*_{ei} - x^*_{ci}\right)^2\right]^{\frac{1}{2}} \tag{6}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(x^*_{ei} - x^*_{ci}\right)^2}{N - z} \tag{7}$$

$$SE_{\bar{X}} = \frac{s}{\sqrt{N}}, \tag{8}$$

where x^*_{ei} and x^*_{ci} are dimensionless moisture contents, experimental and estimated, respectively; N is the number of observations; s is the standard deviation; and z is the number of constants of the model.

Effect of Temperature

To evaluate the dependence of the kinetic parameters on the temperature of rehydration, the Arrhenius equation was used,[4] where E_a is the activation energy (kJ/mol), ψ_0 is the pre-exponential factor (m^2/s), R is the gas constant (8.314 J mol^{-1} K^{-1}), and T is the temperature (K) (Eq. (9)).

$$\psi = \psi_0 e^{\frac{-E_a}{RT}} \tag{9}$$

E_a was obtained from the slope of the Arrhenius plot, ln (D_{eff}) vs. $1/T$.

Degree of Swelling

The geometric measures of each experimental condition were studied (axial and equatorial radius) in four fruits with a caliper. Using Eq. (10), the volume of the fruit was calculated, which corresponds to the volume of an ellipsoid of revolution (the shape that the particles tend to take on during rehydration):

$$V = \frac{4}{3}\pi R r^2. \tag{10}$$

Statistical Methods

All results reported here are averages of triplicate determinations. Results were examined by analysis of variance ($\alpha = 0.05$) and the conclusions were confirmed by least significant difference test.

RESULTS AND DISCUSSION

Effect of Drying Temperature on Rehydration

Tables 1 and 2 show the rehydration for perforated and nonperforated fruits, dehydrated at different air temperatures (60, 70, and 80°C) and rehydrated at different water temperatures (20, 40, 60 and 80°C), depending on the rehydration time. There is a first segment with a linear trend, because the dehydrated sample contained molecules that formed hydrogen bridges in the hydrophilic regions, which in contact with water molecules were retained by Van der Waals interactions saturating the surface pores of the dehydrated samples and incorporated to the solid phase.[27] The second period shows an exponential trend for the moisture absorption, corresponding to a typical diffusion phenomenon, when water diffused inside the solid phase, dissolving solutes and forming the liquid phase. After enough water was diffused the system reached equilibrium.

In general, it was found that the temperature of the water affected the speed of hydration and equilibrium moisture in a positive way.[4,27,28] Tables 1 and 2 show that

TABLE 1
Moisture content (db) of nonperforated (NP) and perforated (P) fruits, dehydrated (60, 70, and 80°C) and rehydrated (60 and 80°C)

Rehyd. temp. (°C)	Rehyd. time (h)	X(db) NP 60°C	P 60°C	NP 70°C	P 70°C	NP 80°C	P 80°C
80	0	0.17	0.16	0.13	0.09	0.15	0.11
	1	0.37	0.36	0.33	0.37	0.39	0.36
	2	0.48	0.56	0.42	0.51	0.49	0.48
	4	0.71	0.74	0.59	0.71	0.72	0.70
	6.5	0.92	0.94	0.81	0.93	0.95	0.91
	10.5	1.15	1.09	1.02	1.07	1.23	1.16
	12	1.18	1.09	1.07	1.07	1.31	1.21
	17	1.18	1.09	1.07	1.07	1.41	1.23
	20	1.18	1.09	1.07	1.07	1.41	1.23
60	0	0.17	0.16	0.13	0.09	0.15	0.11
	2	0.33	0.32	0.29	0.30	0.35	0.34
	4.5	0.38	0.42	0.40	0.43	0.46	0.49
	7	0.49	0.56	0.47	0.61	0.59	0.62
	11	0.63	0.71	0.61	0.74	0.70	0.77
	15	0.74	0.85	0.69	0.84	0.81	0.87
	22	0.87	1.00	0.84	1.00	0.95	1.03
	25	0.93	1.03	0.87	1.03	1.01	1.05
	28	0.98	1.08	0.92	1.05	1.03	1.05
	33	1.01	1.08	0.98	1.08	1.06	1.05
	38	1.01	1.08	0.98	1.08	1.06	1.05

TABLE 2
Moisture content (db) of nonperforated (NP) and perforated (P) fruits, dehydrated (60, 70, and 80°C) and rehydrated (20 and 40°C)

Rehyd. temp. (°C)	Rehyd. time (h)	X(db) NP 60°C	P 60°C	NP 70°C	P 70°C	NP 80°C	P 80°C
40	0	0.17	0.16	0.13	0.09	0.15	0.11
	3	0.24	0.28	0.20	0.19	0.22	0.24
	8	0.31	0.41	0.30	0.35	0.34	0.37
	11.5	0.36	0.48	0.35	0.43	0.40	0.45
	24	0.53	0.78	0.52	0.66	0.58	0.71
	31.5	0.65	0.90	0.61	0.82	0.70	0.84
	48	0.80	1.07	0.76	0.97	0.85	1.02
	52.75	0.85	1.12	0.83	1.03	0.94	1.07
	58.5	0.90	1.15	0.88	1.08	1.01	1.13
	71	0.99	1.17	0.98	1.13	1.10	1.20
	76	1.04	1.18	1.00	1.16	1.16	1.23
	82	1.09	1.20	1.05	1.18	1.19	1.28
	87	1.14	1.22	1.07	1.21	1.22	1.31
	95	1.14	1.22	1.07	1.21	1.22	1.31
20	0	0.17	0.16	0.13	0.09	0.15	0.11
	8	0.22	0.27	0.19	0.22	0.25	0.27
	11.5	0.24	0.33	0.21	0.28	0.28	0.30
	24	0.34	0.50	0.27	0.52	0.38	0.49
	31.5	0.37	0.58	0.32	0.62	0.41	0.61
	47	0.43	0.73	0.38	0.76	0.51	0.73
	52.5	0.47	0.78	0.40	0.81	0.57	0.80
	58.5	0.52	0.84	0.43	0.86	0.60	0.89
	71	0.60	0.92	0.48	0.94	0.67	0.98
	76	0.64	0.98	0.51	0.97	0.70	1.01
	82	0.67	1.04	0.54	0.99	0.73	1.07
	95	0.72	1.07	0.56	1.07	0.76	1.11
	103	0.72	1.07	0.56	1.07	0.76	1.11

the temperature of the rehydration water exerted a marked effect on the rehydration speed of rosehip fruits and on the amount of water absorbed by these fruits. These two parameters increased with temperature in all cases studied. Similar findings have been reported by other authors working with different foods: García-Pascual et al.[22] with edible mushrooms; Kaymak-Ertekin[29] with green and red pepper; Krokida and Marinos-Kouris[11] with apple, potato, carrot, banana, pepper, garlic, onion, zucchini, and tomato; and Goula and Adamopoulos[4] with tomato.

Effect of Rehydration Temperature on Rehydration

Figure 1 shows the experimental curves of rehydration for both nonperforated and perforated rosehip fruits dehydrated at different temperatures (60, 70, and 80°C) and rehydrated at constant temperature (40 and 80°C) as a function of the rehydration time. It was noted that the perforation effect was higher when the rehydration temperature decreased. At 80°C there was no difference between nonperforated and perforated fruits, probably because the high temperature of rehydration produced a type of cooking, by elimination of the waxy cuticle. At 40°C it was noted that the drying temperature did not affect the rehydration for both nonperforated and perforated fruits. The effect of temperature on rehydration was not as marked in the perforated fruits as in the nonperforated fruits for all dehydration temperatures (60, 70, and 80°C). This was attributed to the perforation, which facilitated the incorporation of water by the rupture of the impermeable cuticle.

The equilibrium moisture content of the rehydrated rosehip was higher than that of the fresh fruits, a phenomenon attributed to the incorporation of water in the free spaces generated by drying in the fruit center, occupied by seeds and hairs. This behavior was evident in both nonperforated and perforated samples. In order to simulate the rehydration kinetics, all of the obtained experimental moisture content data were used. However, the need to limit the range of validity of simulation models to

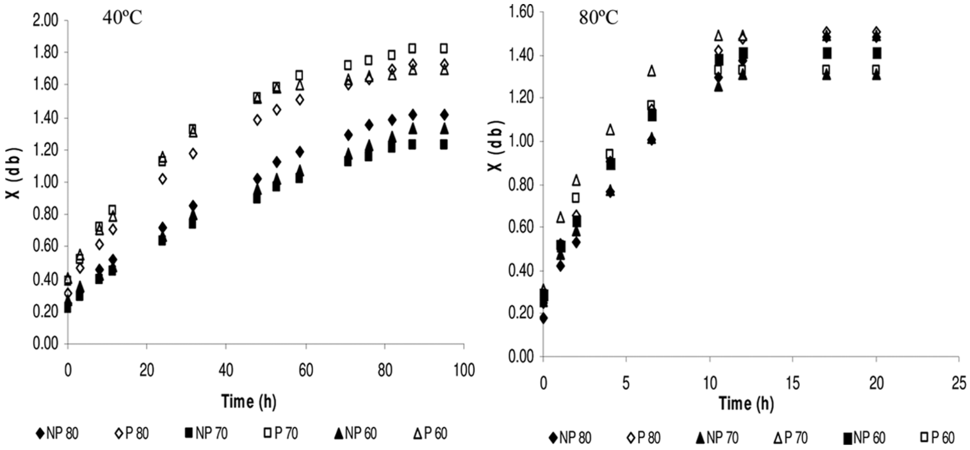

FIG. 1. Experimental rehydration curves for nonperforated (NP) and perforated fruits (P) rehydrated at 40 and 80°C as a function of dehydration temperature.

optimally control the rehydration process of these fruits must be emphasized.

Modeling of Rehydration Curves

Peleg Model

The parameter k_1 showed a tendency to decrease with an increase in rehydration temperature between 20 and 80°C, regardless of the drying temperature, in both nonperforated and perforated fruits. This suggests a higher speed of absorption of water at a higher temperature of rehydration under the present experimental conditions. The constant k_2 tended to increase along with the temperature of rehydration. These results are not in agreement with those reported by some authors, who came to the conclusion that k_2 is independent of temperature, taking into account that it is a characteristic parameter of each material.[4,30,31] However, in accordance with the results of other authors, k_2 can change with the temperature if there is a change in the media. This conclusion was reported by Lopez et al.[32] for hazelnuts, Maskan[33] for wheat products, Sanjuán et al.[34] for stalks of broccoli, Turhan et al.[35] for chickpeas, and Bakalis and Karathanos[36] for some fruits. The water absorption capacity of biological products depends on the type of material, ultrastructure of the tissue, and chemical composition of the cells. Therefore, changes in the chemical or physical structure of the materials may promote variations in X_e with respect to the oral rehydration therapy or to the temperature of the water soak and, of course, k_2 should vary.[22] In addition, the values obtained confirm that rehydration of the pretreated samples was more rapid than rehydration of the untreated ones, regardless of the drying temperature.

In the literature[10,11,34] the results of the effect of rehydration temperature on the equilibrium moisture content (X_e) depend on the product. Some researchers have pointed out that X_e decreased as the rehydration temperature increased,[34,37] whereas others found that this value increased with an increase in temperature[38] and, in some cases, no significant differences were found at the end of the process.[37]

Weibull Model

The Weibull shape parameter (α) increased as the rehydration temperature increased at all dehydration temperatures for both samples. This observation is supported by an r^2 value of 0.999. The high values of α indicate a low rate of water absorption at the beginning of rehydration, and this behavior worsened with the increase in temperature of rehydration. It may be assumed that this behavior was associated with the characteristics of the fruit, particularly with regard to the presence of the waxy cuticle, which acted as a physical barrier. On the other hand, the high values of β suggest a great difficulty of the product to absorb water during the entire process, resulting in a low speed of rehydration. This is evident when the time of rehydration of these fruits (days) is compared with that of other fruits, where equilibrium is reached within in a few hours.

Kinetic parameters of the two empirical models (k_1 and β) showed the same behavior: they increased as the rehydration temperature decreased, in both nonperforated and perforated fruits, regardless of the temperature of dehydration. This means that the higher the rehydration temperature of rosehip fruits, perforated or not, the higher the water absorption capacity. A similar behavior was reported by Cunningham et al.[28] in pasta, García-Pascual et al.[22] in edible mushrooms, Machado et al.[39] in puffed breakfast cereal, and Markowski et al.[40] for potato cubes.

Figures 2 and 3 show the rehydration kinetics at four different temperatures (20, 40, 60, and 80°C) for nonperforated and perforated fruits previously dehydrated at 70°C.

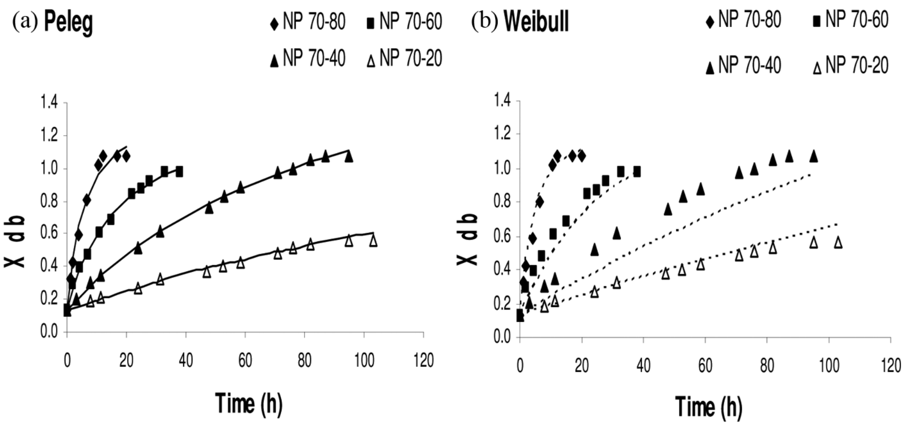

FIG. 2. Experimental moisture content (db) as a function of time during rehydration (20, 40, 60, and 80°C) and corresponding predictions (solid lines) by (a) Peleg and (b) Weibull models for nonperforated fruits dehydrated at 70°C.

They also show a comparison between experimental and estimated moisture content.

Calculated r^2 (>0.99), SSE (<0.005), RMSE (<0.07), $SE_{\bar{X}}$ (<0.05), and χ^2 (<0.007) values suggest that the experimental data were well-fitted by the proposed models. Moreover, the figures show the effect of perforation on the reduction in rehydration times within the range of temperature evaluated.

Temperature Dependence of Kinetic Parameters

The kinetic parameters of each model showed a dependence on temperature and were evaluated by an Arrhenius-type equation, in which the activation energy (E_a) can be estimated according to the representation of either $\ln(k_1)$ (Peleg model) or $\ln(\beta)$ (Weibull model), as a function of $1/T$ (K^{-1}).[22,41] Figure 4 confirms the Arrhenius-type relationship proposed. Similar findings have been reported by other authors working with different foods, including dehydrated spinach,[42] mushrooms,[22] and aloe vera.[26]

For nonperforated fruits, E_a values were 47.5 kJ/mol ($r^2 = 0.986$) and 55.9 kJ/mol ($r^2 = 0.987$) for the Peleg and Weibull model, respectively. In the case of perforated fruits, E_a values were 40.1 kJ/mol ($r^2 = 0.985$) and 45.5 kJ/mol ($r^2 = 0.997$) for the Peleg and Weibull model, respectively. E_a values indicate that perforated fruits were influenced more by rehydration temperature than nonperforated fruits. These values are similar to those obtained in other research, such as 16.5 kJ/mol in mushrooms[22] and 42 kJ/mol in corn flakes[39] for the β parameter of Weibull's model and 23.8 kJ/mol in dehydrated spinach,[42] 19.2 in mushrooms,[22] 22.01 kJ/mol for green peas,[43] and 11.1 in carrot[44] for the k_1 parameter of Peleg's model.

Volume Changes

Figure 5 shows the effect of drying (60, 70, and 80°C) and rehydration (20, 40, 60, and 80°C) on fruit volume. It was observed that after drying at 60 and 70°C, perforated fruits suffered more pronounced shrinkage, whereas

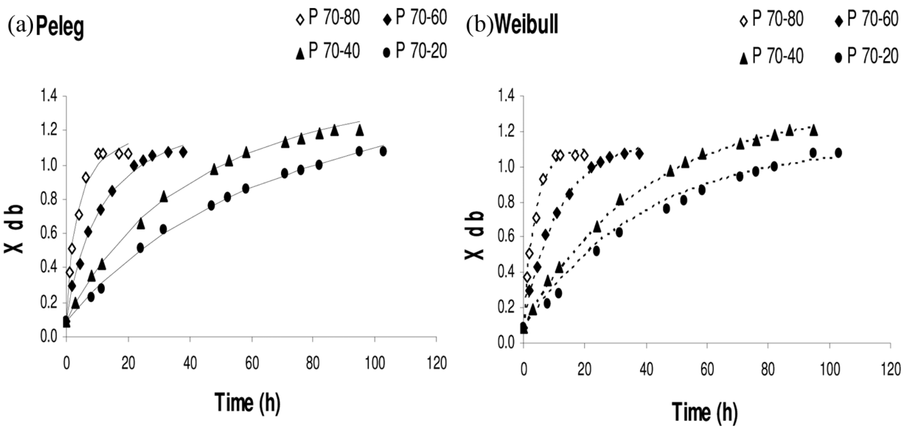

FIG. 3. Experimental moisture content (db) as a function of time during rehydration (20, 40, 60, and 80°C) and corresponding predictions (solid lines) by (a) Peleg and (b) Weibull models for perforated fruits dehydrated at 70°C.

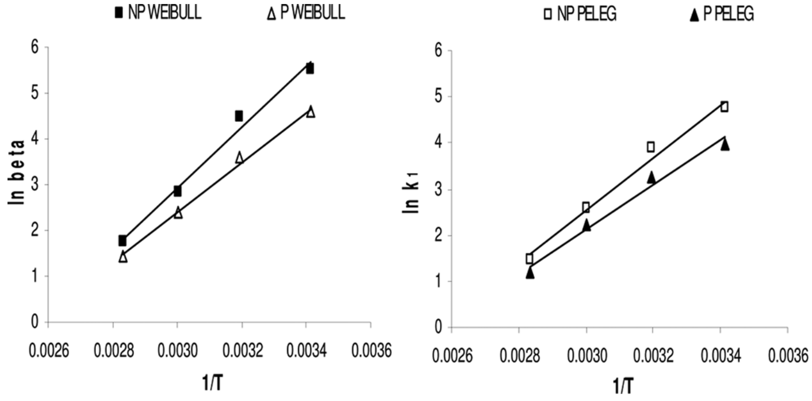

FIG. 4. Dependence of kinetic parameters on temperature for nonperforated (NP) and perforated (P) fruits.

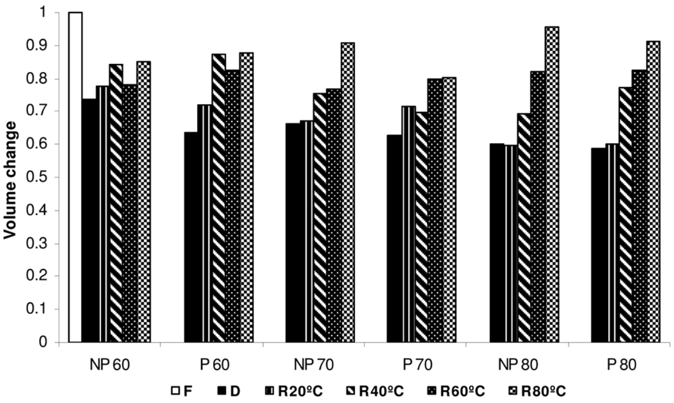

FIG. 5. Volume change of dehydrated rosehip fruits at different temperatures (60, 70, and 80°C), nonperforated (NP) and perforated (P), and rehydrated at 20, 40, 60, and 80°C.

at 80°C there was no significant difference between nonperforated and perforated fruits.

Regarding the rehydration temperature, Fig. 5 shows that perforated fruits recovered more volume than the untreated samples in all cases evaluated. Results also show that ambient temperatures of rehydration were not appropriate to achieve good final rosehip fruits; the results agree with those reported by Krokida and Philippopoulos.[2] The higher temperatures of rehydration (60 and 80°C), while increasing the capacity of water absorption, affected the color in both the nonperforated and perforated fruits. Therefore, 40°C was an appropriate rehydration temperature.

CONCLUSIONS

The rehydration kinetics of rosehip fruits, with and without perforation and previously dried at different temperatures, was studied. The study was conducted using the Peleg and Weibull models, which according to the statistical analysis correlated very well with the experimental results. No influence of the different drying temperatures was observed on the rate of rehydration in either nonperforated or perforated fruits.

The kinetic parameters obtained with the two empirical models (k_1 and β) showed the same behavior: they increased as the rehydration temperature decreased in both nonperforated and perforated fruits, regardless of the temperature of dehydration. This result indicates that the higher the rehydration temperature of rosehip fruits, perforated or not, the higher the water absorption capacity.

These kinetic parameters were correlated with temperature using an Arrhenius-type model, which showed good agreement, and the values were within the range found in other foods. For nonperforated fruits, E_a values were 47.5 kJ/mol ($r^2 = 0.986$) and 55.9 kJ/mol ($r^2 = 0.987$) for the Peleg and Weibull model, respectively. In the case of perforated fruits, E_a values were 40.1 kJ/mol ($r^2 = 0.985$) and 45.5 kJ/mol ($r^2 = 0.997$) for the Peleg and Weibull model, respectively. The differences in the E_a values would suggest that perforated fruits were influenced more by rehydration temperature than nonperforated fruits. Thus, perforation accelerated the rehydration of *Rosa rubiginosa* fruits by 30%, regardless of the temperature at which they were dried.

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REFERENCES

1. Falade, K.O.; Abbo, E.S. Air-drying and rehydration characteristics of date palm (*Phoenix dactylifera* L.) fruits. *Journal of Food Engineering* **2007**, *79*, 724–730.
2. Krokida, M.K.; Philippopoulos, C. Rehydration of dehydrated foods. *Drying Technology* **2005**, *23*(4), 799–830.

3. Lewicki, P. Some remarks on rehydration of dried foods. *Journal of Food Engineering* **1998**, *36*, 81–87.
4. Goula, A.M.; Adamopoulos, K.G. Modeling the rehydration process of dried tomato. *Drying Technology* **2009**, *27*(10), 1078–1088.
5. Moreira, R.; Chenlo, F.; Chaguri, L.; Fernandes, C. Water absorption, texture and color kinetics of air-dried chestnuts during rehydration. *Journal of Food Engineering* **2008**, *86*, 584–594.
6. Ogwal, M.O.; Davis, D.R. Rapid rehydration methods for dried beans. *Journal of Food Science* **1994**, *59*(3), 611–621.
7. García-Pascual, P.; Sanjuán, N.; Benedito, J.J.; Mateos, M.; Mulet, A. Hydration behavior of dehydrated *Morchella esculenta* mushrooms through Peleg's equation. In *Proceedings of the 12th International Symposium*, Noordwikerhut, The Netherlands, August 28–31, 2000.
8. Sopade, P.A.; Ajisegiri, E.S.; Badau, M.H. The use of Peleg's equation to model water absorption in some cereal grains during soaking. *Journal of Food Engineering* **1992**, *15*, 269–283.
9. McMinn, W.A.M.; Magee, T.R.A. Quality and physical structure of dehydrated starch-based system. *Drying Technology* **1997**, *15*(6–8), 1961–1971.
10. Krokida, M.K.; Zogzas, N.P.; Maroulis, Z.B. Mass transfer coefficient in food processing: Compilation of literature data. *International Journal of Food Properties* **2001**, *4*, 373–382.
11. Krokida, M.K.; Marinos-Kouris, D. Rehydration kinetics of dehydrated products. *Journal of Food Engineering* **2003**, *57*, 1–7.
12. Lewicki, P.; Witrowa-Rajchert, D.; Mariak, J. Changes of structure during rehydration of dried apples. *Journal of Food Engineering* **1997**, *32*(4), 347–350.
13. Mabellini, A.; Ohaco, E.; Márquez, C.A.; De Michelis, A.; Lozano, J.E. Effects of pretreatments on convective drying of rosehip (*Rosa eglanteria*). *International Journal of Food Studies* **2012**, *1*, 42–51.
14. Erenturk, S.; Gulaboglu, M.; Gultekin, S. The thin-layer drying characteristics of Rosehip. *Biosystems Engineering* **2004**, *89*, 159–166.
15. Jaworska, G.; Pogoń, K.; Bernaś, E.; Skrzypczak, A. Effect of different drying methods and 24-month storage on water activity, rehydration capacity, and antioxidants in *Boletus edulis* mushrooms. *Drying Technology* **2014**, *32*(3), 291–300.
16. Doymaz, I. An experimental study on drying of green apples. *Drying Technology* **2009**, *27*, 478–485.
17. Ohaco Domínguez, E.H. *Secado Convectivo de Frutos de Rosa Mosqueta. Modelos del Producto para Optimizar Equipos de Secado*; Editorial EAE de AV Akademikerverlag GmbH and Co. KG: Saarbrucken, Germany 2013.
18. AOAC International. *Official Methods of Analysis of AOAC International*, 16th Ed; Association of Analytical Chemists: Arlington, VA, 1995.
19. Peleg, M. A empírical model for the description of moisture sorption curves. *Journal of Food Science* **1988**, *53*(4), 1216–1219.
20. De Michelis, A.; Márquez, C.; Ohaco, E. *Deshidratación Convectiva de Alimentos. Un Aporte Metodológico al Estudio del Proceso Durante el Secado de Frutas*; Editorial EAE de AV Akademikerverlag GmbH and Co. KG: Saarbrucken, Germany, 2012.
21. Solomon, W.K. Hydration kinetics of lupin (*Lupinus albus*) seeds. *Journal of Food Process Engineering* **2007**, *30*(1), 119–130.
22. García-Pascual, P.; Sanjuán, N.; Melis, R.; Mulet, A. *Morchella esculenta* (morel) rehydration process modelling. *Journal of Food Engineering* **2006**, *72*(4), 346–353.
23. Saguy, I.S.; Marabi, A.; Wallach, R. Liquid imbibition during rehydration of dry porous foods. *Innovative Food Science and Emerging Technologies* **2005**, *6*, 37–43.
24. Goyal, R.K.; Kingsly, A.R.P.; Manikantan, M.R.; Ilyas, S.M. Mathematical modelling of thin layer drying kinetics of plum in a tunnel dryer. *Journal of Food Engineering* **2007**, *79*, 176–180.
25. Sacilik, K. Effect of drying methods on thin layer drying characteristics of hull-less seed pumpkin (*Curcubita pepo* L.). *Journal of Food Engineering* **2007**, *79*, 23–30.
26. Vega-Gálvez, A.; Notte-Cuello, E.; Lemus-Mondaca, R.; Zura, L.; Miranda, M. Mathematical modelling of mass transfer during rehydration process of aloe vera (*Aloe barbadensis* Miller). *Food and Bioproducts Processing* **2009**, *87*, 254–260.
27. Sanjuán, N.; Simal, S.; Bon, J.; Mulet, A. Modelling of brocoli items rehydration process. *Journal of Food Engineering* **1999**, *42*, 27–31.
28. Cunningham, S.E.; McMinn, W.A.M.; Magee, T.R.A.; Richardson, P.S. Experimental study of rehydration kinetics of potato cylinders. *Food and Bioproducts Processing* **2008**, *86*, 15–24.
29. Kaymak-Ertekin, E. Drying and rehydration kinetics of green and red peppers. *Journal of Food Science* **2002**, *67*(1), 168–175.
30. Sopade, P.A.; Kaimur, K. Application of Peleg's equation in desorption studies of food systems: A case study with sago (*Metroxylon sagu* Rottb.) starch. *Drying Technology* **1999**, *17*(4–5), 975–989.
31. Sopade, P.A.; Obepka, J.A. Modelling water absorption in soybean, cowpea and peanuts at three temperatures using Peleg's equation. *Journal of Food Science* **1990**, *55*(4), 1084–1087.
32. López, A.; Piqué, M.T.; Clop, M.; Tasias, J.; Romero, A.; Boatella, J. The hygroscopic behaviour of the hazelnut. *Journal of Food Process Engineering* **1995**, *25*, 197–208.
33. Maskan, M. Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. *Journal of Food Engineering* **2001**, *48*, 177–182.
34. Sanjuán, N.; Andrés, J.; Clemente, G.; Mulet, A. Modeling of the rehydration process of brocolli florets. *European Food Research Technology* **2001**, *212*(4), 449–453.
35. Turhan, M.; Sayar, S.; Gunasekaran, S. Application of Peleg model to study water absorption in cheakpea during soaking. *Journal of Food Engineering* **2002**, *53*, 153–159.
36. Bakalis, S.; Karathanos, V.T. Study of rehydration of osmotically pretreated dried fruit samples. *Drying Technology* **2005**, *23*(3), 533–549.
37. Abu-ghannam, N.; McJenna, B. The application of Peleg's equation to model water absorption during the soaking of red kidney beans (*Phaseolus vulgaris* L.). *Journal of Food Engineering* **1997**, *32*(4), 391–401.
38. Lin, T.M.; Durance, T.D.; Scaman, C.H. Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International* **1998**, *31*(2), 111–117.
39. Machado, M.; Oliveira, F.A.R.; Gekas, V.; Singh, R.P. Kinetics of moisture uptake and soluble-solids loss by puffed breakfast cereals immersed in water. *International Journal of Food Science Technology* **1998**, *33*(3), 225–237.
40. Markowski, M.; Bondaruk, J.; Błaszczak, W. Rehydration behavior of vacuum–microwave-dried potato cubes. *Drying Technology* **2009**, *27*(2), 296–305.
41. Kaptso, K.G.; Njintang, Y.N.; Komnek, A.E.; Hounhouigan, J.; Scher, J.; Mbofung, C.M.F. Physical properties and rehydration kinetics of two varieties of cowpea (*Vigna unguiculata*) and bambara groundnuts (*Voandzeia subterranea*) seeds. *Journal of Food Engineering* **2008**, *86*, 91–99.
42. Dadali, G.; Demirhan, E.; Ozbeck, B. Effect of drying conditions on rehydration kinetics of microwave dried spinach. *Food and Bioproducts Processing* **2008**, *86*, 235–241.
43. Doymaz, I.; Kocayigit, F. Drying and rehydration behaviors of convection drying of green peas. *Drying Technology* **2011**, *29*(11), 1273–1282.
44. Planinic, M.; Velic, D.; Tomas, S.; Bilic, M.; Bucic, A. Modeling of drying and rehydration of carrots using Peleg's model. *European Food Research Technology* **2005**, *221*(3–4), 446–451.