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# Application of Weibull distribution model in describing the pile salting of goat meat slices

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**Application of Weibull model in the pile salting of goat meat slices was studied to predict the moisture and salt contents and determine the effective water diffusion coefficient ($D_e$). The high coefficients of determination ($R^2$ > 0.99) and low mean relative error (< 10%) indicated the acceptability of Weibull model for predicting both the moisture and salt contents and determining $D_e$. Values of scale (α) and shape (β) parameters of Weibull model for fractional amount of moisture content ranged from 0.667 to 0.873 day and from 0.527 to 0.743 day, respectively. Values of α and β parameters of Weibull model for fractional amount of salt content ranged from 0.350 to 1.192 day and from 0.578 to 0.885 day, respectively. Values of $D_e$ ranged approximately from 1.66 × $10^{-10}$ to 2.44 × $10^{-10}$ $m^2/s$.**

**Key words:** Weibull model, partial replacement, salting mixtures, effective water diffusion coefficient.

## INTRODUCTION

Dry salting is the traditional salt-curing technique used during processing of meat. Two main simultaneous flows, water loss and salt uptake occur during salting (Jittinandana et al., 2002; Sannaveerappa et al., 2004; Thorarinsdottir et al., 2002, 2004). During the process, the salt and moisture concentrations change and, finally, an equilibrium state is reached. To obtain a better understanding of the industrial process applications it is important to model and quantify kinetics and process yield. Fick's law of diffusion, based on effective diffusivity approach, has been used to describe the moisture diffusion process for food products by many researchers (Seth and Sarkar, 2004; Ramallo and Albani, 2007; Kaya and Aydin, 2008). Although this mathematical model provides insights into mechanistic relevance of an observed phenomenon, it frequently sacrifices the precision of the representations due to overlooked existence of uncertainties (Saguy et al., 2005).On the other hand, the development of empirical models requires considerably less effort. A model, with an exponential approach to the equilibrium value of these parameters was proposed by Zugarramurdi and Lupín (1980) to explain observed behavior on fish salting. This model has been used to explain the changes of moisture and salt contents during osmotic dehydration of sardine (Corzo and Bracho, 2005). Peleg (1988) proposed two parameters model to describe sorption curves that approach equilibrium asymptotically. This empirical model has been used to model the sorption curves of sardine during osmotic dehydration (Corzo and Bracho, 2006b; Corzo et al., 2007). From a mass balance on water, Azuara et al. (1992) proposed a model avoiding the limitations of Fick's diffusion model for practical purposes. The Azuara et al. (1992) model has been applied to model the osmotic dehydration of sardine with osmotic solutions at different concentrations and

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temperatures (Corzo and Bracho, 2006a). The probabilistic Weibull model has been used to describe the behavior of pressure inactivation of bacteria (Cheng and Hoover, 2004; Buzrul et al., 2005), thermal resistance of bacteria (Corradini et al., 2005; González et al., 2009; Dong, 2011), spore germination (Collado et al., 2006), inactivation kinetics (Shivhare et al., 2009; Ma et al., 2011), survival curves (Yang et al., 2002; Aragao et al., 2007), rehydration (Solomon, 2008), oil migration (Motwani et al., 2011, leaching kinetics (Quispe-Fuentes et al., 2012) and changes during storage (Oms-Oliu et al., 2009; Palazón et al., 2009). The Weibull distribution model was normalized by Marabi et al. (2003) to describe water uptake during rehydration of food particulates. Internal diffusion, external resistance and relaxation processes can be described with a normalized Weibull model (Corzo et al., 2008, 20010). The method for estimating Weibull parameters can be classified into two categories: graphical and analytical methods. Usually, the graphical methods are used because of their simplicity and speed. The analytical methods are: maximum likelihood estimators (Jankovic, 2010) least square method (Dong, 2011; Poças et al. 2012), and the method of moments (Lei, 2008). NaCl is an essential ingredient in processed meat products, contributing to the water holding capacity, protein binding, colour, flavour and texture (Blesa et al., 2008). Increased sodium and magnesium intake is associated with hypertension, whereas increased potassium and calcium intake may slightly decrease hypertension. An approach to reducing the sodium content in processed foods is the partial or total replacement of NaCl with chloride salts such as KCl, $CaCl_2$ and $MgCl_2$ (Aliño et al. 2009; Blesa et al., 2008; Ruusunen and Puolanne, 2005). In meat research, water-holding capacity (WHC) is a ubiquitous term used to describe the ability of meat to retain its natural water content. WHC is studied extensively because of its enormous economic importance. The salting induces changes in the muscle proteins resulting in changes in texture and water holding capacity (Sannaveerappa et al., 2004; Thorarinsdottir et al., 2002, 2004). There is not information available in the literature about using Weibull model to describe the salting of meat. The objectives of this study were: 1) the determination of the applicability of Weibull frequency distribution model in predicting moisture and salt contents of goat meat slices during pile salting using different mixtures; and 2) analyze the effect of salting mixtures on water holding capacity of salted goat meat slices.

## MATERIALS AND METHODS

### Sample preparation

Meat of hind limb goat was acquired from a slaughter situated in Punta Cardón, Falcón state, Venezuela. Meat was manually filleted with stainless steel knives, and then the fillets were cut into slices with an average length of $4.0 \times 10^{-2}$ m, average width of $4.0 \times 10^{-2}$ m and average thickness of $1.0 \times 10^{-2}$ m using a metal mold. Average weight of slices was 0.0236 kg. Chemical characterization of fresh meat was carried out. The moisture content was determined by drying under vacuum (1.93 Pa) at 60°C until constant weight (AOAC, 1990). The chloride content was determined by the Mohr method (AOAC, 1990) and expressed as NaCl content. The pH was measured by insertion of a glass electrode into the core of slice. Ash content was determined by charring in a crucible at 600°C until the ash had a white appearance (AOAC, 1990). Water activity (Aw), was determined on minced samples and each sample was read three times by CX-3 AquaLab (Decagon Devices Inc., Pullman, Washington). The analyses were run in triplicate.

### Pile salting

The slices were randomly divided into six groups, with 36 sheets in each of them, and pile salted with different mixtures of sodium, potassium, calcium, and magnesium chloride (Table 1). All the salts used in the experiment (NaCl, KCl, $CaCl_2$ and $MgCl_2$) were white crystalline powder. Curing agents (150 ppm of $KNO_3$ and 150 ppm of $NaNO_2$) were added to each mixture. Pile salting was carried out by covering the slices with solid mixture (using 1.7 kg mixture per kg of slice), at ambient temperature (29°C). Slices were set out in a plastic container without drainage, two layers of six slices within a layer of salt in between them, another above the upper layer and below the lower layer of slices. In all the treatments, 6 slices were removed at intervals of 1 day during 6 days. After the removal from pile the salted slices of each treatment were brushed to remove the excess of mixture, and their moisture and salt contents were measured. Each experimental treatment was performed in duplicate. All reported results are average values of twelve replicates.

### Weibull 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 et al., 1998; Cunha et al., 2001), such as the pile salting kinetics.

The fractional amount of moisture content during salting can be expressed as (Cunha et al., 1998):

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

where $X_{wo}$ is the initial moisture content, $X_w$ is the moisture content at a salting time t, $X_{we}$ is the equilibrium moisture content, $\alpha_w$ is the scale parameter of the Weibull model, $\beta_w$ is the shape parameter (dimensionless) of the Weibull model, and *t* is the salting time.

The fractional amount of salt content during salting can be expressed as (Cunha et al., 1998):

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

where $X_{so}$ is the initial salt content, $X_s$ is the salt content at a salting time t, $X_{se}$ is the equilibrium salt content, $\alpha_s$ is the scale parameter of the Weibull model, $\beta_s$ is the shape parameter (dimensionless) of the Weibull model, and *t* is the salting time.

**Table 1.** Composition of different salting mixtures.

| Mixture | NaCl (%) | KCl (%) | $CaCl_2$ (%) | $MgCl_2$ (%) |
|---|---|---|---|---|
| 0 | 100 | - | - | - |
| 1 | 75 | 25 | - | - |
| 2 | 65 | 35 | - | - |
| 3 | 50 | 50 | - | - |
| 4 | 55 | 25 | 15 | 5 |
| 5 | 45 | 25 | 20 | 10 |

### Normalized Weibull model

The Weibull model was modified and the scale parameter was normalized with a characteristic dimension for the thickness in order to consider the water diffusion coefficient (Marabi et al., 2003, 2004):

$$MR = \frac{X_s - X_{se}}{X_{s0} - X_{se}} = exp\left[-\left[\frac{t\,D}{L}\right]^{\beta_s}\right] \qquad (5)$$

where D is the water diffusion coefficient, β is the shape parameter (dimensionless) and *L* is the half-thickness of the slice for diffusion from both sides, and t is the diffusion time.

If the effective diffusion coefficient ($D_e$) is required for experimental data, it follows (Marabi et al., 2003):

$$D_e = \frac{D}{R_g} \qquad (6)$$

where $R_g$ is the geometric factor.

To establish the adequate geometric factor ($R_g$) to be utilized for the implementation of the normalized Weibull model, Fick model was used:

$$MR = \frac{X_t - X_e}{X_0 - X_e} = \frac{8}{\pi^2}\sum_{n=0}^{n=\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\,\pi^2\,D_e\,t}{4L^2}\right] \qquad (7)$$

This model was utilized to simulate the conditions prevailing under theoretical processes and also as a basis for comparison. The moisture ratio data at the different drying conditions were derived from simulation using the first four terms of the series in the analytical solution of the Fickian diffusion model. Then, the normalized Weibull model equation (5) was fitting to derived data from simulation and D values were determined from this fitting. Finally the $R_g$ value is determined with the theoretical and derived values of D using equation 6.

### Water holding capacity

Water holding capacity (WHC) of salted goat meat slices was calculated as the variation between the moisture content after salting ($X_w$) and the initial moisture content ($X_{w0}$) referred to this last value (Graiver et al., 2006):

$$WHC = \frac{X_{w0} - X_w}{X_{w0}} \qquad (8)$$

### Statistical analysis

Statistical evaluation of the results was performed using a 6x6 split factorial design (six salting mixtures, and six time intervals). Non linear regression using Levenberg-Marquandt method (Bates and Watts, 1988) was used to fit experimental data to Weibull model and normalized Weibull model for each salting mixture. The scale and shape parameters of Weibull model and equilibrium contents were estimated as parameters of Equations (3) and (4). An interactive procedure was used for determining parameters of the equation using the method of least squares. The statistical analysis of fit for nonlinear regression reports parameter error estimates which are readily obtained from the variance–covariance matrix after the final iteration. Analysis of variance (ANOVA) was carried out to find effects ($p < 0.05$) of salting mixture on the scale and shape parameters of the Weibull model, effective water diffusion coefficient and WHC. Multiple comparison tests were performed using least square differences test at the 95% confidence level. Statistical analysis was performed using the SPSS 10.0 statistical package (SPSS Inc., Chicago, IL., U.S.A.).

To evaluate the goodness of fit of each model, two criteria were used: the coefficient of determination ($R^2$). The prediction capability of Weibull model was evaluated using cross validation and the mean relative error (MRE) expressed as:

$$MRE = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|Y_{ei} - Y_{pi}\right|}{Y_{ei}} \qquad (9)$$

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 and Marions-Kouris, 2003).

The residual analysis of models was made in order to check assumptions of independence, normality, homoscedasticity and zero mean of errors. In this work, it was assumed that all data have been collected independently; that is, it was assumed that independence is satisfied.

## RESULTS AND DISCUSSION

### Characterization of raw samples

The moisture, salt, ashes, contents in the fresh goat meat, as well as activity (Aw) and pH, are shown in Table 2.

### Determination of moisture and salt contents

The variation of moisture and salt contents during pile

**Table 2.** Characterization of fresh goat meat.

| Characteristic | Estimate |
|---|---|
| Moisture content (g water/g db) | 3.27 ± 0.03 |
| Total chloride content (g NaCl/g db) | 0.00623 ± 0.00009 |
| Ash (g/g) | 0.0115 ± 0.0003 |
| pH | 6.04 ± 0.02 |
| **Aw** | 0.994 ± 0.002 |

Values of characteristics are means of three replicates.

**Table 3.** Variation of moisture and salt contents of goat meat slices during salting using different salting mixtures.

| Salting time (day) | Salting mixture | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 |
| | **Moisture content (g water/g db)** | | | | | |
| 1 | 1.024 ± 0.007 | 0.918 ± 0.006 | 1.067 ± 0.009 | 0.973 ± 0.008 | 0.878 ± 0.007 | 0.775 ± 0.010 |
| 2 | 0.973 ± 0.006 | 0.906 ± 0.008 | 0.948 ± 0.007 | 0.926 ± 0.007 | 0.804 ± 0.010 | 0.751 ± 0.008 |
| 3 | 0.937 ± 0.005 | 0.900 ± 0.012 | 0.945 ± 0.010 | 0.909 ± 0.005 | 0.760 ± 0.010 | 0.692 ± 0.009 |
| 4 | 0.907 ± 0.007 | 0.886 ± 0.009 | 0.911 ± 0.006 | 0.879 ± 0.011 | 0.720 ± 0.007 | 0.663 ± 0.007 |
| 5 | 0.898 ± 0.006 | 0.869 ± 0.007 | 0.904 ± 0.009 | 0.860 ± 0.007 | 0.701 ± 0.008 | 0.582 ± 0.012 |
| 6 | 0.865 ± 0.004 | 0.849 ± 0.010 | 0.897 ± 0.007 | 0.836 ± 0.008 | 0.621 ± 0.009 | 0.565 ± 0.010 |
| | **Salt content (g NaCl/g db)** | | | | | |
| 1 | 0.300 ± 0.010 | 0.299 ± 0.007 | 0.310 ± 0.004 | 0.327 ± 0.006 | 0.324 ± 0.007 | 0.260 ± 0.005 |
| 2 | 0.317 ± 0.008 | 0.312 ± 0.005 | 0.326 ± 0.007 | 0.333 ± 0.005 | 0.325 ± 0.007 | 0.286 ± 0.007 |
| 3 | 0.320 ± 0.012 | 0.325 ± 0.006 | 0.341 ± 0.010 | 0.337 ± 0.004 | 0.327 ± 0.005 | 0.301 ± 0.005 |
| 4 | 0.322 ± 0.007 | 0.329 ± 0.004 | 0.343 ± 0.005 | 0.339 ± 0.004 | 0.330 ± 0.005 | 0.314 ± 0.004 |
| 5 | 0.325 ± 0.005 | 0.330 ± 0.007 | 0.345 ± 0.006 | 0.342 ± 0.006 | 0.335 ± 0.004 | 0.316 ± 0.007 |
| 6 | 0.329 ± 0.004 | 0.332 ± 0.006 | 0.348 ± 0.004 | 0.344 ± 0.004 | 0.338 ± 0.007 | 0.325 ± 0.006 |

Values of moisture and salt contents are means of twelve replicates.

salting using different mixtures are shown in Table 3.

Moisture content decreased ($p < 0.05$) with increasing salting time while salt content increased ($p < 0.05$) for all salting mixtures. Generally, moisture decreased ($p < 0.05$) with increasing partial replacement of NaCl by KCl, $CaCl_2$ and $MgCl_2$ in salting mixtures while salt content increased ($p < 0.05$).

The results of the non linear regression to fitting fractional amount of moisture and salt contents to Weibull models are shown in Tables 4 and 5. The coefficients of determination, $R^2$ values, are higher than 0.99 for both fractional amount of moisture and salt contents. The MRE values for the models are lower than 10%. Such $R^2$ as MRE values indicate a good fit to the experimental data. The residual analysis (non shown) showed: 1) straight lines in the normal probability plots, therefore is reasonable to assume that the observed errors come from a normal distribution; 2) standardized residuals varying randomly around zero without obvious trends or shapes in the scatterplots of the standardized residuals against the fitted values of moisture and salt contents to models, therefore, homoscedasticity and zero mean of errors were satisfied. This suggests that Weibull models (Equations (3) and (4)) are suitable for predicting the moisture and salt contents of goat meat sheets during pile salting using salting mixtures of NaCl, KCl, $CaCl_2$ and $MgCl_2$. Similar results were found to describe the behavior of rehydration kinetics (Sanjuán et al., 2001; Marabi et al., 2003; Garcìa-Pascual et al., 2006), osmotic dehydration (Cunha et al., 2001; Corzo and Bracho, 2008), and air drying (Corzo et al., 2008; Corzo et al., 2010).

### Parameters of Weibull model for moisture content

The values of scale ($\alpha_w$) and shape ($\beta_w$) parameters of Weibull model for fractional amount of moisture content (Equation (3)) at different salting mixtures are shown in Table 4. Values of $\beta_w$ ranged from 0.527 to 0.743 and

**Table 4.** Scale (α) and shape (β) parameters of Weibull model for fractional amount of moisture content of goat meat slices during salting.

| Salting mixture | $\alpha_w$ (d) | $\beta_w$ | $X_{we}$ | $R^2$ | MRE |
|---|---|---|---|---|---|
| 0 | 0.873 ± 0.138 | 0.527 ± 0.040 | 0.839 ± 0.027 | 0.998 | 0.00835 |
| 1 | 0.674 ± 0.057 | 0.547 ± 0.086 | 0.850 ± 0.007 | 0.998 | 0.00423 |
| 2 | 0.707 ± 0.052 | 0.743 ± 0.085 | 0.885 ± 0.027 | 0.997 | 0.010152 |
| 3 | 0.667 ± 0.109 | 0.553 ± 0.064 | 0.840 ± 0.007 | 0.997 | 0.006826 |
| 4 | 0.816 ± 0.065 | 0.610 ± 0.031 | 0.664 ± 0.012 | 0.998 | 0.018184 |
| 5 | 0.837 ± 0.048 | 0.591 ± 0.041 | 0.578 ± 0.019 | 0.997 | 0.017566 |

Values of α and β are means of twelve replicates. MRE = mean relative error.

**Table 5.** Scale (α) and shape (β) parameters of Weibull model for fractional amount of salt content of goat meat slices during salting.

| Salting mixture | $\alpha_s$ (d) | $\beta_s$ | $X_{se}$ | $R^2$ | MRE |
|---|---|---|---|---|---|
| 0 | 0.350 ± 0.040 | 0.839 ± 0.038 | 0.315 ± 0.011 | 0.999 | 0.003784 |
| 1 | 0.623 ± 0.047 | 0.850 ± 0.057 | 0.329 ± 0.005 | 0.999 | 0.002953 |
| 2 | 0.725 ± 0.039 | 0.885 ± 0.052 | 0.345 ± 0.019 | 0.999 | 0.003596 |
| 3 | 0.602 ± 0.045 | 0.840 ± 0.039 | 0.343 ± 0.016 | 0.998 | 0.004641 |
| 4 | 1.192 ± 0.021 | 0.664 ± 0.065 | 0.335 ± 0.009 | 0.998 | 0.005006 |
| 5 | 0.998 ± 0.036 | 0.578 ± 0.048 | 0.325 ± 0.017 | 0.999 | 0.007139 |

Values of α and β are means of twelve replicates. MRE = mean relative error.

values of $\alpha_w$ ranged from 0.667 to 0.873 days (d). Value of $\beta_w$ lower than 1 is related to a decreasing Weibull distribution function. The parameters variation was subjected to analysis of variance across salting mixture effects. The results show that both $\alpha_w$ and $\beta_w$ were affected by composition of mixtures. Higher value of $\alpha_w$ was found for salting of slices using only NaCl (mixture 0). In general, the scale parameter for fractional amount moisture content decreased ($p < 0.05$) with increasing partial replacement of NaCl by KCl, $CaCl_2$ and $MgCl_2$ (mixtures 1, 2, 3, 4 and 5). A higher decreasing in $\alpha_w$ was observed when only KCl was added to NaCl (mixtures 1, 2 and 3). However, low differences in $\alpha_w$ were observed with regards to composition of these mixtures. Increasing in $\alpha_w$ was observed when $CaCl_2$ and $MgCl_2$ were added to mixture containing 25% KCl and different percentage of NaCl (mixtures 4 and 5). The reciprocal of $\alpha_w$ 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 increased ($p < 0.05$) with increasing partial replacement of NaCl by KCl, $CaCl_2$ and $MgCl_2$ (mixtures 1, 2, 3, 4 and 5). Lower value was found for salting of slices using only NaCl (mixture 0). Effect of composition of mixture containing NaCl and KCl (mixtures 1, 2 and 3) on the shape parameter is mixed. Increasing in $\beta_w$ was observed when $CaCl_2$ and $MgCl_2$ were added to mixture containing 25% KCl and different percentage of NaCl (mixtures 4 and 5). The shape parameter decreased ($p < 0.05$) with increasing percentage of $CaCl_2$ and $MgCl_2$. The shape parameter is related to velocity of the mass transfer at the beginning, for example, the lower is the $\beta_w$ value, the faster the moisture loss rate at the beginning.

### Parameters of Weibull model for salt content

The values of scale ($\alpha_s$) and shape ($\beta_s$) parameters of Weibull model for fractional amount of salt content (equation (4)) at different salting mixtures are shown in Table 5. It shows values of $\alpha_s$ and $\beta_s$ lower than 1 except for mixture 4. Higher value of $\alpha_w$ was found for salting of slices using only NaCl (100% NaCl). The parameters variation was subjected to analysis of variance across composition of salting mixtures. The results show that both $\alpha_s$ and $\beta_s$ were affected by composition. The scale parameter for fractional amount salt content increased ($p < 0.05$) with increasing partial replacement of NaCl by KCl, $CaCl_2$ and $MgCl_2$ (mixtures 1, 2, 3, 4 and 5). Effect of composition of mixture containing only NaCl and KCl (mixtures 1, 2 and 3) on the shape parameter is mixed. Increasing in $\alpha_s$ ($p < 0.05$) was observed when $CaCl_2$ and $MgCl_2$ were added to mixture containing 25% KCl and different percentage of NaCl (mixtures 4 and 5). Increasing in $\beta_s$ ($p < 0.05$) was observed when KCl was added to NaCl (mixtures 1, 2 and 3); however, low differences were found caused by composition of mixture.

**Table 6.** Calculated effective water diffusion coefficient ($D_e$) during salting of goat meat slices using different salting mixtures.

| Mixture | $D_e$ x$10^{10}$ $m^2/s$ | $R^2$ | MRE |
|---|---|---|---|
| 0 | 1.81 ± 0.02 | 0.999 | 0.004677 |
| 1 | 2.44 ± 0.01 | 0.999 | 0.001688 |
| 2 | 2.12 ± 0.01 | 0.998 | 0.002486 |
| 3 | 2.21 ± 0.02 | 0.999 | 0.001743 |
| 4 | 1.66 ± 0.01 | 0.997 | 0.003070 |
| 5 | 1.74 ± 0.01 | 0.999 | 0.003343 |

Values of $D_e$ and β are means of twelve replicates. MRE = mean relative error.

The scale parameter decreased ($p < 0.05$) when $CaCl_2$ and $MgCl_2$ were added to mixture containing 25% KCl and different percentage of NaCl (mixtures 4 and 5). The $\beta_w$ values are lower than $\beta_s$ values indicating that the partial replacement of NaCl by KCl, $CaCl_2$ and $MgCl_2$ was more favorable to water loss than salt uptake.

## Determination of effective water diffusion coefficient

The high coefficients of determination ($R^2$ > 0.996) and the low MRE values (Table 6), and no pattern evident with the residuals across the range of diffusion coefficients (not shown) indicated the goodness of fit of experimental data to Equation 5.

The value of $D_e$ was calculated by equation 6 using *R*g equals 13.1. The $D_e$ values ranged approximately from 1.66 × $10^{-10}$ (using mixture 4) to 2.44 × $10^{-10}$ $m^2/s$ (using mixture 1) for salting using different salting mixtures (Table 6). ANOVA showed that $D_e$ increased ($p < 0.05$) with increasing partial replacement of NaCl by KCl (mixtures 1, 2 and 3) while decreased with increasing partial replacement of NaCl by $CaCl_2$ and $MgCl_2$ (mixtures 5 and 6). Similar results were found for rehydration of food particulates (Marabi et al. 2004, drying of coroba slices (Corzo et al., 2008), drying of mango slices (Corzo et al., 2010) and osmotic dehydration of sardine sheets (Corzo and Bracho, 2008). These values fell within the normally expected range of $D_e$ ($10^{-8}$ to $10^{-12}$ $m^2/s$) for dehydrated foods (Gely and Santalla, 2007; Kaya and Aydin, 2008; Vega-Gálvez et al*.,* 2008) or obtained by other techniques for different foods (Akanbi et al, 2006; Nguyen et al*.,* 2006; Kaya et al*.,* 2007).

## Water holding capacity of salted goat sheets

WHC of salted slices using different salting mixtures after 6 days of salting are shown in Table 7. Generally, WHC of salted sheets increased ($p < 0.05$) with increasing partial replacement of NaCl by KCl (mixtures 1, 2 and 3), and $CaCl_2$ and $MgCl_2$ (mixtures 4 and 5). It is generally accepted that only myosin and actin, and to some extent tropomyosin, are responsible for the water-holding capacity of meat. Hofmeister series has an effect on the ion distribution of actin and myosin filaments, their stability and water-holding. The series can be used to make conclusions about the stability of proteins (Poulanne and Jalonen, 2010). For instance, the order of effectiveness to stabilize proteins is $K^+$, $Na^+$, $Mg^{2+}$, $Ca^{2+}$ (Zhao, 2005). The increase in water holding capacity might be attributed to the lateral expansion of myofibrils, which is coupled to protein solubilization. According to Xiong et al. (2000), an increase in water binding and hydration in salted meat and muscle fibers are generally attributed to enhanced electrostatic repulsion between myofibril filaments causing the filament lattices to expand for water entrapment. WHC can be determined using methods based on applying a specific force to the sample and analyzing how well the sample holds on to water under the specified stress. Applying this methodology during salting of milkfish (Sannaveerappa et al., 2004), cod and salmon (Gallart-Jornet et al., 2007) using high salt concentration brine a decreasing in the WHC was observed. However, during salting of cod with diluted brines, an increase in the WHC was observed (Barat et al., 2002; Thorarinsdottir et al., 2002).

## Relationship between WHC and salt content

Linear simple regressions were used to fit the WHC of goat meat slices during salting as a function of the salt content ($X_s$). The model as fitted corresponds to:

$$WHC = A + B\ X_s \quad (9)$$

where A and B are the constant parameters.

The model as fitted explained the 94.4 to 98.6% of the variability in the WHC at 95% confidence level (Table 7). The A and B constant values varies from -0.034 to -0.057 and from 2.259 to 2.732, respectively. With this model the

**Table 7.** Fitting of water holding capacity (WHC) as a function of salt content for salted goat meat slices using different salting mixtures $WHC = A + B\ X_s$.

| Mixture | Parameter value | p-value | $R^2$ | WHC at 6 days |
|---|---|---|---|---|
| 0 | A = -0.045 ± 0.006 | < 0.0001 | 0.958 | 0.736 ± 0.015 |
| | B = 2.427 ± 0.079 | < 0.0001 | | |
| 1 | A = -0.057 ± 0.009 | < 0.0001 | 0.986 | 0.740 ± 0.003 |
| | B = 2.445 ± 0.045 | < 0.0001 | | |
| 2 | A = -0.048 ± 0.008 | 0.0041 | 0.980 | 0.725 ± 0.004 |
| | B = 2.259 ± 0.031 | < 0.0001 | | |
| 3 | A = -0.047 ± 0.008 | 0.0015 | 0.974 | 0.745 ± 0.006 |
| | B = 2.283 ± 0.039 | < 0.0001 | | |
| 4 | A = -0.055 ± 0.005 | 0.0026 | 0.965 | 0.819 ± 0.010 |
| | B = 2.525 ± 0.066 | < 0.0001 | | |
| 5 | A = -0.034 ± 0.003 | < 0.0025 | 0.944 | 0.847 ± 0.016 |
| | B = 2.732 ± 0.012 | 0.0073 | | |

WHC can be calculated when the goat meat slices are salting using NaCl and mixtures of NaCl, KCl, $CaCl_2$ and $MgCl_2$.

## Conclusions

Weibull frequency distribution model adequately predicts the moisture and salt contents of goat meat slices during pile salting using NaCl and different mixtures of NaCl, KCl, $CaCl_2$ and $MgCl_2$. Effect of salting mixture on the scale and shape parameters for moisture loss and salt uptake is mixed and depends on their composition. The water holding capacity of salted goat meat slices during 6 days increased with increasing partial replacement of NaCl by KCl, and $CaCl_2$ and $MgCl_2$. A relationship between water holding capacity and salt content was found.

### REFERENCES


Akanbi CT, Adeyemi RS, Ojo A (2006). Drying characteristics and sorption isotherm of tomato slices. J. Food Eng. 73:157–163.

Aragao GMF, Corradini MG, Normand MD, Peleg M (2007). Evaluation of the Weibull and log normal distribution functions as survival models of *Escherichia coli* under isothermal and non isothermal conditions. Int. J. Food Microbiol. 119:243–257.

Aliño M, Grau R, Baigts D, Barat JM (2009). Influence of sodium replacement on the salting kinetics of pork loin. J. Food Eng. 95:551–557.

AOAC (1990). Official Methods of Analysis (15th ed.). Association of Official Analytical Chemists, Washington, D. C.

Barat JM, Rodríguez-Barona S, Andrés A, Fito P (2002). Influence of increasing brine concentration in the cod salting process. J. Food Sci. 65(7):1922-1925.

Bates DM, Watts DG (1988). Nonlinear regression and its applications. Wiley, New York.

Blesa E, Aliño M, Barat JM, Grau R, Toldrá F, Pagán MJ (2008). Microbiology and physico-chemical changes of dry-cured ham during the post-salting stage as affected by partial replacement of NaCl by other salts. Meat Sci. 78:135-142.

Buzrul S, Alpas H, Bozoglu F (2005). Use of Weibull frequency distribution model to describe the inactivation of *Alicyclobacillus acidoterrestris* by high pressure at different temperatures. Food Res. Int. 38:151-157.

Cheng H, Hoover DG (2004). Use of Weibull model to describe and predict pressure inactivation of *Listeria monocytogenes* Scout A in whole milk. Innovat. Food Sci. Emerg. Technol. 5:269-276.

Collado J, Fernández A, Rodrigo M, Martinez A (2006). Modelling the effect of a heat shock and germinant concentration on spore germination of a wild strain of *Bacillus cereus.* Int. J. Food Microbiol. 106(1):85-89.

Corradini MG, Normand MD, Peleg M (2005). Calculating the efficacy of heat sterilization processes. J. Food Eng. 67:59-69.

Corzo O, Bracho N (2005). Osmotic dehydration kinetics of sardine sheets using Zugarramurdi and Lupin_ınodel. J. Food Eng. 66:51–56.

Corzo O, Bracho N (2006a). Equilibrium water and salt contents of sardine sheets during osmotic dehydration. LWT-Food Sci. Technol. 39:357–363.

Corzo O, Bracho N (2006b). Application of Peleg's model to study mass transfer during osmotic dehydration of sardine sheets. J. Food Eng. 75:535–541.

Corzo O, Bracho N (2008). Application of Weibull distribution model to describe the vacuum pulse osmotic dehydration of sardine sheets. LWT-Food Sci. Technol. 41(6):1108-1115.

Corzo O, Bracho N, Alvarez C (2010). Weibull model for thin-layer drying of mango slices at different maturity stages. J. Food Process. Preserv. 34(6):993-1008.

Corzo O, Bracho N, Pereira A, Vasquez A (2008). Weibull distribution for modeling air drying of coroba slices. LWT-Food Sci. Technol. 41:2023-2028.

Corzo O, Bracho N, Rodríguez J, González M (2007). Predicting the moisture and salt contents of sardine sheets during vacuum pulse osmotic dehydration. J. Food Eng. 80:781–790.

Cunha LM, Oliveira FAR, Aboim AP, Frías JM (2001). Stochastic approach to the modelling of water losses during osmotic dehydration and improved parameter estimation. Int. J. Food Sci. Technol. 36:253-262.

Cunha LM, Oliveira FAR, Oliveira JC (1998). Optimal experimental design for estimating the kinetic parameters of process described by the Weibull probability distribution function. J. Food Eng. 37:175-191.

Dong Q (2011). Modeling the thermal resistance of C*lostridium sporogenes* spores under different temperature, pH and NaCl concentrations. J. Food Process. Eng. 34:1965–1981.

Gallart-Jornet L, Barat JM, Rustad T, Erikson U, Escriche I, Fito P (2007). A comparative study of brine salting of Atlantic cod (*Gadus*

*morhua*) and Atlantic salmon (*Salmo salar*). ). J. Food Eng. 79:261-270.
García-Pascual P, Sanjuán N, Melis R, Mulet A (2006). *Morchella esculenta* (morel) rehydration process modeling. J. Food Eng. 72:346-353.
Gely MC, Santalla EM (2007). Moisture diffusivity in quinoa (*Chenpodiun quinoa* Willd.) seeds: Effect of air temperature and initial moisture content of seeds. J. Food Eng. 78:1029-1033.
González M, Skandamis PN, Hanninen ML (2009). A modified Weibull model for describing the survival of *Campylobacter jejuni* in minced chicken meat. Int. J. Food Microbiol. 136:52-58.
Graiver N, Pinotti A, Califano A, Zaritzky N (2006). Diffusion of sodium chloride in pork tissue. J. Food Eng. 77:910–918.
Jankovic B (2010). Identification of the effective distribution function for determination of the distributed activation energy models using Bayesian statistics: Application of isothermal thermogravimetric data. Int. J. Chem. Kinet. 42(11):641–658.
Jittinandana S, Kenney PB, Slider SD, Kiser RA (2002). Effect of brine concentration and brining time on quality of smoked rainbow trout fillets. J. Food Sci. 67:2095–2099.
Kaya A, Aydin O (2008). Experimental investigation of drying kinetics of cherry laurel. J. Food Process. Eng. 31:398–412.
Kaya A, Aydin O, Demirtas C (2007). Concentration boundary conditions in the theoretical analysis of convective drying process. J. Food Process. Eng. 30:564-577.
Krokida MK, Marinos-Kouris D (2003). Rehydration kinetics of dehydrated products. J. Food Eng. 57:1-7.
Lei Y (2008). Evaluation of three methods for estimating the Weibull distribution parameters of Chinese pine (*Pinus tabulaeformis*). J. For. Sci. 5(12):566–571.
Ma H, Huang L, Zhu C (2011). The effect of pulsed magnetic field on horseradish peroxidase. J. Food Process. Eng. 34:1609–1622.
Marabi A, Jacobson M, Livings S, Saguy IS (2004). Effect of mixing and viscosity on rehydration of dry food particulates. Eur. Food Res. Technol. 218:339–344.
Marabi A, Livings S, Jacobson M, Saguy IS (2003). Normalized Weibull distribution for modeling rehydration of food particulates. Eur. Food Res. Technol. 217:311-318.
Motwani T, Hanselmann W, Anantheswaran RC (2011). Diffusion, counter-diffusion and lipid phase changes occurring during oil migration in model confectionery systems. J. Food Eng. 104:186–195.
Oms-Oliu G, Odriozola-Serrano I, Soliva-Fortuny R, Martín-Belloso O (2009). Use of Weibull distribution for describing kinetics of antioxidant potential changes in fresh-cut watermelon. J. Food Eng. 95:99-105
Palazón MA, Pérez-Conesa D, Abellán P, Ros G, Romero F, Vidal ML (2009). Determination of shelf-life of homogenized apple-based beikost storage at different temperatures using Weibull hazard model. LWT - Food Sci. Technol. 42:319–326.
Poças MF, Oliveira JC, Brandsch R, Hogg T (2012). Analysis of mathematical models to describe the migration of additives from packaging plastics to foods. J. Food Process. Eng. 35:657–676.
Puolanne E, Jalonen M (2010). Theoretical aspects of water-holding in meat. Meat Sci. 86:151–165.
Quispe-Fuentes I, Vega-Gálvez A, Miranda M, Lemus-Mondaca R, Lozano M, Ah-Hen K (2012). A kinetic approach to saponin extraction during washing of quinoa (C*henopodium quinoa* willd.). J. Food Process. Eng. doi: 10.1111/j.1745-4530.2012.00673.
Ramallo G, Albani OA (2007). Water diffusion coefficient and modeling of water uptake in packaged yerba mate. J. Food Process. Preserv. 31:406–419.
Ruusunen M, Puolanne E (2005). Reducing sodium intake from meat products. Meat Sci. 70: 531–541.
Saguy IS, Marabi A, Wallach R (2005). Liquid imbibition during rehydration of dry porous foods. Innovat. Food Sci. Emerg. Technol. 6:37-43.
Shivhare US, Gupta M, Basu S, Raghavan GSV (2009). Optimization of blanching process for carrots. J. Food Process. Eng. 32:587–605.
Solomon WK (2008). Effect of barrel temperature on rehydration kinetics of direct-expanded *tef* flour breakfast cereal. J. Food Process. Eng. 31:469–487.
Sanjuán N, Cárcel JA, Clemente G, Mulet A (2001). Modelling of the rehydration process of broccoli florets. Eur. Food Res. Technol. 212:449-453.
Sannaveerappa T, Ammu K, Joseph J (2004). Protein-related changes during salting of milkfish (*Chanos chanos*). J. Sci. Food Agric. 84:863–869.
Seth D, Sarkar A 2004. A lumped parameter model for effective moisture diffusivity in air drying of foods. Food Bioprod. Process. 82:183–192.
Thorarinsdottir KA, Arason S, Geirsdottir M, Bogason S, Kristbergsson K (2002). Changes in myofibrillar proteins during processing of salted cod (*Gadus morhua*) as determined by electrophoresis and differential scanning calorimetry. Food Chem. 77:377–385.
Thorarinsdottir KA, Arason S, Bogason S, Kristbergsson K (2004). The effects of various salt concentrations during brine curing of cod. Int. J. Food Sci. Technol. 39:79–89.
Vega-Gálvez A, Lemus-Mondaca R, Bilbao-Sáinz C, Yagnam F, Rojas A (2008). Mass transfer kinetics during convective drying of red pepper var. Hungarian (*Capsicum annuum* l.): Mathematical modeling and evaluation of kinetic parameters. J. Food Process. Eng. 31:120–137.
Xiong Y, Lou X, Harmon R, Wang C, Moody W (2000). Saltand pyrophosphate-induced structural changes in myofibrils from chicken red and white muscle. J. Sci. Food Agric. 80:1176–1182.
Yang H, Wang S, Li Y, Johnson MG (2002). Predictive models for the survival/death of *Campylobacter jejuni* and *Salmonella typhimurium* in poultry scalding and chilling. J. Food Sci. 67:1836-1842.
Zhao H (2005). Effect of ions and other compatible solutes on enzyme activity, and its implication for biocatalysis using ionic liquids. J. Mol. Catal. B: Enzym. 37:16−25.
Zugarramurdi A, Lupín HM (1980) A model to explain observed behavior on fish salting. J. Food Sci. 45:1305-1311.