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LWT 41 (2008) 1108–1115
LWT
www.elsevier.com/locate/lwt

Application of Weibull distribution model to describe the vacuum pulse osmotic dehydration of sardine sheets

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Received 1 September 2006; received in revised form 10 June 2007; accepted 22 June 2007

Abstract

Application of Weibull frequency distribution model was investigated for predicting the moisture and salt contents of sardine sheets during vacuum pulse osmotic dehydration using brine at different concentrations (0.15–0.27 g NaCl/g), temperatures (30–38 °C), and applying a vacuum pulse at 11.0 kPa for 10 min. The high regression coefficients ($R^2 > 0.99$) and low mean relative error (<10%) indicated the acceptability of Weibull model for predicting both moisture and salt contents. The scale parameters for moisture and salt contents as a function of temperature all followed an Arrhenius relationship. Models for scale and shape parameters for moisture and salt contents as a function of brine concentration and temperature were found.

Keywords: Weibull model; Vacuum pulse osmotic dehydration; Sardine sheets

1. Introduction

The osmotic dehydration process enhanced by a vacuum pulse is a technique which consists of submerging the food into an osmotic solution and applying sub-atmospheric pressure at a short interval followed by a large osmotic dehydration period at atmospheric pressure. This leads to the introduction of osmotic liquid into the pores of the food through the hydrodynamic mechanism (Fito & Chiralt, 1997), increasing the area of mass transfer in the food and producing a greater solid–liquid exchange. During the process, the solute and moisture concentrations, and consequently, the mass, change, and finally there will be an equilibrium state. A model, with an exponential approach to the equilibrium value of water and salt contents was proposed by Zugarramurdi and Lupin (1980) to explain observed behavior on fish salting. This model was applied to study the osmotic dehydration with vacuum of codfish (Escriche, Serra, Fito, & Rivero, 1998) and the osmotic dehydration at atmospheric pressure of sardine (Corzo & Bracho, 2005). The probabilistic Weibull model has been used to describe the behavior of rehydration kinetics (Garcia-Pascual, Sanjuán, Melis, & Mullet, 2006; Machado, Oliveira, & Cunha, 1999; Machado, Oliveira, Gekas, & Singh, 1998; Marabi, Livings, Jacobson, & Saguy, 2003;), microbial death kinetics (Heinz & Knorr, 1996), pressure inactivation of bacteria (Buzrul, Alpas, & Bozoglu, 2005; Chen & Hoover, 2004), thermal resistance of bacteria (Corradini, Normand, & Peleg, 2005; Fernández, Collado, Cunha, Ocio, & Martinez, 2002), spore germination (Collado, Fernández, Rodrigo, & Martinez, 2006), thermal preservation (Mafart, Couvert, Guillard, & Leguerinel, 2002; van Broekel, 2002), survival curves (Yang, Wang, Li, & Johnson, 2002) and water loss during osmotic dehydration (Cunha, Oliveira, Aboim, Frias, & Pinheiro-Torres, 2001) In the literature, there is not information available about using Weibull model for the osmotic dehydration of fish. The objectives of this study were 1) the determination of the applicability of Weibull frequency distribution model in predicting moisture and salt contents of sardine sheets during vacuum pulse

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doi:10.1016/j.lwt.2007.06.018

osmotic dehydration; and 2) the determination of effects of concentration and temperature on shape and scale parameters of Weibull model.

2. Materials and methods

2.1. Sample preparation

The fresh sardine (*Sardinella aurita*) was acquired from the fishermen from the same capture zone of Margarita Island, Venezuela, who caught the fish within 1 h before selling them. Sardines were 15–20 cm long and weighed 30–35 g/fish. Sardines were manually filleted with stainless-steel knives, and then the fillets were cut into sheets from the muscle nearest to head. The samples were sheets with an average length of 20.1±0.4 mm, average width of 15.0±0.6 mm, and average thickness of 6.4±0.2 mm. The moisture and salt contents were determined for fresh sardine by quadruplicate.

2.2. Osmotic dehydration

Randomly groups with four sheets in each were formed. A basket with four-marked compartment was used to put in it the sheets of each group to avoid interference between them. Four groups were introduced simultaneously into an osmotic solution of a given concentration and temperature. A vacuum pulse at 11.0 kPa for 10 min was applied and the osmotic dehydration was carried out at atmosphere pressure. One group was removed at intervals of 1 h during 4 h. After the removal from brine the dehydrated sheets of each group were drained for 5 min, blotted with absorbent paper to remove the excess solution. The moisture content and salt content were measured. This procedure took place in each experience to the corresponding conditions according to a 5 × 5 × 4 factorial design where the temperature, concentration an dehydration time were 30, 32, 34, 36, and 38 °C, 0.15, 0.18, 0.21, 0.24 and 0.27 g NaCl/g, and 1, 2, 3 and 4 h, respectively.

The osmotic solution was prepared by mixing commercial grade salt with distilled water. The brine to sample ratio was always higher than 20:1 to avoid significant dilution of the medium by water removal, which would lead to local reduction of the osmotic driving force during the process. The concentration of the brine was monitored throughout each experiment. The brine was agitated continuously with a magnetic stirrer to maintain a uniform temperature throughout the experiment, thus enhancing equilibrium conditions. The temperatures were also monitored using digital thermometers within the accuracy of ±0.1 °C.

The concentration of the brine (g NaCl/g) was adjusted initially and thereafter monitored throughout each run by the Mohr method (AOAC, 1990). The moisture content of fresh and treated sardine sheets was determined by drying under vacuum (1.93 Pa) at 60 °C until constant weight (AOAC, 1990). The salt content of fresh and treated sardine sheets was determined by the Mohr method (AOAC, 1990).

2.3. Weibull distribution model

The Weibull model represents the distribution of the breaking strength of materials and later to describe the behavior of systems or events that have some degree of variability (Cunha, Oliveira, Aboim, & Frias, 2001; Cunha, Oliveira, & Oliveira, 1998), such as the osmotic dehydration kinetics. The probability density function of the Weibull distribution may be described as (Hahn & Shapiro, 1967)

$$f(t) = \begin{cases} \dfrac{\beta}{\alpha}\left(\dfrac{t}{\alpha}\right)^{\beta-1} \exp\left(-\dfrac{t}{\alpha}\right)^{\beta}, & t > 0, \\ 0, \text{elsewhere} \end{cases} \tag{1}$$

where α is the scale parameter of the Weibull model, β is the shape parameter and t is the sampling time.

If one considers that (1) n_t corresponds to the fractional amount of a given component X, changing from an initial value (X_0) to a final equilibrium value (X_e), and that (2) the time required to reach a certain value of n_t is represented by the continuous random variable T, with probability density function $f(t)$, where $f(t)$ is the Weibull distribution function, then $n(t)$ can be defined as the probability of having a certain fractional amount of X for, at least, a specified time t, under specified experimental conditions (Cunha et al., 1998). Therefore,

$$n(t) = P(T > t) = \int_t^{\infty} f(u)\,\mathrm{d}u = 1 - F(t) = \exp\left[-\left[\frac{t}{\alpha}\right]^{\beta}\right], \tag{2}$$

where $F(t)$ is the corresponding cumulative distribution.

The fractional amount of moisture content during vacuum pulse osmotic dehydration can be expressed as (Cunha et al., 1998)

$$n_w(t) = \frac{X_w - X_{we}}{X_{w0} - X_{we}} = \exp\left[-\left[\frac{t}{\alpha_w}\right]^{\beta_w}\right], \tag{3}$$

where X_{w0}, X_w and X_{we} are the initial, at a time t, and at equilibrium moisture content, respectively, α_w is the scale parameter of the Weibull model, β_w is the shape parameter (dimensionless), and t is the sampling time.

The fractional amount of salt content during vacuum pulse osmotic dehydration can be expressed as (Cunha et al., 1998)

$$n_s(t) = \frac{X_s - X_{se}}{X_{s0} - X_{se}} = \exp\left[-\left[\frac{t}{\alpha_s}\right]^{\beta_s}\right], \tag{4}$$

where X_{s0}, X_s and X_{se} are the initial, at a time t, and at equilibrium salt content, respectively, α_s is the scale parameter of the Weibull model, β_s is the shape parameter (dimensionless) and t is the sampling time.

The parameters of the models were estimated by non-linear regression. To evaluate the goodness of each model fit, two criteria were used: the coefficient of determination (R^2) and the mean relative error (MRE) expressed as

$$\mathrm{MRE} = \frac{100}{N}\sum_{i=1}^{N}\frac{|Y_{ei} - Y_{pi}|}{Y_{ei}}, \tag{5}$$

where Y_{ei} is the experimental value, Y_{pi} is the predicted value from the model and N is the number of experimental data points. A model is considered acceptable if MRE values are below 10% (Krokida & Marinos-Kouris, 2003).

The predicted values from the Weibull model can be expressed as

$$X_{\mathrm{w}} = X_{\mathrm{we}} + (X_{\mathrm{w0}} - X_{\mathrm{we}})\exp\left[-\left[\frac{t}{\alpha_{\mathrm{w}}}\right]^{\beta_{\mathrm{w}}}\right], \tag{6}$$

$$X_{\mathrm{s}} = X_{\mathrm{se}} + (X_{\mathrm{s0}} - X_{\mathrm{se}})\exp\left[-\left[\frac{t}{\alpha_{\mathrm{s}}}\right]^{\beta_{\mathrm{s}}}\right]. \tag{7}$$

2.4. *Statistical analysis*

Statistical evaluation of the results was performed using a 5 × 5 × 4 split (on time) factorial design (five concentrations, five temperatures, and four time intervals). Non-linear regression using Levenberg–Marquardt method (Bates & Watts, 1988) was used to fitting database to Weibull model, for each combination of concentration and temperature of brine. The scale and shape parameters of Weibull model and equilibrium contents were estimated as parameters of Eqs. (3) and (4). Analysis of variance was carried out to find effects ($p < 0.05$) of brine concentration and temperature on the parameters of Weibull model. Multiple comparison tests were performed using LSD's test at the 95% confidence level. Non-linear regression was used to fitting data of scale parameter to Arrhenius equation in order to estimate dependence of temperature. Multiple linear regression was used to fitting models of shape and scale parameters as a function of brine concentration and temperature. Non-linear regression was used to fitting data of scale and shape parameters to these models in order to estimate dependence of concentration and temperature. All the analysis was carried out by using the SPSS 10.0 statistical software (SPSS Inc., Chicago, IL, USA).

3. Results and discussion

3.1. *Estimation of moisture and salt contents*

Moisture and salt contents of fresh sardine were 2.143 ± 0.346 g water/g db and 0.0774 ± 0.0042 g NaCl/g db, respectively. Equilibrium moisture and salt contents estimated in this study were similar those estimated by Peleg model (Corzo & Bracho, 2006). The results of the non-linear regression to fitting fractional amount of

Table 1
Scale (α_w) and shape (β_w) parameters of Weibull model for fractional amount of moisture content during vacuum pulse osmotic dehydration

Concentration (g NaCl/g)	Temperature (°C)	α_w (h)	β_w	R^2	MRE
0.15	30	180.40 ± 27.15	0.665 ± 0.009	0.997	2.93
	32	107.26 ± 10.87	0.618 ± 0.011	0.998	0.91
	34	94.96 ± 2.65	0.607 ± 0.007	0.999	1.01
	36	78.06 ± 3.62	0.556 ± 0.005	0.997	5.19
	38	67.71 ± 3.15	0.555 ± 0.004	0.998	1.50
0.18	30	155.24 ± 2.35	0.660 ± 0.007	0.987	2.13
	32	64.10 ± 4.19	0.543 ± 0.011	0.987	5.11
	34	54.74 ± 0.35	0.516 ± 0.003	0.995	5.46
	36	64.13 ± 2.26	0.566 ± 0.012	0.999	7.22
	38	41.30 ± 4.61	0.488 ± 0.014	0.998	4.06
0.21	30	49.08 ± 0.44	0.511 ± 0.006	0.996	3.88
	32	60.95 ± 0.24	0.528 ± 0.002	0.995	1.61
	34	43.74 ± 0.12	0.470 ± 0.004	0.996	6.01
	36	22.22 ± 1.07	0.434 ± 0.005	0.999	2.16
	38	24.06 ± 2.13	0.446 ± 0.004	0.997	8.08
0.24	30	47.30 ± 1.11	0.498 ± 0.006	0.998	6.21
	32	37.79 ± 2.38	0.492 ± 0.007	0.997	5.87
	34	28.44 ± 1.08	0.455 ± 0.010	0.998	5.47
	36	31.99 ± 0.48	0.465 ± 0.005	0.998	4.57
	38	49.63 ± 2.06	0.507 ± 0.007	0.996	4.94
0.27	30	31.42 ± 1.76	0.469 ± 0.006	0.997	4.22
	32	31.36 ± 1.34	0.462 ± 0.006	0.996	3.80
	34	31.52 ± 1.49	0.469 ± 0.012	0.994	8.11
	36	16.24 ± 1.80	0.400 ± 0.014	0.994	4.03
	38	15.84 ± 1.78	0.407 ± 0.008	0.995	5.39

Values of α and β are means of four replicates.

Table 2
Scale (α_s) and shape (β_s) parameters of Weibull model for fractional amount of salt content during vacuum pulse osmotic dehydration

Concentration (g NaCl/g)	Temperature (°C)	α_s (h)	β_s	R^2	MRE
0.15	30	60.17±1.30	0.525±0.003	0.998	0.93
	32	66.94±4.96	0.536±0.010	0.998	3.37
	34	65.29±2.37	0.531±0.004	0.999	3.62
	36	64.37±0.57	0.535±0.003	0.997	3.06
	38	62.65±0.91	0.532±0.002	0.999	1.68
0.18	30	48.68±0.78	0.510±0.005	0.989	3.48
	32	79.10±4.84	0.378±0.008	0.996	3.87
	34	93.10±1.12	0.557±0.003	0.993	5.68
	36	117.20±1.35	0.592±0.004	0.999	5.64
	38	119.99±2.29	0.603±0.002	0.998	2.57
0.21	30	82.02±2.46	0.549±0.003	0.997	4.81
	32	66.66±0.91	0.524±0.001	0.997	4.97
	34	84.39±1.05	0.551±0.001	0.996	4.05
	36	109.91±3.36	0.634±0.023	0.998	1.99
	38	97.61±3.05	0.595±0.002	0.998	2.36
0.24	30	69.87±2.15	0.541±0.002	0.998	2.12
	32	65.49±2.47	0.522±0.004	0.996	6.14
	34	87.65±1.70	0.569±0.006	0.998	2.01
	36	115.14±1.11	0.620±0.001	0.998	0.27
	38	126.04±2.18	0.625±0.001	0.995	1.49
0.27	30	87.47±2.52	0.573±0.002	0.997	1.88
	32	120.35±3.32	0.618±0.002	0.994	1.36
	34	111.81±1.85	0.595±0.003	0.997	3.92
	36	137.43±1.55	0.657±0.001	0.994	1.41
	38	154.34±2.70	0.680±0.001	0.998	1.66

Values of α and β are means of four replicates.

moisture and salt contents to Weibull models are shown in Tables 1 and 2. The coefficients of determination, R^2 values, were higher than 0.99 for both fractional amount of moisture and salt contents. The MRE values for models were lower than 10%. Such R^2 as MRE values indicate a good fit to the experimental data. This suggests that Weibull models (Eqs. (3) and (4)) are suitable for predicting the moisture and salt contents of sardine sheets during vacuum pulse osmotic dehydration at both brine concentrations between 0.15 and 0.27 g NaCl/g and temperatures between 30 and 38 °C.

3.2. Parameters of Weibull model for moisture content

The values of scale (α_w) and shape (β_w) parameters of Weibull model for fractional amount of moisture content (Eq. (3)) at different brine concentration and temperature are shown in Table 1. Values of β_w ranged from 0.400 to 0.665 and values of α_w ranged from 15.84 to 180.40 (h) such as was found for the kinetics of moisture uptake by ready-to-eat breakfast cereal (Machado et al., 1999), the modeling of water losses during osmotic dehydration of apple (Cunha et al., 2001) and the rehydration kinetics of mushrooms (García-Pascual, Sanjuán, Melis, & Mulet, 2006). Value of shape parameter lower than 1 is related to a decreasing Weibull distribution function. The parameters variation was subjected to analysis of variance across concentration and temperature effects. The results show that both α_w and β_w were affected by concentration, temperature and its interaction. In general, the scale parameter for fractional amount moisture content decreased ($p<0.05$) with increasing concentration and temperature. Interactive effects between temperature and concentration (Fig. 1) were observed: the effect of temperature was more pronounced for lower osmotic medium concentrations (0.15 and 0.18 g NaCl/g). The reciprocal of α_w could be compared to the effective diffusion coefficient of diffusion model, since those two parameters are the kinetic constants for each models (García-Pascual et al., 2006).

The shape parameter for fractional amount of moisture content decreased ($p<0.05$) with increasing brine concentration. Effect of temperature on the shape parameter is mixed and depends on concentration. The shape parameter is related to velocity of the mass transfer at the beginning, e.g., the lower is the β_w value, the faster the water loss rate at the beginning. Interactive effects between temperature and concentration (Fig. 1) were observed: the effect of temperature was more pronounced for lower osmotic medium concentrations (0.15 and 0.18 g NaCl/g). High salt concentration denatures the proteins and reduces their water holding capacity (WHC) during salting of milkfish (Sannaveerappa, Ammu, & Joseph, 2004), cod and salmon (Gallart-Jornet et al., 2006). However during salting of cod with diluted brines, an increase in the WHC was observed (Barat, Rodríguez-Barona, Andrés, & Fito,

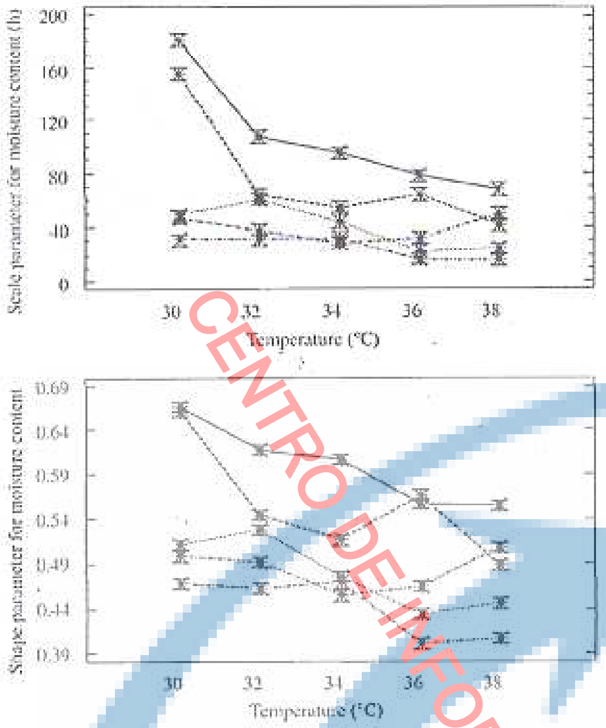

Fig. 1. Multiple comparison test for scale and shape parameters of Weibull model for fractional amount of moisture content during vacuum pulse osmotic dehydration at different concentration and temperature. (—) 0.15 g NaCl/g; (— —) 0.18 g NaCl/g; (···) 0.21 g NaCl/g; (—·) 0.24 g NaCl/g; (—··) 0.27 g NaCl/g.

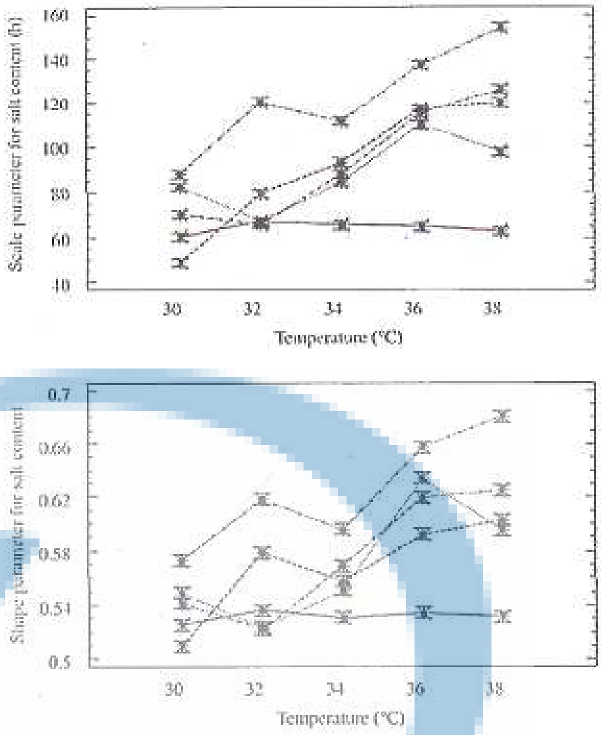

Fig. 2. Multiple comparison test of scale and shape parameters of Weibull model for fractional amount of salt content during vacuum pulse osmotic dehydration at different concentration and temperature. (—) 0.15 g NaCl/g; (— —) 0.18 g NaCl/g; (···) 0.21 g NaCl/g; (—·) 0.24 g NaCl/g; (—··) 0.27 g NaCl/g.

2002; Thorarinsdottir, Arason, Geirsdottir, Bogason, & Kristbergsson, 2002). Increased protein denaturation at a high brine concentration compared with at low brine concentrations causes less sample swelling (Barat et al., 2002) and may promote loss of water from the fish (Deng, 1977). The lower WHC at the higher temperature may be due to increased thermal denaturation of proteins at the higher compared with the lower temperature (Birkeland, Sivertsvik, Nielsen, & Skåra, 2005; Sankar & Ramachandran, 2005). However, Sankar and Ramachandran (2005) observed that proteins from Indian carp appeared labile to denaturation at relatively low temperatures (20 °C).

3.3. Parameters of Weibull model for salt content

The values of scale (α_s) and shape (β_s) parameters of Weibull model for fractional amount of salt content (Eq. (4)) at different brine concentration and temperature are shown in Table 2. It shows values of β_s lower than 0.680 and values of α_s higher than 48.68. The parameters variation was subjected to analysis of variance across concentration and temperature effects. The results show that both α_s and β_s were affected by concentration, temperature and its interaction (Fig. 2). Effect of temperature on the parameters is mixed and depends on concentration. In general, the scale and shape parameter for fractional amount salt content increased ($p<0.05$) with increasing concentration and temperature. Interactive effects between temperature and concentration were observed: the effect of temperature was more pronounced for higher osmotic medium concentrations, and there are not differences ($p<0.05$) at 0.15 g NaCl/g. The β_w values are lower than β_s value indicating that the vacuum pulse was more favorable to water loss than salt uptake. Porous gas replacement by osmotic solution during vacuum increases the pathway for solute uptake and water loss. These new pathways for mass transfer are helpful to solute uptake because of the absence of cell membranes in those spaces (Barat, Talens, Barrera, Chiralt, & Fito, 2004).

3.4. Modeling effects of temperature and concentration on the parameters

Dependence on air temperature: Dependence of the scale and shape parameters for fractional amount of moisture content on temperature is represented by the Arrhenius equation

$$\frac{1}{A}=\frac{1}{A_0}\exp\left[-\frac{E_a}{RT}\right], \qquad (8)$$

Table 3
Activation energy and frequency factor values for scale parameters of Weibull model for fractional amount of moisture and salt content during vacuum pulse osmotic dehydration of sardine sheets at different brine concentrations

Parameter	Concentration (g NaCl/g)				
	0.15	0.18	0.21	0.24	0.27
α_w					
ln $(1/\alpha_o)$	29.67±2.12	36.98±3.75	24.31±2.54	16.77±2.37	16.67±1.76
E (kJ/mol)	87.48±5.40	105.23±9.52	71.36±6.42	51.69±6.04	50.75±4.45
R^2	0.944	0.867	0.912	0.890	0.947
MRE	1.389	2.059	1.166	1.600	2.184
α_s					
ln $(1/\alpha_o)$	−17.96±0.69	−34.75±1.53	−15.84±1.56	−29.36±1.21	−23.62±1.06
E (kJ/mol)	56.10±1.75	77.27±3.90	29.00±3.99	63.41±3.09	49.04±2.70
R^2	0.953	0.967	0.951	0.926	0.979
MRE	1.578	3.048	1.122	2.550	2.510

where A corresponds to the parameter, A_o is the frequency factor ($\min^{-1}$), E_a is the activation energy (kJ/mol), R the universal gas constant (8.314 J/mol K) and T is the absolute temperature (K).

Then, the Weibull models can be written as

$$\frac{X_w - X_{we}}{X_{w0} - X_{we}} = \exp\left[-\left[\frac{t}{(1/\alpha_{0w})\exp(E_{aw}R/T)}\right]^{\beta_w}\right], \tag{9}$$

$$\frac{X_s - X_{se}}{X_{s0} - X_{se}} = \exp\left[-\left[\frac{t}{(1/\alpha_{0s})\exp(E_{as}R/T)}\right]^{\beta_s}\right], \tag{10}$$

where α_{0w}, E_{aw} and β_w are the Arrhenius parameters for moisture content and α_{0s}, E_{as} and β_s are the Arrhenius parameters for salt content. Non-linear regression was used to fitting database to Eqs. (9) and (10) and the Arrhenius parameters were determined.

The results of the non-linear regression used to fitting data to Eqs. (9) and (10) are shown in Table 3. The coefficients of determination ($R^2 > 0.86$ for moisture and $R^2 > 0.95$ for salt) and mean relative error (MRE < 10%) indicates that the inverse of scale parameters both for fractional amount of moisture and salt contents as a function of temperature followed an Arrhenius relationship, for all the concentrations (Table 3). This result was according to that found by Cunha et al. (2001), and Garcia-Pascual et al. (2006) for scale parameter. The computed values of activation energy (E_a) and natural logarithm of frequency factor (ln $(1/\alpha_o)$) are reported in Table 3. Higher E_a value indicated greater temperature sensitivity of parameters of Weibull models. Temperature sensitivity of scale parameter for fractional amount of moisture content increased with increasing concentration from 0.15 to 0.18 g NaCl and then decreased with increasing concentration. Sensitivity of scale parameter for fractional amount of salt content did not exhibit a trend with increasing concentration. Scale parameter for moisture content was found to be greater temperature sensitive ($p < 0.05$) than that for salt content.

Table 4
Multiple linear regression for scale (α_w) and shape (β_w) parameters of Weibull model for fractional amount moisture content as a function of brine concentration (C) and temperature (T)

Source of variation	α_w			β_w	
	Estimate	Standard error		Estimate	Standard error
Constant	11.152*	0.231		1.767*	0.183
C	−13.590*	0.518		−3.864*	0.390
T	−0.135*	0.0016		−0.050*	0.006
R^2			0.920		
MRE			3.479		

* p-Value < 0.001. $\ln(\alpha, \beta) = a + b(C) + d(T)$.

Table 5
Multiple linear regression for scale (α_s) and shape (β_s) parameters of Weibull model for fractional amount salt content as a function of brine concentration (C) and temperature (T)

Source of variation	α_s			β_s	
	Estimate	Standard error		Estimate	Standard error
Constant	1.338*	0.129		−1.510*	0.181
C	4.369*	0.222		1.487*	0.332
T	0.064*	0.003		0.019*	0.005
R^2			0.940		
RME			3.058		

*p-Value < 0.001. $\ln(\alpha, \beta) = a + b(C) + d(T)$.

Dependence on air temperature and velocity: An analysis was performed to generalize of Weibull parameters for this model as functions of the drying air conditions (air temperature and air velocity). Several equations were tested in the stepwise linear regression procedure to generalize α and β. The best models were

$$\ln \alpha = a_1 + b_1 T + c_1 V, \tag{11}$$

$$\ln \beta = a_2 + b_2 T + c_2 V. \tag{12}$$

Then, the Weibull model can be written as

$$\frac{X_w - X_{we}}{X_{w0} - X_{we}} = \exp\left[-\left[\frac{t}{\exp(a_{1w} + b_{1w}T + c_{1w}V)}\right]^{\exp(a_{2w}+b_{2w}T+c_{2w}V)}\right], \tag{13}$$

$$\frac{X_s - X_{se}}{X_{s0} - X_{se}} = \exp\left[-\left[\frac{t}{\exp(a_{1s} + b_{1s}T + c_{1s}V)}\right]^{\exp(a_{2s}+b_{2s}T+c_{2s}V)}\right], \tag{14}$$

where a_{1w}, b_{1w}, c_{1w}, a_{2w}, b_{2w} and c_{2w} are the parameters for moisture content and a_{1s}, b_{1s}, c_{1s}, a_{2s}, b_{2s} and c_{2s} are the parameters for salt content. Non-linear regression was used to fitting database to Eqs. (13) and (14) and the models parameters were determined.

The models as fitted for Weibull parameters as a function of brine concentration (C) and temperature (T) corresponded to (Tables 4 and 5)

$$\ln \alpha_w = 9.458 - 11.389(C) - 0.0946(T), \tag{15}$$

$$\ln \alpha_s = 1.494 + 4.310(C) + 0.0010(T), \tag{16}$$

$$\ln \beta_w = 0.506 - 2.493(C) - 0.0195(T), \tag{17}$$

$$\ln \beta_s = -1.332 + 1.103(C) + 0.0159(T). \tag{18}$$

The models as fitted explained the 92.0% and 94.0% of the variability in α_w, α_s, β_w, and β_s at the 99% confidence level, respectively (Tables 4 and 5). The mean relative error was lower than 10%. With these models the scale and shape parameters of Weibull models for fractional amount of moisture and salt contents can be calculated when the sardine sheets are vacuum pulse osmotic dehydrated in brine concentrations in the range 0.15–0.24 g NaCl/g, temperatures in the range 32–38 °C, applying a vacuum pulse at 11.0 kPa for 10 min. In Eqs. (15) and (16), the coefficients for brine concentration and temperature are negatives. This indicates that scale and shape parameter decreases with increase in brine concentration and temperature. In Eqs. (17) and (18), the coefficients for brine concentration and temperature are positives. This indicates that scale and shape parameters increase with increase in brine concentration and temperature. Effects of brine concentration and temperature were analyzed previously in the sections of parameters of Weibull model for moisture and salt contents.

4. Conclusions

Weibull frequency distribution model adequately predicts the moisture and salt contents of sardine sheets during vacuum pulse osmotic dehydration at brine concentration between 0.15 and 0.27 g NaCl/g, temperature between 30 and 38 °C, applying a vacuum pulse at 11.0 kPa for 10 min. Effects of brine concentration and temperature on the scale and shape parameters for moisture loss and salt uptake is mixed and depends on their interaction. The scale parameter for fractional amount of moisture and salt content were temperature dependent according to an Arrhenius-type equation. Models for scale and shape parameters of Weibull models for fractional amount of moisture and salt contents as a function of brine concentration and temperature were found.

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