Kinetic modeling to study the quality of tambaqui (*Colossoma macropomum*) sous vide during storage at different temperatures

Fabiane C. P. Ramos¹ · Suezilde C. A. Ribeiro² · Maria R. S. Peixoto Joele² ·
Consuelo L. Sousa¹ · Lúcia F. H. Lourenço¹

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Abstract This study aimed to assess the changes in quality of tambaqui sous vide during refrigerated storage using degradation kinetics. Tambaqui sous vide was prepared and stored at three temperatures (1, 4, 10 °C). The microorganism counts and the physicochemical analyses were analyzed every three days. The results obtained were fitted to the Labuza models and by Arrhenius equation. The results of the microbiological and physicochemical analyses obtained better fits to the zero-order model. The Arrhenius equation better fit to the velocity constants of the zero-order model, which showed that the changes in the values of attributes are related to temperature. Higher E_a values were found for the microorganism counts than for the physicochemical parameters, which proves the greater dependency of microorganisms on variations in temperature. The assessment of changes in quality based on temperature allows the storage conditions to be optimized.

Keywords *Colossoma macropomun* · Processing · Degradation · Kinetic · Shelf life · Sous vide

Introduction

The shelf life of fish-based refrigerated products is limited due to the spoilage attributed to microbial activity and chemical and biochemical changes. Using mathematical models to predict quality allows industries to optimize

storage in order to minimize economic losses (Raab et al. 2008; Tsironi and Taoukis 2010; Zhang et al. 2011).

The sous vide technique consists in creating a vacuum and combining it with controlled cooking, which results in a ready-to-eat product that can be consumed immediately or be refrigerated/frozen to be consumed later. The use of vacuum packaging and pasteurization in sous vide preparation is responsible for maintaining sensory quality and physicochemical and microbiological stability during storage (Cosansu et al. 2011; Picouet et al. 2011).

Temperature control during storage until consumption is one of the main parameters that affect product quality, thus, studies have used models to predict changes in quality during storage and the effect of different conditions, time, and temperature on shelf life (Tsironi and Taoukis 2010; Zhang et al. 2011; Olivera and Salvadori 2012).

The chemical and biochemical reactions that affect the product during processing and storage are very complex, hence it is easier to analyze them using mathematical models based on laws of chemistry. Therefore, kinetic studies are required to develop appropriate mathematical models able to predict the effects of time, temperature, water activity, and other parameters on the changes during processing and/or storage (Olivera and Salvadori 2012).

The classic Arrhenius model is commonly employed to describe the relations between temperatures and the rate of reactions on biological and food systems. It is particularly appropriate for systems with a broad range of temperatures with no great changes in the mechanisms that determine the kinetic reaction rate constant (Kong et al. 2007).

When storage temperature is constant (isothermal condition), the kinetic orders (zero, first, and second orders) can be easily integrated to obtain decreasing functions with estimated values of the reaction rate constant (k). (Derossi et al. 2010). Once the values of k are estimated, the

✉ Lúcia F. H. Lourenço
luciah1@ufpa.br

¹ Universidade Federal do Pará (UFPA), Belém, PA, Brazil

² Instituto Federal de Educação, Ciência e Tecnologia do Pará, Campus Castanhal, Castanhal, PA, Brazil

Arrhenius equation is traditionally used to describe the dependency of k values on temperature and to estimate the reaction's activation energy. A large amount of experimental data supports this method to predict product shelf life (Garcia–Garcia et al. 2008). Studies have established quality predictive models for different fish-based products (Tsironi and Taoukis 2010; Tsironi et al. 2011; Zhang et al. 2011).

This study aimed to assess the changes in quality of tambaqui sous vide during refrigerated storage at different temperatures using degradation kinetics.

Materials and methods

Tambaqui sous vide preparation

Product preparation followed the good practice guidelines for food preparation, beginning with unthawing the fillets under refrigeration and standardizing the pieces of approximately $5 \times 7 \times 2.5$ cm of the lumbar portion of the fillets. A sauce was prepared containing 3% basil (*Ocimum basilicum*), 2% oregano (*Origanum vulgare*) and 3% onions (*Allium caepa*) dehydrated, 16.5% apple vinegar, 16.5% rice vinegar, 4% salt, and 55% water.

Fish portions with 200 g were placed in nylon/smooth polyethylene coextruded sous vide packaging ($20 \times 25 \times 18$ cm) (Solupack, Barueri, SP, Brazil) along with 50 g sauce, at a 1:4 fish fillet:sauce ratio, and 10 mL 5% sodium lactate. After sauce was added, the samples were placed in a vacuum sealer (Fastvac, F200, Rio de Janeiro, RJ, Brazil) and then the products were pasteurized in a water bath (Quimis, Q-350-2, São Paulo, SP, Brazil) at 65 °C for 12.5 min counted from the moment the center of the sous vide package reached the process temperature (Baldwin 2012). Immediately after the heat treatment, the samples were cooled down in ice water until reaching 0 °C and were then stored at 1 ± 1 °C, 4 ± 1 °C, and 10 ± 1 °C (Mol et al. 2012).

Microbiological analysis

Counts of aerobic mesophilic and psychrotrophic microorganisms were performed in Standard Plate Count Agar (PCA-OXOID CM 325), of lactic bacteria in Man Rogosa Sharpe agar (MRS-OXOID CM 361), and of molds and yeasts in Dichloran Rose Bengal Chlortetracycline Agar (DRBC-DIFCO 258710). All analyses were performed in triplicate at time 0 and every 3 days during storage and followed the methodologies described in the Compendium of Methods for the Microbiological Examination of Foods (Downes and Ito 2001).

Physical and physicochemical analyses

A Minolta CR 310 colorimeter was used to determine instrumental color in the CIE (Commission Internationale de L'Eclairage) space for the parameters L^* (lightness), a^* (red color intensity), and b^* (yellow color intensity). The color analyses calculated total color difference

$$\Delta E^* = \sqrt{[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]} \quad (1)$$

$$\text{Chroma index } C^* = \sqrt{[(a^*)^2 + (b^*)^2]} \quad (2)$$

$$\text{Hue angle } h^* = \tan^{-1} \left(\frac{a^*}{b^*} \right) \quad (3)$$

Instrumental texture was analyzed using a texturometer (Brookfield, QTS, Midleboro, USA). The test conditions were: room temperature; compression force measure; testing velocity: 2.0 mm/s; trigger point: 0.1 N; distance: 114 mm; target value: 20 N; and deformation: 7 mm. The firmness parameter was assessed in standardized sous vide cuts ($2 \times 2 \times 1.5$ cm) with six repetitions.

pH was analyzed according to AOAC method 981.12 (2000) and the total volatile basic nitrogen (TVB-N) was determined according to Brasil (1999). The thiobarbituric acid reactive substances (TBA) were determined using the methodology proposed by Vynck (1970) and the results were expressed in mg malondialdehyde (MDA)/kg. All analyses were performed at time 0 and every three days during storage.

Quality prediction models: kinetic parameters

The results obtained through the microbiological and physicochemical quality indices of tambaqui sous vide stored under controlled temperatures (1 ± 1 °C, 4 ± 1 °C, and 10 ± 1 °C) were fitted by the zero-order and first-order models (Labuza and Shapero 1978) represented in Eqs. 4 and 5, respectively

$$C_t = C_0 - k \cdot t \quad (4)$$

$$\ln \frac{C_t}{C_0} = -kt \quad (5)$$

where C_0 = initial concentration of the attribute analyzed at time 0; C_t = concentration of the attribute analyzed at a time t ; k = reaction rate constant (days^{-1}); and t = storage time (days).

The values of k were obtained through the slope of the regression of $\ln (C/C_0)$ versus time. The dependency of k on temperature was analyzed using the Arrhenius equation or Arrhenius modified equation (Ratkowsky et al. 1982), i.e., Equations 6 and 7:

$$k = k_0 \exp\left(-\frac{E_A}{RT}\right) \quad (6)$$

$$\ln k = \ln k_0 - \frac{E_A}{RT} \quad (7)$$

where k_0 is the frequency factor; E_A is the activation energy (J/mol); T is absolute temperature (K); R is the gas constant (8.3144 kJ/mol); and k_0 and E_A are the trial's constants related to the nature of the response system.

In the reaction rate constants calculated at different temperatures, the slope of the regression line ($-E_A/R$) was obtained from the plot $\ln K$ versus $1/T$. The activation energy (E_A) was obtained from the slope of the regression line, while the frequency factor (k_0) was obtained from the intercept of the regression line. Predictive models of tambaqui sous vide stored at 1, 4, and 10 °C were estimated based on the calculations of E_a and K_0 .

Statistical analysis

All data underwent analyses of variance (ANOVA) and Tukey's test was used to compare the means ($p < 0.05$) in the software STATISTICA 6.0. Determination coefficients (R^2) above 80% and mean relative error (P) below 10% were considered indicators of well-fitted models. The linear and non-linear regression models were used for the kinetic modeling and the interaction criteria used were Quasi Newton and Hooke-Jeeves pattern moves. All analyses were carried out in triplicate.

Results and discussion

Microbiological evaluation

Storage temperature had a significant effect ($p < 0.05$) on the counts of mesophilic, psychrotrophic, and lactic bacteria over the 45 days of storage. The initial mesophilic bacteria count—considered a microbiological quality indicator—was 3.6×10^2 CFU/g and the samples stored at 10 °C reached counts above the limit set by the ICMSF (2005) of 10^6 CFU/g by the 27th day. The samples stored at 1 and 4 °C remained below the maximum limit throughout the 45 days.

The initial count of psychrotrophic bacteria in tambaqui sous vide was 1.0×10^1 CFU/g and remained below 10^4 CFU/g at all temperatures studied. The psychrotrophic bacteria indicate the spoilage level of refrigerated products. The mesophilic and psychrotrophic aerobic bacteria, although not related to public health problems, have the capacity to deteriorate fish through proteolytic and lipolytic processes, even in freezing temperatures, reducing their commercial life time (Lanzarin et al. 2011). Several

authors have found mesophilic and psychrotrophic bacteria counts in Black Sea whiting sous vide (*Merlangius merlangus euxinus*) above 10^6 CFU/g after the 35th day of storage at 4 °C (Gonzalez-Fandos et al. 2005; Cosansu et al. 2011; Mol et al. 2012).

High cooking temperatures decrease the mesophilic and psychrotrophic bacteria counts during storage. However, cooking sous vide at high temperatures for a long time may cause loss of the product's sensory acceptability (Garcia-Linares et al. 2004; Gonzalez-Fandos et al. 2005). According to Paik et al. (2006), mesophilic microorganisms, which survive the pasteurization process, also grow in refrigeration conditions and cause product spoilage at abusive temperatures.

The initial lactic bacteria count was 5.0×10^1 CFU/g, however, it increased to 10^4 CFU/g by the 12th day of storage at 10 °C. Lactic acid bacteria are able to grow in anaerobic/microaerobic environments and may be associated with the spoilage of sous vide products. They are reported as prevalent microorganisms in the spoilage of meat products and vacuum-packaged products provide an ecosystem that stimulates the growth of such bacteria (Shakila et al. 2009).

The initial count of molds and yeasts was 5.0×10^0 CFU/g and reached 10^5 CFU/g on the 45th day of storage at 10 °C. The presence and growth of this microorganism may occur in vacuum-packaged products due to the presence of residual oxygen. Díaz et al. (2011), when analyzing salmon sous vide stored at 2 °C, reported mean values of 10^4 CFU/g and found no significant difference ($p > 0.05$) during storage.

Physicochemical evaluation

The initial A_w value was 0.989 and variations were observed over the 45 days of storage at the three temperatures, with a significant difference ($p < 0.05$) between the 3rd and 33rd days of storage. Similar results were reported by Gonzalez-Fandos et al. (2005) and Díaz et al. (2011) when storing salmon sous vide at 2 °C for 45 days and 5 weeks, respectively.

The initial pH of the sous vide was 5.22, with a difference ($p < 0.05$) between the 3rd and 45th days of storage at the different temperatures, never exceeding the limit set by the Brazilian legislation (Brasil 1997). Studies with salmon sous vide (Cosansu et al. 2011; Picouet et al. 2011) and Atlantic bonito sous vide (Mol et al. 2012) reported pH above 6.12 during storage at 4 and 12 °C.

The initial TVB-N value was 8.28 mg N/100 g and a significant increase ($p < 0.05$) was observed over the 45 days of storage. The samples stored at 10 °C reached values of 33 mg N/100 g on the 45th day, above the one set as the limit (30 mg N/100 g) by the legislation (Brasil

Table 1 Zero-order and first-order kinetic parameters for the physicochemical changes in tambaqui sous vide at different storage temperatures

Analyses	Temp (°C)	1st phase			2nd phase			3rd phase		
		K (d ^{−1})	R ²	p*	K(d ^{−1})	R ²	p*	K(d ^{−1})	R ²	p*
Zero order										
Texture	1	−0.049	0.933	0.795						
	4	−0.036	0.989	0.270						
	10	−0.050	0.906	0.880						
TVB-N	1	0.504	0.988	3.42						
	4	0.581	0.982	5.77						
	10	0.620	0.967	6.62						
TBA	1	0.002	0.964	3.40	0.0002	0.949	0.12	0.009	0.974	3.27
	4	0.002	0.965	2.23	0.001	0.969	1.09	0.014	0.901	10.39
	10	0.002	0.984	2.26	0.001	0.934	7.45	0.006	0.981	1.61
C*	1	0.150	0.963	1.50	0.985	1.000	0.10	0.2748	0.980	1.22
	4	0.129	0.989	0.702	0.323	0.997	0.65			
	10	0.133	0.993	0.442	0.290	0.999	0.52			
ΔE	1	0.260	0.997	9.530	0.912	0.999	0.98	0.353	0.991	1.89
	4	0.429	0.999	1.156	0.165	0.989	3.01	0.448	0.992	4.95
	10	0.431	0.996	7.98						
First order										
Texture	1	−0.002	0.940	0.76						
	4	−0.001	0.990	0.25						
	10	−0.002	0.914	0.83						
TVB-N	1	0.031	0.920	1.68						
	4	0.033	0.851	2.62						
	10	0.035	0.787	3.03						
TBA	1	0.017	0.979	2.52	0.001	0.949	0.13	0.044	0.974	4.10
	4	0.016	0.973	1.97	0.007	0.969	0.90	0.062	0.901	9.34
	10	0.016	0.994	1.45	0.008	0.934	0.95	0.029	0.981	1.24
C*	1	0.010	0.970	1.32	0.051	1.000	0.41	0.011	0.980	1.43
	4	0.009	0.991	0.69	0.009	0.992	8.96			
	10	0.009	0.992	0.50	0.015	0.999	0.75			
ΔE	1	0.133	0.995	12.52	0.123	0.999	1.97	0.025	0.991	3.00
	4	0.242	0.999	0.001	0.048	0.988	2.02	0.048	0.988	2.55
	10	0.045	0.998	12.86						

1997). Can (2011), when analyzing carp sous vide, found 40.7 N/100 g TVB-N on the 56th day of storage at 10 °C and values below 30 mg N/100 g at 2 °C. However, Mol et al. (2012) stored Atlantic bonito sous vide for 27 days and found TVB-N values of 47.72 and 49.04 mg N/100 g at 4 and 12 °C, respectively.

The initial TBA value in sous vide was 0.103 mg MDA/kg, with a significant increase ($p < 0.05$) between the 3rd and 45th days of storage at the temperatures studied. The maximum value found was 0.291 mg MDA/kg in the sous vide stored at 4 °C. Bhat and Pathak (2010) to analyze Harrisia using mutton meat also found a increase significant ($p < 0.05$) in the TBA values with storage period at 4 °C. According to Schormüller (1968), TBA values below 3 mg MDA/kg indicate excellent quality, between 3 and 5 mg

MDA/kg are considered good quality, and the maximum limit for food consumption is 8 mg MDA/kg.

The firmness analysis of sous vide showed a decrease in this parameter over storage at the temperatures studied, with a significant difference ($p < 0.05$) between the 3rd and 45th days; the highest value was 20.86 N at 4 °C on the 45th day. Olivera et al. (2013) was also observed a decrease in texture vacuum packed raw meat at the same temperature.

The values of L* in the sous vide samples decreased over storage ($p < 0.05$), with a darkening trend, due to the influence of the color of the sauce. The lowest values of this parameter were observed at 10 °C. The combined effects of vacuum cooking and fish exudate (in the sauce) caused increased the parameters a* and b*, referring to red

Table 2 Zero-order and first-order kinetic parameters for the microbiological changes in tambaqui sous vide at different storage temperatures

Analyses	Temp (°C)	1st phase			2nd phase			3rd phase			4th phase			5th phase		
		K(d ⁻¹)	R ²	p*	K(d ⁻¹)	R ²	p*	K(d ⁻¹)	R ²	p*	K(d ⁻¹)	R ²	p*	K(d ⁻¹)	R ²	*p
Zero order																
Mesophilic bacteria	1	90.71	0.919	8.76	168.06	0.998	2.53	379.00	0.989	1.38						
	4	258.09	0.979	5.92	528.00	0.992	5.62	2.5 × 10 ³	0.993	6.22	5.1.10 ³	1.000	0.04			
	10	951.43	0.989	5.26	1.0 × 10 ⁵	0.932	8.53	1.5 × 10 ⁶	0.967	10.39						
Psychrotrophic bacteria	1	19.05	0.969	3.25	9.00	0.894	7.57	51.00	0.997	3.31	2.1.10 ³	0.995	1.52			
	4	17.62	0.918	3.98	19.33	0.949	8.91	223.33	0.825	5.01						
	10	19.45	0.949	11.73	618.33	0.942	3.18	133.33	0.894	4.50	122.85	0.966	5.01			
Lactic bacteria	1	2.86	0.922	4.91	5.62	0.971	6.69	43.33	0.997	2.98						
	4	4.52	0.989	2.58	5.00	0.964	2.09	21.17	0.986	5.21	78.33	0.970	8.42	217.3	0.979	9.30
	10	8.09	0.929	1.73	806.09	0.979	4.67	4.8 × 10 ³	0.978	7.38	1.3.10 ⁴	0.978	7.32			
Molds and yeasts	1	1.40	0.988	3.69	4.50	0.978	6.56	22.61	0.994	4.42	273.3	0.984	15.2			
	4	40.62	0.972	9.80	208.33	0.987	3.73	1.7 × 10 ³	0.960	13.51						
	10	4.33	0.992	4.44	67.51	0.927	4.77	3.9 × 10 ³	0.980	11.76						
First order																
Mesophilic bacteria	1	0.142	0.978	4.59	0.050	0.998	8.90	0.050	0.994	0.995						
	4	0.305	0.987	5.05	0.092	0.990	1.53	0.097	0.992	6.99	0.081	1.000	1.28			
	10	0.494	0.919	0.99	0.404	0.925	10.28	0.087	0.961	3.76						
Psychrotrophic bacteria	1	0.338	0.967	7.76	0.037	0.894	6.97	0.104	0.996	2.26	0.127	0.996	8.59			
	4	0.333	0.972	0.62	0.049	0.949	2.56	0.104	0.825	6.27						
	10	0.353	0.994	1.92	0.234	0.806	14.94	0.030	0.894	4.48	0.120	0.980	4.39	0.106	0.979	3.03
Lactic bacteria	1	0.005	0.999	5.90	0.009	0.995	3.91	0.084	0.997	2.76	0.167	0.999	5.99			
	4	0.068	0.985	2.68	0.048	0.982	2.49	0.107	0.986	5.48	0.134	0.985	1.27			
	10	0.109	0.996	1.52	0.309	0.972	12.62	0.092	0.947	6.59						
Molds and yeasts	1	0.166	0.946	7.23	0.187	0.989	11.94	0.083	0.993	10.21	0.181	0.984	4.68			
	4	0.493	0.779	15.93	0.135	0.852	15.57									
	10	0.307	0.904	1.65	0.275	0.997	11.37

Fig. 1 Model fit to the parameters analyzed in tambaqui sous vide: **a** texture (zero order), **b** texture (first order); **c** TVB-N (zero order); **d** TBA (zero order); **e** TBA (first order)

and yellow color intensity, respectively, over storage ($p < 0.05$).

The parameter chroma (C^*) in the tambaqui sous vide samples differed ($p < 0.05$) between the 3rd and 45th days of at the storage temperatures assessed. These results had a greater impact on the yellow color than on the red. Pulgar

et al. (2012) stated that chroma is related to the myoglobin levels and its denaturation.

The hue angle (h^*) decreased at all storage temperatures ($p < 0.05$), ranging from 85 to 70. Despite the decrease in this parameter, the samples still tended to yellow. The samples stored at the lowest temperature (1 °C) obtained

Fig. 2 Model fit to the parameters analyzed in tambaqui sous vide: **a** chroma (zero order); **b** chroma (first order); **c** ΔE —color difference (zero order)

higher values. The hue angle is affected by the chemical state of myoglobin and is inversely related with the value of a^* (Pulgar et al. 2012).

The sous vide samples stored at 1, 4, and 10 °C significantly differed ($p < 0.05$) in ΔE (difference between the initial and final color) over storage. The color of those stored at 1 °C changed the least, which is considered a quality parameter related to product stability at different storage temperatures.

Kinetic parameters

The kinetic modeling was performed considering that all attributes analyzed had a single behavior over storage, with values of the determination coefficient above 0.90 and of the mean relative error below 10% as suggested by

Lomauro et al. (1985). When the data were analyzed through the plots, several distinct regions were observed, thus the data were separated into phases.

Table 1 shows the parameters separated by phases for the zero-order and first-order Labuza models. When these values are compared, both models are shown to have good fits to the results of the physical and physicochemical analyses, with R^2 above 0.90, except for the TVB-N in the first-order model with R^2 of 0.787 at 10 °C. The zero-order model better fit the results of the parameters analyzed in tambaqui sous vide ($R^2 > 0.90$; $p < 10\%$). The mean relative errors were lower, matching what Lomauro et al. (1985) suggested, for both models, except the TBA values (4 °C/3rd phase) for the zero-order model and ΔE (1 and 10 °C/1st phase) for the first-order model; nevertheless, they were very close to the standard.

Fig. 3 Model fit to the microorganisms analyzed in tambaqui sous vide: **a** mesophilic (first order); **b** psychrotrophic (zero order); **c** psychrotrophic (first order); lactic (zero order); **e** lactic (first order); **f** molds and yeasts (zero order)

The results of the reaction rate constants (k) in both models varied for some parameters studied (Table 1). The values of k obtained for TVB-N increased with temperature. Since this index indicates spoilage in fish products, using lower temperatures is important.

Zhang et al. (2011), while studying predictive models to monitor the quality of carp (*Ctenopharyngodon idellus*) fillets stored at different temperatures (-3 , 0 , 3 , 9 , and 15 °C), reported high R^2 values (>0.90) using the first-order Labuza model for the values of TVB-N, TBA, and

Table 3 Kinetic parameters of the Arrhenius equation fitted to the zero-order and first-order models for the physicochemical changes in tambaqui sous vide

Analyses	1st phase				2nd phase				3rd phase			
	K_0	E_A (Kj/mol K)	R^2	p^*	K_0	E_A (Kj/mol K)	R^2	p^*	K_0	E_A (Kj/mol K)	R^2	p^*
Zero order												
TVB–N	3.92	7.5×10^3	0.933	2.89								
TBA	0.002	0	0.999	0.00	35.68	49.53	0.7612	6.19	–20.96	3.7×10^4	0.629	5.49
C*	–5.01	6.9×10^3	0.623	2.37	–34.24	7.7×10^4	0.810	2.37				
ΔE	12.56	3.2×10^4	0.766	2.42	–157.95	3.6×10^5	0.999	0.005	20.96	5.0×10^4	0.999	0.003
First order												
TVB–N	0.214	8.4×10^3	0.980	0.26								
TBA	–9.67	1.3×10^4	0.999	0.00	51.00	1.3×10^5	0.797	9.78	–19.16	3.6×10^4	0.690	6.95
C*	–7.49	6.5×10^3	0.761	0.63	–33.49	6.8×10^4	0.543	14.58				
ΔE	–41.94	9.2×10^4	0.765	23.74	56.54	1.9×10^5	0.999	0.00	56.54	1.4×10^5	0.999	0.00

Prediction models - TVB–N: $C=Co-(3.92 \text{ t exp } (-7.5 \times 10^3/RT))$; TBA (first phase): $C=Co-(0.0002t.exp(0/RT))$; C*(second phase): $C=Co-(-34.24 \text{ t exp } (-7.7 \times 10^4/RT))$

ΔE (second phase): $C=Co-(-157.95 \text{ t exp } (-3.65 \times 10^5/RT))$; ΔE (third phase): $C=Co-(20.6 \text{ t exp } (-5.0 \times 10^4/RT))$

mesophilic bacteria count. Tsironi et al. (2011) found a better fit of the first-order Labuza model ($R^2 = 0.97$) regarding the changes in color parameters when working with gilthead seabream (*Sparus aurata*) stored at 0, 2.5, 5, 10, and 15 °C.

Table 2 shows the microbiological analysis parameters at the different phases found for the zero-order and first-order Labuza model. Both models obtained good fits to the data since the coefficients of determination values were above 0.80.

Regarding the mean relative errors of both models, most values were within the standard 10% suggested by Lomauro et al. (1985). The counts of psychrotrophic bacteria at 10 °C/1st phase and of mold and yeasts at 4 °C/3rd phase for the zero-order model and the counts of psychrotrophic bacteria at 1 °C/4th phase and at 4 °C/2nd phase and of lactic bacteria at 10 °C/2nd phase had p values out of the standard range. Hence, the zero-order model better fit the results found for psychrotrophic bacteria, lactic bacteria, and molds and yeasts, while the first-order model had the best fit to the mesophilic bacteria counts. It was found that the zero-order model had the best fit to the physicochemical and microbiological parameters since it is a simpler model that facilitates the fit of the model to the data.

The reaction rate constant increased with temperature for mesophilic and lactic bacteria in both models and was in accordance with the behavior of these bacteria to develop at higher temperatures. As these microorganisms multiply more quickly, this contributes to product spoilage.

Such behavior was not observed for the psychrotrophic bacteria and molds and yeasts (Table 2).

Figure 1 shows both the zero-order and first-order Labuza models fitted to the results of the physicochemical analyses over storage at the temperatures studied. It can be seen that only one phase obtained good fits for texture in both models, with the force applied on the product decreasing over storage (Fig. 1a, b). TVB–N had the best fit to the zero-order model, i.e., this parameter increased linearly (Fig. 1c). TBA values had three behavior phases: The values increased linearly until the 24th day, entered steady state in the second phase, and increased between the 33rd day (3rd phase) and the end of storage (Fig. 1d, e).

The values of chroma (C*) at 1 °C had three phases for either model and only two phases at 4 and 10 °C, increasing over storage. As previously mentioned, the samples depend more on parameter b^* (yellow intensity) than on a^* (Fig. 2a, b). For parameter ΔE , the zero-order model had a better fit than the first-order model, increasing over storage (Fig. 2c, d).

The mesophilic bacteria counts had more than three phases and the first-order model had the best fit exponentially with the increase in the counts of these microorganisms at 10 °C (Fig. 3a). In order to slow down the growth of these microorganisms, tambaqui sous vide must be stored at lower refrigeration temperatures. The psychrotrophic bacteria counts had more than three phases for either model, with lower development at the lower temperatures studied (Fig. 3b, c). The behavior of the lactic bacteria fitted both Labuza models (Fig. 3d, e). For molds

Table 4 Zero-order and first-order kinetic parameters for the microbiological changes in tambaqui sous vide at different storage temperatures

Analyses	1st phase			2nd phase			3rd phase			4th phase		
	K_0	E_A (KJ/molK)	R^2	p^*	K_0	E_A (KJ/molK)	R^2	p^*	K_0	E_A (KJ/molK)	R^2	p^*
Zero order												
Mesophilic bacteria	29.20	7.0×10^4	0.899	14.68	89.43	7.6×10^2	0.997	8.07				
Psychrotrophic bacteria	3.62	5.9×10^3	0.997	2.38	-58.55	1.3×10^5	0.999	0.02	47.95	1.1×10^5	0.999	10.64
Lactic bacteria	18.45	4.9×10^4	0.998	0.59	35.37	8.6×10^4	0.991	3.11	-17.89	3.6×10^4	0.999	0.00
Molds and yeasts	23.49	5.6×10^4	0.647	27.38	-78.18	1.7×10^5	0.944	10.36	17.85	4.5×10^4	0.817	10.30
First order												
Mesophilic bacteria	22.29	5.9×10^4	0.855	5.93	91.86	7.6×10^2	0.746	21.26				
Psychrotrophic bacteria	2.87	1.3×10^3	0.761	0.25	-12.23	1.7×10^4	0.999	0.01	42.58	1.1×10^4	0.912	6.67
Lactic bacteria	2.24	1.3×10^4	0.780	6.67	12.64	3.8×10^4	0.999	0.01	-34.21	6.9×10^4	0.999	0.001
Molds and yeasts	21.96	5.6×10^4	0.722	13.79	-4.71	0	0.999	0.00	9.48	3.0×10^4	0.621	5.47

*mean relative error

Prediction models—Mesophilic bacteria (first phase): $C=Co-(29.0 \text{ t e} \times p(-7.0 \times 10^4/RT)$; Mesophilic bacteria (second phase): $C=Co-(89.43 \text{ t e} \times p(-7.6 \times 10^2/RT)$; Psychrotrophic bacteria (first phase): $C=Co-(3.62 \text{ t e} \times p(-5.9 \times 10^3/RT)$; Psychrotrophic bacteria (second phase): $C=Co-(58.55 \text{ t e} \times p(-1.3 \times 10^5/RT)$; Psychrotrophic bacteria (third phase): $C=Co-(47.95 \text{ t e} \times p(-1.1 \times 10^5/RT)$; Psychrotrophic bacteria (fourth phase): $C=Co-(44.74 \text{ t e} \times p(-9.7 \times 10^4/RT)$; Lactic bacteria (first phase): $C=Co-(18.45 \text{ t e} \times p(-4.9 \times 10^4/RT)$; Lactic bacteria (second phase): $C=Co-(35.37 \text{ t e} \times p(-8.6 \times 10^4/RT)$; Lactic bacteria (third phase): $C=Co-(17.89 \text{ t e} \times p(-3.6 \times 10^4/RT)$; Molds and yeasts (second phase): $C=Co-(78.18 \text{ t e} \times p(-1.7 \times 10^5/RT)$; Molds and yeasts (third phase): $C=Co-(17.85 \text{ t e} \times p(-4.5 \times 10^4/RT)$

and yeasts, the zero-order model had the best fit to the data at all temperatures studied (Fig. 3f).

Table 3 shows that the kinetic parameters were determined in a single phase for TVB-N, while for C* the fit was in two phases and for TBA and ΔE the fit was in three distinct phases. The reaction rate constants (k) found in the zero-order model (Table 3) show that the Arrhenius equation fitted the TVB-N and TBA data in the 1st phase. The variables C* and ΔE did not have good fits in the first phase since the coefficient of determination values were below 80%. For the same reason, only the parameter TBA did not have a good fit in the second phase.

Table 4 shows the values for activation energy obtained by the Arrhenius equation for the microbiological analyses. According to the reaction rate constants (k) found in the zero-order model, it can be seen that the Arrhenius equation fitted the data of mesophilic, psychrotrophic, and lactic bacteria and molds and yeasts (third phase) with higher R^2 and p (%) values, except for mesophilic samples (first phase) with p above 10%, but close to the limit established (Table 4). The values of k for the counts of molds and yeasts in the first and second phases did not fit the Arrhenius model with R^2 values below 0.80 and p above 10%.

For the reaction rate constants of the first-order model, the Arrhenius model fitted the data of mesophilic (first phase), while it only fit the data of psychrotrophic and lactic bacteria and molds and yeasts in the second and third phases. The reaction rate constant of the zero-order model had the best fits to the Arrhenius equation for the results of the microbiological and physicochemical analyses.

It is also seen that the difference of the activation energy values for tambaqui sous vide in the microorganism counts (mesophilic, psychrotrophic, and lactic bacteria and molds and yeasts) was due to the different microorganism groups analyzed and the different temperatures used, which impacted the grow rate of these microorganisms. Higher E_A values were found for the microbiological than for the physicochemical parameters, which proves the greater dependence of microorganisms on variations in temperature.

Tsironi and Taoukis (2010) and Tsironi et al. (2011), while using predictive models to monitor the shelf life of gilthead seabream (*S. aurata*) stored under refrigeration, found that the results fitted the Arrhenius equation, confirming the dependency of the growth of lactic bacteria and molds and yeasts on temperature. Zhang et al. (2011), when using models to predict the shelf life of carp (*C. idellus*) fillets stored under refrigeration, found R^2 values above 0.90 and low p values using the Arrhenius equation for TVB-N, TBA, and mesophilic bacteria count.

Conclusion

The results of this research indicate that maintaining the quality of tambaqui sous vide depends on storage conditions. With storage at 1 °C, sous vide microbiological and physicochemical quality remained good for 45 days, slowing spoilage and yielding better product quality than the other temperatures studied.

The Arrhenius equation best fit to the reaction rate constants of the zero-order model for the microbiological, physical, and physicochemical results. Higher E_A values were found for the microorganism counts than for the physicochemical parameters, which proves the greater dependency of microorganisms on variations in temperature.

It is concluded that quick calculations to assess changes in quality based on temperature allows the storage conditions to be optimized, costs to be cut down, and losses to be prevented.

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References

- AOAC (2000) Official methods of analysis of the Association of Official Analytical Chemists, 17th edn. Washington
- Baldwin DE (2012) Sous vide *cooking*: a review. Int J Gastronomy Food Sci 1:15–30
- Bhat ZF, Pathak V (2010) Quality evaluation of mutton *Harris* during one week refrigerated storage. J Food Sci Tech 49:620–625
- Brasil (1997) Ministério da Agricultura, Pecuária e Abastecimento. Regulamento da Inspeção Industrial e Sanitária de Produtos de Origem Animal - RIISPOA. Brasília, DF, p. 241
- Brasil (1999) Ministério da Agricultura, Pecuária e Abastecimento. Instrução Normativa nº 20, de 21 de julho de 1999. Oficializa os métodos analíticos físico-químicos para controle de produtos carnes e seus ingredientes – sal e salmoura. Diário Oficial da União, Brasília, DF. Julho 27, 1999, n. 142, Seção 1
- Can OP (2011) Evaluation of the microbiological, chemical and sensory quality of carp processed by the sous vide method. Int J Biol Biom Agr Food Biotech Eng 5:8
- Cosansu S, Mol S, Alakavuk DU, Ozturan S (2011) The effect of lemon juice on bonito (*Sarda sarda*, Bloch, 1793) preserved by sous vide packaging. Int J Food Sci Tech 46:395–401
- Derossi A, Pilli T, Fiore AG (2010) Vitamin C kinetic degradation of strawberry juice stored under non-isothermal conditions. LWT Food Sci Technol 43:590–595
- Díaz P, Garrido MD, Bañón S (2011) Spoilage of sous vide cooked salmon (*Salmo salar*) stored under refrigeration. Food Sci Technol 17:31–37
- Downes FP, Ito K (eds) (2001) Compendium of methods for the microbiological. Examinations of Foods, 4th edn. APHA, Washington, DC
- Garcia-Garcia P, Lopez-Lopez A, Garrido-Fernandez A (2008) Study of the shelf life of ripe olives using an accelerated test approach. J Food Eng 84:569–575

- Garcia-Linares MC, Gonzalez-Fandos E, Garcia-Arias MT, Garcia-Fernandez MC (2004) Microbiological and nutritional quality of sous vide or traditionally processed fish: influence of fat content. *J Food Qual* 27:371–387
- Gonzalez-Fandos E, Villarino-Rodriguez A, Garcia-Linares MC, Garcia-Arias MT, Garcia-Fernandez MC (2005) Microbiological safety and sensory characteristics of salmon slices processed by the sous vide method. *Food Control* 16:77–85
- ICMSF (Internacional Comission on Microbiological Specifications for Foods) (2005) Microorganisms in foods 6: microbial ecology of food commodity (Chap 3), 2nd edn. Kluwer Academic, New York, pp 174–249
- Kong FA, Tang JA, Rasco BB, Crapo C (2007) Kinetics of salmon quality changes during thermal processing. *J Food Eng* 83:510–520
- Labuza TP, Shapero M (1978) Prediction of nutrient losses. *J Food Proc Pres* 2:91–99
- Lanzarin M, Almeida Filho ES, Ritter DO, Mello CA, Corrêa GSS, Ignácio CMS (2011) Ocorrência de *Aeromonas* sp. e microrganismos psicrófilos e estimativa do prazo de validade comercial de filé de pintado (*Pseudoplatystoma coruscans*) mantidos sob refrigeração. *Arq Bras Med Vet Zootec* 63:1541–1546. doi:10.1590/S0102-09352011000600035
- Lomauro CJ, Bakshi AS, Labuza TP (1985) Evaluation of food moisture sorption isotherm equation. Part I: fruit, vegetables and meat products. *LWT Food Sci Technol* 18:111–117
- Mol S, Ozturan S, Cosansu S (2012) Determination of the quality and shelf life of sous vide packaged bonito (*Sarda sarda*, bloch, 1793) stored at 4 and 12°C. *J Food Qual* 35:137–143
- Olivera DF, Salvadori VO (2012) Kinetic modeling of quality changes of chilled ready to serve lasagna. *J Food Eng* 110:487–492
- Olivera DF, Bambicha R, Laporte G, Cárdenas FC, Mestorin N (2013) Kinetics of colour and texture changes of beef during storage. *J Food Sci Technol* 50:821–825
- Paik HD, Kim HJ, Namb KF, Kim AJ, Lee SE, Lee DS (2006) Effect of nisin on the storage of sous vide processed Korean seasoned beef. *Food Control* 17:994–1000
- Picouet PA, Cofan-Carbo S, Vilaseca H, Ballbè LC, Castells P (2011) Stability of sous-vide cooked salmon loins processed by high pressure. *Innov Food Sci Emerg Tech* 12:26–31
- Pulgar JS, Gázquez A, Ruiz-Carrascal J (2012) Physico-chemical, textural and structural characteristics of sous-vide cooked pork cheeks as affected by vacuum, cooking temperature, and cooking time. *Meat Sci* 90:828–835
- Raab V, Bruckner S, Beierle E, Kampmann Y, Petersen B, Kreyenschmidt J (2008) Generic model for the prediction of remaining shelf life in support of cold chain management in pork and poultry supply chains. *J Chain Net Sci* 8:59–73
- Ratkowsky DA, Olley J, Mcmeekin TA (1982) Relationship between temperature and growth rate of bacterial cultures. *J Bacter* 149:1–5
- Schormuller J (1968) *Handbuch der Lebensmittel Chemie*, Band III/2 Teil. Tierische Lebensmittel Eier, Fleisch, Buttermilch. Springer, Berlin, pp 1482–1537
- Shakila RJ, Jeyasekaran G, Vijayakumar A, Sukumar D (2009) Microbiological quality of sous-vide cook chill fish cakes during chilled storage. *Int J Food Sci Tech* 44:2120–2126
- Tsironi TN, Taoukis PS (2010) Modeling microbial spoilage and quality of gilthead seabream fillets: combined effect of osmotic pretreatment, modified atmosphere packaging, and nisin on shelf life. *J Food Sci* 75:243–251. doi:10.1111/j.1750-3841.2010.01574.x
- Tsironi T, Stamatiou A, Giannoglou M, Velliou E, Taoukis PS (2011) Predictive modelling and selection of Time Temperature Integrators for monitoring the shelf life of modified atmosphere packed gilthead seabream fillets. *LWT Food Sci Technol* 44:1156–1163
- Vynck BW (1970) Direct determination of the thiobarbituric acid value in trichloroacetic acid extracts of fish as a measure of oxidative rancidity. *Fette Seifen Anstrichm* 72:1084–1087
- Zhang L, Li X, Lu W, Shen H, Luo Y (2011) Quality predictive models of grass carp (*Ctenopharyngodon idellus*) at different temperatures during storage. *Food Control* 22:1197–1202