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Influence of air-drying temperature on drying kinetics, colour, firmness and biochemical characteristics of Atlantic salmon (*Salmo salar* L.) fillets

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ABSTRACT

In this work the drying kinetics of Atlantic salmon (*Salmo salar* L.) fillets and the influence of air drying temperature on colour, firmness and biochemical characteristics were studied. Experiments were conducted at 40, 50 and 60 °C. Effective moisture diffusivity increased with temperature from 1.08×10^{-10} to 1.90×10^{-10} $m^2 s^{-1}$. The colour difference, determined as ΔE values (from 9.3 to 19.3), as well as firmness (from 25 to 75 N mm^{-1}) of dried samples increased with dehydration temperature. The lightness value L^* and yellowness value b^* indicated formation of browning products at higher drying temperatures, while redness value a^* showed dependence on astaxanthin value. Compared with fresh fish samples, palmitic acid and tocopherol content decreased in a 20% and 40%, respectively, with temperature. While eicosapentaenoic acid (EPA) content remained unchanged and docosahexaenoic acid (DHA) content changed slightly. Anisidine and thiobarbituric acid values indicated the formation of secondary lipid oxidation products, which is more relevant for longer drying time than for higher drying temperatures.

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1. Introduction

Atlantic salmon (*Salmo salar* L.) is the main salmon species in marine aquaculture in Chile. Its current production occupies 18% (39.68 ha) of the total territorial area under aquacultural use with 98% of this production being carried out in Chile between the 8th Region, *Región del Maule*, and the 10th Region, *Región de los Lagos* (Odepa, 2011). Over the past 20–30 years salmon export from Chile has steadily increased. More recently, processed products like smoked-dried and frozen salmon have had a greater demand on the major export markets that include the USA, the European community and Japan (Chilealimentos, 2012).

Marine foods have attracted much attention as a source of important components for human health and nutrition. However, marine products present a rapid *post mortem* degradation of most of their components through numerous biochemical reactions that lead to a loss in quality and commercial value of these products. To solve these problems inherent to fresh fish, the use of adequate processing and preservation technology is necessary. Therefore, many researches and applications have been focussed on different drying methods as a preservation technique (Bala & Mondol, 2001; Deng et al., 2011; Djendoubi, Boudhrioua, Bonazzi, & Kechaou, 2009; Duan, Jiang, Wang, Yu, & Wang, 2011; Duan, Zhang, & Tang, 2004; Morkore et al., 2001). However, for preservation of perishable foods hot air drying is commonly used, despite significant limitations, like high specific energy consumption and long processing time. Hot air drying is used to preserve fish by inactivating enzymes and removing moisture (Duan et al., 2004). The removal of moisture prevents growth and reproduction of microorganisms that cause decay and minimizes many of the moisture mediated deteriorative reactions (Bala & Mondol, 2001; Bellagha, Sahli, Farhat, Kechaou, & Glenza, 2007). It is generally accepted that the mechanism that regulates the drying of foods is based on water diffusivity from within the material to its surface, and can be modelled using Fick's second law (Duan et al., 2011; Vega-Gálvez et al., 2011).

Dried fish fillets can be stored for a long period of time and are convenient to use. During drying, many chemical and physical reactions occur, causing an increase in digestibility of proteins through denaturation, but very often the contents of thermolabile compounds and polyunsaturated fatty acids are also reduced (Wu & Mao, 2008). The quality of the dried product is also influenced by the drying conditions (temperature, air velocity and relative humidity). When operating at high temperatures, the nutritional properties of the product must be considered, since a loss of some

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functional characteristics may occur. High temperature usually causes irreversible biological or chemical reactions (oxidation, Maillard reaction, discolouration or changes in nutritional-functional properties), as well as structural, textural and mechanical modifications like shrinkage or loss of firmness (Erdogdu & Balaban, 2000; Luangmalawat, Prachayawarakorn, Nathakaranakule, & Soponronnarit, 2008; Veland & Torrissen, 1999).

Nutrient uptake into muscle fillet, known to be influenced by dietary lipid concentration, includes vitamin E, vitamin A (Hamre & Lie, 1995) and astaxanthin (Barbosa, Morais, & Choubert, 1999; Jensen, Birk, Jokumsen, Skibsted, & Bertelsen, 1998). Besides being important nutrients for human consumption, both vitamin E and astaxanthin function as efficient antioxidants in fish flesh, protecting polyunsaturated fatty acids (PUFAs) against free-radical-mediated oxidation (Bell, McEvoy, Tocher, & Sargent, 2000; Sigurgisladottir, Sigurgisladottir, Torrissen, Vallet, & Hafsteinsson, 2000). The long-chain PUFAs in fish flesh also have a variety of health benefits (Rafflenbeul, 2001). However, PUFAs are highly susceptible to undergoing oxidation reactions and their composition varies largely from species to species (Jensen et al., 1998). Oxidation of fats is one of the most important mechanisms that lead to food spoilage, second only to alterations produced by microorganisms. This leads to a reduction in shelf life due to changes in taste and/or odour, deterioration of texture and functionality of the muscle, and reduction in nutritional quality.

Astaxanthin is the primary carotenoid contributing to the yellow–orange colour of farmed salmon, and its content is regarded as one of the most important quality parameters in fresh salmon (Meyers, 1994). Astaxanthin accounts for more than 90% of the total carotenoid content found in the flesh of wild salmons, which is obtained from ingested crustaceans. Research also indicates additional benefits from dietary carotenoids beyond the resulting colouration; carotenoids have excellent antioxidative characteristics. In addition, salmons have a high level of polyunsaturated fat in their membranes, and protection of lipid tissue from peroxidation seems to be a metabolic function of astaxanthin (Bell et al., 2000) that has been shown to be hundred times more effective than vitamin E as an antioxidant.

Sources of n-3 PUFAs include some plant oils, such as linseed oil, and green leaves, which contain α-linolenic acid, which in mammals can be converted via desaturation and elongation to eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). EPA and DHA biosynthesis in animal and human organisms is a rather slow process which is further decelerated with ageing. Since the human body cannot synthesise them, EPA and DHA are essential nutrients in human diet (Leaf, Xiao, Kang, & Billman, 2003). EPA and DHA can be ingested directly as they are present in high concentrations in oily fish, like mackerel, herring, sardine and salmon, and in fish oil extracts such as cod liver oil. High levels of EPA and DHA are found in seafood, because these fatty acids are transferred up the food chain in the oceans from the phytoplanktons that produce them (Jensen et al., 2012).

Tocopherols are known to be endogenous antioxidants that can act as scavengers of free radicals, so that protection against the very early stages of lipid oxidation would be favoured (Jensen et al., 1998). Different tocopherols (α-, β-, γ- and δ-tocopherol) have been identified in plants and all have been found in most seaweeds and unicellular algae. The α-, β-, γ- and δ-tocopherols occur as mixtures in vegetable oils and are the main natural antioxidants in fats (Hraš, Hadolin, Knez, & Bauman, 2000). However, the most abundant and the most biologically active tocopherol in food is α-tocopherol that inhibits free radical oxidation by reacting with peroxyl radicals to stop chain propagation, and with the alkoxyl radical to inhibit the decomposition of the hydroperoxides and decrease the formation of aldehydes (Kalucka et al., 2005). Moreover, α-tocopherol has been reported to be the only tocopherol that is accumulated in higher marine animals from natural diets that presumably include originally all four tocopherols. Deposition of different tocopherol molecules (primarily α and γ) in farmed fish did occur and could be strongly influenced by the feed provided (Parazo, Lall, Castell, & Ackman, 1998; Sigurgisladottir et al., 2000).

Thiobarbituric acid reactive substances (TBARs) can be degraded or interact with other components, such as proteins, to form polymers that decrease the quality of salmon. The TBARs index is widely used as a quality index for lipid oxidation (Goulas & Kontominas, 2007). Lipids and proteins do not react to form complexes unless the fat or fatty acids are oxidised (Bhattacharya, Sajilata, & Singhal, 2008). Another important indicator of the fat oxidation process is the anisidine value, which defines the secondary oxidation product content. The anisidine value is a measure of the production of aldehydes during oxidation of fats or oils and is used as an indicator of the oxidative history of the fat or oil, as the aldehydes normally originate from the oxidation of unsaturated fatty acids (ÓSullivan, Mayr, Shaw, Murphy, & Kerry, 2005).

Information on the drying kinetics and nutritional quality related to drying process of salmon fillets are not available in literature. Therefore the aim of this work was to determine the drying kinetics of salmon fillets at 40, 50 and 60 °C and to assess the effect of air temperature on colour and firmness development, on TBA index and anisidine values (lipid oxidation) and on contents of astaxanthin, tocopherols, palmitic acid, EPA and DHA in dried Atlantic salmon (*Salmo salar*) fillets.

2. Materials and methods

2.1. Raw material

Atlantic salmon (*Salmo salar* L.) fillets were purchased from a local market in the city of Santiago, Chile. Freshness, colour, size and absence of any mechanical damage were used as selection criteria. The fillets thickness was of 10.50 ± 0.15 mm approximately. Samples were stored at 4.5 ± 0.1 °C until analysis. Initial moisture content was determined according to AOAC official method 934.06 (AOAC, 1990), using a vacuum drying oven (Gallenkamp, OVL570, Leicester, UK) and an analytical balance (CHYO, Jex120, Kyoto, Japan) with an accuracy of ±0.0001 g.

2.2. Drying process

The salmon fillets were dried in a laboratory-scale convective dryer at 40, 50 and 60 °C with an air flow of 2.0 ± 0.1 m s^{-1}. The inlet relative humidity was 72.0 ± 4.0%, measured by an ambient digital hygro-thermometer (Extech Instrument Inc., 445703, MA, USA) and the load density was 4.4 ± 0.4 kg m^{-2}. All drying experiments were carried out in triplicate using a mass of 100.0 ± 1.0 g, taken each time from a whole fillet. The fillet samples were placed as a thin-layer in a stainless steel basket and fillet mass during drying was measured on an analytical balance (Ohaus, SP402, NJ, USA) with a precision of ±0.01 g at defined time intervals, connected by an interface system (Ohaus, RS232, NJ, USA) to a PC, which recorded and stored data. Experiments were performed until equilibrium condition was achieved and constant weight of sample registered. The dried samples were kept in sealed polypropylene bags until further analysis.

2.3. Effective moisture diffusivity measurement

Fick's second law of diffusion (Eq. (1)) was used to model the drying process since moisture diffusion is one of the main mass transport mechanisms that describe this process (Corzo & Bracho, 2007). In this model, the dependent variable is the moisture ratio

(MR) which relates the gradient of the sample moisture content in real time to both initial and equilibrium moisture content (Eq. (2)).

$$\frac{\partial MR}{\partial t} = D_{\text{eff}} \frac{\partial^2 MR}{\partial z^2} \quad (1)$$

$$MR = \frac{X - X_e}{X_o - X_e} \quad (2)$$

In Eq. (1) D_{eff} is the effective moisture diffusivity ($m^2\,s^{-1}$), t is the drying time (s) and z is the spatial dimension (m). In Eq. (2) X is the moisture content (g water g^{-1} dry matter (d.m.)), X_o the initial moisture content (g water/g d.m.) and X_e the equilibrium moisture content (g water/g d.m.). The mathematical solution of Fick's second law, when internal mass transfer is the controlling mechanism and one-dimensional transport in an infinite slab is assumed, is given by Eq. (3). For sufficiently long drying times, the first term in the series expansion gives a good estimate of the solution (Crank, 1975). In this case, a linear relationship between the logarithm of MR and time is obtained, which can be used to determine effective moisture diffusivity according to Eq. (4) (Babalis & Belessiotis, 2004).

$$MR = \frac{8}{\pi^2} \sum_{j=0}^{\infty} \frac{1}{(2j+1)^2} \exp\left[\frac{-(2j+1)^2 D_{\text{eff}} \pi^2 t}{4L^2}\right] \quad (3)$$

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

where L is the half-thickness of the slab (m) and j is number of terms. The use of Eq. (4) is based on the assumption of a constant D_{eff} for each drying experiment and a linear behaviour between the mentioned variables. This hypothesis of isothermia is only a simple assumption since drying is a complex process involving simultaneous heat and mass transfer, thus all the complexity of the drying process relies on D_{eff} (Corzo & Bracho, 2007). In practice, the D_{eff} value for each temperature is determined from the slope of the straight line obtained by plotting experimental drying data in terms of $\ln MR$ versus drying time. Moreover, the temperature dependence of the effective moisture diffusivity can be represented by an Arrhenius relationship (Eq. (5)). Both kinetic parameters (E_a and D_0) can be estimated from the slope and intercept of the plot $\ln D_{\text{eff}}$ versus the reciprocal of absolute temperature:

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

In Eq. (5) R is the universal gas constant (8.314 J $mol^{-1}\,K^{-1}$), E_a the activation energy (kJ mol^{-1}), D_0 the Arrhenius factor ($m^2\,s^{-1}$) and T the absolute temperature (K).

3. Quality attributes

3.1. Surface colour

The surface colour of the salmon fillet was measured using a colorimeter (Minolta, CM-1000, Tokyo, Japan) based on the CIELab colour space, after calibration with the white and black glass standards. Three equidistant spots were examined on the major axis of each fish fillet sample. Since the spot diameter of the instrument was 10 mm, the total area of the slab, from which information was taken, was 10 cm^2. The experiments were performed in triplicate. Colour changes were measured by colorimetric evaluation of the three CIE parameters: Lightness (L^*), greenness-redness (a^*) and blueness-yellowness (b^*). CIE L^*, a^* and b^* colour coordinates were calculated considering the standard illuminant D_{65} and an observer angle of 10° (Vega-Gálvez et al., 2011). The colorimeter yielded L^*, a^* and b^* values for each spot, which were converted to the total value of colour difference (ΔE) according to Eq. (6).

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (6)$$

3.2. Firmness

The firmness of samples, as an indicator of texture, was defined as the maximum force applied to puncture the salmon tissue. This physical property was measured using a Texture Analyzer (Texture Technologies Corp., TA XT2 Scardale, NY, USA). The probe had a puncture diameter of 2 mm, and was adjusted for a travel distance of 20 mm at a test speed of 1.7 mm s^{-1}. The maximum force was measured by making 1 puncture in each dehydrated fish sample, using 10 slices per treatment. The mean value of firmness for each treatment was then calculated and expressed in N mm^{-1}.

3.3. Astaxanthin

The astaxanthin (AX) content in the fish samples was measured according to Sheehan, O'Connor, Sheehy, Buckley, & Fitzgerald, 1998). The fish muscle was extracted with acetone. The combined extracts were dried under nitrogen flux and dissolved in the mobile phase, which consisted of 20% ethyl acetate and 80% methanol/water in a ratio of 9:1. HPLC separation of the samples was carried out on a Nucleosil 5 C18 (25 cm 64 cm i.d.) reverse-phase column; detection was carried out at 470 nm. The absence of 9*Z*- and 13*Z*-isomers was confirmed; only *E*-isomers were detected in the analysed salmon samples. Results were expressed as mg all-*E*-AX kg^{-1} fish muscle.

3.4. Alpha and gamma tocopherol content

Tocopherols were analysed according to Cabrini, Landi, Stefanelli, Barzanti, and Sechi (1992). The lipophilic antioxidants were extracted from the muscle with hexane, brought to dryness under nitrogen flux, dissolved in isopropanol and injected for HPLC analysis. An ultrasphere ODS column (15 cm 60.46 cm i.d.) was employed, applying a gradient from 0% to 50% isopropanol. The flow rate was 1.5 mL min^{-1}. Detection was achieved at 280 nm. α-, and γ-isomers were detected in farmed salmon samples, with their contents being expressed as mg/kg muscle.

3.5. Palmitic acid, EPA and DHA

Lipid extracts were converted into fatty acid methyl esters (FAME) by employing acetyl chloride and then analysed by gas chromatography, according to Aubourg, Medina, and Gallardo (1998). Analysis was performed on a Perkin-Elmer 8700 chromatograph employing a fused-silica capillary column SP-2330 (0.25 mm i.d.630 m; Supelco, Bellefonte, PA, USA). Nitrogen at 10 psi as carrier gas and a flame ionization detector (FID) at 250 °C were used. Peaks corresponding to fatty acids were identified by comparison of their retention times with standard mixtures (Qualmix Fish, Larodan, Malmo, Sweden; FAME Mix, Supelco). Peak areas were automatically integrated, with 19:0 fatty acid being used as internal standard for the quantitative analysis.

3.6. Thiobarbituric acid index

The thiobarbituric acid index (TBA-i) was determined according to Vyncke (1970). This method is based on the reaction between a trichloroacetic acid extract of the fish muscle, and thiobarbituric acid at high temperature (95–97 °C); the resulting chromophore

was spectrophotometrically measured at 532 nm. Results were expressed as mg malondialdehyde kg^{-1} fish muscle.

3.7. Anisidine value

The anisidine value was determined in fish muscle according to the AOCS (1993) method, based on the reaction between α- and β-unsaturated aldehydes (primarily 2-alkenals) and p-anisidine reagent. Anisidine value was expressed as 100 times the absorbance measured at 350 nm in a 1 cm path length cuvette from a solution containing 10 mg lipid ml^{-1} reaction medium.

3.8. Statistical analysis

An analysis of variance (ANOVA) was carried out to estimate least significant differences (LSD) among the media of the effective moisture diffusivities, 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 diffusivities. The statistical estimation was done using the Statgraphics® Plus 5.1 software.

4. Results and discussion

4.1. Drying curves and effective moisture diffusivity

Prior to approaching the study of drying of any food, it is necessary to evaluate its moisture sorption isotherms as these mathematically describe the relationship between water activity and equilibrium moisture content of the food product. They have a fundamental influence on many aspects of the dehydration process and the storage stability of the dried product. For food systems, these isotherms also give useful information about the sorption mechanism and the interaction of food biopolymers with water (Vega-Gálvez et al., 2011). The initial and equilibrium moisture contents of the Atlantic salmon (*Salmo salar* L.) fillets were 3.07 ± 0.10 g water g^{-1} d.m. and 0.18 ± 0.04 g water g^{-1} d.m. respectively. In Fig. 1 the experimental drying curves at the three temperatures (40, 50 and 60 °C) are shown. A clear effect of temperature on the drying behaviour of the salmon fillets can be observed. An increase in drying temperature is accompanied by a decrease in drying time. The time needed to achieve equilibrium moisture content in all experiments was between 2000 and 4000 min. In addition, Fig. 1 shows a prolonged period of falling drying rate. Similar results were obtained by other authors working with seafoods as prawn and chelwa fish (Jain & Pathare, 2007), sardine (Corzo & Bracho, 2007; Djendoubi et al., 2009), rainbow trout (Kilic, 2009), jumbo squid (Vega-Gálvez et al., 2011) and shark fillets (Mujaffar & Sankat, 2005).

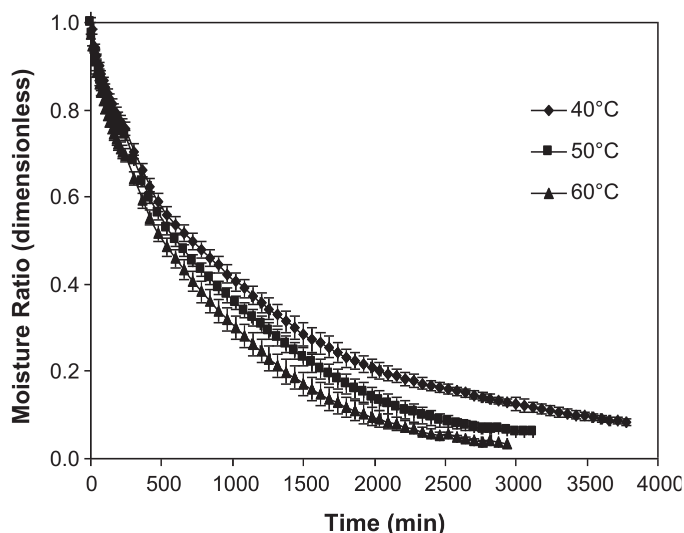

Fig. 1. Drying curves for Atlantic salmon (*Salmo salar* L.) fillets at three drying temperatures.

An analysis of variance on the media of D_{eff} for the salmon fillets showed significant differences ($p < 0.05$) when observing the influence of temperature (Table 1). The highest value of D_{eff} ($1.90 \pm 0.22 \times 10^{-10}$ m^2 s^{-1}) was obtained at 60 °C, while the lowest value ($1.08 \pm 0.12 \times 10^{-10}$ m^2 s^{-1}) occurred at 40 °C. These values are within the general range of 10^{-11}–10^{-9} m^2 s^{-1} for drying of fish as reported by Panagiotou, Krokida, Maroulis, and Saravacos (2004). They are slightly higher than those reported for Brazilian squid (Teixeira & Tobinaga, 1998), or those for sun drying of prawn (11.11×10^{-11} m^2 s^{-1}) or chelwa fish (8.708×10^{-11} m^2 s^{-1}) (Jain & Pathare, 2007). However, they are comparably lower than the values of D_{eff} determined under convective air-drying for jumbo squid between 0.78×10^{-9} m^2 s^{-1} at 50 °C and 3.2×10^{-9} m^2 s^{-1} at 90 °C (Vega-Gálvez et al., 2011), or shark fillets between 2.47×10^{-10} m^2 s^{-1} at 30 °C and 6.75×10^{-10} m^2 s^{-1} at 60 °C (Mujaffar & Sankat, 2005). On the other hand, the D_{eff} values mentioned are similar to the corresponding values of moisture diffusivity obtained under osmotic dehydration of tilapia fillets (Medina-Vivanco, Sobral, & Hubinger, 2002) or sardine sheets (Corzo & Bracho, 2007). The observed differences could be explained by the diversity of seafood species, process temperature, muscle orientation, fat content and presence or absence of skin (Medina-Vivanco et al., 2002). A linear relationship due to the Arrhenius type dependence ($R^2 = 0.98$) was obtained when plotting the natural logarithm of D_{eff} as a function of the reciprocal of absolute temperature. From the slope of this line, an activation energy value of 24.57 kJ mol^{-1} was determined, according to Eq. (4).

4.2. Colour changes

The appearance of food products is of major importance to consumers, both from the point of view of acceptability and preference. The colour of salmon products is generally accepted to be one of the most relevant quality parameters. Therefore, colour plays a decisive role when evaluating the quality of the product at the point of sale (Anderson, 2000). The average values of the chromatic coordinates L^*, a^* and b^*, for the fresh and the dehydrated fish samples are shown in Fig. 2. These colour parameters for the dried Atlantic salmon were significantly different ($p < 0.05$) to those for the fresh salmon. Although the lowest L^* value was determined in the fresh sample, indicating an overall darker tone for the fresh salmon compared to the dehydrated samples, only slight differences in lightness of samples were observed. Surface drying removed the surface moisture leaving a protein coating (pellicle) that probably enhanced the lightness of the dried samples. At 50 and 60 °C the L^* value decreased compared to treatment at 40 °C and may be due to colour development through more severe browning near the end of drying period, when moisture level

Table 1
Values of effective moisture diffusivity under hot-air conditions during drying of Atlantic salmon fillets at three different temperatures.

Drying temperature (°C)	D_{eff}·10^{-10} (m^2 s^{-1})	r^2
40	1.08 ± 0.12^a	0.99
50	1.56 ± 0.24^b	1.00
60	1.90 ± 0.22^c	1.00

*Data are expressed as average ± standard deviation in three replicates. Different letters in the same column indicate that the D_{eff} values are significantly different ($p < 0.05$).

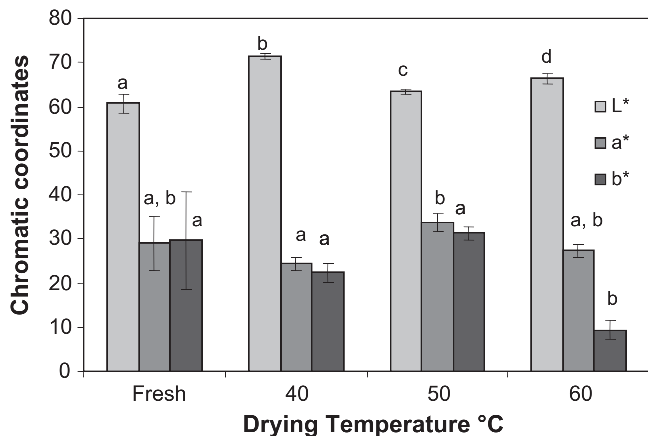

Fig. 2. Effect of air-drying temperature on the chromatic coordinates (L^*, a^* and b^*) of fresh and dehydrated salmon fillet samples. Identical letters above the bars indicate no significant difference ($p < 0.05$).

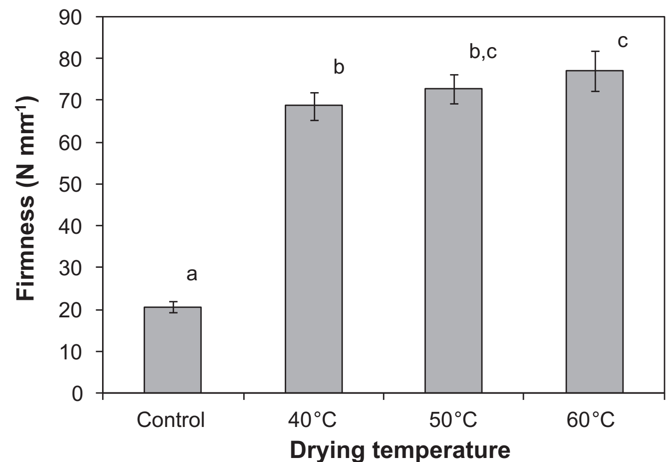

Fig. 3. Effect of air-drying temperature on firmness of fresh and dehydrated salmon fillets. Identical letters above the bars indicate no significant difference ($p < 0.05$).

of sample is low and less evaporative cooling takes place. Prolonged drying at higher temperatures favoured browning reactions that caused a decrease in lightness value, which is frequently reported to occur during thermal treatment (Leadley, Tucker, & Fryer, 2008; Patras, Tiwari, Brunton, & Butler, 2009). Several suggestions to reduce browning during drying emphasised in all cases that product should not experience unnecessary heat when it is in its critical moisture content range (Rahman, 2006). On the other hand changes in coordinate a^* (greenness-redness) due to drying of samples at the three temperatures (40, 50 and 60 °C) were not evident with respect to fresh samples ($p < 0.05$). Dietary carotenoids (e.g. astaxanthin) deposited in the muscle give fillets of Atlantic salmon their characteristic and attractive pink colour, an important quality parameter of both raw and processed products of salmonid fishes (Sigurgisladottir et al., 2000). During the drying assays, it appeared that astaxanthin was not significantly deteriorated, which may explain the maintenance of the redness coordinate. For values of coordinate b^* (blueness-yellowness) no significant influences were found between fresh samples and samples dried at 40 and 50 °C ($p < 0.05$). However, as drying temperature is raised to 60 °C coordinate b^* decreased significantly. This is equivalent to a shift to yellowness, which is an indication of sample browning during drying (Fu, Xue, Miao, Li, & Zhang, 2007), confirming the tendence observed for lightness value.

The values of colour difference (ΔE) for all drying treatments with respect to the fresh sample were also examined, showing ΔE values to increase significantly ($p < 0.05$) with dehydration temperature (9.27 at 40 °C, 12.37 at 50 °C and 19.31 at 60 °C). Considering the L^*, a^* and b^* values determined in this study, it can be assumed that colour difference is mainly due to some browning that occurred at temperatures around 60 °C. The experiments described here demonstrated that external factors, such as drying temperature and time, have considerable impact on colour parameters of the dried salmon fillets. If consumers would dislike the colour of the product, then other quality parameters such as flavour and texture may not be judged at all.

4.3. Firmness

The fish muscular tissue consists mainly of muscle fibres or cells and some extracellular space (interstitial space and capillary space). The muscle cells consist of mainly fibrils (working units of cell), sarcoplasma (transport and regulatory space filled with liquid and functional units), and finally connective tissue, mainly collagen (Veland & Torrissen, 1999). The major structural factors affecting texture are associated with the connective tissues and the myofibrillar proteins (myosin and actin) (Erdogdu & Balaban, 2000). Drying causes denaturation of the protein by concentration of the solutes and irreversible structural changes leading to textural modification. The firmness of the dried salmon filtet is a critical quality parameter that may affect appearance and thus acceptability of the product. The dried fish muscles should tolerate a minimum stress or deformation without falling apart when cut in slices or being handled (Rahman, 2006). In this study the firmness of the dehydrated salmon fillet was evaluated by a puncture test and the effect of drying temperature on its behaviour is illustrated in Fig. 3. The fresh salmon presented a firmness of 20.59 ± 1.18 N mm^{-1}, which is significantly the lowest value ($p < 0.05$), compared to the firmness of all fillet samples dried at 40, 50 and 60 °C. Firmness increased as the drying temperature was raised. It reached a value of 77.05 ± 4.75 N mm^{-1} at dehydration temperature of 60 °C, which can be considered a major increase compared to the firmness of the fresh sample ($p < 0.05$).

4.4. Astaxanthin

Astaxanthin is a dietary carotenoid well known as the main pigment responsible for the pink colour of salmonoid species, so that its retention during processing should be very important to guarantee consumer acceptance and retain the commercial value of the product (Rodríguez et al., 2007). In addition to their colouring properties, carotenoids have major biological functions (Anderson, 2000). Carotenoids like astaxanthin are also known as relevant endogenous antioxidants that can act as scavengers of free radicals, so that protection against lipid oxidation would be favoured and, accordingly, PUFA content and composition maintained (Jensen et al., 1998). The AX value measured in the raw salmon samples (Table 2) was similar to the one obtained by Sheehan et al. (1998). Previous research has also shown that AX can deteriorate either through enzymatic degradation by lipoxygenase and peroxidase or through non-enzymatic degradation by light, heat or oxygen. In the present study, it was observed that the AX content in samples dried at 40 °C was not significantly different to that in fresh samples. However, at drying temperatures of 50 and 60 °C the AX content was significantly higher in the dried salmon fillets compared to that of the fresh samples. This showed that the drying process up to 60 °C did not cause significant destruction of AX but had rather a concentrating effect.

Table 2
Effect of drying temperature on quality index of dried Atlantic salmon (*Salmo solar* L.) fillets.

Quality index	Control	Drying temperature (°C)		
		40	50	60
Astaxanthin (μg/g)	17.25 ± 2.27[a]	15.60 ± 3.49[a]	30.35 ± 4.07[b]	24.20 ± 8.31[b]
α-Tocopherol (ppm)	21.02 ± 0.34[a]	10.48 ± 1.01[b]	18.52 ± 1.81[c]	12.36 ± 2.56[b]
γ-Tocopherol (ppm)	7.34 ± 1.53[a]	3.75 ± 0.74[b]	7.33 ± 0.93[a]	6.29 ± 1.02[a]
Palmitic acid (% area)	21.24 ± 0.50[a]	18.58 ± 0.40[b]	17.90 ± 0.25[c]	17.30 ± 0.20[c]
EPA (% area)	11.17 ± 0.34[a]	9.10 ± 0.31[b]	8.90 ± 0.35[b]	9.10 ± 0.18[b]
DHA (% area)	9.46 ± 0.33[a]	8.30 ± 0.13[b,c]	8.60 ± 0.57[b]	7.60 ± 0.47[c]
TBA-i (mg malonaldehyde/kg sample)	0.24 ± 0.02[a]	2.01 ± 0.04[b]	1.65 ± 0.03[c]	1.47 ± 0.05[d]
Anisidine value (meq/kg)	2.23 ± 0.92[a]	9.07 ± 3.27[b]	5.43 ± 0.24[c]	4.85 ± 1.87[c]

*Data are expressed as average ± standard deviation in three replicates. Values in the same row having the same letter (a, b and c) for each parameter are not significantly different at a confidence level of 95%.

4.5. α- and γ-tocopherol

Tocopherol isomer assessment is shown in Table 2. The content of these compounds provided some differences throughout the experiment that could be explained rather as a result of inherent differences within the fish samples than as a consequence of the drying process. Both α- and γ-isomers of tocopherol showed similar results to those obtained in other studies of cultivated fish species such as rainbow trout and Atlantic salmon (Jensen et al., 1998; Nordgarden, Ørnsrud, Hansen, & Hemre, 2003). In the present experiment, α-tocopherol decreased significantly ($p < 0.05$) after drying at all three temperatures, whereas γ-tocopherol decreased only significantly ($p > 0.05$) at the drying temperature of 40 °C. At 50 and 60 °C there were no significant differences in γ-tocopherol content compared with the fresh fish fillet sample, which may be attributed to shorter exposure to processing compared to drying at 40 °C. The lowest content of α-tocopherol was also found in the samples dried at 40 °C, which may be due to degradation due to longer exposure time. On the other hand, it is interesting to note that α-tocopherol content was higher in samples dried at 50 °C that those dried at 60 °C. In this study, an explanation based on observations can be given. At 60 °C more melted fat was observed on the surface of the sample. Considering a decrease in viscosity of the lipid phase with temperature, a flowing out of the melted fat from the muscle tissues at 60 °C may be responsible for the greater loss of the liposoluble α-tocopherol.

4.6. Palmitic acid, EPA and DHA

The compositional or technological research, accounting for studies of fatty acid distribution, appears to be scarce (Aubourg et al., 2007). Palmitic acid, EPA and DHA composition of the raw material is shown in Table 2. This composition was similar to that observed in farmed and wild Atlantic salmon (Jensen et al., 2012) and Coho salmon (Aubourg et al., 2005), where these fatty acids are among the most abundant. During drying of the Atlantic salmon (*Salmo solar*) fatty acids composition of the fillets showed slight changes (Table 2). The content of palmitic acid, EPA (C20:5) and DHA (C22:6) was significantly higher in the raw fillets compared to the dried fish samples ($p < 0.05$). The palmitic acid content further decreased significantly with increase of drying temperature ($p < 0.05$), whereas content of the typical fish fatty acids remained practically unchanged (EPA) or showed only a slight decrease (DHA). However, in a study on grass carp, Wu and Mao (2008) showed that drying processes significantly increased the relative contents of palmitic acid, EPA and DHA ($p < 0.05$). Therefore, under the drying conditions of this assay fatty acids of the fresh salmon fillets were only slightly oxidised.

4.7. Thiobarbituric acid index

Secondary lipid oxidation compounds formed during drying were measured by the thiobarbituric acid index, (TBA-i). An increase in this value was observed in the salmon samples after drying at all temperatures (Table 2), showing a significant difference between the fresh and the dried fish samples ($p > 0.05$). The formation of secondary oxidation compounds has proved to be an interesting tool to assess the chemical changes produced as a result of the drying process. Similar results were observed for smoked-dried and sun-dried flesh of two fish species (*Silurus glanis* and *Arius parkii*), where an increase in TBA-i value was observed (Ali, Ahmadou, Mohamadou, Saidou, & Tenin, 2011). On the other hand TBA-i decreased with increase in drying temperature, so that this index can be useful in order to evaluate the effect of the air drying process. At higher temperature shorter drying time is achieved. Since TBA-i decreased as drying temperature increased from 40 to 60 °C, it can be assumed that exposure time during drying would have a greater effect on formation of secondary lipid oxidation compounds in the dried fish samples.

4.8. Anisidine value

The anisidine value was also used as a measure of secondary oxidation products. In Table 2 the effect of drying temperature on anisidine value of dried Atlantic salmon (*Salmo salar*) fillets is shown. Drying significantly increased the anisidine values in the dried fish samples ($p < 0.05$), being higher at all temperature treatments from 40 to 60 °C. This is a clear indication of the rapid decomposition of hydroperoxides into secondary oxidation products at high temperatures. These data indicate that hydrolytic and oxidative degradations took place during drying. Hydroperoxides are unstable and decompose via fission during dehydration at elevated temperatures to form free radicals and a variety of chemical products, such as alcohols, aldehydes, ketones, acids, dimers, trimers, polymers, and cyclic compounds (Tan, Che Man, Jinap, & Yusoff, 2002). Similar results were observed during hot air and microwave drying of grass carp fillets (Wu & Mao, 2008). The anisidine value could therefore be reliable and meaningful for evaluating the fat quality in dried Atlantic salmon fillets. Similar to TBA-i, the anisidine value of the dried fillet samples decreased as drying temperature increased from 40 to 60 °C, which confirmed the greater effect of exposure time over drying temperature.

5. Conclusions

In conclusion, the results of this work indicate that the drying kinetics together with the reported quality attributes of the dried Atlantic salmon fillets can be used to improve the final characteristics

of the product. Higher moisture diffusivity determined at 60 °C is associated to a shorter drying time, which is favourable for a better quality of the dried fish. Formation of secondary lipid oxidation products, as expressed by the TBA index and the anisidine value, depended during drying more on exposure time than on temperature. The drying temperature was less detrimental than the exposure time on quality characteristics, such as palmitic acid, EPA DHA, α- and γ-tocopherol. Astaxanthin was not deteriorated during drying and therefore the redness of dried sample was maintained. The colour difference was due only to some browning products that occurred mainly at 60 °C. The firmness of dried samples would also increase with temperature. Finally, optimisation of food quality during processing requires more investigation in order to overcome the constraints related to structural and functional food behaviour and their role in the coupling of heat and mass transfer mechanisms.

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