International Journal of
Food Science & Technology
www.ifst.org
International Journal of Food Science and Technology


Original article

# Brining kinetics of different cuts of anchovy (*Engraulis anchoita*)

**Marina Czerner* & María I. Yeannes**

Grupo de Investigación Preservación y Calidad de Alimentos, Departamento de Ingeniería Química, Facultad de Ingeniería, Universidad Nacional de Mar del Plata-CONICET, Juan. B. Justo 4302, (7600) Mar del Plata, Argentina

*(Received 1 March 2010; Accepted in revised form 23 June 2010)*

**Summary** Brining is a preliminary operation in the process of salting–ripening anchovy in which, conventionally, whole fish is immersed in saturated brine (osmotic solution) until equilibrium. The aim of this work was to study the mass transfer kinetics in three different cuts of anchovy (whole fish, gutted fish and fillet) and to model it using the Zugarramurdi and Lupín and the Peleg equations. Fillet reached equilibrium after 5 h, gutted fish after 10.42 h and whole fish after 19.75 h. Equilibrium constants were 1.054, 0.706 and 0.603 for fillet, gutted fish and whole anchovy, respectively. These results indicate that the presence of skin affects both the initial rate of mass transfer and the equilibrium water and salt content. The Peleg model was more suitable to describe the salt gain kinetics, and the Zugarramurdi and Lupín model results in a more accurate prediction of water loss and equilibrium conditions.

**Keywords** Equilibrium, fish, mass transfer, mathematical models, wet salting.

## Introduction

*Engraulis anchoita* is the most abundant pelagic species in the south-western Atlantic Ocean, distributed from Brazilian to Argentinean waters. Argentina is a pioneer country in the exploitation and manufacture of this species for human consumption, being salted ripened anchovy the main product. This is a traditional product with typical sensorial characteristics and strongly positioned in the international market. It is exported as a commodity in barrels mainly to Spain, Peru, the United States, Italy and Morocco, and a small amount is locally processed to supply the domestic market (Madureira *et al*., 2007).

The conventional process of salting–ripening of anchovy is based on empirical knowledge developed in European countries, where the raw material for this product is *Engraulis encrasicolus*. Other anchovy-type products are also produced from herring (*Clupea harengus*), sprats (*Sprattus sprattus*) and sardine (*Sardina pilchardus*) (Steffánson & Guðmundsdóttir, 1995). In Argentina, the procedure was adapted to the species *E. anchoita*. The process involves a preliminary operation of wet salting (brining), where whole fish is immersed in saturated brine until equilibrium of water and salt content is reached in the muscle. During this stage, water activity ($a_w$) is reduced from 0.99, corresponding to raw fish, to 0.80–0.84 (Filsinger, 1987). Following this, anchovies are handled beheaded and partially gutted (leaving gonads and pyloric caeca), placed in barrels alternating layers of fish and salt and pressed. The ripening process may take from 8 to 12 months and implies several transformations, which include proteolysis and lipolysis. As a result of these changes, the product acquires firm consistency, reddish colour, juicy texture and a characteristic odour and flavour (Filsinger *et al*., 1982).

The stage of brining can be described as an osmotic dehydration process (OD), in which driving force for water removal is set up owing to a dissimilar osmotic pressure between the food and the surrounding solution. The internal structure of the muscle is not a perfect semipermeable membrane; thus, mass transport in the OD is actually a combination of simultaneous water and solute transfer. During brining, the major transported solutes are salt from brine to fish flesh and proteins in the opposite direction (Barat *et al*., 2003; Gallart-Jornet *et al*., 2007a). The rate of diffusion depends on operative factors such as temperature and concentration of the osmotic solution, size and geometry of the material, the solution to material mass ratio and the level of agitation of the solution (Rastogi *et al*., 2002, 2005; Barat *et al*., 2003; Ochoa Martinez & Ayala Aponte, 2005).

Different theoretical and empirical approaches have been employed to study and model the OD process. Models based on solution of Fick's second law have

*Correspondent: E-mail: mczerner@fi.mdp.edu.ar

doi:10.1111/j.1365-2621.2010.02361.x

been broadly used to describe OD process in different fish and meat products (Wang *et al*., 2000; Gou *et al*., 2003; Telis *et al*., 2003; Graiver *et al*., 2006; Corzo & Bracho, 2007; between others). On the other hand, empirical models are preferred in some cases because of their relatively simple applicability. Zugarramurdi & Lupín (1980) established a general model that allows the achievement of general relationships for fish salting kinetics and process equilibrium. Several authors showed that the empirical model of Zugarramurdi and Lupín adequately describes water and salt kinetics of osmotically dehydrated fish, for which yellowtail (Berhimpon *et al*., 1990) and sardine fillets under various conditions (Corzo & Bracho, 2005, 2006a; Bellagha *et al*., 2007) are good examples. The Peleg (1988) model also describes sorption curves that approaches to the equilibrium asymptotically, and it have been used to describe OD in chickpea (Turhan *et al*., 2002), sardine sheets (Corzo & Bracho, 2006b), potato (Khin *et al*., 2006), apricot (Khoyi & Hesari, 2007) and chicken breast (Schmidt *et al*., 2009).

The possibility to modify the traditional process of salting–ripening was explored in a previous work (Czerner & Yeannes, 2008). Salting and ripening stages were modified using nontraditional fish cuts in this species (fillet and beheaded-partially gutted). Products obtained showed sensory characteristics similar to those obtained by traditional methods, indicating that the modifications proposed were potentially applicable from the sensorial point of view. The analysis of mass transfer behaviour in these cuts during OD is of great technological importance because it will eventually allow for the estimation of immersion time and composition at equilibrium. There is scarce literature related to whole fish salting, and up to our knowledge, no attempts have been made to study OD process in whole or beheaded-partially gutted fish by applying the Peleg model. The studies have been oriented to process of mass transfer on fillet or pieces with defined shape and dimensions, but not with the presence of skin, head or viscera. As regards the Zugarramurdi and Lupín model, it has been applied to study wet salting in whole anchovy and dry salting in gutted anchovy (Zugarramurdi & Lupín, 1980).

The objectives of this study were to analyse the mass transfer process in different cuts of *E. anchoita* during brining stage and to model the kinetics of OD by two empirical models: the Zugarramurdi & Lupín (1980) and the Peleg (1988) models.

## Materials and methods

### Raw material

Anchovy used for the experiment was caught near Mar del Plata, Argentina, during November. Following catch, fish was placed in bins with ample ice and maintained in this condition until they arrived to the laboratory.

### Sample preparation and experimental design

Fish was arranged into three lots depending on the gutting method applied: W, whole anchovy (traditional method) (length: 136 ± 5 cm, thickness: 11 ± 1 mm); H&G, beheaded-partially gutted (length: 112 ± 9 cm, thickness: 11 ± 1 mm); and F, fillet (length: 112 ± 9 cm, thickness: 5 ± 1 mm). Cuts were performed by hand according to standard industrial procedures.

Saturated brine (26% NaCl) was prepared with salt (NaCl). Anchovies were immersed in the brine at a 1:1 ratio to maintain the relationship used in industry and kept immersed by a screen cover. Brine was maintained at saturation by adding extra salt. During the experience, the NaCl content of brine was checked following Mohr's method (Kirk *et al*., 1996). The three lots were maintained at 15 °C in an adiabatic chamber, and samples of approximately 200 g (~15–20 pieces for lot W, ~40–60 pieces for lot H&G, ~80–100 pieces for lot F) were periodically taken until equilibrium was reached. An equal mass of brine was extracted at each sample time to maintain the brine-to-fish ratio.

### Chemical analyses

Fresh anchovy was analysed to determine chemical proximal composition. Minced anchovy flesh was analysed for water content by oven-drying at 105 ± 1 °C until constant weight (AOAC, 1990); fat content by acid hydrolysis method (AOAC, 1990); protein content by Kjeldhal (AOAC, 1993); and ashes by incineration at 500 °C (AOAC, 1993).

During brining, samples were analysed for their water (AOAC, 1990) and NaCl content (Kirk *et al*., 1996). For NaCl determination in brined anchovy, the dry residue was boiled with distilled water during 5 min and then filtered and made up to 250 mL. In fresh anchovy, the dry residue was calcined at 500 °C (AOAC, 1993) and made up to 100 mL. Titration was performed on aliquots of these extracts. At the end of brining, protein content was determined in fish muscle, and water activity ($a_w$) was measured in muscle and brine. The $a_w$ was measured by a digital hygrometer Aqualab, model CX-2T (Decagon, Pulman, WA, USA). Analyses were conducted in triplicate for water content and in quadruplicate for salt content and $a_w$.

### Mathematical models

*The Peleg model*

Mass transfer kinetics of salt and water were modelled using the Peleg equation as follows:

 

$$X_i = X_i^0 \pm \frac{t}{k_1 + k_2 t} \quad (1)$$

where $X_i$ and $X_i^0$ are the water or salt content (dry basis, $g/g_{db}$) at dehydration time $t$ (h) and at instant 0, respectively. In Eqn (1), '±' becomes '+' if the process is salt gain and '−' if the process is water loss. The constant $k_1$ (h $(g/g_{db})^{-1}$) (the Peleg rate constant) is related to mass transfer rate at the beginning of the OD process: $t = t^0$, according to Eqn (2). The constant $k_2$ ($(g/g_{db})^{-1}$) (capacity constant) is related to moisture and salt content attainable at $t \to \infty$, being $X_i = X_i^{eq}$ (Eqn 3).

$$\frac{dX_i}{dt} = \pm \frac{1}{k_1} \quad (2)$$

$$X_i^{eq} = X_i^0 \pm \frac{1}{k_2} \quad (3)$$

*The Zugarramurdi and Lupín model (Z&L model)*
The following mathematical model, with an exponential approach to the equilibrium value of salt and water concentrations, was proposed by Zugarramurdi & Lupín (1977, 1980).

$$\frac{dX_i}{dt} = -k.(X_i^{eq} - X_i) \quad (4)$$

where $X_i$ and $X_i^{eq}$ are the water or salt content (dry basis, $g/g_{db}$) at dehydration time $t$ (h) and at equilibrium, respectively, and $k$ ($(g/g_{db})$ $h^{-2}$) the corresponding specific rate constant.

Integration of Eqn (4) with the initial condition $X_i(0) = X_i^0$ results in:

$$X_i = X_i^0.e^{-k.t} + X_i^{eq}.(1 - e^{-k.t}) \quad (5)$$

The fitting of the two models to experimental data was performed by nonlinear regression analyses using the software OriginPro 7.5 (OriginLab Corporation, Northampton, MA, USA).

### Statistical analysis

The analysis of variance (ANOVA) was carried out to find effects of the gutting method and time on water and salt transfer. Differences between means were analysed using the Tukey's test for post hoc comparison. Analyses were performed using STATISTICA 6.0 (Statsoft, Inc., Tulsa, OK, USA).

For each case, the goodness of fit was evaluated by the correlation coefficient ($R^2$) and the root mean square error ($RMSE$, Eqn 6)

$$RMSE = 100\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - X_{ip}}{X_i}\right)^2} \quad (6)$$

where $X_i$ is the experimental value, $X_{ip}$ is the predicted value and $n$ is the number of experimental data.

## Results and discussion

### Characterisation of raw material

The proximal composition of fresh anchovy given in g/g was: 0.752 ± 0.008 for water, 0.037 ± 0.003 for fat, 0.018 ± 0.001 for ash and 0.194 ± 0.005 for protein content. Initial salt content was $0.0037 \pm 3.5 \times 10^{-5}$ g/g.

### Mass transfer during brining

Figure 1 shows the evolution of water and salt content in the different lots during brining. The curves exhibit typical mass transfer behaviour with an exponential approach to equilibrium values. The data were subjected to analysis of variance and means comparison across gutting method and time effects. The effect of the gutting method on both water loss and salt gain was highly significant ($P < 0.001$). Interaction between gutting method and brining time was detected ($P < 0.001$).

The equilibrium condition was defined as not significant variations in water and salt content. In lot W, equilibrium was achieved after 19.75 h; in lot H&G, after 10.42 h and in lot F, after 5 h ($P < 0.01$). Equilibrium time obtained for lot W agrees with the results obtained by Zugarramurdi & Lupín (1977) for whole anchovy. The dynamics of salt gain and water loss showed interesting differences between lots. As it can be seen in Fig. 1, lot F shows a higher slope at the beginning of the brining process indicating high initial rate of salt and water transfer. As pointed out in earlier works, various factors must be considered to explain this behaviour: (i) lot F is half the thickness of H&G and W; therefore, the length of the diffusion pass is shorter, resulting in more rapid mass transfer; (ii) the ratio of the surface area to the characteristic length is bigger in lot F; thus, the water loss and solid gain increase (Rastogi *et al.*, 2005); and (iii) lots W and H&G had skin in both surfaces offering and additional resistance to mass transfer between fish muscle and brine (Zugarramurdi & Lupín, 1980), whereas in lot F the complete internal surface of the fillet is directly exposed to brine facilitating the diffusion process.

The results of ANOVA showed that salt content increased significantly from the beginning of brining until equilibrium in the three lots. However, the reduction in water content at the beginning of OD showed different behaviour between lots. During the first 1.5 h of treatment, the reduction in water content was

 

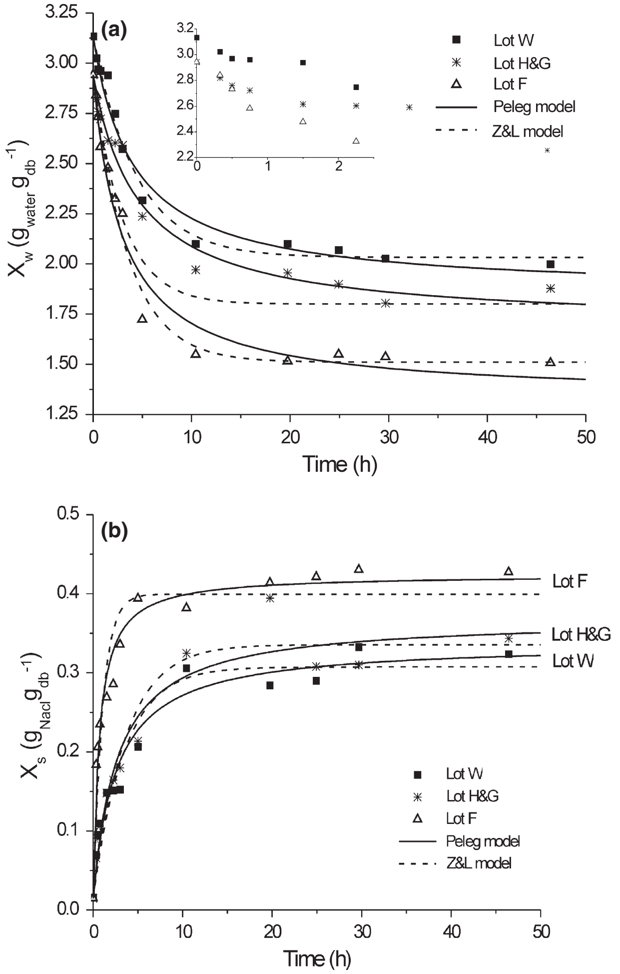


**Figure 1** Evolution of water (a) and salt (b) content during brining different cuts of anchovy. Adjustments of the Zugarramurdi and Lupín (Z&L) and Peleg models to the experimental data.

significative in lot F, while it was not in lots W and H&G ($P < 0.01$). At 1.5 h, salt concentration was 0.87 and 0.99 M for lot W and H&G, respectively. These values are in the range of maximum swelling and maximum water holding capacity (0.8–1 M) (Offer & Trinick, 1983), which could explain water retention observed in these lots. In lot F, salt content increased rapidly up to 1.1 M (at 0.3 h), when proteins may have stronger protein–protein bonds resulting in shrinkage of the muscle and dehydration (Offer & Trinick, 1983; Thorarinsdottir *et al.*, 2002; Gallart-Jornet *et al.*, 2007b); thus, no water retention was observed in this lot.

## Equilibrium analysis

As shown in Fig. 1, at equilibrium lot F presented higher dehydration than lots W and H&G, reaching lower water content and higher salt content ($P < 0.01$). The equilibrium constant can be calculated, according to Eqn 7, as the relationship between salt concentration in the total water content inside the muscle and in the brine, experimentally obtained (Zugarramurdi & Lupín, 1976).

$$K_{eq} = \frac{Y_{NaCl}^{fish}}{Y_{NaCl}^{brine}} \tag{7}$$

where $K_{eq}$ is the equilibrium constant, $Y_{NaCl}^{fish}$ is the molarity of NaCl considering it to be in true solution in the total water content of the fish and $Y_{NaCl}^{brine}$ is the molarity of NaCl in the brine.

The values of $K_{eq}$ indicate that despite the lots are submitted to the same osmotic solution, the concentration attainable at equilibrium is different, depending on the gutting method applied (See Table 1). The tendency observed for equilibrium constant values indicates that the larger the fish flesh exposed directly to brine (lot F > lot H&G > lot W), the higher the salt concentration attainable in the muscle. The values of $K_{eq}$ determined for the different cuts are in correspondence with those reported for salting different fish species. Zugarramurdi & Lupín (1976, 1980) studied wet salting in whole anchovy and pickled salting in beheaded-partially gutted anchovy. The authors determined that $K_{eq}$ corresponding to H&G anchovy was near to unity, whereas for whole anchovy, $K_{eq}$ reached an approximate value of 0.60. In the case of cod fillet salting, the equilibrium concentration value resulted equal to that corresponding to external brine ($K_{eq} \approx 1$) when working with saturated brine and dry pile salting (Barat *et al.*, 2003). The equilibrium constant for osmotic dehydration of sardine sheets in brine with different concentrations (between 0.15 and 0.27 $g_{NaCl}/g$) varies between 0.85 and 1.36, according to the results reported by Corzo & Bracho (2005). To understand the difference in $K_{eq}$ observed in the different cuts, it must be considered that equilibrium is actually given by the equality of chemical potentials at both sides of the membrane, which mainly depend on the reduction in $a_w$ inside the muscle (Ochoa Martinez & Ayala Aponte, 2005; Rastogi *et al.*, 2005), as shown in Table 1. The $a_w$ in fish muscle is affected not only by salt content, but also by salt–protein interaction and by the presence of solubilised compounds. During salting operation, the increasing salt concentration into the flesh promotes protein extraction (Offer & Trinick, 1983; Barat *et al.*, 2003). At the end of the treatment, the protein loss in lot F was higher compared to lots W and H&G (See Table 1). These results are consistent with the hypothesis proposed by Zugarramurdi & Lupín (1976, 1980), who exposed that the diffusion of solubilised protein towards the brine in whole fish is difficult because of the

**Table 1** Equilibrium data and constants for the different gutting methods

| | $X^{eq}_{water}$ * | $X^{eq}_{NaCl}$ * | $Y^{fish}_{NaCl}$ | $K_{eq}$ † | $a^{fish}_{w}$ | $a^{brine}_{w}$ | Protein content (g/g) |
|---|---|---|---|---|---|---|---|
| Lot W | 2.048 ± 0.059 | 0.309 ± 0.022 | 2.581 | 0.603 | 0.861 | 0.856 | 0.243 ± 0.007 |
| Lot H&G | 1.902 ± 0.065 | 0.336 ± 0.034 | 3.022 | 0.706 | 0.857 | 0.851 | 0.237 ± 0.010 |
| Lot F | 1.563 ± 0.077 | 0.412 ± 0.019 | 4.510 | 1.054 | 0.792 | 0.787 | 0.204 ± 0.011 |

*Weigh fraction of water ($X^{eq}_{water}$) and salt ($X^{eq}_{NaCl}$). Equilibrium condition was not significant variations in water and NaCl content ($P < 0.01$). The value presented was calculated as the mean of the samples taken once equilibrium was achieved.
†Equilibrium brine concentration was 4.28 ± 0.27 mol L$^{-1}$.

presence of skin and then exert an additional osmotic effect that contributes to the equality of pressure between both sides of the membrane.

## Parameters of the Peleg and the Zugarramurdi & Lupín models

The major advantage of the Peleg model is that equilibrium values can be estimated using short time experimental data (Turhan *et al.*, 2002). However, former literature states different criteria to select the range of data used to obtain the Peleg equation parameters (Peleg, 1988; Corzo & Bracho, 2006b; Khoyi & Hesari, 2007; Schmidt *et al.*, 2009). It is important to take into account that the range of data selected will affect the values of $k_1$ and $k_2$ and also the model fit. In this sense, Turhan *et al.* (2002) applied the Peleg model to study water absorption in chickpea and found that the fit of the equation improved with increasing sections included in the data selection. On the other hand, Sopade *et al.* (2007) demonstrated that the Peleg, Pilosof and Singh–Kulshrestha models are sensitive to the length of the sorption segment used in the calculation. Regarding the Z&L model, the authors include experimental equilibrium data to obtain the model parameters (Zugarramurdi & Lupín, 1977, 1980). However, criteria applied in other papers are not explained (Corzo & Bracho, 2005, 2006a; Bellagha *et al.*, 2007). Consequently, two options in data range selection were assessed in this work: model parameters for each lot were calculated based on data corresponding to the dynamic period (i.e. before reaching equilibrium) and from the complete data set. The values of model parameters are shown in Tables 2 and 3 (Confidence level = 95%). The $R^2 > 0.8232$ indicates that both models selected can satisfactorily explain the salting behaviour. Based on the statistical parameters $R^2$ and $RMSE$, the fit of both models improved when the whole curve was used, especially for water loss. These results agree with previous work related to the Peleg model (Turhan *et al.*, 2002; Sopade *et al.*, 2007) and confirm the same behaviour for the Z&L model. Consequently, hereafter, the analyses will be based on parameters obtained from the complete data set. The fit of both models are also presented in Fig. 1.

Regarding the meaning of model parameters, the inverse of $k_1$ in the Peleg model and $k$ in the Z&L model are related to initial mass transfer rate. Constants $k_1^w$ and $k_1^s$ result lower in Lot F indicating a higher initial mass transfer rate, which agrees with that observed in Fig. 1. Likewise, parameter $k$ is higher in lot F than in lot W. As expected, for lot H&G, these parameters take an intermediate value. Moreover, the equilibrium content is related to the Peleg capacity constant ($k_2$) and parameter $X_s^{eq}$ of the Z&L model. In general terms, the tendency obtained for these parameters agrees with the experimental results.

**Table 2** Peleg's Equation parameters for mass transfer during OD of anchovy (W: whole fish; H&G: beheaded-partially gutted; F: fillet)

| | Water content | | | | Salt content | | | |
|---|---|---|---|---|---|---|---|---|
| | Parameters of the Peleg model | | Statistical parameters | | Parameters of the Peleg model | | Statistical parameters | |
| | $k_1^w$ h $(g_w/g_{db})^{-1}$ | $k_2^w$ $(g_w/g_{db})^{-1}$ | $R^2$ | $RMSE$ (%) | $k_1^s$ h $(g_s/g_{db})^{-1}$ | $k_2^s$ $(g_s/g_{db})^{-1}$ | $R^2$ | $RMSE$ (%) |
| Model fit considering dynamic period data | | | | | | | | |
| Lot W | 4.0415 (0.3424) | 0.5510 (0.0558) | 0.9596 | 11.89 | 8.0898 (1.2194) | 3.0651 (0.3012) | 0.9108 | 15.18 |
| Lot H&G | 3.9829 (0.7611) | 0.7873 (0.2300) | 0.8307 | 2.98 | 5.0609 (0.3388) | 4.1741 (0.1565) | 0.9869 | 17.79 |
| Lot F | 1.8785 (0.2603) | 0.8097 (0.1284) | 0.9357 | 13.65 | 1.0869 (0.1178) | 3.0104 (0.1084) | 0.9787 | 12.58 |
| Model fit considering complete data set | | | | | | | | |
| Lot W | 3.1876 (0.2572) | 0.7849 (0.0222) | 0.9668 | 2.72 | 8.0547 (0.8229) | 3.1029 (0.0981) | 0.9571 | 15.04 |
| Lot H&G | 3.6961 (0.3117) | 0.8009 (0.0247) | 0.9627 | 2.88 | 7.6267 (0.9256) | 2.8241 (0.1071) | 0.9433 | 12.47 |
| Lot F | 1.8536 (0.1448) | 0.6223 (0.0156) | 0.9670 | 5.10 | 1.6594 (0.1353) | 2.4418 (0.0432) | 0.9694 | 8.13 |

 

**Table 3** Zugarramurdi and Lupín's (Z&L) Equation parameters for mass transfer during OD of anchovy (W: whole fish; H&G: beheaded-partially gutted; F: fillet)

| | Water content | | | | Salt content | | | |
|---|---|---|---|---|---|---|---|---|
| | Parameters of the Z&L model | | Statistical parameters | | Parameters of the Z&L model | | Statistical parameters | |
| | $k_w$ ($g_w/g_{db}$) $h^{-2}$ | $X_w^{eq}$ $g_w/g_{db}$ | $R^2$ | *RMSE* (%) | $k_s$ ($g_s/g_{db}$) $h^{-2}$ | $X_s^{eq}$ $g_s/g_{db}$ | $R^2$ | *RMSE* (%) |
| Model fit considering dynamic period data | | | | | | | | |
| Lot W | 0.1902 (0.0236) | 1.9089 (0.0838) | 0.9628 | 3.86 | 0.3309 (0.0649) | 0.2893 (0.0247) | 0.8732 | 20.26 |
| Lot H&G | 0.2362 (0.1014) | 2.0108 (0.2624) | 0.8232 | 4.95 | 0.8435 (0.0830) | 0.2039 (0.0070) | 0.9733 | 24.81 |
| Lot F | 0.6070 (0.1302) | 2.1190 (0.0918) | 0.9361 | 24.89 | 2.2337 (0.2558) | 0.3012 (0.0096) | 0.9584 | 18.96 |
| Model fit considering complete data set | | | | | | | | |
| Lot W | 0.2254 (0.0133) | 2.0324 (0.0189) | 0.9776 | 1.96 | 0.2898 (0.0314) | 0.3074 (0.0091) | 0.9351 | 21.10 |
| Lot H&G | 0.3308 (0.0455) | 1.8000 (0.0448) | 0.8364 | 6.63 | 0.2781 (0.0304) | 0.3356 (0.0101) | 0.9382 | 18.83 |
| Lot F | 0.2806 (0.0143) | 1.5108 (0.0211) | 0.9813 | 3.16 | 0.9514 (0.1147) | 0.3995 (0.0108) | 0.9041 | 15.04 |

According to the statistical parameters ($R^2$ and *RMSE*), the Peleg model is more suitable than the Z&L model in describing salt gain kinetics. In contrast, for $X_w$, the best fit was obtained with the Z&L model for lots W and F, and with the Peleg model for lot H&G.

## Model performance in the prediction of equilibrium values

In most cases, when using predictive models, the objective is the prediction of equilibrium values. However, the comparison between these predicted values and real ones is not always done. In this work, the predicted equilibrium water and salt contents by both the Peleg and the Z&L models are contrasted against experimental equilibrium values. As previously mentioned, experimental equilibrium values were calculated as the mean of samples taken once equilibrium was achieved, considering the equilibrium condition as not significant variations in water and NaCl content ($P < 0.01$). The predicted equilibrium values were obtained from Eqn (3) according to the Peleg model and directly from the parameter $X_w^{eq}$ of the Z&L model. Results obtained are presented in Table 4. If the two models are compared, it can be seen that the Peleg model predict lower equilibrium water content and higher equilibrium salt content than the Z&L model. In addition, and taking into account the experimental equilibrium values, the Peleg model underestimates the equilibrium water content and overestimates the equilibrium salt content. On the other hand, the equilibrium values predicted by the Z&L model are more similar to the experimental ones, verified by a lower *E*. This result is of great interest because according to the statistical parameters $R^2$ and *RMSE*, the Peleg model was more suitable for describing the salt gain kinetics and the Z&L model predicts better the equilibrium conditions.

## Conclusion

During the operation of brining *E. anchoita*, both mass transfer kinetics and the equilibrium water and salt content are affected by the gutting method applied. The geometric factors and the presence of skin, which constitute a barrier to mass transport, exert an effect on mass transfer rate, being the trend obtained whole < H&G < fillet. As regards the equilibrium conditions, whole anchovy was the least dehydrated, followed by H&G and fillet. Maximum salt intake at equilibrium was in fillet followed by H&G and whole fish.

**Table 4** Performance of the Peleg and the Zugarramurdi and Lupín models in predicting equilibrium water and salt content during OD of anchovy (W: whole fish; H&G: beheaded-partially gutted; F: fillet)

| | Water content | | | | | Salt content | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Peleg model | | | Z&L model | | Peleg model | | | Z&L model | |
| | $X_w$* ($g_w/g_{db}$) | $X_{wp}$ ($g_w/g_{db}$) | *E* | $X_{wp}$ ($g_w/g_{db}$) | *E* | $X_s$* ($g_w/g_{db}$) | $X_{sp}$ ($g_w/g_{db}$) | *E* | $X_{sp}$ ($g_w/g_{db}$) | *E* |
| Lot W | 2.0483 | 1.8592 | 9.23 | 2.0324 | 0.77 | 0.3075 | 0.3379 | 9.88 | 0.3074 | 0.04 |
| Lot H&G | 1.9017 | 1.6934 | 10.96 | 1.8000 | 5.35 | 0.3362 | 0.3688 | 9.71 | 0.3356 | 0.16 |
| Lot F | 1.5630 | 1.3350 | 14.58 | 1.5108 | 3.34 | 0.4116 | 0.4243 | 3.09 | 0.3995 | 2.93 |

*Values calculated as a mean of the points once no significance variations in water and salt content.
*E*: Relative error, calculated as $\left|\frac{X_i - X_{ip}}{X_i}\right| \times 100$, where $X_i$, Experimental equilibrium value and $X_{ip}$, Predicted equilibrium value.

The Peleg model was more suitable for describing the salt gain kinetics, and the Z&L model results in a more accurate prediction of water loss and equilibrium conditions.


## Acknowledgments

This work was supported by the *Consejo Nacional de Investigaciones Científicas y Técnicas* (CONICET-PIP 5052) and the *Universidad Nacional de Mar del Plata* (15/G206 and 15/G264). The authors are indebted to these institutions. The authors thank Ana Cosulich for text supervision and enterprise CENTAURO SA for the supply of raw material.


## References


AOAC (1990). *Official Methods of Analysis*, 15th edn. Washington, DC: Association of Official Analytical Chemists.

AOAC (1993). *Official Methods of Analysis*, 16th edn. Washington DC: Association of Official Analytical Chemists.

Barat, J., Rodríguez-Barona, S., Andrés, A. & Fito, P. (2003). Cod salting manufacturing analysis. *Food Research International*, **36**, 447–453.

Bellagha, S., Sahli, A., Farhat, A., Kechaou, N. & Glenza, A. (2007). Studies on salting and drying of sardine (*Sardinella aurita*): Experimental kinetics and modeling. *Journal of Food Engineering*, **78**, 947–952.

Berhimpon, S., Souness, R.A., Buckle, K.A. & Edwards, R.A. (1990). Salting and drying of yellowtail (*Trachurus mccullochi Nichols*). *International Journal of Food Science and Technology*, **25**, 409–419.

Corzo, O. & Bracho, N. (2005). Osmotic dehydration kinetics of sardine sheets using Zugarramurdi and Lupín model. *Journal of Food Engineering*, **66**, 51–56.

Corzo, O. & Bracho, N. (2006a). Equilibrium water and salt contents of sardine sheets during osmotic dehydration. *LWT*, **39**, 358–364.

Corzo, O. & Bracho, N. (2006b). Application of Peleg model to study mass transfer during osmotic dehydration of sardine sheets. *Journal of Food Engineering*, **75**, 535–541.

Corzo, O. & Bracho, N. (2007). Water effective diffusion coefficient of sardine sheets during osmotic dehydration at different brine concentrations and temperatures. *Journal of Food Engineering*, **80**, 497–502.

Czerner, M. & Yeannes, M.I. (2008). Influencia de los cortes utilizados en el salado madurado de E. anchoita sobre el desarrollo de las características sensoriales. *La Industria Cárnica Latinoamericana*, **152**, 50–54.

Filsinger, B. (1987). Effect of pressure on the salting and ripening process of anchovies (*Engraulis anchoita*). *Journal of Food Science*, **52**, 919–921.

Filsinger, B., Barassi, C., Lupín, H. & Trucco, R. (1982). An objective index for the evaluation of the ripening of salted anchovy. *International Journal of Food Science and Technology*, **17**, 193–200.

Gallart-Jornet, L., Barat, J.M., Rustad, T., Erikson, U., Escriche, I. & Fito, P. (2007a). A comparative study of brine salting of Atlantic cod (*Gadus morhua*) and Atlantic salmon (*Salmo salar*). *Journal of Food Engineering*, **79**, 261–270.

Gallart-Jornet, L., Barat, J.M., Rustad, T., Erikson, U., Escriche, I. & Fito, P. (2007b). Influence of brine concentration on Atlantic salmon fillet salting. *Journal of Food Engineering*, **80**, 267–275.

Gou, P., Comaposada, J. & Arnau, J. (2003). NaCl content and temperature effects on moisture diffusivity in the *Gluteus medius* muscle of pork ham. *Meat Science*, **63**, 29–34.

Graiver, N., Pinotti, A., Califano, A. & Zaritzky, N. (2006). Diffusion of sodium chloride in pork tissue. *Journal of Food Engineering*, **77**, 910–918.

Khin, M., Zhou, W. & Perera, C. (2006). A study of the mass transfer in osmotic dehydration of coated potato cubes. *Journal of Food Engineering*, **77**, 84–95.

Khoyi, M. & Hesari, J. (2007). Osmotic dehydration kinetics of apricot using sucrose solution. *Journal of Food Engineering*, **78**, 1355–1360.

Kirk, R., Sawyer, R. & Egan, H. (1996). *Composición y Análisis de Alimentos de Pearson*, 2nd edn. México: Editorial Continental S.A.

Madureira, L., Queiroz, I., Santo, M.E. *et al*. (2007). Use of wild fish and/or other Aquatic Species to Feed. Case Study: South American Anchovy (*Engraulis anchoita*). In: *Food and Agricultural Organization of the United Nations*. (Org.). FAO Fisheries Technical Paper: Towards Sustainable Aquaculture: Selected Issues and Guidelines, 1st edn. Pp. 1–29. Rome: FAO Fish Utilization and and Marketing Service, v. 466.

Ochoa Martinez, C. & Ayala Aponte, A. (2005). Modelos matemáticos de transferencia de masa en deshidratación osmótica. *Ciencia y Tecnología Alimentaria*, **4**, 330–342.

Offer, G. & Trinick, J. (1983). On the mechanism of water holding in meat: the swelling and shrinking of myofibrils. *Meat Science*, **8**, 245–281.

Peleg, M. (1988). An empirical model for the description of moisture sorption curves. *Journal of Food Science*, **53**, 1216–1217, 1219.

Rastogi, N., Raghavarao, K., Nirajan, K. & Knorr, D. (2002). Recent developments in food dehydration: methods for enhance mass transfer. *Trends in Food Science and Technology*, **13**, 48–59.

Rastogi, N.K., Raghavarao, K.S.M.S. & Nirajan, K. (2005). Developments in osmotic dehydration. In: *Emerging Technologies and Food Processing* (edited by S. Da-Wen). Pp. 226. London: Academic Press.

Schmidt, F., Carciofi, B. & Laurindo, J. (2009). Application of diffusive and empirical models to hydration, dehydration and salt gain during osmotic treatment of chicken breast cuts. *Journal of Food Engineering*, **91**, 553–559.

Sopade, P.A., Xun, P.Y., Halley, P.J. & Hardin, M. (2007). Equivalence of the Peleg, Pilosof and Singh–Kulshrestha models for water absorption in food. *Journal of Food Engineering*, **78**, 730–734.

Stefánsson, G. & Gudmundsdóttir, G. (1995). Free amino acids and their relationship to taste in (salt) ripened pelagic fish products. Rf Report No. 91, Reykjavík, Iceland.

Telis, V., Romanelli, P., Gabas, A. & Telis-Romero, J. (2003). Salting kinetics and salt diffusivities in farmed pantanal caiman muscle. *Pesquisa Agropecuária Brasileira*, **38**, 529–535.

Thorarinsdottir, K.A., Arasona, S., Geirsdottirb, M., Bogasonc, S.G. & Kristbergsson, K. (2002). Changes in myofibrillar proteins during processing of salted cod (*Gadus morhua*) as determined by electrophoresis and differential scanning calorimetry. *Food Chemistry*, **77**, 377–385.

Turhan, M., Sayar, S. & Gunasekaran, S. (2002). Application of Peleg model to study water absorption in chickpea during soaking. *Journal of Food Engineering*, **53**, 153–159.

Wang, D., Tang, J. & Correia, L. (2000). Salt diffusivities and salt diffusion in farmed Atlantic salmon muscle as influenced by rigor mortis. *Journal of Food Engineering*, **43**, 115–123.

Zugarramurdi, A. & Lupín, H. (1976). Studies on anchovy salting I. Equilibrium considerations and concentration profiles. *Latin American Journal of Chemical Engineering and Applied Chemistry*, **6**, 79–90.

Zugarramurdi, A. & Lupín, H. (1977). Studies on anchovy salting II. Dynamics of the process. *Latin American Journal of Chemical Engineering and Applied Chemistry*, **7**, 25–38.

Zugarramurdi, A. & Lupín, H. (1980). A model to explain observed behavior of fish salting. *Journal of Food Science*, **45**, 1305–1311, 1317.