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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)

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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 0.84-1.94×10^{-10} m^2/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 convenção, assim como três composições de dieta diferentes (Dietas 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 0,84-1,94×10^{-10} m^2/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, Singapure 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

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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

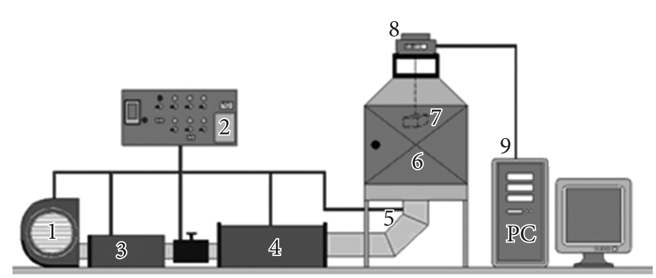
The formulation of the diets was done using bibliographic information of the nutritional requirements, behavior and feeding habits of the abalone under study (FLEMMING; VAN BAMEVELD; HONE, 1996; CORAZANI; ILLANES, 1998; MAI, 1998; SCHNEIDER et al., 2005). These diets are characterized for presenting 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 ± 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 ± 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 ± 0.1 m/s, and measured with a unidirectional anemometer (*Extech Instrument Inc., 451112,*

Table 1. Diets formulated for Japanese Abalone, expressed in $g.100\ g^{-1}$ 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



1. Blower air-filter
2. Control panel
3. Pre-heating air section
4. Heating air section
5. Thermocuple
6. Oven
7. Sample
8. Digital balance & RS 232
9. PC

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 ± 4.2%. A load density of 8.0 ± 0.1 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 ± 0.01 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 °C. Then, the moisture content was determined following the A.O.A.C (1990) methodology nº 934.06, using a vacuum oven (*Gallenkamp, OVL570, Leicester, UK*) and an analytical scale (*CHYO, Jex120, Tokio, Japan*) of accuracy ± 0.0001 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).

Table 2. Decoded levels of the variables.

	Decodified 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

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

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

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

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 α are kinetic parameters of the models (/min), and *n, yo, a, b, c, d, g, h and β* are empirical parameters of the models (dimensionless).

Page $$MR = \exp\left(-kt^n\right) \quad (4)$$

Modified Page $$MR = \exp\left(-(kt)^n\right) \quad (5)$$

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

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

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

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

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

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

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

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

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 (χ^2) (Equation 15) were evaluated. The lowest values for SSE and x^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.

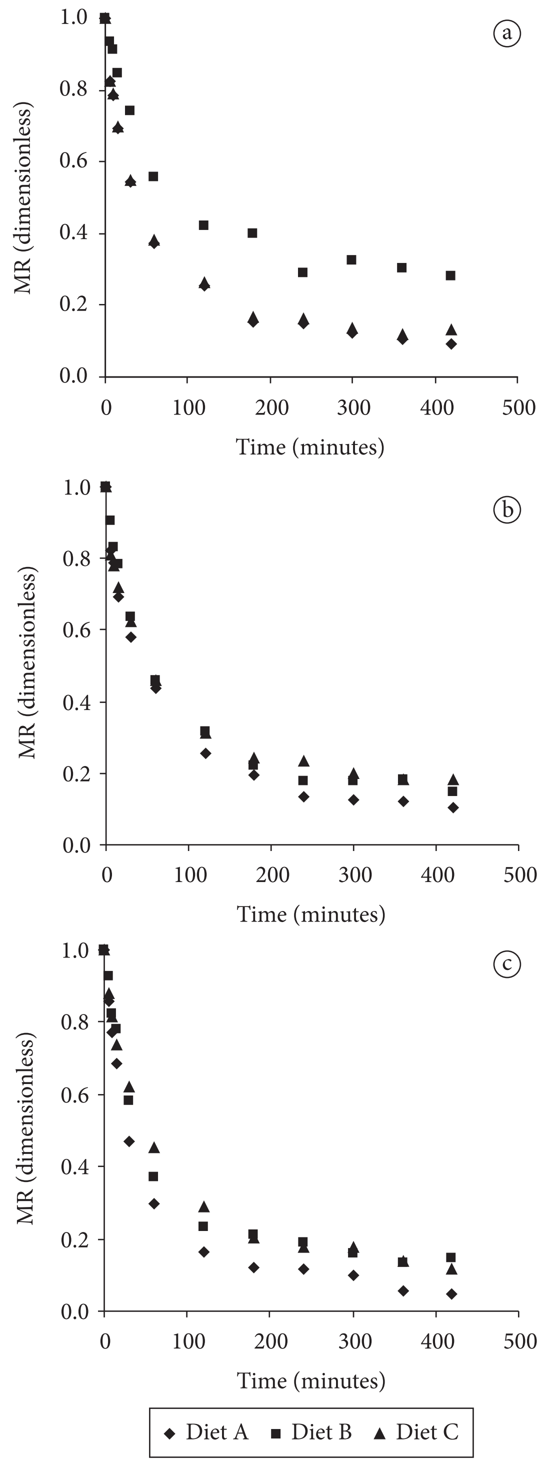


Figure 2. Drying curves at a) 60°; b) 70°; and c) 80 °C.

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

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

*Data are expressed as average ± 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%.

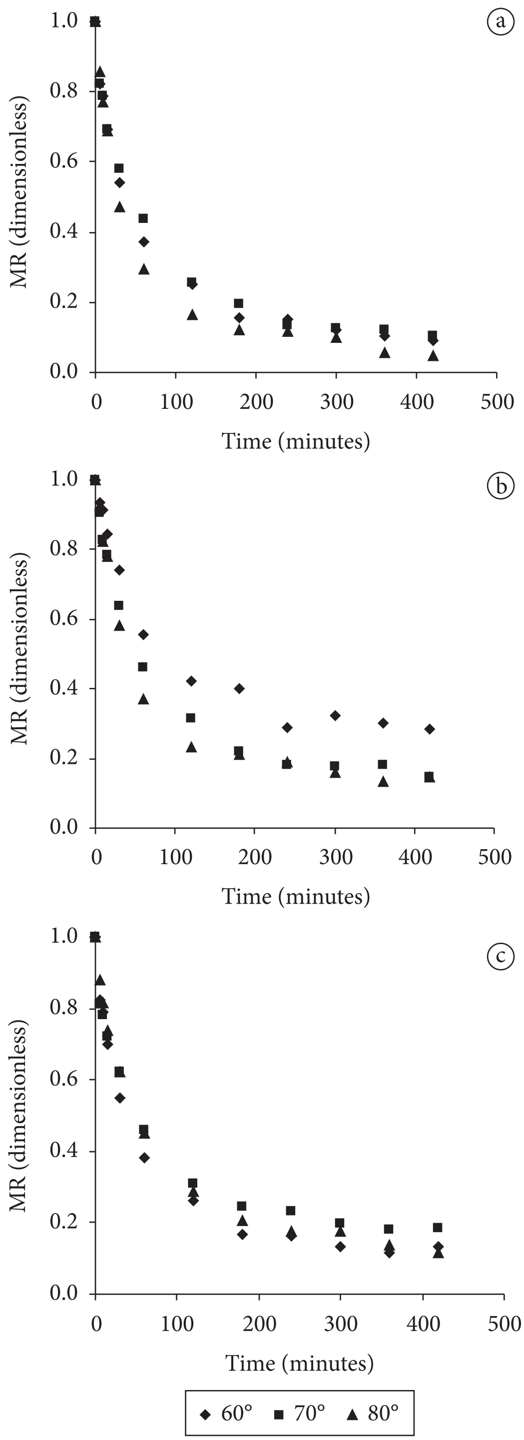


Figure 3. Drying curves for the a) A; b) B; and c) C diets.

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 5. Diffusion coefficients (D_{we} ×10^{-10} m^2/s) for the pellets.

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

*Data are expressed as average ± 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%.

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	*k*	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
	n	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	*k*	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
	n	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	*k*	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
	n	-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	*k*	-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
	n	-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	α	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
	β (x10^1)	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	y_o	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
	a	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
	b	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
Two terms	*a*	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
	b	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
	c	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
	d	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
Modified H-P	*a*	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
	b	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
	c	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
	d	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
	g	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
	h	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

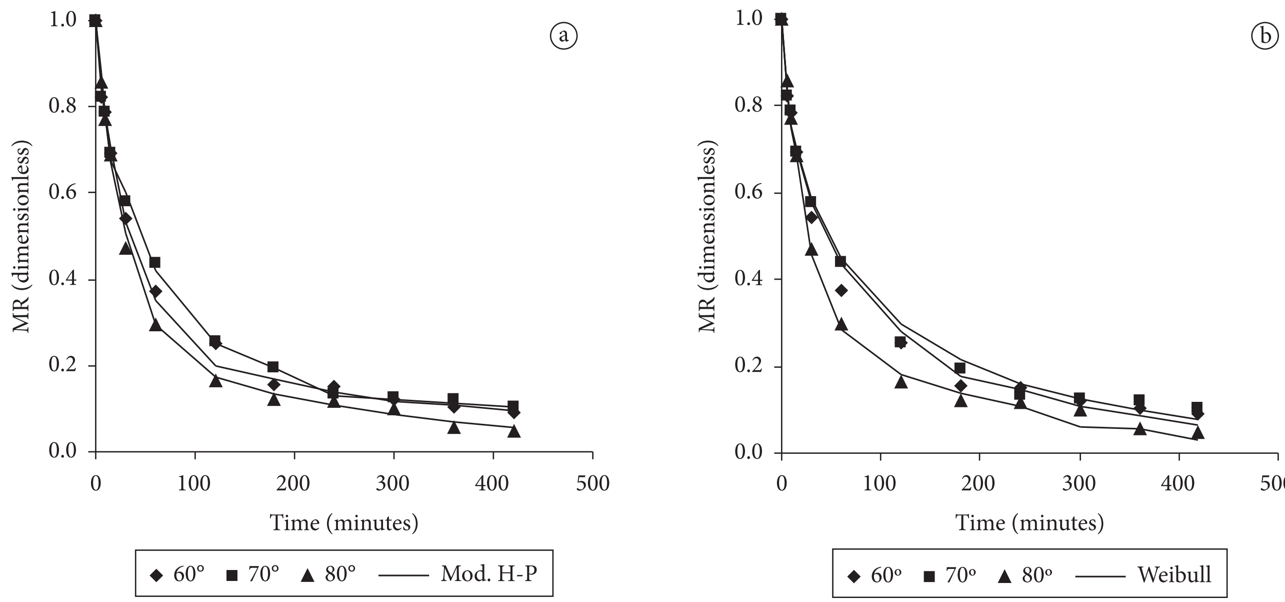


Figure 4. Experimental and calculated drying curves for Diet A at different temperatures: a) Modified H-P; and b) Weibull.

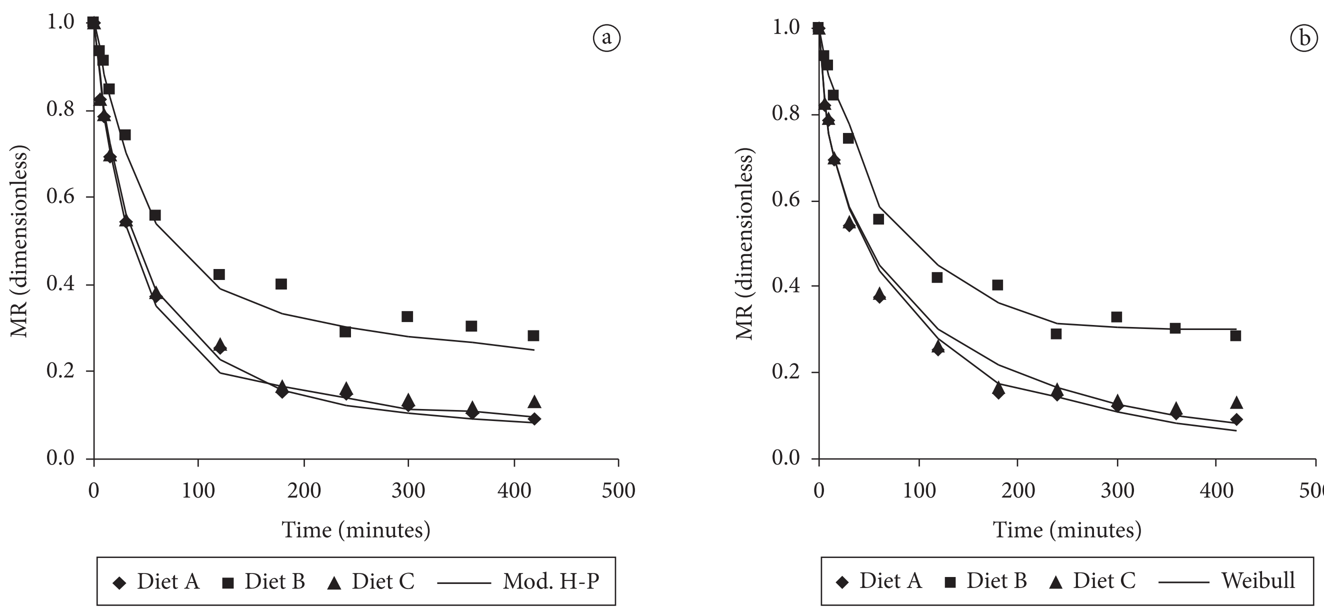


Figure 5. Experimental and calculated drying curves at 60 °C for the three diets: a) Modified H-P; and b) Weibull.

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 3.00-37.6 × 10^{-11} m^2/s for grape leather (MASKAN; KAYA; MASKAN, 2002); 0.3-1.1 × 10^{-8} m^2/s for olive cake (AKGUN; DOYMAZ, 2005); 2.40-6.28 × 10^{-9} m^2/s for lobster fishery waste (VEGA-GÁLVEZ et al., 2009); and 1.14-12.82 × 10^{-9} m^2/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 $\mathcal{X}^2$, 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*).

$$D_{we} = 7.1150x10^{-11} + 1.1017x10^{-12} * T - 9.1500x10^{-12} * D \quad (16)$$

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

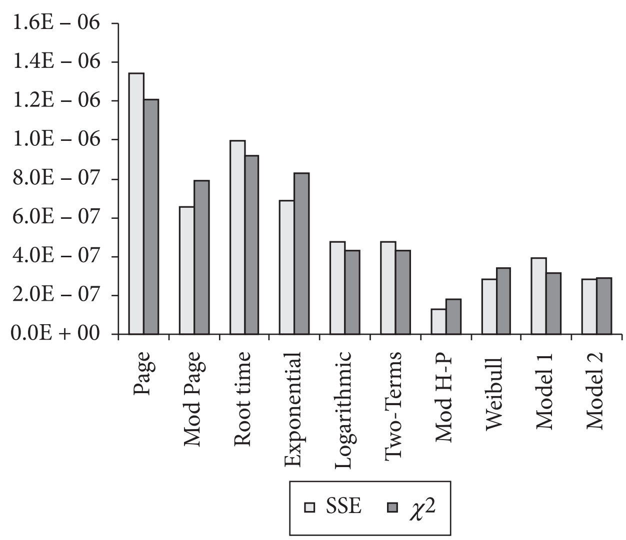


Figure 6. Statistical tests on all models.

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 $\mathcal{X}^2$, 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 $\mathcal{X}^2$ 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.

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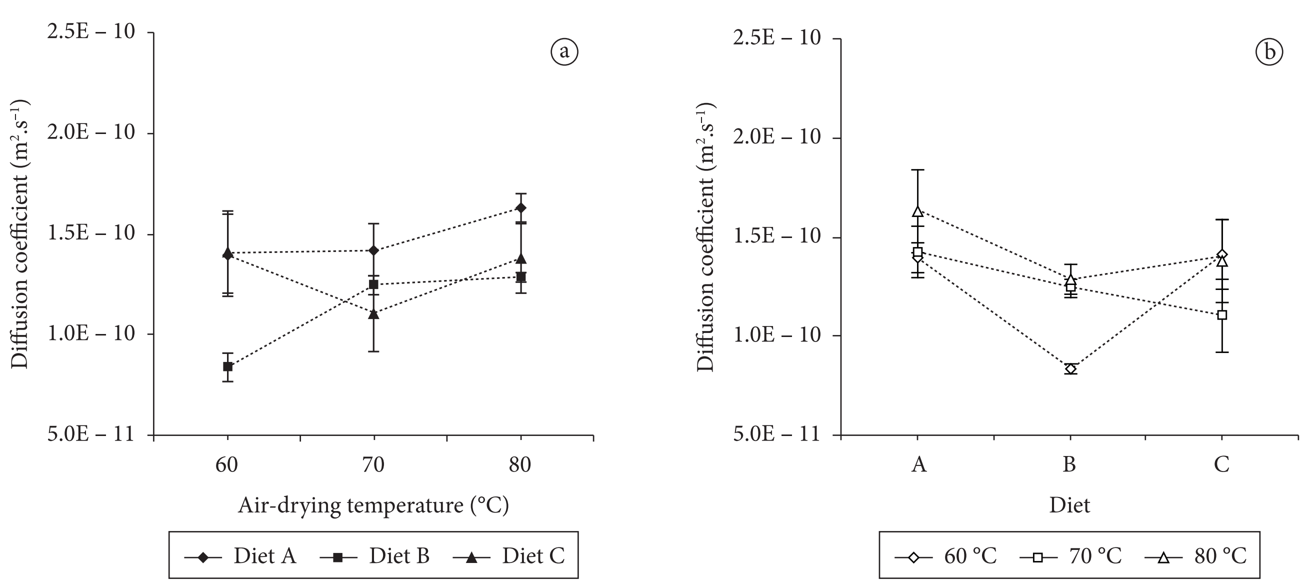

Figure 7. Interaction graphic between drying temperature and type of diet on the diffusional coefficient for the Japanese abalone pellet.

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