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COMMUNICATION

Rehydration Capacity of Chilean Papaya (*Vasconcellea pubescens*): Effect of Process Temperature on Kinetic Parameters and Functional Properties

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Abstract Slabs of Chilean papaya hot air-dried at 60 °C were rehydrated at 20, 40, 60, and 80 °C to study the influence of process temperature on mass transfer kinetics during rehydration. Diffusive and empirical models were selected to simulate the experimental rehydration curves. All models parameters showed dependence with temperature, thus activation energy could be estimated according to an Arrhenius-type equation. Among the applied models, Weibull provided the best fit for each rehydration curve based on the statistical tests RMSE, SSE, and chi-square. According to these results, this model could be used to estimate the rehydration time of Chilean papaya. In addition, rehydration ratio and water-holding capacity were analyzed. Both indices showed a decrease with increasing rehydration temperature indicating modification of the papaya cell structure due to thermal treatment which resulted in a reduction of the rehydration ability, in particular at high rehydration temperatures.

Keywords Chilean papaya · Rehydration kinetics · Mathematical modeling · Water-holding capacity · Rehydration ratio

Nomenclature

a_w	Water activity (−)
A	Parameter of Eq. 3 (in minutes gram d.m. per gram water)
B	Parameter of Eq. 3 (in grams d.m. per gram water)
C	Parameter of Eq. 5 (in grams water per gram d.m)
D	Parameter of Eq. 5 (in minutes·gram water per gram d.m.)
D_{eff}	Effective moisture diffusivity (in meters per second)
α	Shape parameter of Weibull model (−)
β	Scale parameter of Weibull model (min)
λ	Parameter of Eq. 5 (−)
E_a	Activation energy (in kilojoules per mole)

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ϕ_o	Arrhenius factor (in square meters per second)
L	Thickness half (in meters)
MR	Moisture ratio (−)
N	Number of data
R	Universal gas constant (8.314 J mol^{-1} K^{-1})
RR	Rehydration ratio (in grams absorbed water per gram d.m.)
WHC	Water-holding capacity (in grams retained water per gram water)
t	Process time (in minutes)
T	Absolute temperature (in Kelvin)
X_{wt}	Sample moisture content (in grams water per gram d.m.)
X_{wo}	Initial sample moisture content (in grams water per gram d.m.)
X_d	Sample moisture content after the drying process (in grams water per gram d.m.)
X_{eq}	Equilibrium sample moisture content (in grams water per gram d.m.)
X_r	Sample moisture content after rehydration (in grams water per gram d.m.)
W_r	Sample weight after the rehydration process (in grams)
W_d	Sample weight after the drying process (in grams)
W_l	Weight of the drained liquid after centrifugation (in grams)
z	Number of constants
exp	Experimental
cal	Calculated
∞	Infinite

Introduction

Chilean papaya (*Vasconcellea pubescens*) grows in a Mediterranean-type climate regime from the region around La Serena. It presents great firmness, yellow-green-colored flesh and small size (Van Droogenbroeck et al. 2002). The Chilean papaya is consumed as a whole, only after cooking, with the seeds removed. The fruit without peel has an edible yield of 46%, a sugar content of about 5%, and is high in papain content (Lemus-Mondaca et al. 2009a). The national marketing of this product has included traditional products such as candying, canning, juice, syrup, and jam. A recent report of agricultural markets of Chile showed hand-processed papaya to account for 50% of sales, while its industrialized products accounted for 30%, and the remaining production was sold as fresh fruit (INDAP 2009).

In the last decade, due to modern lifestyles, there has been a continuous rise in the demand for convenience foods including dehydrated products, leading consumers to choose foods that are readily available with minimal preparation before consumption (Marabi and Saguy 2009). Dehydrated products often need to be rehydrated for utilization (Aversa et al. 2009). Safety, nutritional, and sensory aspects of foods are often related to the rehydration process as well as to the severity of the drying process used (Marabi and Saguy 2009). Thus, rehydration can be considered as a measure of the damage to the product caused by dehydration since rehydration capacity is related to modifications in food structure during processing (Krokida and Maroulis 2001; Bilbao-Sáinz and Fito 2005; Garcia-Pascual et al. 2006; Moreira et al. 2008). Rehydration of dried food tissues is composed of three simultaneous processes: the imbibitions of water into dried material, the swelling of the rehydrated products, and the leaching of soluble solids to rehydration medium (Krokida and Marinos-Kouris 2003). The concern for meeting quality specifications and saving energy emphasizes the need for a thorough understanding of the rehydration processes in order to optimize the dehydration processes (Lee et al. 2006). In particular, rehydrated papaya is a very promising new product with a high nutritive value (vitamins, minerals, and fiber) and furthermore its high commercial value demanded by the gastronomic business (dessert, ice cream, cocktails, salads, and sweet course), based on its aroma, color, and flavor characteristics.

There are several empirical models used for mass transfer kinetics modeling throughout rehydration process. Most of them are based on the diffusional model of Fick's second law for different geometries (Kaymak-Ertekin 2002). Among empirical equations, the model proposed by Peleg (1998) is simple to calculate compared to other equations (Maskan 2002). Another equation widely used in food engineering to model the kinetics of chemical, enzymatic, or microbiological degradation processes is the probabilistic model of Weibull due to its simplicity and flexibility in the estimation of its two parameters (Marabi et al. 2003; Uribe et al. 2009). The aim of this research was to study the effect of process temperature on rehydration kinetics of Chilean papaya slabs as well as to evaluate the fruit rehydration ability based on rehydration indices.

Materials and Methods

Raw Material and Drying Experiment

Papayas were purchased from a local market in Elqui Valley, La Serena, Chile. Homogeneous lots for the tests were selected according to guidelines for ripeness index given in the work of Moyano et al. (2002), size (axial 100.2±4.4 mm and equatorial 67.7±1.9 mm), uniformity in color, and with no signs of mechanical damage. Fruits were then stored for 6 h at 5 °C before being used.

Samples were washed and peeled using a solution of NaOH (10%) and Fastpeel additive (1%; Quimica Norte Verde Ltda., La Serena, Chile) and washed immediately with cold water in order to remove skin remains. The fruits were cut vertically to their axis into slabs of 10.0± 0.5 mm of thickness using a cutting machine (Robot Coupe, CL50, Tokyo, Japan). Hot air-drying process of papaya samples was carried out in triplicate in a convective tray dryer (Lemus-Mondaca et al. 2009b). Drying air temperature and flow rate were kept constant with values of 60.0±0.2 °C and 2.0±0.2 m s^{-1}, respectively. The drying process was stopped as soon as the sample reached constant weight over time (equilibrium condition), approximately by 6 h (Lemus-Mondaca et al. 2009a, b). Dehydrated samples were kept in polyethylene bags and stored at refrigeration conditions at 4.6±0.4 °C (refrigerator Samsung, SR-34RMB, Seoul, South Korea).

Physicochemical Analysis of Raw Material

The crude protein content was determined using the Kjeldahl method with a conversion factor of 6.25 (AOAC no. 960.52). The lipid content was analyzed gravimetrically following Soxhlet extraction (AOAC no. 960.39). The crude fibre was estimated by acid/alkaline hydrolysis of insoluble residues (AOAC no. 962.09). The crude ash content was estimated by incineration in a muffle furnace at 550 °C (AOAC no. 923.03). The available carbohydrate was estimated by difference. All methodologies followed the recommendations of the Association of Official Analytical Chemists (AOAC 1990). The water activity (a_w) was measured at 25 °C by means of a water activity meter (Novasina, model TH-500, Pfäffikon, Lachen, Switzerland). All determinations were done in triplicate.

Rehydration Experiments

Rehydration experiments were carried out in a distilled water bath at constant temperatures of 20, 40, 60, and 80 °C (±0.2 °C). Dried papaya samples (100.0±2.0 g) were placed inside a 5-L flask. For all assays, the solid to liquid ratio was kept at 1:50. Rehydration times were 5 min for the first 45 min, then every 15 min for the next 3 h, and finally every 60 min until 10 h (process final stage). At these intervals, samples were removed from liquid, carefully blotted with tissue paper to remove superficial water, and weighed. Every assay was done in triplicate. Moisture content for dried and rehydrated samples was determined according to methodology AOAC no. 934.06 (AOAC 1990) using a vacuum oven (Gallenkamp, OVL570, Leicester, UK) and an analytic balance (CHYO, Jex120, Kyoto, Japan) of accuracy 0.0001 g.

Mathematical Modeling

In food rehydration processes, water is transported mainly by moisture diffusion. The mathematical solution of Fick's second diffusion law was assumed, when internal mass transfer is the controlling mechanism and one-dimensional transport in an infinite slab. Moreover, the first term in the series expansion gives a good estimate of the solution (Eq. 1). The dependent variable of this model, the moisture ratio (MR), was calculated using the mathematical expression of Eq. 2:

$$\mathrm{MR} = \frac{8}{\pi^2} \exp\left[\frac{-D_{\mathrm{eff}}\pi^2 t}{4L^2}\right] \quad (1)$$

$$\mathrm{MR} = \frac{X_{\mathrm{wt}} - X_{\mathrm{eq}}}{X_{\mathrm{wo}} - X_{\mathrm{eq}}} \quad (2)$$

In practice, the effective moisture diffusivity for each temperature was calculated by plotting experimental rehydration data in terms of ln (MR) versus rehydration time and the D_{eff} value obtained from the straight line's slope.

Peleg (1998) proposed a nonexponential model with two parameters (Eq. 3). This equation has been applied to describe rehydration processes of different foods (Resio et al. 2006; Garcia-Pascual et al. 2006; Moreira et al. 2008). The Weibull distribution (Eq. 4) has found wide application in food processing, in particular in rehydration studies (Marabi et al. 2003; Garcia-Pascual et al. 2006; Cunningham et al. 2007). In addition, the model proposed by Vega-Gálvez et al. (2009) was used (Eq. 5).

$$X_{\mathrm{wt}} = X_{\mathrm{wo}} + \left[\frac{t}{A + B \times t}\right] \quad (3)$$

$$X_{\mathrm{wt}} = X_{\mathrm{eq}} + \left(X_{\mathrm{wo}} - X_{\mathrm{eq}}\right) \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \quad (4)$$

$$X_{\mathrm{wt}} = C \exp\left[\frac{-D}{(1+t)^{\lambda}}\right] \quad (5)$$

In order to evaluate the dependence of the diffusivity coefficient and empirical parameters A and B on temperature, an Arrhenius-type equation was used (Eq. 6).

$$\varphi = \varphi_o \times \exp\left[\frac{-E_{\mathrm{a}}}{\mathrm{RT}}\right] \quad (6)$$

Functional Properties: Rehydration Ratio and Water-Holding Capacity

To study the temperature effect on the rehydration phenomenon, two typical rehydration indices were evaluated for dried papaya. These rehydration indices were determined by centrifuging the rehydrated samples at 4000×*g* for 10 min at 5 °C in tubes fitted with a centrally placed plastic mesh which allowed water to drain freely from the sample during centrifugation. The rehydration ratio (RR) was calculated by Eq. 7. The water-holding capacity (WHC) was calculated by means of Eq. 8. All measurements were done in triplicate and means were calculated for each sample (Miranda et al. 2010).

$$\mathrm{RR} = \frac{W_\mathrm{r} \times X_\mathrm{r} - W_\mathrm{d} \times X_\mathrm{d}}{W_\mathrm{d}(1 - X_\mathrm{d})} \tag{7}$$

$$\mathrm{WHC} = \frac{W_\mathrm{r} \times X_\mathrm{r} - W_\mathrm{l}}{W_\mathrm{r} \times X_\mathrm{r}} \tag{8}$$

Statistical Analysis

The statistical analysis of experimental data was determined using StatGraphics Plus 5.1® (Manugistic Inc. USA), applying analysis of variance (ANOVA) to estimate significant differences at a confidence level of 95% ($p<0.05$). The multiple range test was used to prove the existence of homogeneous groups within each of the analyzed groups. Goodness of fit of the selected models was evaluated according to the following statistically tests: correlation coefficient (r^2), sum of square error (SSE, Eq. 9), root mean square error (RMSE, Eq. 10) and chi-square (χ^2, Eq. 11).

$$\mathrm{SSE} = \frac{1}{N}\sum_{i=1}^{N}\left(X_{\mathrm{exp}} - X_{\mathrm{cal}}\right)^2 \tag{9}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(X_{\mathrm{cal}} - X_{\mathrm{exp}}\right)^2\right]^{1/2} \tag{10}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(X_{\mathrm{exp}} - X_{\mathrm{cal}}\right)^2}{N - z} \tag{11}$$

Results and Discussion

Physicochemical Analysis of Raw Material

The proximal analysis of fresh papaya (in grams 100 g^{-1}) presented a moisture content of 13.28±0.17, crude protein (nitrogen×6.25) of 5.35±0.78, total lipids of 1.20±0.21, crude fibre of 19.04±1.22, crude ash of 7.02±1.08, and available carbohydrates (by difference) of 48.04±2.61. At the end of the drying process at 60 °C, equilibrium moisture content and water activity were 0.105±0.003 g water g^{-1} dry matter and 0.075±0.005 (dimensionless), respectively. This moisture content represents initial moisture content for the rehydration process at each working temperature.

Rehydration Experiments

Experimental rehydration curves of papaya samples at the four working temperatures are shown in Fig. 1. It is observed that the rehydration temperature has an important effect on water absorption of papaya slabs. All curves showed a typical rehydration behavior with a high water absorption rate mainly at the beginning of the process. Absorption rate decreases until equilibrium is reached after 10 h of process. Equilibrium moisture content of the rehydration process was higher than the moisture content of fresh papaya slabs, reaching 17.66±0.18, 19.95±0.32, 21.90±0.22, and 24.35±0.34 g water g^{-1} d.m. for 20, 40, 60, and 80 °C, and with rehydration times in order to reach equilibrium condition (constant weight) of 480, 360, 420, and 280 min, respectively. 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); carrots (Planinić et al. 2005); apples (Bilbao-Sáinz and Fito 2005); amaranth grain (Resio et al. 2006); mushroom (Garcia-Pascual et al. 2006); and chestnuts (Moreira et al. 2008).

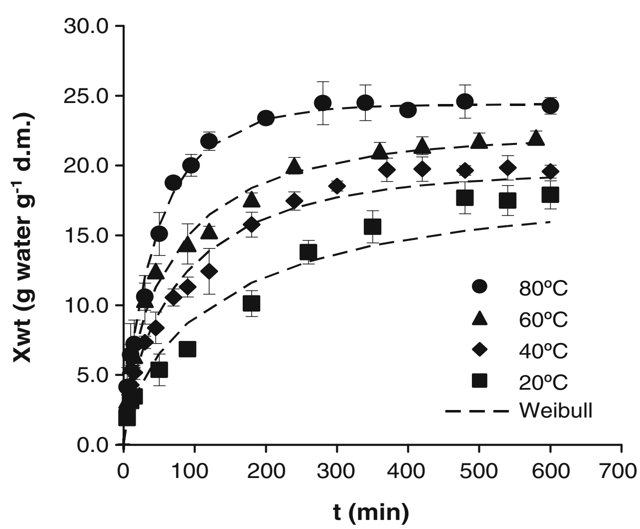

Fig. 1 Experimental and Weibull-estimated moisture content of papaya samples at different temperatures during rehydration. Values are mean±standard deviation (n=3)

Modeling of Rehydration Process

Table 1 presents the mean values of the parameters of the different mathematical models describing the rehydration kinetics of papaya samples. The results showed that D_{eff} values increased as water rehydration temperature increase presenting values from 9.01 to 27.80×10^{-10} m^2 s^{-1} under the studied temperature range. Similar results have been reported for different rehydrated foods: $0.22–99.63 \times 10^{-11}$ m^2 s^{-1} for broccoli florets (25–80 °C), 5.69–9.90 and $4.20–8.02 \times 10^{-11}$ m^2 s^{-1} for pasta (20–80 °C), $2.16–59.50 \times 10^{-10}$ m^2 s^{-1} for cowpea and groundnuts seeds (25–45 °C), and $1.52–9.32 \times 10^{-10}$ m^2 s^{-1} for potato (20–80 °C, Kaptso et al. 2008; Cunningham et al. 2007, 2008). Regarding to parameter A for the Peleg model, it shows a clear tendency to decrease as temperature increases, indicating that the higher the temperature, the higher the water absorption rate. Similar tendencies for this parameter have been reported for firik, dövme, and wheat (Maskan 2002); amaranth grain (Resio et al. 2006); lupin (Solomon 2007); and chestnuts (Moreira et al. 2008).

The parameter B (Peleg model) decreases as temperature increases as shown in Table 1. Solomon (2007) suggested that this parameter is related to the 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 and vice versa. Thus, results show that water absorption capacity increases as water rehydration temperature increases. Comparable results have been reported in previous works (Maskan 2002; Resio et al. 2006; Moreira et al. 2008). Table 1 also shows the values of parameters α and β of Weibull model. Parameter α increased with process temperature except at 60 °C. This parameter is related to the velocity of the mass transfer at the beginning, e.g., the lower the α value, the faster the drying rate at the beginning (Uribe et al. 2009). In addition, parameter β decreases as temperature increases. Similar behavior has been reported working with mushroom (8.5–2.5 min, Garcia-Pascual et al. 2006) and pasta (1193–60 min, Cunningham et al. 2007). Some authors suggested that parameter β represents the time needed to accomplish approximately 63% of the process (Marabi et al. 2003; Cunningham et al. 2007). Marabi et al. (2003) using the Weibull model concluded that for high porosity products (e.g. freeze-dried), capillarity controls mass transfer, while for products with low porosity (those that are air-dried), diffusion is predominant. Besides, Table 1 shows the parameters of the Vega-Gálvez et al. (2009) model for $\lambda = 0.45$ (λ is also an empirical parameter). Parameter C increases as temperature increases, while D decreases gradually according to the work of Vega-Gálvez et al. (2009).

Influence of Temperature on Kinetic Parameters

From the ANOVA performed to D_{eff} as well as the parameters of the models, there was a significant influence of process temperature on these kinetic parameters ($p<0.05$), which allowed to apply an Arrhenius-type equation. Estimated activation energy ranged from 0.85 ($r^2=0.996$) to 20.50 ($r^2=0.996$) kJ mol^{-1}, being the smallest value the corresponding to the C parameter of Vega-Gálvez et al. (2009) and A of Peleg, respectively. The values of these parameters are comparable with those obtained in previous investigations for mushroom (19.20 kJ mol^{-1}, Garcia-Pascual et al. 2006), potato (16.39 and 23.24 kJ mol^{-1}, Cunningham et al. 2008), and cowpea and groundnuts seeds (11.20 and 78.81 kJ mol^{-1}, Kaptso et al. 2008). Furthermore, regarding parameter A (Peleg model) and parameter β of Weibull, the results are comparable with previous works (Maskan 2002; Garcia-Pascual et al. 2006; Planinić et al. 2005).

Rehydration Ratio and Water-Holding Capacity

Figure 2 shows the RR and WHC indices at 20, 40, 60, and 80 °C. RR tends to decrease as water rehydration temperature increases ($p<0.05$). Maximum value of RR was 16.02± 0.22 g absorbed water g^{-1} d.m. at 20 °C. Figure 2 shows the

Table 1 Parameters of the selected mathematical models used to simulate papaya rehydration kinetics

T (°C)	Fick	Peleg		Weibull		Vega-Gálvez et al. (2009)	
	$D_{eff} \times 10^{-10}$ (m^{2}s^{-1})	$A \times 10^2$ (min·g d.m. g^{-1} water)	$B \times 10^{-2}$ (g d.m. g^{-1} water)	$\alpha \times 10^{-1}$[a]	$\beta \times 10^3$ (min)	C (g water g^{-1} d.m)	D (min·g water g^{-1} d.m)
20	9.01±0.81a	2.77±0.31a	5.05±0.17a	6.61±0.18a	9.68±0.54a	20.62±0.28a	5.64±0.15a
40	14.41±0.32b	1.52±0.03b	4.62±0.09b	7.12±0.26b	5.34±0.17b	27.33±0.12b	5.81±0.09b
60	16.81±0.63c	1.03±0.12c	4.29±0.06c	6.64±0.59c	4.51±0.35c	32.70±0.19c	5.85±0.18b
80	27.80±2.46d	0.64±0.02d	3.87±0.05d	8.09±0.62d	2.92±0.19d	40.21±0.21d	6.01±0.22b

Similar letters in the same column show there are no significant differences ($p<0.05$)

[a] Dimensionless

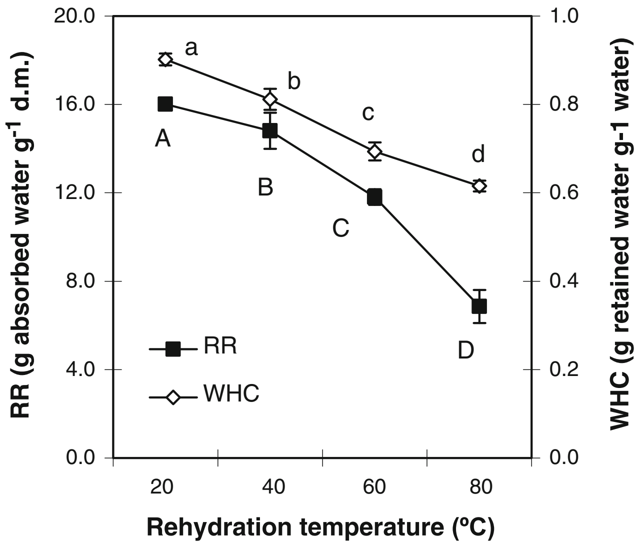

Fig. 2 Rehydration ratio (*RR*) and water-holding capacity (*WHC*) for rehydrated papaya samples at different temperatures. Similar letters above the bars indicate no significant differences ($p<0.05$). Values are mean±standard deviation ($n=3$)

values of WHC that decrease gradually as water rehydration temperature increases, reaching a maximum value of 0.902± 0.13 g retained water g^{-1} water at 20 °C ($p<0.05$). As Fig. 2 shows, a higher process temperature results in a lower water-holding capacity of the cell membrane, probably due to its denaturation of polysaccharides of cell wall, with which the firmness of cell is lost (Chang et al. 2006). Krokida and Maroulis (2001) suggest that the physicochemical basis for the structural deformation was the loss of selective semipermeability of the cytoplasmatic membranes and the resultant loss of turgor pressure in the cell. Although high hydration temperatures results in high equilibrium water content (sponge effect), the fruit structure was modified due to processing, losing its initial ability of retaining water.

Statistical Analysis of the Models

Statistical analyses applied to the proposed equations to simulate the rehydration kinetics of dried papaya are shown in Table 2. In general, all models showed a good fit with values close to 0 for SSE, RMSE, and χ^2. Nevertheless, the Weibull model presented the best fit to experimental data. Therefore, Fig. 1 also presents the Weibull-calculated moisture contents for each rehydration curve. Several authors suggested that the Weibull distribution model is suitable for predicting the rehydration times of several products (Marabi et al. 2003; Garcia-Pascual et al. 2006).

Conclusions

Effects of rehydration temperatures (20, 40, 60, and 80 °C) on rehydration kinetics as well as on rehydration indices of papaya were investigated in this work. All equations used proved to be useful to describe rehydration kinetics; however, the Weibull model presented the best fit for the experimental rehydration curves based on the statistical tests employed. The diffusion coefficient (D_{eff}) increased with the temperature from 9.01 to 27.80×10^{-10} m^2 s^{-1} (20–80 °C). An activation energy value of 15.16 kJ/mol was obtained for D_{eff} by means of an Arrhenius-type equation.

Table 2 Statistical tests of the selected models used to simulate papaya rehydration curves

Model	Statistical test	Rehydration temperature (°C)			
		20	40	60	80
Fick	r^2	9.5491×10^{-1}	9.9240×10^{-1}	9.9387×10^{-1}	9.9546×10^{-1}
	SSE	2.0211×10^{-1}	1.4324×10^{-1}	1.5293×10^{-1}	1.1196×10^{-1}
	RMSE	4.4957×10^{-1}	3.7848×10^{-1}	3.9106×10^{-1}	3.3460×10^{-1}
	χ^2	2.3886×10^{-1}	1.6010×10^{-1}	1.7477×10^{-1}	1.2795×10^{-1}
Peleg	r^2	9.3491×10^{-1}	9.7985×10^{-1}	9.5669×10^{-1}	9.6784×10^{-1}
	SSE	8.4088×10^{-5}	6.7070×10^{-6}	1.8523×10^{-6}	5.4802×10^{-7}
	RMSE	2.7643×10^{-7}	2.5898×10^{-3}	1.3610×10^{-3}	7.4028×10^{-4}
	χ^2	2.7643×10^{-7}	7.4961×10^{-6}	2.1169×10^{-6}	6.2631×10^{-7}
Weibull	r^2	9.7499×10^{-1}	$9.758g7\times10^{-1}$	9.0095×10^{-1}	9.7020×10^{-1}
	SSE	3.7409×10^{-6}	4.7716×10^{-7}	4.1355×10^{-7}	5.4893×10^{-7}
	RMSE	1.9341×10^{-3}	6.9076×10^{-4}	6.4307×10^{-4}	7.4090×10^{-4}
	χ^2	4.4211×10^{-6}	5.3329×10^{-7}	4.7262×10^{-7}	6.2735×10^{-7}
Vega-Gálvez et al. (2009)	r^2	9.8050×10^{-1}	9.929×10^{-1}	9.973×10^{-1}	9.959×10^{-1}
	SSE	1.7867×10^{-4}	6.6864×10^{-4}	3.0328×10^{-3}	5.0724×10^{-3}
	RMSE	1.3367×10^{-2}	2.5858×10^{-2}	5.5071×10^{-2}	7.1221×10^{-2}
	χ^2	2.1116×10^{-4}	7.4731×10^{-4}	3.4660×10^{-3}	5.7970×10^{-3}

The kinetic parameters of Peleg, Weibull, and the proposed model showed positive dependence with respect to temperature ($p<0.05$). Both rehydration indices, RR and WHC, decreased as rehydration temperature increased, indicating that thermal process causes damage to the cell structure of papaya slabs. Thus, gentle hydration temperatures (e.g. 20 or 40 °C) are required to achieve a final dried product with optimal rehydration characteristics.

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