



Ciência e Tecnologia de Alimentos

ISSN: 0101-2061

revista@sbcta.org.br

Sociedade Brasileira de Ciência e  
Tecnologia de Alimentos  
Brasil

VEGA-GÁLVEZ, Antonio; LEMUS-MONDACA, Roberto; PLAZA-SÁEZ, Daniel; PÉREZ-  
WON, Mario

Effect of air-temperature and diet composition on the drying process of pellets for  
japanese abalone (*Haliotis discus hannai*) feeding

Ciência e Tecnologia de Alimentos, vol. 31, núm. 3, julio-septiembre, 2011, pp. 694-702

Sociedade Brasileira de Ciência e Tecnologia de Alimentos  
Campinas, Brasil

Available in: <http://www.redalyc.org/articulo.oa?id=395940110022>

- How to cite
- Complete issue
- More information about this article
- Journal's homepage in redalyc.org

redalyc.org

Scientific Information System

Network of Scientific Journals from Latin America, the Caribbean, Spain and Portugal

Non-profit academic project, developed under the open access initiative

## Effect of air-temperature and diet composition on the drying process of pellets for japanese abalone (*Haliotis discus hannai*) feeding

*Efeito da temperatura do ar e da composição da dieta durante o processo de secagem de pellets usados na alimentação do haliote japonês (Haliotis discus hannai)*

Antonio VEGA-GÁLVEZ<sup>1\*</sup>, Roberto LEMUS-MONDACA<sup>1</sup>, Daniel PLAZA-SÁEZ<sup>1,2</sup>, Mario PÉREZ-WON<sup>1</sup>

### Abstract

The aim of this research was to study the effect of air-temperature and diet composition on the mass transfer kinetics during the drying process of pellets used for Japanese Abalone (*Haliotis discus hannai*) feeding. In the experimental design, three temperatures were used for convective drying, as well as three different diet compositions (Diets A, B and C), in which the amount of fishmeal, spirulin, algae, fish oil and cornstarch varied. The water diffusion coefficient of the pellets was determined using the equation of Fick's second law, which resulted in values between  $0.84-1.94 \times 10^{-10} \text{ m}^2/\text{s}$ . The drying kinetics was modeled using Page, Modified Page, Root of time, Exponential, Logarithmic, Two-Terms, Modified Henderson-Pabis and Weibull models. In addition, two new models, referred to as 'Proposed' models 1 and 2, were used to simulate this process. According to the statistical tests applied, the models that best fitted the experimental data were Modified Henderson-Pabis, Weibull and Proposed model 2, respectively. Bifactorial analysis of variance ANOVA showed that Diet A (fishmeal 44%, spirulin 9%, fish oil 1% and cornstarch 36%) presented the highest diffusion coefficient values, which were favored by the temperature increase in the drying process.

**Keywords:** *japanese abalone; pellets; drying kinetics; diffusion coefficient; weibull.*

### Resumo

O objetivo deste trabalho foi estudar o efeito da temperatura do ar e da composição da dieta na cinética de transferência de massa durante o processo de secagem de pellets usados na alimentação do haliote japonês (*Haliotis discus hannai*). No planejamento experimental, se usaram três temperaturas para a secagem por convecção, assim como três composições de dieta diferentes (Diets A, B e C), nas quais a quantidade de farinha, espirulina, alga, óleo de peixe e maisena variou. O coeficiente de difusão da água dos pellets foi determinado através da equação da segunda lei de Fick, encontrando-se valores entre  $0,84-1,94 \times 10^{-10} \text{ m}^2/\text{s}$ . A cinética de secagem foi modelada utilizando os modelos de Page, Page modificado, Raiz do tempo, Exponencial, Logarítmico, Dois Termos, Henderson-Pabis modificado e de Weibull. Além disso, dois novos modelos, referidos como modelos propostos 1 e 2, foram usados para simular este processo. De acordo com os testes estatísticos aplicados, os modelos que melhor se ajustaram aos dados experimentais foram o de Henderson-Pabis modificado, Weibull e o modelo proposto 2, respectivamente. A análise de variância bifatorial mostrou que a dieta A (44% farinha, 9% espirulina, 1% óleo de peixe e 36% maisena) foi a que apresentou os valores de coeficiente de difusão mais altos, os quais foram favorecidos pelo aumento de temperatura no processo de secagem.

**Palavras-chave:** *haliote japonês; pellets; cinética de secagem; coeficiente de difusão; weibull.*

## 1 Introduction

Aquaculture in Chile has experienced a significant increase in the past decade, mainly in the cultures of univalve (abalone), bivalve (scallop), crustacean (lobster), cephalopod (cuttlefish) and salmonide species, all of increasing worldwide demand (SERVICIO NACIONAL DE PESCA DE CHILE, 2008). The culture of abalone has considerably increased, since it is highly appreciated as a sea product of high commercial value, especially in countries like China, Japan, Taiwan, Singapore and Korea. The Red Abalone (*Haliotis rufescens*) and Japanese Abalone (*Haliotis discus hannai*) species, marketed frozen (90%) and fresh (10%) are mainly exported to Japan.

The abalone is an herbivorous gastropod mollusk that belongs to the *Haliotidae* family, *Haliotis* genus. It is characterized by several respiratory holes in a row near the shell

outer edge and a broad muscular foot of great suction capacity that allows clinging solidly to rocky surfaces (PARK et al., 2008). However, one of its most distinctive characteristics is the slow growth rate, which in most of the species, covers a period of more than three years until reaching a commercial size. Out of more than the 70 species of the *Haliotis* genus, eight are native from the northeast of the Pacific and others concentrate in the southeast area of the Pacific and the Indic Oceans (FLEMMING; VAN BAMEVELD; HONE, 1996).

In order to assure competitiveness of Chilean aquaculture products in world markets it is imperative to develop balanced diets aimed to achieve optimum growth rates and fattening for these sea products. This has already been developed for the salmon industry, unlike Red and Japanese Abalones, or other sea

Received 8/10/2009

Accepted 24/3/2010 (004450)

<sup>1</sup> Department of Food Engineering, Universidad de La Serena, Av. Raúl Bitrán, s/n, P.O. Box 599, La Serena, Chile, e-mail: avegag@userena.cl

<sup>2</sup> Centro de Estudios Avanzados en Zonas Áridas - CEAZA, Universidad de La Serena, Av. Raúl Bitrán, s/n, P.O. Box 599, La Serena, Chile

\*Corresponding author

products, such as the Northern cojinova and the Chilean frog (INSTITUTO DEL FOMENTO PESQUERO, 2008). The need to develop balanced diets for abalone feeding entails certain difficulties, where physical properties and commercial stability are significant variables to be considered. Different techniques have been developed to determine the nutritional requirements of aquaculture species, aiming at the formulation and design of balanced diets to optimize the growth and fattening in the culture (PEREIRA; RASSE, 2007). For example, shape, size, shelf life and texture of artificial food should be designed to produce an enhanced attraction for young abalones (HAHN, 1989). The abalone ingests from the borders to the core of pellet. This food must be flat and smooth. When it is consumed by the abalone, this covers the pellet with its radula and scrapes it, forming small particles that go into its mouth. The young abalone usually ingests at night; however, once it is accustomed to an artificial diet, it may feed during the day (SALES; JANSSENS, 2004). This is the main reason why the drying process of pellets, especially for abalone feeding, must be studied in depth, considering that the literature is scarce on this subject.

Different surveys have suggested the mechanism that adjusts the drying of various materials of organic source is based on the diffusional model of Fick's second law. Consequently, the effective diffusion coefficient of water for different geometries is calculated (LEMUS et al., 2008). Therefore, in order to control and optimize the drying process, it is necessary to use mathematical equations for modeling the mass transfer kinetics (water), as a function of the drying operational variables. Some models have parameters, which take into account properties of the samples such as thickness, shape, and particle size, while others consider operational parameters of the drying air such as temperature, velocity, and relative humidity (AKPINAR; BICER; YILDIZ, 2003). In addition, the knowledge of the drying process in organic materials is a complex task, since some drying materials present heterogeneity, which consists of pieces of many different components and dimensions (VEGA-GÁLVEZ et al., 2009).

The aim of this research was to study and model the drying behavior of pellets for abalone feeding and to analyze the influence of air temperature and diet composition on water diffusion coefficient and other kinetic parameters.

## 2 Materials and methods

### 2.1 Composition of diets and pelletization

The formulation of the diets was done using bibliographic information of the nutritional requirements, behavior and feeding habits of the abalone under study (FLEMMING; VAN BAMEVELD; HONE, 1996; CORAZANI; ILLANES, 1998; MAI, 1998; SCHNEIDER et al., 2005). These diets are characterized for presenting a very high nutritional quality for the growth of this mollusk, as in some macroalgae and microalgae used in this study; these have already been used for feeding mammals and fowls (GLENCROSS; BOOTH; ALLAN, 2007). Table 1 shows the components of different diets for the Japanese abalone. The main component is the microalga *Spirulina*, which is used for its high protein content (SÁNCHEZ-LUNA et al., 2004). All the components were

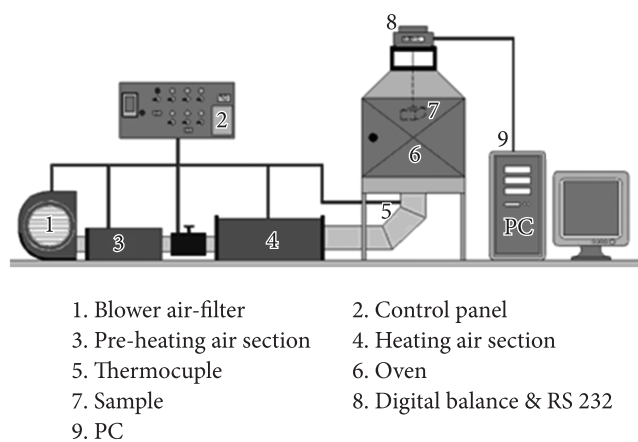
weighed in an analytic scale (*CHYO, Jex120, Tokio, Japan*) of accuracy  $\pm 0.0001$  g, according to the percentages showed in Table 1. The components were manually mixed and homogenized for 10 minutes in a stainless steel bin. Then, fishmeal was added (lipid source), and the components were homogenized again for 10 minutes in order to stabilize the non-alike components, and thus obtain a totally homogenous composition. Water was then added at  $82.0 \pm 0.8$  °C in a ratio 1:1 with respect to the weight of this mixture. Immediately thereafter, a new batch was mixed for 15 minutes, in order to pre-condition the mixture for the next stage (pelletization) using pelletizing equipment, designed and built by the Department of Food Engineering of Universidad de La Serena. This equipment compacted and produced the pellets (material to be dried) in slab shape of thickness 0.0025 m, which were uniformly cut into 0.02 m lengthwise.

### 2.2 Drying experiments

Several drying experiments were carried out at 60, 70 and 80 °C, in triplicate and at random order, for each diet. The drying experiments were performed using a convective dryer designed and built in the Department of Food Engineering of Universidad de La Serena (Figure 1). The drying airflow was maintained constant at  $2.0 \pm 0.1$  m/s, and measured with a unidirectional anemometer (*Extech Instrument Inc., 451112*,

**Table 1.** Diets formulated for Japanese Abalone, expressed in g.100 g<sup>-1</sup> sample.

Components	Type of diet		
	A	B	C
Fishmeal	43.79	35.58	27.37
Spirulin flour	9.33	18.67	28.00
Fish oil	0.89	1.54	2.20
Cornstarch	35.84	34.06	32.28
Sodium alginate	7.00	7.00	7.00
Premix minerals	2.00	2.00	2.00
Premix vitamins	1.00	1.00	1.00
Vitamin C	0.13	0.13	0.13
Choline	0.01	0.01	0.01
Tocopherol	0.01	0.01	0.01



**Figure 1.** Hot-air convective dryer.

MA, USA). In addition, the outlet relative humidity, which was measured with an ambient digital hygro-thermometer (Extech Instrument Inc., 445703, MA, USA), was  $60.0 \pm 4.2\%$ . A load density of  $8.0 \pm 0.1 \text{ kg/m}^2$  was used. Within the drying oven, the pellets were placed as a thin-layer on a stainless steel bin connected to a scale (Ohaus, SP402, NJ, USA) of accuracy  $\pm 0.01 \text{ g}$ . The data on the variation in the mass of the pellets were recorded and stored in a PC through an interface system (Ohaus, RS232, NJ, USA), using Microsoft® HyperTerminal® software. The drying process was stopped as soon as the sample reached constant weight over time (equilibrium condition), i.e. the relative humidity of the air surrounding the test material was the same as the water activity of the material. The dried samples were vacuum-sealed in polyethylene bags and stored at  $5^\circ\text{C}$ . Then, the moisture content was determined following the A.O.A.C (1990) methodology n° 934.06, using a vacuum oven (Gallenkamp, OVL570, Leicester, UK) and an analytical scale (CHYO, Jex120, Tokio, Japan) of accuracy  $\pm 0.0001 \text{ g}$ .

### 2.3 Experimental design

The experimental design used for the drying of pellets is based on a factorial design  $n^m$ , where  $n$  is the number of levels and  $k$  is the number of factors, where temperature and type of diet are the two factors under study ( $m = 2$ ), each with three levels ( $n = 3$ ). Therefore, 9 experiments were required ( $3^2$ ). Table 2 shows the decoding levels of the variables to be used in the experimental design to later represent the experiments already codified in Table 3 (RODRIGUEZ, 1982).

### 2.4 Modeling of drying kinetics

The data on the variation in the mass of the pellets samples employed the concept of moisture ratio (Equation 1), as the dependent variable represents the relation between the gradient of moisture content of the sample in real time, comparing initial moisture content and equilibrium moisture content (VEGA-GÁLVEZ et al., 2009; WANG et al., 2007; LEMUS et al.,

2008). In the present experiment, the integrated equation of Fick's second law was used over long periods of time, for an infinite slab (thin-layer) of given thickness (Equation 2), representing the first term in the development of the series in Equation 3 (CRANK, 1975), from which the diffusion coefficient was obtained for each drying experiment. Where,  $X_{wt}$  is real time moisture content (g water/g d.m.);  $X_{wo}$  is initial moisture content (g water/g d.m.);  $X_{we}$  is equilibrium moisture content (g water/g d.m.);  $i$  is number of terms;  $t$  is time (minute); and  $L$  is the thin-layer thickness (m).

$$MR = \frac{X_{wt} - X_{we}}{X_{wo} - X_{we}} \quad (1)$$

$$MR = \frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp \left[ \frac{-(2i+1)^2 D_{we} \pi^2 t}{4L^2} \right] \quad (2)$$

$$MR = \frac{8}{\pi^2} \exp \left[ \frac{-D_{we} \pi^2 t}{4L^2} \right] \quad (3)$$

The drying kinetics was modeled using Page (Equation 4), Modified Page (Equation 5), Root of time (Equation 6), Exponential (Equation 7), Logarithmic (Equation 8), Two-Terms (Equation 9), Modified Henderson-Pabis (Equation 10), and Weibull (Equation 11) models. In addition, two new models were used to simulate the process: Proposed model 1 (Equation 12) and Proposed model 2 (Equation 13), (AKPINAR, 2006). In this research, the shrinkage and external resistance were taken as negligible (MWITHIGA; OLWAL, 2004; VEGA-GÁLVEZ et al., 2009). Where,  $k$  and  $\alpha$  are kinetic parameters of the models (/min), and  $n$ ,  $y_o$ ,  $a$ ,  $b$ ,  $c$ ,  $d$ ,  $g$ ,  $h$  and  $\beta$  are empirical parameters of the models (dimensionless).

$$\text{Page} \quad MR = \exp(-kt^n) \quad (4)$$

$$\text{Modified Page} \quad MR = \exp(-(kt)^n) \quad (5)$$

$$\text{Root of time} \quad MR = n + k\sqrt{t} \quad (6)$$

$$\text{Exponential} \quad MR = \exp(n + kt) \quad (7)$$

$$\text{Logarithmic} \quad MR = y_o + a \exp(-bt) \quad (8)$$

$$\text{Two-Terms} \quad MR = a \exp(-bt) + c \exp(-dt) \quad (9)$$

$$\text{Modified Henderson-Pabis} \quad MR = a \exp(-bt) + c \exp(-dt) + g \exp(-ht) \quad (10)$$

$$\text{Weibull} \quad MR = \exp\left(-\left(t/\beta\right)^\alpha\right) \quad (11)$$

$$\text{Proposed model 1} \quad MR = y_o + a \exp(-bt) + c \exp(-dt) \quad (12)$$

$$\text{Proposed model 2} \quad MR = y_o + a \exp(-bt) + ct \quad (13)$$

**Table 2.** Decoded levels of the variables.

Decoded levels		
Codified levels	Air temperature	Diet
-1	60	A
0	70	B
+1	80	C

**Table 3.** Codified matrix of the experimental design ( $3^2$ ).

Experiment	Air temperature	Diet
1	-1	-1
2	0	-1
3	+1	-1
4	-1	0
5	0	0
6	+1	0
7	-1	+1
8	0	+1
9	+1	+1

## 2.5 Statistical analyses

In order to study the influence of the proposed models on the experimental drying data, statistical tests including linear determination coefficient ( $r^2$ ), sum squared errors (SSE) (Equation 14) and chi-square ( $\chi^2$ ) (Equation 15) were evaluated. The lowest values for SSE and  $\chi^2$ , or those approaching zero, together with the highest values of  $r^2$ , which approached the unity, were considered optimal and were used to select the best model (AKGUN; DOYMAZ, 2005; AKPINAR, 2006). Where,  $MR_{ei}$  is experimental moisture ratio (dimensionless);  $MR_{ci}$  is calculated moisture ratio (dimensionless); N is number of data; z is number of parameters; and  $i$  is number of terms.

$$SSE = \frac{1}{N} \sum_{i=1}^N (MR_{ei} - MR_{ci})^2 \quad (14)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{ei} - MR_{ci})^2}{N - z} \quad (15)$$

Bifactorial analysis of variance (ANOVA) was carried out to estimate least significant differences (LSD) between the means of the diffusion coefficients and the kinetic parameters, at a confidence level of 95% ( $p < 0.05$ ). Moreover, the multiple range test (MRT) was used to determine possible homogeneous groups existing among the parameters. The statistical estimation was done using Statgraphics® Plus 5.1 software (STATGRAPHICS GRAPHICS CORPORATION, 1991).

## 3 Results and discussion

### 3.1 Equilibrium moisture content and behavior of drying curves

Table 4 shows the equilibrium moisture contents reached by pellets after every drying experiment. For all experiments, one measure of equilibrium moisture content was obtained lower than 3.67 g water/g d.m., which is very stable for this organic material (PARK et al., 2008). Figure 2 shows the drying curves of the three different diets at their corresponding temperatures under study, and Figure 3 shows the influence of temperature on the established diets. Bifactorial ANOVA carried out on the  $X_{we}$  averages from pellets, showed that there were least significant differences ( $p < 0.05$ ) and influence of temperature on Diets A and C.

Figure 3 shows that there was a clear effect of temperature on the drying process of the pellet, where an increase in the drying temperature was accompanied by a decrease in the drying time.

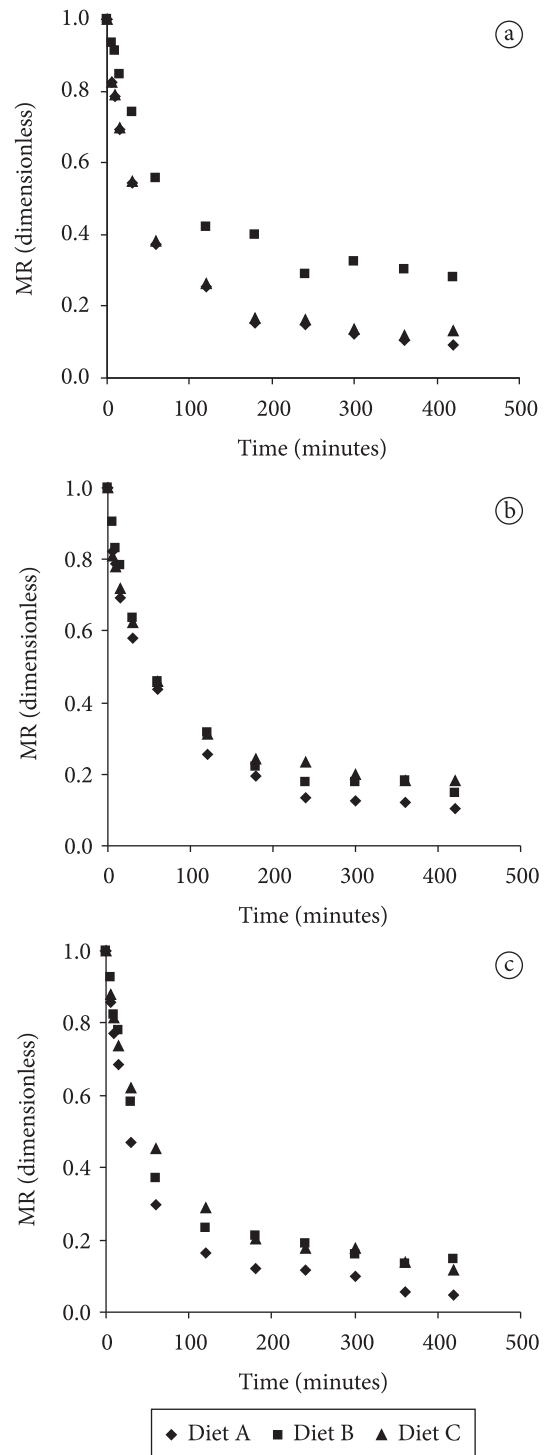


Figure 2. Drying curves at a) 60°; b) 70°; and c) 80 °C.

Table 4. Equilibrium moisture contents ( $X_{we}$  g water/g d.m.) of the pellets.

Air temperature	Diet		
	A	B	C
60	$3.67 \pm 0.82^{xa}$	$3.01 \pm 0.12^{xa}$	$3.34 \pm 0.31^{xa}$
70	$2.01 \pm 0.05^{ya}$	$2.88 \pm 0.73^{xb}$	$2.95 \pm 0.04^{yb}$
80	$1.88 \pm 0.28^{ya}$	$2.54 \pm 0.32^{xb}$	$2.19 \pm 0.13^{yab}$

\*Data are expressed as average  $\pm$  standard deviation in three replicates. Values in the same column having the same letter (x, y and z) for each parameter are not significantly different at a confidence level of 95%. Values in the same file having the same letter (a, b and c) for each parameter are not significantly different at a confidence level of 95%.



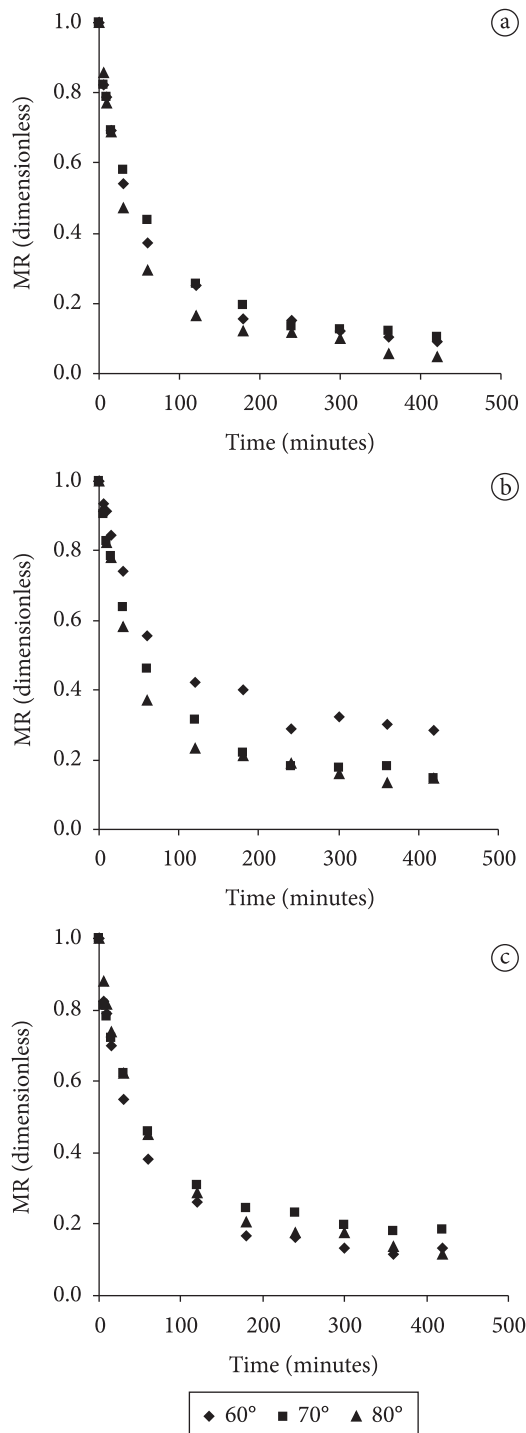


Figure 3. Drying curves for the a) A; b) B; and c) C diets.

Table 5. Diffusion coefficients ( $D_{we} \times 10^{-10} \text{ m}^2/\text{s}$ ) for the pellets.

Air temperature (°C)	Diet		
	A	B	C
60	$1.39 \pm 0.21^{xa}$	$0.84 \pm 0.07^{xb}$	$1.41 \pm 0.21^{xa}$
70	$1.42 \pm 0.13^{xa}$	$1.24 \pm 0.04^{xab}$	$1.10 \pm 0.19^{xb}$
80	$1.63 \pm 0.07^{xa}$	$1.29 \pm 0.05^{yb}$	$1.38 \pm 0.17^{xb}$

\*Data are expressed as average  $\pm$  standard deviation in three replicates. Values in the same column having the same letter (x, y and z) for each parameter are not significantly different at a confidence level of 95%. Values in the same file having the same letter (a, b and c) for each parameter are not significantly different at a confidence level of 95%.

The time needed to achieve equilibrium moisture content in all experiments was between 300 and 400 minutes. This slowness on the diet drying process may be due to the percentage of fish oil and cornstarch, which possibly cause surface crusting and an intense interaction between starch and water (PARK et al., 2008); this phenomenon was not considered in this study. Similar results were obtained by other authors working with other organic materials as reported by, Maskan, Kaya and Maskan, (2002); Akgun and Doymaz (2005); Wang et al. (2007); Vega-Gálvez et al. (2009) and Lemus et al. (2008). Moreover, these figures clearly show an extremely prolonged period of falling drying rate.

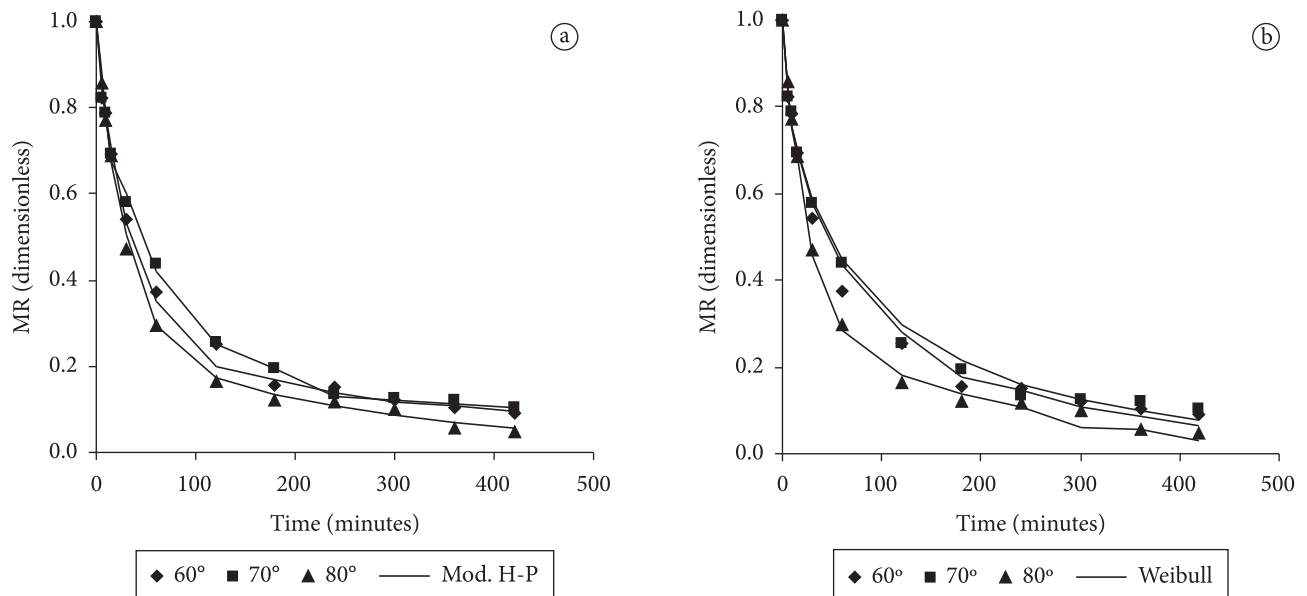
### 3.2 Diffusion coefficients of pellets and modeling of drying curves

Table 5 shows the influence of the drying temperature and the type of diet on the diffusion coefficient of the pellets. It was observed that the increase of the drying temperature caused the diffusion coefficients decrease of the pellets samples, i.e. there is an inversely proportional effect of the drying temperature on the diffusion coefficients of the pellets in Diets A and B, unlike Diet C (values in the same column). This may be due to the higher amount of fish oil in Diet C, which would obstruct normal water diffusion to surface during the drying process. However, when keeping any diet constant and observing the influence of temperature, bifactorial analysis ANOVA on the means of  $D_{we}$  of the pellets showed no significant differences ( $p < 0.05$ ). Furthermore, in Table 5, when keeping the drying temperature constant on the  $D_{we}$  of the pellets and varying the type of diet, there was no directly or inversely proportional effect of the diet (values in the same file). Thus, bifactorial ANOVA on the means of the  $D_{we}$  of the pellets showed there were significant differences ( $p < 0.05$ ).

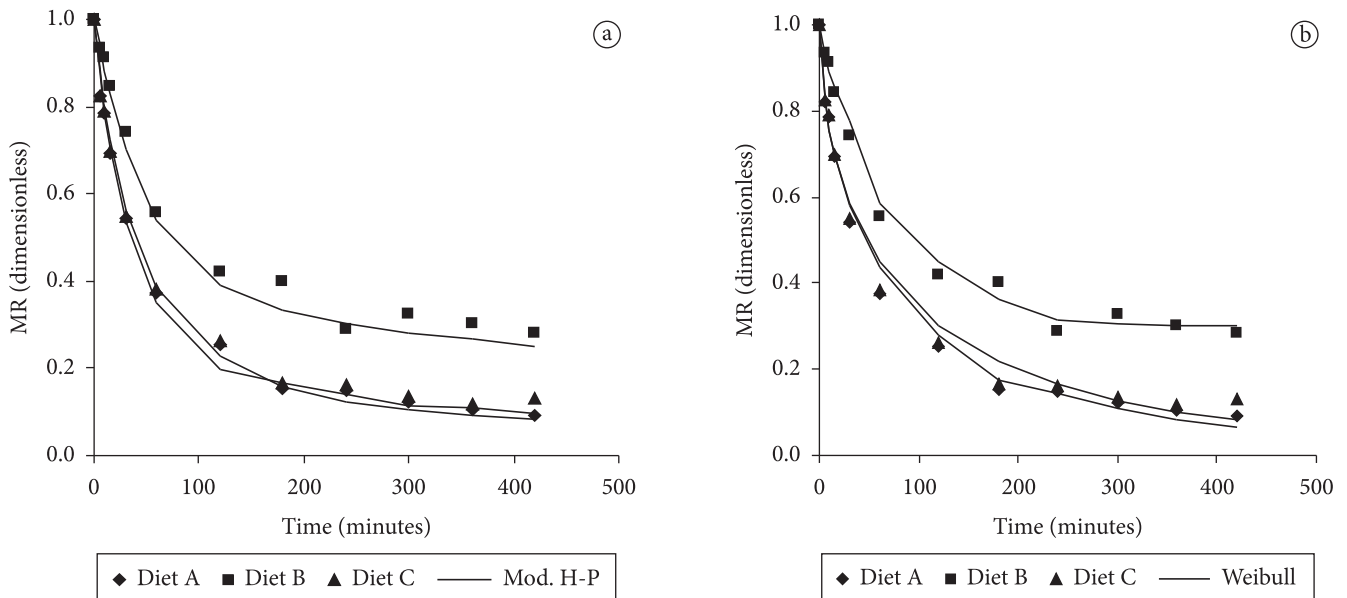
Table 6 shows the main values as well as the standard deviation of the kinetic and empirical parameters obtained from the ten mathematical models applied in this study. ANOVA showed that all the kinetic and empirical parameters of each respective model presented  $p > 0.05$ , thus showing there was no significant difference between them in relation to the drying temperature and the diets. Figure 4 only shows the experimental and calculated drying curves with the Modified H-P and Weibull models for Diet A at the different working temperatures. Conversely, Figure 5 shows the experimental and calculated drying curves with the Modified H-P and Weibull models for the three diets studied at a temperature of 60 °C.

Table 6. Average values of kinetic and empirical parameters.

Model	Parameter	Dieta A			Dieta B			Dieta C		
		60 °C	70 °C	80 °C	60 °C	70 °C	80 °C	60 °C	70 °C	80 °C
Page	<i>k</i>	0.073 ± 0.002	0.072 ± 0.004	0.062 ± 0.009	0.026 ± 0.014	0.041 ± 0.004	0.037 ± 0.006	0.076 ± 0.021	0.085 ± 0.010	0.051 ± 0.010
	<i>n</i>	0.608 ± 0.051	0.591 ± 0.021	0.669 ± 0.053	0.705 ± 0.112	0.667 ± 0.027	0.708 ± 0.041	0.586 ± 0.036	0.520 ± 0.047	0.642 ± 0.027
Mod. page	<i>k</i>	0.013 ± 0.004	0.012 ± 0.001	0.016 ± 0.002	0.005 ± 0.000	0.008 ± 0.000	0.009 ± 0.000	0.012 ± 0.003	0.009 ± 0.001	0.009 ± 0.001
	<i>n</i>	0.608 ± 0.051	0.591 ± 0.021	0.669 ± 0.053	0.705 ± 0.117	0.667 ± 0.027	0.708 ± 0.041	0.586 ± 0.036	0.520 ± 0.047	0.642 ± 0.027
Root of time	<i>k</i>	0.862 ± 0.035	0.875 ± 0.003	0.848 ± 0.013	0.965 ± 0.031	0.923 ± 0.001	0.904 ± 0.004	0.861 ± 0.036	0.871 ± 0.002	0.907 ± 0.014
	<i>n</i>	-0.044 ± 0.001	-0.044 ± 0.001	-0.046 ± 0.001	-0.038 ± 0.002	-0.044 ± 0.001	-0.044 ± 0.001	-0.043 ± 0.001	-0.039 ± 0.003	-0.044 ± 0.001
Exponential	<i>k</i>	-0.359 ± 0.061	-0.347 ± 0.015	-0.375 ± 0.144	-0.205 ± 0.036	-0.293 ± 0.011	-0.353 ± 0.017	-0.391 ± 0.064	-0.343 ± 0.015	-0.297 ± 0.030
	<i>n</i>	-0.061 ± 0.002	-0.005 ± 0.001	-0.008 ± 0.002	-0.003 ± 0.000	-0.005 ± 0.000	-0.005 ± 0.000	-0.005 ± 0.001	-0.004 ± 0.001	-0.005 ± 0.001
Weibull	$\alpha$	0.608 ± 0.051	0.591 ± 0.021	0.669 ± 0.053	0.705 ± 0.117	0.667 ± 0.027	0.708 ± 0.042	0.586 ± 0.036	0.520 ± 0.047	0.642 ± 0.027
	$\beta$ (x10 <sup>1</sup> )	8.121 ± 2.668	8.635 ± 0.566	6.458 ± 0.766	21.29 ± 0.910	12.00 ± 0.515	10.77 ± 0.313	8.752 ± 2.617	11.89 ± 2.504	10.58 ± 1.555
Logarithmic	<i>y</i> <sub>0</sub>	0.127 ± 0.043	0.128 ± 0.020	0.092 ± 0.021	0.302 ± 0.023	0.172 ± 0.011	0.164 ± 0.008	0.145 ± 0.036	0.202 ± 0.047	0.153 ± 0.030
	<i>a</i>	0.815 ± 0.043	0.795 ± 0.016	0.887 ± 0.022	0.692 ± 0.043	0.778 ± 0.048	0.841 ± 0.012	0.800 ± 0.036	0.718 ± 0.055	0.800 ± 0.009
Two terms	<i>b</i>	0.021 ± 0.002	0.017 ± 0.001	0.026 ± 0.003	0.015 ± 0.002	0.016 ± 0.001	0.022 ± 0.001	0.021 ± 0.004	0.018 ± 0.001	0.017 ± 0.001
	<i>a</i>	0.623 ± 0.029	0.514 ± 0.110	0.744 ± 0.095	0.608 ± 0.020	0.693 ± 0.042	0.773 ± 0.012	0.653 ± 0.031	0.580 ± 0.034	0.630 ± 0.081
	<i>b</i>	0.035 ± 0.011	0.041 ± 0.017	0.036 ± 0.007	0.019 ± 0.002	0.021 ± 0.001	0.026 ± 0.001	0.032 ± 0.007	0.027 ± 0.001	0.026 ± 0.005
	<i>c</i>	0.347 ± 0.041	0.450 ± 0.126	0.252 ± 0.098	0.395 ± 0.002	0.289 ± 0.039	0.241 ± 0.006	0.315 ± 0.011	0.361 ± 0.022	0.343 ± 0.084
Modified H-P	<i>d</i>	0.004 ± 0.002	0.004 ± 0.002	0.004 ± 0.002	0.001 ± 0.000	0.002 ± 0.000	0.001 ± 0.000	0.003 ± 0.001	0.002 ± 0.001	0.003 ± 0.001
	<i>a</i>	0.240 ± 0.079	0.161 ± 0.040	0.370 ± 0.063	0.323 ± 0.075	0.161 ± 0.040	0.460 ± 0.124	0.290 ± 0.160	0.134 ± 0.017	0.111 ± 0.033
	<i>b</i>	0.059 ± 0.006	0.200 ± 0.040	0.039 ± 0.005	0.026 ± 0.014	0.200 ± 0.040	0.0285 ± 0.005	0.056 ± 0.001	0.740 ± 0.050	0.116 ± 0.066
	<i>c</i>	0.527 ± 0.170	0.664 ± 0.002	0.500 ± 0.242	0.318 ± 0.113	0.664 ± 0.002	0.349 ± 0.053	0.560 ± 0.107	0.601 ± 0.054	0.622 ± 0.086
	<i>d</i>	0.020 ± 0.010	0.170 ± 0.002	0.035 ± 0.007	0.016 ± 0.004	0.017 ± 0.002	0.020 ± 0.010	0.014 ± 0.005	0.017 ± 0.001	0.018 ± 0.005
	<i>g</i>	0.229 ± 0.111	0.174 ± 0.041	0.247 ± 0.103	0.366 ± 0.050	0.174 ± 0.041	0.207 ± 0.064	0.147 ± 0.052	0.257 ± 0.037	0.267 ± 0.119
	<i>h</i>	0.003 ± 0.002	0.001 ± 0.000	0.004 ± 0.002	0.001 ± 0.000	0.001 ± 0.000	0.001 ± 0.000	0.001 ± 0.000	0.001 ± 0.000	0.003 ± 0.001



**Figure 4.** Experimental and calculated drying curves for Diet A at different temperatures: a) Modified H-P; and b) Weibull.



**Figure 5.** Experimental and calculated drying curves at 60 °C for the three diets: a) Modified H-P; and b) Weibull.

Another observation shows that, in all possible cases, the values of  $D_{we}$  for Diet A were higher compared to Diets B and C, possibly due to the lower proportion of fish oil and cornstarch. Due to the scarcity of data reported in the literature on the drying of pellets for animal feeding, the values of the diffusion coefficient ( $D_{we}$ ) from the present study were compared to those obtained during the drying of organic and biological materials. For example,  $D_{we}$  was  $3.00\text{--}37.6 \times 10^{-11} \text{ m}^2/\text{s}$  for grape leather (MASKAN; KAYA; MASKAN, 2002);  $0.3\text{--}1.1 \times 10^{-8} \text{ m}^2/\text{s}$  for olive cake (AKGUN; DOYMAZ, 2005);  $2.40\text{--}6.28 \times 10^{-9} \text{ m}^2/\text{s}$  for lobster fishery waste (VEGA-GÁLVEZ et al., 2009); and  $1.14\text{--}12.82 \times 10^{-9} \text{ m}^2/\text{s}$  for apple pomace (WANG et al., 2007).

In some models, there was not a clear tendency to an increase or a decrease of the values of kinetic and empirical parameters

with respect to the drying air temperature and type of diet (AKPINAR; BICER; YILDIZ, 2003). As an example, Figure 4 only shows the experimental and calculated drying curves with the Modified H-P and Weibull models for Diet A at the different working temperatures, in which there is no presence of a constant rate period, but a falling rate period, very common in the drying process of organic materials (MWITHIGA; OLWAL, 2004).

### 3.3 Statistical tests

Figure 6 shows the statistical tests used to evaluate the fit quality of the experimental data from all the drying curves studied. Figure 6 also shows that the Modified H-P, Weibull and the proposed models generated the lowest values for SSE and  $\chi^2$ , when compared to Page, Modified Page, Root of time,



Exponential, Logarithmic and Two terms. Figure 7 shows the interaction graphics for the diffusion coefficients of the pellet samples with respect to drying temperature and the type of diet related to the Japanese Abalone. On one hand, Figure 7a shows the influence of the drying temperature on the  $D_{we}$  of pellets when the type of diet is kept constant. On the other hand, Figure 7b shows the  $D_{we}$  of the pellets as function of diet type, when drying temperature is kept constant. Thus, considering both figures and observing the influence of both variables on the process (drying temperature and type of diet), a multiple linear regression test was carried out on the diffusion coefficient of the pellets. Equation 16 was then proposed, where the type of diet ( $D$ ) is the most relevant factor with respect to drying temperature ( $T$ ).

$$D_{we} = 7.1150 \times 10^{-11} + 1.1017 \times 10^{-12} * T - 9.1500 \times 10^{-12} * D \quad (16)$$

In general, and considering the determination coefficients, it is suggested that all used models showed very good fit quality

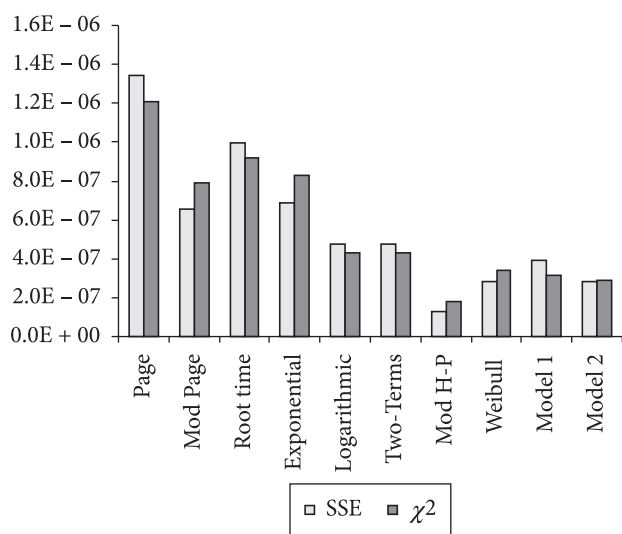
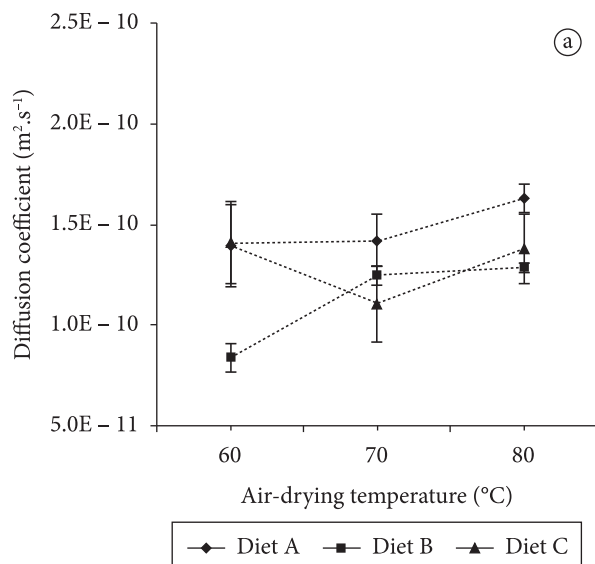


Figure 6. Statistical tests on all models.



of the drying process for the pellets ( $r^2 \geq 0.95$ ). Nevertheless, the Modified Henderson-Pabis and Weibull models provided the best results ( $r^2 \geq 0.99$ ). Similar results were reported by Akpinar, Bicer and Yildiz (2003) and Senadeera et al. (2003). The highest fit quality of the experimental data obtained with the Modified H-P model may have occurred because it has more constants than the other models, providing a better mathematical fit than the other equations. The statistical results applied to the two new 'Proposed' models generated low values for SSE and  $\chi^2$ , suggesting a good fit quality on the experimental data and confirming their usefulness for modeling mass (water) transfer kinetics during the convective drying of this material.

#### 4 Conclusions

This research showed that the study of air drying of pellets is important to the design of animal feeding products based on organic materials. The values of equilibrium moisture content were between 0.03 and 0.05 g water/g d.m., in all drying curves. According to bifactorial ANOVA carried out on the  $D_{we}$  of the pellets, and still in presence of homogeneous groups, it can be stated that this parameter had no dependence on the type of diet ( $p > 0.05$ ). The same happened when the temperature varied for a constant diet, since in all cases at a level of confidence of 95%,  $p > 0.05$  was obtained. In general, all empirical models showed a good fit quality on the experimental data of the different drying processes, based on the SSE and  $\chi^2$  statistical tests. However, Modified H-P, Weibull and Proposed model 2 showed the best fit on experimental data, possibly due to the exponential tendency of the drying curves and the high number of parameters these models show. Finally, this research represents an excellent tool to estimate the drying time of this organic material, with a potential optimization of the total working time, which will enhance the development and use of pellets for the feeding of abalone culture in our country.

#### Acknowledgements

The authors are grateful to the Project Fund for the Promotion for the Scientific and Technological Development

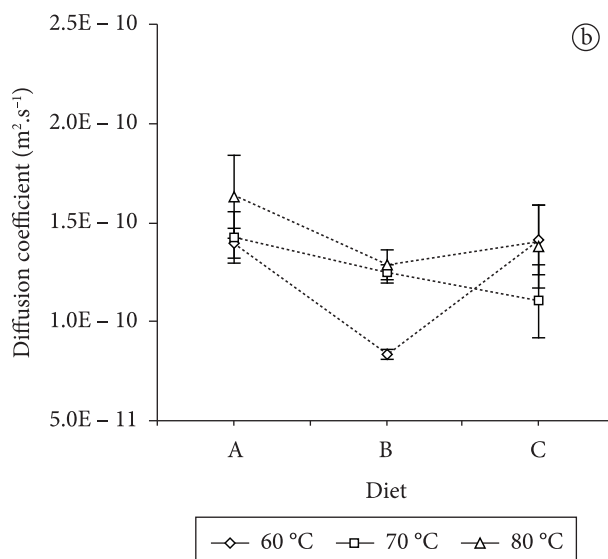


Figure 7. Interaction graphic between drying temperature and type of diet on the diffusional coefficient for the Japanese abalone pellet.

FONDEF AQ0411018 for the financial support on the execution of this research.

## References

- AKGUN, N. A.; DOYMAZ, I. Modelling of olive cake thin-layer drying process. **Journal of Food Engineering**, v. 68, p. 455-461, 2005. <http://dx.doi.org/10.1016/j.jfoodeng.2004.06.023>
- AKPINAR, E. K. Determination of suitable thin layer drying curve model for some vegetables and fruits. **Journal of Food Engineering**, v. 73, p. 75-84, 2006. <http://dx.doi.org/10.1016/j.jfoodeng.2005.01.007>
- AKPINAR, E. K.; BICER, Y.; YILDIZ, C. Thin layer drying of red pepper. **Journal of Food Engineering**, v. 55, p. 99-104, 2003. [http://dx.doi.org/10.1016/S0260-8774\(02\)00425-9](http://dx.doi.org/10.1016/S0260-8774(02)00425-9)
- ASSOCIATION OF OFFICIAL ANALYTICAL CHEMISTS - AOAC. **Official Method of Analysis**. 15th ed. Washington: AOAC, 1990.
- CORAZANI, D.; ILLANES, J. E. Growth of juvenile abalone, *Haliotis discus hannai* Ino 1953 and *Haliotis rufescens* Swainson 1822, fed with different diets. **Journal of Shellfish Research**, v. 17, p. 663-666, 1998.
- CRANK, J. **The mathematical of diffusion**. 2th ed. London: Clarendon Press-Oxford, 1975.
- FLEMMING, A. E.; VAN BAMEVELD, R. J.; HONE, P. W. The development of artificial diets for abalone: A review and future directions. **Aquaculture**, v. 140, p. 5-53, 1996. [http://dx.doi.org/10.1016/0044-8486\(95\)01184-6](http://dx.doi.org/10.1016/0044-8486(95)01184-6)
- GLENCROSS, B. D.; BOOTH, M.; ALLAN, G. L. A feed is only as good as its ingredients - a review of ingredient evaluation strategies for aquaculture feeds. **Aquaculture Nutrition**, v. 13, p. 17-34, 2007. <http://dx.doi.org/10.1111/j.1365-2095.2007.00450.x>
- HAHN, K. **Survey of the commercially import Abalone species in the world**. Florida: CRC Press, 1989. Handbook of culture of abalone and other marine gastropods.
- INSTITUTO DEL FOMENTO PESQUERO - IFOP. **Recursos Pesqueros**. Chile. Disponível em: <<http://www.ifop.cl>>. Acesso em: 18 sep. 2008.
- LEMUS, R. et al. Kinetic study of dehydration and desorption isotherms of red alga *Gracilaria*. **LWT - Food Science and Technology**, v. 41, p. 1592-1599, 2008.
- MAI, K. Comparative studies on the nutrition of two species of abalone, *Haliotis tuberculata* L. and *Haliotis discus hannai* Ino. VII. Effects of dietary vitamin C on survival, growth and tissue concentration of ascorbic acid. **Aquaculture**, v. 161, p. 383-392, 1998. [http://dx.doi.org/10.1016/S0044-8486\(97\)00286-X](http://dx.doi.org/10.1016/S0044-8486(97)00286-X)
- MASKAN, A.; KAYA, S.; MASKAN, M. Hot air and sun drying of grape leather (*pestil*). **Journal of Food Engineering**, v. 54, p. 81-88, 2002. [http://dx.doi.org/10.1016/S0260-8774\(01\)00188-1](http://dx.doi.org/10.1016/S0260-8774(01)00188-1)
- MWITHIGA, G.; OLWAL, J. O. The drying kinetics of kale (*Brassica oleracea*) in a convective hot air dryer. **Journal of Food Engineering**, v. 71, p. 373-378, 2004. <http://dx.doi.org/10.1016/j.jfoodeng.2004.10.041>
- PARK, J. et al. The growth of disk abalone, *Haliotis discus hannai* at different culture densities in a pilot-scale recirculating aquaculture system with a baffled culture tank. **Aquacultural Engineering**, v. 38, p. 161-170, 2008. <http://dx.doi.org/10.1016/j.aquaeng.2008.02.001>
- PEREIRA, L.; RASSE, S. Evaluation of growth and survival of juveniles of the Japanese abalone *Haliotis discus hannai* in two culture systems suspended in tanks. **Journal of Shellfish Research**, v. 26, p. 769-776, 2007. [http://dx.doi.org/10.2983/0730-8000\(2007\)26\[769:EOGAS O\]2.0.CO;2](http://dx.doi.org/10.2983/0730-8000(2007)26[769:EOGAS O]2.0.CO;2)
- RODRIGUEZ, R. N. **Encyclopaedia of Statistical Sciences, Correlation**. 2th ed. New York: New York Wiley, 1982.
- SALES, J.; JANSSENS, G. P. Use of feed ingredients in artificial diets for abalone: a brief update. **Nutrition Abstract Revision, Serie B**, v. 74, p. 13-21, 2004.
- SÁNCHEZ-LUNA, L. D. et al. Continuous and pulse feedings of urea as a nitrogen source in fed-batch cultivation of *Spirulina platensis*. **Aquacultural Engineering**, v. 31, p. 237-245, 2004.
- SCHNEIDER, O. et al. Analysis of nutrient flows in integrated intensive aquaculture systems. **Aquacultural Engineering**, v. 32, p. 379-401, 2005. <http://dx.doi.org/10.1016/j.aquaeng.2004.09.001>
- SENADEERA, W. et al. Influence of shapes of selected vegetable material son drying kinetics during fluidized bed drying. **Journal of Food Engineering**, v. 58, p. 277-283, 2003.
- SERVICIO NACIONAL DE PESCA DE CHILE - SERNAPESCA. **Leyes y Reglamentos; Normativas y Reglamentos**. Valparaíso: Ministerio de Economía, Fomento y Turismo. Disponível em: <<http://www.sernapesca.cl>>. Acesso em: 10 jun. 2008. [http://dx.doi.org/10.1016/S0260-8774\(02\)00386-2](http://dx.doi.org/10.1016/S0260-8774(02)00386-2)
- STATGRAPHICS GRAPHICS CORPORATION - STSC. **Manugistics Inc.** 2115 E. Rockville: Jefferson St., 1991.
- VEGA-GÁLVEZ, A. et al. Mathematical modelling on drying process of yellow squat lobster (*Cervimunida jhoni*) fishery waste for animal feed. **Animal Feed Science and Technology**, v. 151, p. 268-279, 2009.
- WANG, Z. et al. Mathematical modelling on hot air drying of thin layer apple pomace. **Food Research International**, v. 40, p. 39-46, 2007. <http://dx.doi.org/10.1016/j.foodres.2006.07.017>