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Effect of Air Drying on Color, Texture and Shrinkage of Sardine (*Sardina pilchardus*) Muscles

Djendoubi Mrad Nadia[1,2*], Bonazzi Catherine[2,3], Kechaou Nabil[1] and Mihoubi Boudhrioua Nourhène[4]

[1]*Groupe de Recherche en Génie des Procédés Agroalimentaires, Unité de Recherche : Mécanique des Fluides Appliquée et Modélisation, Ecole Nationale d'Ingénieurs de Sfax, BP 1173, 3038, Sfax, TUNISIE*
[2]*INRA, UMR 1145 Ingénierie Procédés Aliments, F-91300 Massy, FRANCE*
[3]*AgroParisTech, UMR 1145 Ingénierie Procédés Aliments, F-91300 Massy, France*
[4]*UR Ecophysiologie Environnementale et Procédés Agroalimentaires, Institut Supérieur de Biotechnologie, Université de la Manouba, TUNISIA*

Introduction

Many fish species have been consumed for quite a long time in the form of fillets, while others were preferentially consumed whole up until now, but have started to be marketed as fillets. Considering worldwide trends consumption of ready-to-eat or ready-to-prepare foods, filleted fish format seems to have greater future. According to fish sale professionals, consumption of fillets will continue to increase in near future because people have less and less time to cook and increasing habits of younger generations to consume prepared products. In this sense, *Sardina pilchardus* shows a good marketing potential; because both its size and its body shape allow an optimal filleting. But some studies have shown that shelf life of filleted fish is shorter than that of whole fish [1-3].

Marine food and fishes constitute an important part of Mediterranean diet. The beneficial effect of fish consumption on human health has been related to other factors such as higher contents of n-3 fatty acids, especially eicosapentaenoic and docosahexaenoic acids. This effect is well reported in numerous investigations [4]. The n-3 fatty acids are involved in brain development of children and have protective effects against heart disease and some types of cancers [5,6]. Therefore, consumers are more and more conscious about the interest of fish consumption on human health and its contribution to ensure a healthy diet.

Sardine is an important fish species commonly consumed in Mediterranean region thus serving as an important source of animal protein for both rural and urban areas. Its production is gaining popularity in some countries. It is a lean and highly nutritious fish with a low commercial value, which is rich in vitamins, proteins, minerals, omega-3 oils and calcium and which is used more and more in the fish processing industries.

When not consumed fresh, various methods of preservation particularly salting, drying, smoking, frying and freezing are normally used. However, drying is very common because it is cheaper, does not need sophisticated equipment and is easily adaptable by local processors [7]. The simplicity of the process makes it particularly suitable for more tropical areas [8] but it has some limitations such as uneconomical energy consumption and long processing times [9]. The basic objective of the process is to remove water from the product up to a certain level, at which microbiological spoilage is minimized.

Drying of fish is mainly carried out traditionally under open sun which represents a low cost processing technique. Open sun drying has limitation to control the drying process and parameters, weather uncertainties, high labor costs, requires large drying areas, insect infestation, contamination with dust and other foreign materials [10,11] which induce a rapid rate of deterioration during transport, distribution and storage. Convective hot air drying is a better technique than open sun drying since it ensures a safer product, faster processing and drying parameters can be effectively controlled.

The quality of dehydrated foods depends not only on the initial quality of raw material, but also on physicochemical changes occurring during processing and storage [12,13]. During drying processes, thermal treatment and water loss induce physical and chemical changes in food, leading to the degradation of quality parameters such as color and texture.

[14] reported that during drying, chemical and physical reactions occur in food products and therefore digestibility can be increased due to protein denaturation, but content in thermolabile compounds and polyunsaturated fatty acids are often reduced. [15] studied the effect of moisture content of pre-dehydrated fish slices, microwave (MW) power output and vacuum degree on the quality of savory crisp bighead carp slices. They found an optimal set-point corresponding to a moisture content of 19.8 ± 2% (50°C hot air drying for 3 hours, a microwave power output of 686 ± 3.5 W, and a vacuum level of 0.09 MPa). The results showed that proper moisture content of the pre-dehydrated fish slices and microwave power could increase the expansion ratio and crispness of the fish slices, and then improve the sensory quality of finished products. A higher vacuum level could enhance puffing effect, improve crispness of fish slices, increase energy efficiency of microwave heating, and obviously decrease burnt spots formation on the surface of the finished products.

A significant influence of convective and/or microwave drying on nutritional (amino acid and fatty acid composition) and sensory qualities (odor evaluation) of grass carp fillets (*Ctenopharyngodon idellus*) has also been demonstrated [9]. The authors showed that air drying resulted in a significant increase of protein but reduced fat contents and they noticed a negative impact of drying on the amino acid composition of grass carp fillets. Also, they had reported that both saturated and mono-unsaturated fatty acid contents decreased, while

***Corresponding author:** Djendoubi Mrad Nadia, 1Groupe de Recherche en Génie des Procédés Agroalimentaires, Unité de Recherche : Mécanique des Fluides Appliquée et Modélisation, Ecole Nationale d'Ingénieurs de Sfax, BP 1173, 3038, Sfax, TUNISIE, E-mail: nadia.djendoubi@agroparistech.fr

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polyunsaturated fatty acids increased by an average value of 24 % after drying.

The quality of dried products is greatly influenced by drying conditions. Higher product temperatures during drying lead to several irreversible biological or chemical reactions as well as structural, physical and mechanical modifications, including coloring, crust formation, decrease of sensory quality, inactivation of bacteria and enzymes, loss of nutrients and aroma, and changes of shape and texture [16]. In that case, undesired food flavor, color, vitamin degradation and the loss of essential amino acids may be produced. However, some of the properties of the fresh food can be kept if drying is being performed at low or moderated temperatures [17]. It is therefore very important to analyze the changes in quality parameters during the drying process in order to control and predict the final quality of dried products. The aim of this work was to study the influence of drying air temperature and humidity on kinetics, color, texture and shrinkage of *Sardina plichardus* muscles.

Material and Methods

Raw material

Fresh sardines (*Sardina pilchardus*) were purchased from a local fish market (Massy, France). Average weight of individual fish was 95 ± 5 g with an overall length of 20 ± 1 cm. Sardines were immediately brought to the laboratory in sealed cooled boxes containing ice. The fishes were then caught, scaled, gutted and their heads were removed. Tails, skins and fins were trimmed off. They were then rinsed and the excess of water was removed. Then, they were sliced lengthwise dorsally, opened and two fillets were obtained from each sardine carcass. Fish muscle samples were cut in rectangular slabs of 0.06 m length and 0.02 m wide. Samples were then used for global chemical characterization, drying experiments and quality parameters measurements.

Global chemical analysis

In order to characterize fresh sardine muscles, chemical analyses were realized according to methods of the Association of Official Analytical Chemists [18]. Moisture content was measured by gravimetric method at 105°C until a constant weight was achieved (≈ 24 h). Total nitrogen contents were analyzed according to the Kjeldahl method and protein contents were calculated by multiplying the total nitrogen content by the universal factor of 6.25. Fat content was determined by the Soxhlet method by using petroleum ether as solvent. Ash content was measured by heating samples at 550°C for 4 hours in a muffle furnace. Mineral compounds (Ca, Mg, Na and Fe) were measured using an atomic absorption spectrophotometer (Hitachi Z 6100 polarized Zieman).

All chemical analyses were performed in triplicate and results were expressed on a wet basis (in g 100 g^{-1} fresh weight (FW) for protein and fat content, and mg g^{-1} FW for mineral compounds). Moisture contents were expressed on a dry basis (in kg kg^{-1} dry matter (DM)). All results were presented as the mean value standard deviation).

Drying experiments and quality analysis

Drying experiments: Drying experiments were performed on an open-loop convective dryer controlled in temperature, relative humidity and air velocity, previously described by [19,20]. During experiments, mass of the product was periodically measured on-line and automatically recorded. All experiments were carried out with an air velocity of 1.5 m s^{-1}. Temperature and relative humidity used for all drying experiments are gathered in (Table 1).

Experiences	Temperature (°C)	Relative humidity (%)
Exp.1	40	14
Exp.2	40	40
Exp.3	50	6
Exp.4	50	40
Exp.5	60	4
Exp.6	70	3

Table 1: Operating conditions used for drying sardine muscles.

Fish muscles were suspended on stainless steel hangers and dried with a parallel air flow. Sardine muscles were dried to a final moisture content of 0.33 kg kg^{-1} DM for further quality comparison. This value was chosen because dried fishes presented then an acceptable sensorial quality as reported by [21]. Samples were taken at regular time intervals for texture, color and shrinkage measurements. Drying curves were expressed by plotting the reduced moisture contents (X_r) versus time, using equation 1:

$$X_r(t) = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} \quad (1)$$

where

X : moisture content (kg kg^{-1} DM)

X_0: initial moisture content (kg kg^{-1} DM)

X_{eq}: equilibrium moisture content (kg kg^{-1} DM) calculated from sardine desorption isotherms [22].

Quality parameters analysis: At different drying times, nine muscles were sampled to evaluate texture, color and shrinkage. Three muscles were used for each measurement. Sampling time did not exceed 35 s.

Color: Colorimetric parameters (L*, a*, b*) were measured in order to investigate color changes of *Sardina pilchardus* muscles as affected by drying conditions. Measurements were performed by using a Minolta CR–200 colorimeter. Color was conventionally defined by using the Hunter *L,a,b* color scale values where L* is the lightness/darkness parameter (varying from dark: L* = 0 to white: L* = 100), a* is the redness/greenness parameter (red (a* > 0) – green (a* < 0)), and b* the yellowness/blueness parameter (yellow (b* > 0) – blue (b* < 0)). For each muscle, three measurements were made on each face (dorsal and ventral). Mean value of each parameter was calculated on 9 measurements (n = 3×3).

Texture: In order to estimate the hardness of the dried muscles, a three points flexion test was carried out by using a stable micro-system texture analyzer TAXT2i (XT RAD, Rheo), connected to a data acquisition system, fitted with a 5 kg force sensor, and equipped with a probe moving at a rate of 1 mm/s.

Measurements were made in the dorsal part of fish muscles. Hardness of *Sardina pilchardus* muscles was expressed as the maximal force (F_{max}) measured during displacement (20 mm at least), corresponding to the maximal resistance of the muscles to the applied force. The results were expressed in Newton (N) as mean value of F_{max}

repeatability standard deviation (measurements in triplicate).

Shrinkage: Length and width of three samples of fresh and dried muscles were measured by using a numerical caliper. Shrinkage was expressed as the percentage of change of the length and the width of the muscle.

Statistical analysis: Statistical analyses were performed by using SPSS software (SPSS, Version 13). An analysis of variance (ANOVA) was used to determine significant differences between fresh and dried samples and between more or less dried samples. A p-value < 0.05 was considered as significant.

Data analysis: Generally, changes in a quality factor "Q" under isothermal conditions can be represented, by analogy with a chemical reaction, by the following equation [23].

$$\frac{dQ}{dt} = -k(Q)^n$$

where k is the rate constant, Q is the quantitative indicator of a quality attribute at time t, and n is the pseudo-order of the "reaction". The integrated forms for zero-, first- and second-order kinetic models are listed in equation 2 to 4, respectively.

zero-order: $Q_t = Q_0 - k \cdot t$ (2)

first-order: $\ln \frac{Q_t}{Q_0} = -k \cdot t$ (3)

second-order: $k \cdot t = \frac{1}{Q_t} - \frac{1}{Q_0}$ (4)

where Q_0 represents the initial value of the quality factor at t = 0, Q_t the value at time t, and k is the pseudo-rate constant.

Results and Discussion

Global chemical composition

Average global chemical composition of fresh *Sardina pilchardus* muscles is presented in (Table 2). Values for moisture, protein and fat contents are in concordance with those reported by [24] for Tunisian fresh *Sardina pilchardus* muscles. Ash content is in the order of magnitude of values published by [25]. It can be noticed that fresh *Sardina pilchardus* muscles are a rich source of Ca, Mg and Na. Iron was detected as traces.

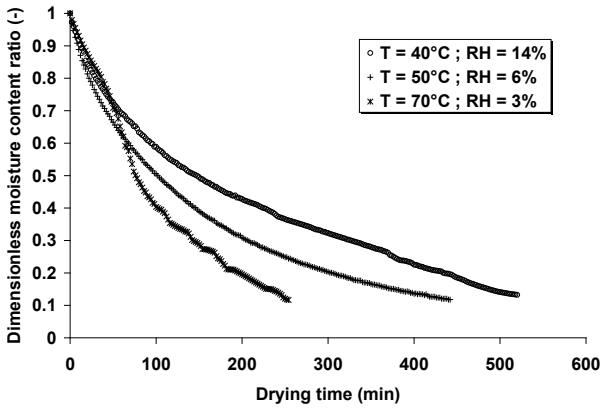
Drying curves

For repeatability acceptance levels of drying experiment, the significance of differences at the 99% level (p< 0.01) between three replicates of a drying experiment (60°C, 4 % RH and 1.5 m s^{-1} air velocity) was determined with a non parametric test using the Kolmogrov-Smirnov test.

Compounds	Contents
Moisture [a]	72.15 ± 2.85
Protein [a]	19.09 ± 0.29
Fat [a]	2.42 ± 0.12
Ashes [a]	1.20 ± 0.12
Na [b]	500.00 ± 0.02
Mg [b]	229.38 ± 0.04
Ca [b]	171.34 ± 0.01
Fe [b]	14.120 ± 0.001

a: g 100 g^{-1} FW; b: mg 100 g^{-1} FW

Table 2: Composition of the fresh fish (*Sardina pilchardus*) muscles.



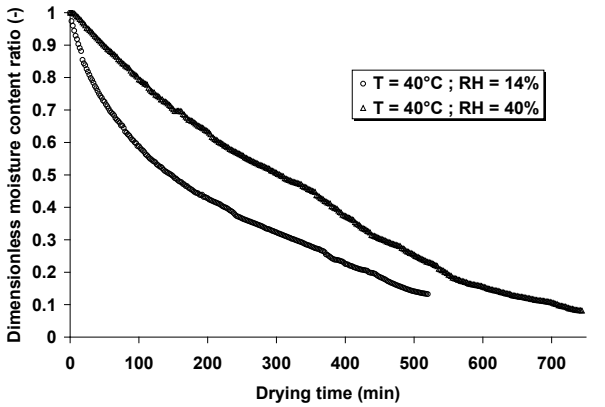


Figure 1: Variation of the reduced moisture content of sardine muscles versus drying time obtained for different drying temperatures (ambient air humidity, Va=1.5m/s) (a) and for two levels of relative humidity (Ta = 40°C, Va =1.5m/s) (b).

Quality parameters	Fisher number	p-value
L*	6.681	<0.001
a*	4.243	<0.001
b*	1.367	0.222
Hardness (F_{max})	1.367	0.001
Length (L)	3.951	<0.001
Width (W)	4.598	<0.001

Table 3: ANOVA analysis of impact of the drying time on quality parameters.

Sardina pilchardus' muscles drying curves obtained at various values of temperatures and relative humidity were represented in (Figure 1).

Figure 1a shows effects of air temperature (T) on the drying curves obtained at ambient air humidity (no vapor injection). Temperature had a significant effect on drying muscles. Drying time was reduced from 10 h at 40°C to 3 h at 70°C. Drying at higher temperature increased drying rates and reduced drying time as reported by many authors [22,26-29].

Figure 1b shows the influence of relative humidity on drying kinetics of *Sardina pilchardus* muscles measured at 40°C. The higher the relative humidity, the longer the drying time was. For example, an increase of relative humidity from 14 % to 40 % resulted in an extend of drying time by almost 30 % at 40°C and 25 % at 50°C. Similar trends have been reported for drying of vegetables products [30,31].

Effect of drying on some quality parameters

Table 3 shows the results of the ANOVA analysis of the drying time effect on measured quality parameters: L*, a*, b*, hardness, length and width of the muscles. It can be seen that, except yellowness (b*), all parameters were significantly affected by the drying time, whatever the applied drying conditions.

Table 4 recapitulates the effect of the drying conditions and their interaction on quality criteria of sardine muscles. As far as colorimetric parameters are concerned, it could be noticed that only a* was significantly affected by air temperature and relative humidity ($p<0.001$). Hardness and length of muscles were significantly affected by drying air conditions (temperature and relative humidity) and interaction between these parameters. Shrinkage or width of muscle was significantly affected by the air temperature.

Color changes: The L*, a* and b* parameters measured on fresh sardines muscles were 54.0 ± 4.5, 7 ± 2.40 and 3.5 ± 2.2, respectively. Color of fish muscles changed markedly when it was dried. For all tested drying conditions, only L* and a* parameters present a significant variation during drying ($p < 0.05$) (Table 3).

The inlet air temperature had a strong effect on color of dried fish, and an increase of relative humidity intensified this effect on a* parameters (Table 4). These trends in color changes were attributed to reactions induced by exposure to unfavorably relatively high temperatures. This led to a dark-colored muscles (lower values of L*), and caused the sugar-amine to grow brown, which was the result of the reaction between the amine groups of muscle proteins and available reduced sugars in the connective tissue of *Sardina pilchardus* muscles. Although Maillard reaction is an obvious candidate to explain the yellow-brown color after processing, low amounts of reducing sugar, particularly at beginning of processing, makes this hypothesis less convincing. However, a small degree of browning could result from the degradation of L-methylhistidine, even in absence of sugar as reported by [32,33]. Furthermore, oxidation of lipids is an important factor that also leads to browning of dried fish-muscles by interacting with proteins [34]. As processing temperature and time increased or moisture content decreased, more browning products were produced [35,36]. The L* and a* parameters of fish's muscles were significantly affected by time or moisture contents of the muscle ($p < 0.05$). Higher temperature resulted in greater rates of increased in a* values. However,

Parameters	Color						Hardness		Length		Width	
	L*		a*		b*		F_{max}		L		W	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
T	0.741	0.491	15.748	<0.001	0.005	0.995	53.235	<0.001	39.117	<0.001	16.858	0.003
RH	0.5790	0.456	47.201	<0.001	4.002	0.060	188.953	<0.001	38.708	0.001	2.903	0.139
T × RH	0.017	0.899	2.221	0.153	1.523	0.233	15.263	0.003	10.788	0.017	0.886	0.383

T: air temperature, RH: relative humidity, T× RH: air temperature and relative humidity interaction.
F: Fisher number, *p*: *p-value*.

Table 4: ANOVA analysis of the impact of drying parameters on the examined quality parameters (*F* = F-value, *p* = p-value).

Quality parameters		Experiments				
		Exp.1	Exp.2	Exp.3	Exp.4	Exp.5
a*	k (min^{-1})-10^3	0.177	-0.277	-1.220	-0.2858	0.125
	R^2	0.844	0.814	0.212	0.963	0.960
	S	0.025	0.044	0.017	0.015	0.004
L*	k (min^{-1})-10^5	0.9692	1.386	1.667	2.002	4.220
	R^2	0.943	0.958	0.994	0.994	0.990
	S	0.0007	0.0009	0.0003	0.0004	0.0006
Hardness (F_{max})	k (min^{-1})-10^3	-2.4	-0.915	-3	1.290	6.472
	R^2	0.953	0.895	0.936	0.926	0.946
	S	0.166	0.140	0.238	0.138	0.257
Width	k (min^{-1})-10^3	8.543	4.065	8.723	7.552	21.182
	R^2	0.925	0.970	0.988	0.976	0.985
	S	0.529	0.250	0.245	0.375	0.380
Length	k (min^{-1})-10^3	29.320	9.105	31	23.457	82.277
	R^2	0.977	0.987	0.974	0.984	0.989
	S	1.279	0.357	1.445	1.13	1.125

Where k: Constant rate, R^2: Coefficient of correlation and S: Standard erro.

Table 5: Zero-order reaction parameters for studied quality parameters changes of *Sardina pilchardus* fillets during drying.

b* values generally did not show significant changes ($p > 0.05$). It can also be noticed that *Sardina pilchardus* muscles, dried at 40°C, were more luminous than those dried at 70°C.

The kinetics of changes of L*and a* parameters in the browning phase were analyzed. Over the tested temperature and relative humidity range, experimental data were best fitted to a second-order reaction (Table 5).

Texture: Figure 2 represents the variations of hardness of the muscles (F_{max}) versus moisture content of *Sardina pilchardus* muscles obtained for different drying conditions.

F_{max} values showed significant variation with moisture content. The highest values of F_{max} corresponded to the lowest values of X indicating an increase of the muscles hardness during drying. Hardness of dried muscles increased slightly with decrease in water content in the range 2.6-1.5 g g^{-1} DM. However, below this critical moisture content there was an important increase in hardness that could be related to crust development at surface which is a textural problem in the external zones of dried muscles.

Figure 2 a shows that the effect of air temperature on muscle hardness was more pronounced between 40 and 50°C than between 50 and 70°C. This could be explained by a softening of the collagen which was solubilized at T > 60°C. In fact [4] and [21] reported that collagen was denaturated thermally and became soluble at 60°C. It could be also noticed that at ambient air humidity, increase of air temperature induced strong decrease of relative humidity and thus lead to increase of moisture gradient between air drying and surface of the product. Consequently surface dehydration of the muscles was more rapid at 50 than at 40°C and induced an increased hardness of muscles at 50°C. On the other hand, intensity of dehydration of surface of *Sardina pilchardus* muscles at 50 and 70°C was not much different. The last observation shows that the muscle hardness does not depend on the applied air temperature but on mass gradient between product surface and environment drying air. This observation could be confirmed by observing the effect of vapor injection in drying air shown in (Figure 2b). The increase of relative humidity attenuated the drying rate of the surface, and then the moisture gradients inside the product and the hardening of the product.

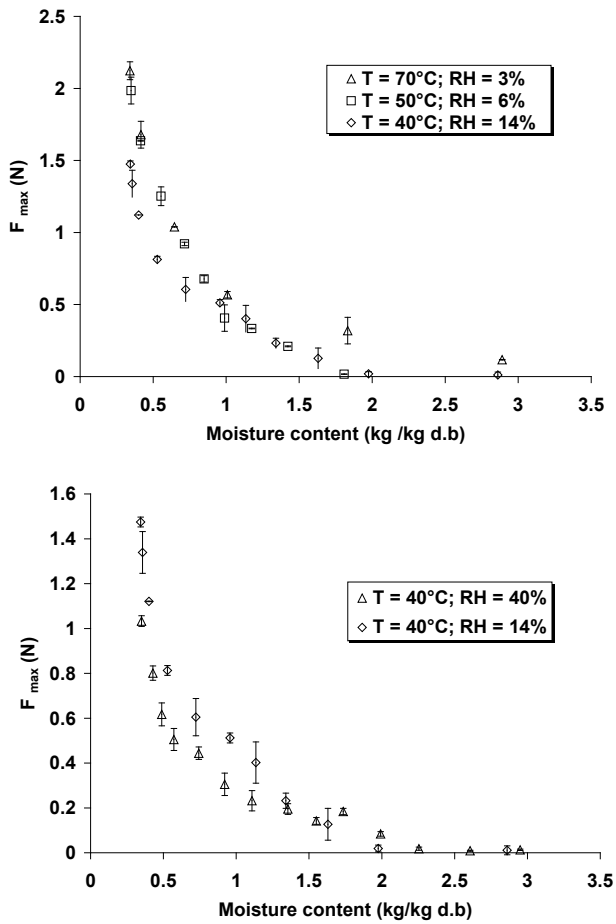


Figure 2: Variation of the maximal resistance of sardine muscles (F max) versus moisture content obtained for different drying temperatures (ambient air humidity, Va = 1.5 m/s) and for two levels of relative humidity (Ta = 40°C, Va =1.5m/s) (b).

Thermal denaturation temperatures of fish muscle proteins have been observed between 40 and 80°C [37]. At the temperatures investigated in this study, both tissue-toughening caused by denaturation of myofibrillar proteins and tissues softening caused by collagen gelation and solubilization might have been contributed to observed changes in sardine fillet texture. Prolonged heating resulted in prevalent shifted reactions and fluctuation in the sheer force of muscle.

Higher temperatures induced faster denaturation of proteins, and subsequently more rapid textural changes. [38] reported that protein denaturation rate increases about 600-fold for every 10°C in temperatures. Similar results were reported by [39]. These authors studied the effect of hydrothermal processing on texture of Pacific chum salmon in the range 60–100°C, and found that hardness increased as heating temperature increased.

According to last observation, it could be concluded that to obtain an acceptable muscle texture with a short drying time, it is possible to accelerate drying process by increasing temperature of drying air. However, this implies a rapid reduction of water activity, and consequently of water contents at the muscle surface. To avoid crusting problem, precise control of water content at the muscle surface by vapor injection should be maintained. Zero-order kinetic model was used to fit the experimental curves. The resultant rate constants and correlation coefficients are shown in (Table 5).

Shrinkage: Shrinkage was evaluated by measuring dimensions (length and width) of fresh and dried muscles at different drying times (after each hour). As for most foodstuffs, fish dehydration induced large changes of fish muscles dimensions. (Figure 3) shows effects of drying air temperature and relative humidity on variations of reduced length (L/L_0).

These figures highlight that shrinkage is particularly influenced by moisture content of the muscle. Air drying temperature had a significant effect on reducing moisture content of the product and consequently on length of *Sardina pilchardus* muscles (Table 4). Similar results were obtained when measuring width of the muscles, with less pronounced effect of temperature on shrinkage. In fact, when proteins of *Sardina pilchardus* muscles were exposed to heat, myofibrils of collagens were physically shortened. Similar explanation was reported by [40,41]. The authors reported that myofibrils constituting collagen

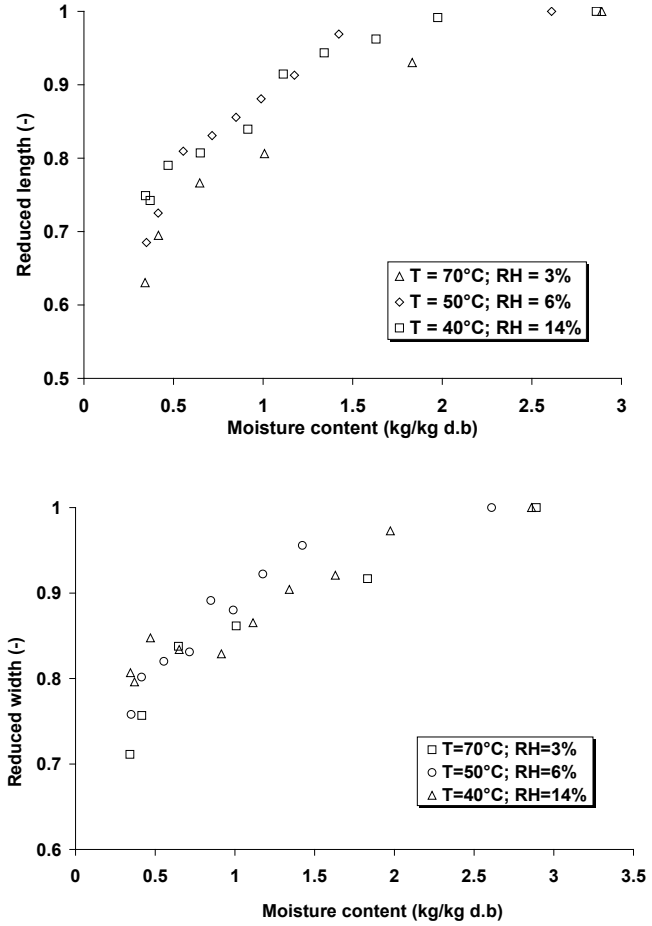


Figure 3: Variation of the reduced length (a) and reduced width (b) versus moisture content of sardine muscles obtained for different drying temperatures (HR = ambient air humidity, Va = 1.5 m/s).

of chicken muscle exposed to heat were shortened to about one-third of its original length at a temperature < 56 °C and to half or more at a temperature > 61 °C.

Heating caused denaturation of myosin and shrinkage of myofibrils. Protein denaturation reduces dimension of myofibrils and collagen, resulting in shrinkage of muscle fiber diameter and sacromere length [36,42-45].

Figure 3 shows also changes in longitudinal and transverse (results not represented) shrinkage, indicating that they mainly occurred along the muscle fiber. For example, sardine shrank of about 37% and 29% in longitudinal and transverse directions, respectively, at 70°C and 3% RH. [38] reported that extend of muscle fiber deformation during cooking depends on compression stress due to collagen fibers and the resistance of muscle fibers to compression, while compression force applied by collagen networks on muscle fiber bundles depends on the amount of collagen and its thermal solubility.

The decrease of width and length with drying time was fitted to a zero-order kinetic equation. (Table 5) shows the kinetic parameters. The high correlation coefficients ($R^2 > 0.92$) suggest that this model is satisfactory for describing the length and the width reduction in dried *Sardina pilchardus* products.

Conclusion

The effect of drying conditions (temperature and relative humidity) on drying kinetics, color, texture, and shrinkage of sardine muscle was investigated.

As expected, drying time decreased in line with the drying temperature. The changes in color of the dried *Sardina pilchardus* muscles were due to browning reaction occurring at higher drying temperature, leading to the reduction of lightness of *Sardina pilchardus* muscles.

Investigation of the textural properties changes of *Sardina pilchardus* muscles during drying indicated a considerable effect of temperature and moisture content decrease on muscle hardness. In fact, the increase of air temperature induced hardness of the muscles and this effect was attenuated by humidifying the drying air and reducing the rate of surface dehydration.

The shrinkage of dried *Sardina pilchardus* muscles depended on moisture contents of the muscles, also due to changes in fibers properties and denaturation of the proteins. The muscles length and width measured during drying decreased with decreasing moisture contents of the muscle.

References

1. Chytiri S, Chouliara, I, Savvaidis IN, Kontominas MG (2004) Microbiological, chemical and sensory assessment of iced whole and filleted aquacultured rainbow trout. Food Microbiology 21: 157-165.
2. Paleologos EK, Savvaidis IN, Kontominas MG (2004) Biogenic amines formation and its relation to microbiological and sensory attributes in ice-stored whole, gutted and filleted Mediterranean Sea bass (*Dicentrarchus labrax*). Food Microbiology 21: 549-557.
3. Taliadourou D, Papadopoulos V, Domvridou E, Savvaidis IN, Kontominas MG (2003) Microbiological, chemical and sensory changes of whole and filleted Mediterranean aquacultured sea bass (*Dicentrarchus labrax*) stored in ice. J Sci Food Agric 83: 1373-1379.
4. Sainclivier M (1985) L'industrie alimentaire halieutique vol.2. : Des techniques ancestrales à leur réalisations contemporaines : salage, séchage, fumage, marinage, hydrolysats. Sciences Agronomiques, ENSAR, Rennes, France.
5. Shahidi F, Miraliakbari H (2005) Omega-3 fatty acids in health and disease: part 2. Health effects of omega-3 fatty acids in autoimmune diseases, mental health, and gene expression. J Med Food 8: 133-148.
6. Shahidi F, Miraliakbari H (2004) Omega-3 (n-3) fatty acids in health and disease: part 1 - cardiovascular disease and cancer. J Med Food 7: 387-401.
7. Bala BK, Mondol MRA (2001) Experimental investigation of solar drying of fish using solar tunnel dryer. Drying Technology 19: 427-436.
8. Zakhia N (1992). Drying of fish (Tilapia spp.). Study of the process quality. Application of land in Mali. PhD thesis, Food Science, ENSIA, Massy, France.
9. Wu T, Mao L (2008) Influences of hot air drying and microwave drying on nutritional and odorous properties of grass carp (*Ctenopharyngodon idellus*) fillets. Food Chemistry 110: 647–653.
10. Jain D, Pathare PB (2007) Study the drying kinetics of open sun drying of fish. Journal of Food Engineering 78: 1315–1319.
11. Sobukola OP, Dairo OU, Sanni LO, Odunewu VA, Fafiolu, BO (2007) Thin layer drying of some leafy vegetables under open sun. Food Science and Technology International 13: 35–40.
12. Villota R, Saguy I, Karel M (1980) Storage Stability of Dehydrated Food. Evaluation of Literature Data. J Food Qual 3: 123-212.
13. Karel M (1991) Physical Structure and Quality of Dehydrated Foods. Drying Technology 91: 26-35.
14. Finot PA (1997) Effects of processing and storage on the nutritional value of food protein, in Food protein and their applications, ed. by Damodaran S, Paraf A, Marcel Dekker Inc., New York.

15. Zhang J, Zhang M, Shan L, Fang Z (2007) Microwave-vacuum heating parameters for processing savory crisp bighead carp (*Hypophthalmichthys nobilis*) slices. Journal of Food Engineering 79: 885–891.

16. Abid M, Gibert R, Laguerie C (1990) An experimental and theoretical analysis of the mechanisms of heat and mass transfer during the drying of corn grains in a fluidized bed. Int Chem Eng 30: 632–642.

17. Kosuke N, Jin LiY, Fukumuro Z, Ando M, Akaishi YA (2006) Low-temperature desiccant-based food drying system with airflow and temperature control. Journal of Food Engineering 75: 71–77.

18. AOAC (1984) Official methods of analysis of the association of official analytical chemists (13th.ed). Washington, DC: Association of Official Analytical Chemists.

19. Boudhrioua N, Giampaoli P, Bonazzi C (2003) Changes in aromatic components of banana during ripening and air drying. Lebensem.-wiss.u-Technol 36: 633–642.

20. Boudhrioua N, Michon C, Cuvelier GP, Bonazzi C (2002) Influence of ripeness and air temperature on changes in banana texture during drying. Journal of Food Engineering 55: 115–121.

21. Groupe de Recherche et d'Echange Technologique (1993) Conserver et transformer le poisson, GRET, Paris.

22. Djendoubi N, Boudhrioua N, Bonazzi C, Kechaou N (2009) Drying of Sardine Muscles: Experimental and mathematical investigations. Food and Bioproducts Processing 87: 115–123.

23. Wang Y, Lau MH, Tang J, Mao R (2004) Kinetics of chemical marker M-1 formation in whey protein gels for developing sterilization processes based on dielectric heating. Journal of Food Engineering 64: 111–118.

24. Abdelmouleh A, Katari MH, Hadj Ali Salem M (1980) Seasonal variations in the overall chemical composition of the sardine: Sardina pilchardus in the region of Bizerte (Tunisia). Bulletin of the National Institute of Science, Technology and Salammbo Oceanographic Fishing 7: 91–101.

25. FAO (1999) La qualité et son évolution dans le poisson frais. Documents techniques sur la pêche n°348.

26. Prachayawarakorn S, Soponronnarit S, Wetchacama S, Jaisut D (2002) Desorption isotherms and drying characteristics of shrimp in superheated steam and hot air. Drying Technology 20: 669-684.

27. Hadrich B, Boudhrioua N, Kechaou N (2008) Drying of Tunisian sardine (*Sardinella aurita*) experimental study and three-dimensional transfer modelling of drying kinetics. Journal of Food Engineering 84: 92-100.

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

29. Sobukola OP, Olatunde SO (2011) Effect of salting techniques on salt uptake and drying kinetics of African catfish *(Clarias gariepinus)*. Food and Bioproducts Processing 89: 170-177.

30. Viswanathan R, Jayas, DS, Hulasare RB (2003) Sorption iostherms of tomato slices and onion shreds. Biosysytem Engineering 86: 465-472.

31. Kiranoudis CT, Dimitratos J, Maroulis ZB, Marinos-Kouris D (1993) State estimation in the batch drying of foods. Drying Technology 11: 1053-1069.

32. Pokorny J (1981) Browning from lipid-protein interactions. Prog Food Nutr Sci 5: 421-428.

33. Sainclivier M (1983) L'industrie alimentaire halieutique, vol.1. : Le poisson matière première. Sciences Agronomiques, ENSAR, Rennes, France.

34. Louka N, Juhel F, Fazilleau V, Loonis P (2004) A novel colorimetry analysis used to compare different drying fish processes. Food Control 15: 327-334.

35. Whistler RL, Daniel JR (1985) Carbohydrates, in Food chemistry, ed. by Fennema OR, Marcel Dekker Inc.

36. Kong F, Tang J, Rasco B, Barbara Rasco, Crapo C (2007) Kinetics of salmon quality changes during thermal processing. Journal of Food Engineering 83: 510–520.

37. Ofstad R, Kidman S, Hermansson AM (1996) Ultramicroscopical structures and liquid loss in heated cod (*Gadus morhua L*) and salmon (*Salmo salar)* muscle. Journal of the Science of Food and Agriculture 72: 337–347.

38. Anglemier AF, Montgomery MW (1976) Amino acids, peptides, and proteins, in Principles of food science. Part I. Food chemistry, ed. By Fennema OR, Marcel Dekker Inc, New York, USA.

39. Bhattacharya S, Choudhury GS, Studebaker S (1993) Hydrothermal processing of Pacific chum salmon: Effects on texture and invitro digestibility. J Food Qual 16: 243–251.

40. Forrest JC, Aberle ED, Hedrick HB, Judge MD, Merkel RA (1975) Principles of meat science. W. H. Freeman & Co, San Francisco, USA.

41. Nathakaranakule A, Kraiwanichkul WA, Soponronnarit S (2007) Comparative study of different combined superheated-steam drying techniques for chicken meat. Journal of Food Engineering 80: 1023-1030.

42. Kong FB, Tang JM, Rasco B, Crapo C, Smiley S (2007) Quality changes of salmon (*Oncorhynchus gorbuscha*) muscle during thermal processing. Journal of Food Science 72: S103–S111.

43. Bell JW, Farkas BE, Hale SA, Lanier TC (2001) Effect of thermal treatment on moisture transport during steam cooking of Skipjack Tuna (*Katsuwonas pelamis*). Journal of Food Science 66: 307–313.

44. Palka K, Daun H (1999) Changes in texture, cooking losses, and myofibrillar structure of bovine M. semitendinosus during heating. Meat Science 51: 237–243.

45. Lepetit J, Grajales A, Favier R (2000) Modelling the effect of sarcomere length on collagen thermal shortening in cooked meat: consequence on meat toughness. Meat Science 54: 239-250.