Aukin gæði og stöðugleiki frosinna síldarafurða

Increased quality and stability of frozen herring products

Magnea Karlsdóttir, Matís

Huong Thi Thu Dang, Matís, University of Iceland

María Guðjónsdóttir, University of Iceland

Ásbjörn Jónsson, Matís

Sigurjón Arason, Matís ohf, University of Iceland

Skýrsluágrip Matís ohf
Icelandic Food and Biotech R&D

Report summary

Titill / Title	**Aukin gæði og stöðugleiki frosinna síldarafurða** Increased quality and stability of frozen herring products
Höfundar / Authors	Magnea Karlsdóttir[1], Huong Thi Thu Dang[1,2], María Guðjónsdóttir[2], Ásbjörn Jónsson[1] og Sigurjón Arason[1,2] [1]Matís ohf.; [2]University of Iceland
Skýrsla / Report no.	14-19 *Útgáfudagur / Date:* Ágúst 2019
Verknr. / Project no.	2283
Styrktaraðilar /Funding:	AVS R&D Fund (R 069-14)
Ágrip á íslensku:	Frysting og frostgeymsla er skilvirk aðferð til að viðhalda gæðum og lengja geymsluþol sjávarafurða. Framleiðsla á frosnum afurðum jafnar framboð afurða þar sem veiðar eru árstíðabundnar. Það eru margir þættir sem geta haft áhrif á gæði og stöðugleika frosinna afurða. Þar má meðal annars nefna. ástand hráefnis, vinnsluaðferðir og skilyrði við geymslu og flutning svo fátt eitt sé nefnt. Markmið rannsóknarinnar var að kanna þær breytingar sem eiga sér stað á efna- og eðliseiginleikum frosinna síldarflaka m.t.t. ástand hráefnis við vinnslu og aðstæður í frostgeymslu. Atlantshafssíld var unnin fyrir og eftir, og flökin geymd annars vegar við stöðugar geymsluaðstæður (- 25 °C) og hins vegar við óstöðugar aðstæður (við -25 °C í 2 mánuði, svo -12 °C í mánuð og svo aftur við -25 °C út geymslutímann). Til að rannsaka stöðugleika og eðliseiginleika afurðanna var m.a. mælt vatnstap (drip), suðunýting og litur fyrir einstök flök, en samtímis voru mæld bæði í ljósum og dökkum fiskvöðva vatnsheldni, pH, efnasamsetning, fitusýru-samsetning, ensímvirkni og þránun. Rannsóknin sýndi að það er mikilvægt fyrir sjávarútveginn að tryggja samræmda og rétta hitastýringu þegar afurðir eru geymdar í frosti. Vinnsla og frysting fyrir dauðastirðnun, samhliða stöðugum geymsluaðstæðum., hefur jákvæð áhrif á gæði og stöðugleika síldarfalka. Auk þessa, þá staðfesti rannsóknin að fituríki vöðvi síldarinnar, oft nefndur dökki vöðvinn, er mjög viðkvæmur fyrir þránun. Til þess að lengja geymsluþol frosinna síldarflaka er mælt með því að þessi vöðvi sé fjarlægður samhliða roðflettingu (e. *deep skinning*).
Lykilorð á íslensku:	Síld; frostgeymsla; hitastigssveiflur; gæðarýrnun; dauðastirðnun

Summary in English:	Freezing and frozen storage has proven to be an effective method to preserve and prolong the storage life of seafood products. Production of frozen products provides all year around product availability although the catching is seasonal. There are several factors that can affect the quality and stability of frozen fish products, including the state of the raw material, processing methods and storage conditions.
	The aim of the study was to explore how the physicochemical properties of frozen herring fillets are affected regarding the state of the raw material during processing as well as storage conditions. Atlantic herring was processed and frozen pre- and post-rigor and stored at stable (-25 °C) and abused storage conditions. To investigate the storage stability and physical properties of the fillets, thawing drip, cooking yield and colour were evaluated, as well as proximate composition, fatty acid composition, pH and lipid degradation of the light and the dark muscle.
	The study demonstrated the importance of stable and controlled temperature during storage and transportation of frozen herring products. Processing and freezing pre-rigor, in combination with stable storage conditions, was shown to be beneficial in terms of preventing lipid oxidation, as well as reducing thawing loss and maintaining the cooking yield of the herring fillets.
English keywords:	Atlantic herring; frozen storage; temperature abuse; quality degradation; rigor mortis

1 INTRODUCTION

1.1 Atlantic herring

Atlantic herring (*Clupea harengus*) is a pelagic fish and found on both sides of the North Atlantic Ocean. In the Northeast Atlantic Ocean it occurs from the Bay of Biscay in the south to Spitzbergen and Novaya Zemlya in the north, while in the Northwest Atlantic Ocean it occurs from the coast of Maine northwards (Stroud, 2001). Herring is a popular fatty fish and is usually frozen before being processed. Herring is not normally gutted at sea, since it is impractical to handle the large numbers of small fish coming aboard in a short time; chilling or freezing soon after capture is therefore the most important to prevent spoilage (Stroud, 2001).

The chemical composition of herring varies considerably with season, catching ground, sexual maturation and feeding pattern (Nielsen *et al*., 2005). The lipid content of herring can be less than 1% immediately after spawning, and more than 20% as spawning time approaches again. The herring as a food has a high energy value since most of the lipids are stored in the muscles (Stroud, 2001). The herring muscle is very rich of valuable omega-3 fatty acids and antioxidants (Hølmer 1993; Hamre *et al*., 2003 and Ackman 1980). The omega-3 fatty acids in herring are beneficial for human health. On the other hand, polyunsaturated fatty acids are susceptible to oxidation and therefore represent a risk of developing rancid off-flavours (Hølmer 1993; Hultin 1994; Undeland *et al.*, 1998, 1999).

1.2 Effects of temperature abuse on fish quality

Freezing is one of the most common procedures applied to preserve physicochemical properties and to prolong storage life of fish, especially for fatty fish because of their high

contents of unsaturated fatty acids. The main purpose of freezing is to prevent or slow down bacterial spoilage, enzyme activity and oxidation reactions.

Quality changes of frozen fish during storage can be influenced by several factors including fish species, the biological status of fish at catch, handling on board, temperature and storage time before freezing, freezing rate, frozen storage temperature, temperature fluctuations, thawing procedure and protection from light and oxygen (Nielsen and Jørgensen, 2004). Optimal handling and transport conditions can be used to ensure high quality of the final fish products, which arrive on the market (Ólafsdóttir, 2005). However, temperature fluctuations and abuse through the production and distribution chain can affect the fish quality and safety. These fluctuations mainly occur during handover from one party/function to the next in the value chain (Moureh and Derens, 2000). Studies have shown that unstable temperature accelerates the growth of specific spoilage organisms as well as pathogens (Rediers *et al.*, 2009), which can cause quality and safety problems and moreover economic losses. Furthermore, extracellular formation of ice crystals is accelerated during temperature fluctuations and hence cellular disruption is increased (Hagyard *et al.*, 1993; Bak *et al.*, 1999). Unstable temperature can therefore cause formation of large ice crystals within the fish muscle which have negative effects on its overall quality. Therefore, controlled temperature throughout the whole value chain is necessary to ensure product quality and stability. The effects of the temperature fluctuations and abuse on the product quality are depending on the temperature range. For example, fluctuations around -18 °C has proven to cause worse effects on the product quality than fluctuations around -25 °C due to the fact that the freezing point of sodium chloride is -21.1 °C. For sensitive products, such as fish, even short periods of temperature abuse can lead to significant loss of quality (WFLO, 2008). Temperature fluctuations can lead to an increase in the amount of unfrozen water in the product and

changes in the structure of ice crystals and recrystallization. Thus, physicochemical deterioration increases as a result of enzymatic activity, lipid oxidation and breakdown of the physical structure (Nesvadba, 2008; Benjakul and Bauer, 2001; Karlsdottir *et al.*, 2014; Zaritzky, 2008).

1.3 Effect of rigor mortis on fish quality

Rigor mortis is a process that takes place post-mortem and is responsible for transforming muscle into meat (Kiessling *et al.*, 2006). This transformation is critical for the quality of the final product and is directly affected by both pre- and post-mortem factors (Stien *et al.*, 2006). A growing demand for quality assurance from consumer organizations and retailers makes measuring and documenting the rigor process more and more important (Erikson, 2000).

The onset and development of rigor mortis depends on the fish species, temperature and handling before catching, pre-slaughter stress, the biological status of the fish and temperature of pre-rigor storage, and shows large individual variation (Azam *et al.,* 1989; Jerrett *et al.*, 1998; Skjervold *et al.*, 2001). The stress prior to slaughtering and high storage temperature result in faster and stronger rigor contraction (Skjervold *et al.*, 2001).

The rigor process consists of an initial contractile phase (Tornberg *et al.,* 2000), during which the muscle fibres contract, and a second stiff phase that a permanent binding of the contractile proteins myosin and actin happens. This process can be influenced by post-mortem temperature. In wild-caught fish, in which pre-slaughter stress and temperature at death are difficult to control, rigor takes usually place within short time after catching. Storage temperature is accepted as being a major factor affecting the rate of quality loss and storage life (Dawood *et al.,* 1986). Hence, reducing the fish temperature after catching as soon as possible is an effective way to delay the onset of rigor mortis and to prolong the rigor process.

2 STUDY OBJECTIVES

The aim of the study was twofold. Firstly, to explore the influence of time and temperature during frozen storage on lipid deterioration of herring by comparing the effect of temperature fluctuations and abuse during frozen storage, as can be expected during transportation, on the physicochemical characteristics and lipid stability of herring fillets. Secondly, to investigate the effect of pre- and post-rigor processing.

This study forms part of PhD. research by Houng Thi Thu Dang and the results have been published in reviewed scientific papers. Hence, only the most relevant results and observations are summarized here. More detailed results can be observed in the before mentioned papers (Dang *et al.*, 2017 and Dang *et al.*, 2018).

3 MATERIALS AND METHODS

3.1 *Raw material and experimental design*

Atlantic herring (*Clupea harengus*) was caught off the Southwest coast of Iceland in November 2014. The fish processed pre-rigor was caught by freezing trawler. After being caught and pumped into the hold, the herring was quickly cooled down to -1.5 °C in a tank with refrigerated seawater and within four hours from catch they were graded, headed, gutted, filleted, packed and frozen without glazing. The fish which processed post-rigor was caught by fresh fish trawler. After catching and pumping into the hold, the herring was stored in tanks with refrigerated seawater at -1.5 °C for 2–3 days. The fish was then transported and pumped to the factory for processing and freezing. Both groups were frozen into 16 kg blocks in an automatic plate freezer (Skaginn, Akranes, Iceland), and then stored at -25 °C.

Upon arrival at the laboratory, the blocks were divided into four equal sized parts, packed in plastic bags and put into waxed carton boxes. The raw materials were then distributed into two treatments: the first was stored at stressed/abused temperature conditions (-12 °C) for 1 month, followed by stable storage at -25 °C for the remaining storage period; the second was stored at a stable temperature of -25 °C for up to 14 months (Figure 1).

These conditions were set up to imitate the increased temperatures, which are a common problem during loading and unloading processes during frozen storage and transportation, especially during intercontinental transport. The temperature is also often not uniform within the container, and the temperature can go up to temperatures of -12 °C or even higher, on chosen locations in poorly temperature controlled containers. Also, even though processors have temperature monitoring systems, few companies use them to actively control the storage conditions in real time. Moreover, temperature stress warmer than -12°C lead to significant loss quality of fish (WFLO, 2008). For these reasons, the stressed temperature conditions were designed to simulate these common conditions which frozen products are often exposed to during transportation and storage.

Prior to analysis, samples were thawed at refrigerated temperatures (4±1 °C) for 24h. After thawing, the light and the dark muscles were manually separated, minced and used for all analyses. As a result of the potential for sample variation in the fish block, at each sampling point, each sample pack was divided into three groups, each group containing 15 fillets (the average weight per fillet was 40–60g). Chemical analyses were performed separately on the light and the dark muscle in triplicate (n=3) per group for lipid hydroperoxides and thiobarbituric acid reactive substances; duplicates (n=2) per group were analysed for water

content, total lipids content, pH, phospholipids content, free fatty acid content and fatty acid composition.
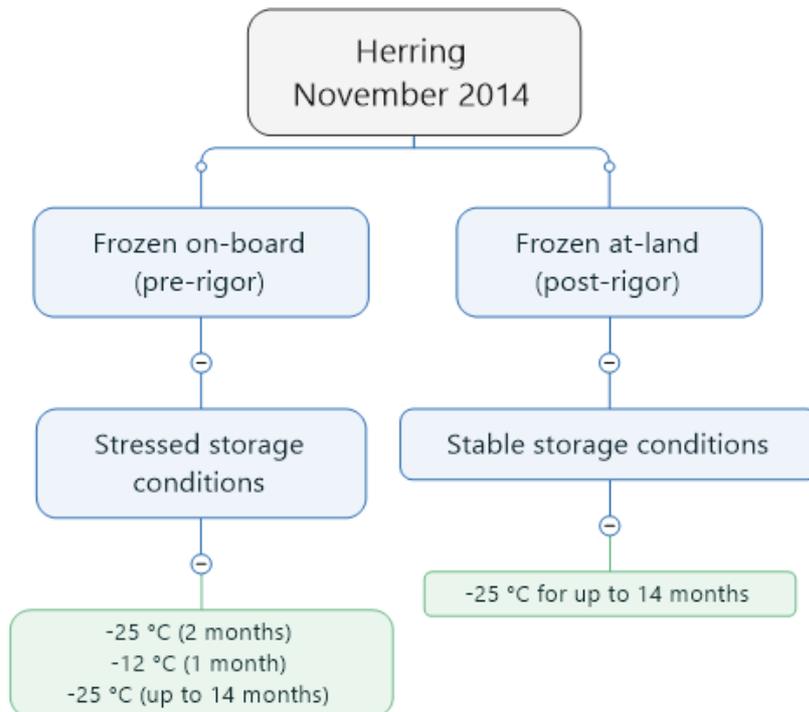
Figure 1. Experimental design.

3.2 Water, total lipids and phospholipid content

Water content was determined by drying 5 g of minced sample at 102 °C–104 °C for 4 h (ISO, 1999). The results were calculated as the weight loss during drying as a percentage of the wet muscle.

Total lipids (TL) of the samples were extracted from 25 g of samples (the weight was adjusted according to the water content of each samples) with methanol/chloroform/0.88% KCl (at 1/1/0.5, v/v/v) according to the method of Bligh and Dyer (1959). The lipid content was determined gravimetrically, and results were expressed as a percentage of the wet muscle.

Phospholipids (PL) content of the fish muscles was determined on the TL extracts by using a colorimetric method (Stewart, 1980). Phosphatidylcholine in chloroform (1 mg/mL) was prepared for a standard curve, and results were expressed as g phospholipids/100 g TL.

3.3 Fatty acid composition

The fatty acid composition of the sample was determined on the TL extracts by gas chromatography (Varian 3900 GC, Varian, Inc., Walnut Creek, CA, USA). The methylation of fatty acids was carried out according to the AOAC Ce 1b-89 (1998) method. The programme was based on the AOAC 996.06 (2001) method. Results were expressed as a percentage of TL.

3.4 Free fatty acid content

Free fatty acids (FFA) content was determined by the Lowry and Tinsley (1976) method with modifications described by Bernardez *et al.* (2005). The absorbance of the solution was read at 710 nm (UV-1800 spectrophotometer, Shimadzu, Japan) and compared to a standard curve prepared from oleic acid in a concentration range of 2–14 µmol. Results were expressed as g FFA per 100 g TL.

3.5 Lipid oxidation

Lipid hydroperoxides (PV), a primary oxidation product, was determined by the ferric thiocyanate method (Shantha & Decker, 1994) with modifications according to Romotowska *et al.* (2016), except that the lower chloroform layer containing lipids was collected (0.2 mL for the dark and 0.5 mL for the light muscle) and mixed with 0.8 and 0.5 mL of the chloroform:methanol (1:1) solution for the dark and light muscle, respectively. The results were expressed as µmol lipid hydroperoxide per kg of the sample (µmol/kg muscle).

Thiobarbituric acid reactive substances (TBARS), secondary oxidation products, were determined by the method of Lemon (1975) with modifications as described by Romotowska *et al.* (2016), except that an amount of 0.8 and 0.5 mL thiobarbituric acid (0.02 M) were mixed with 0.2 mL collected supernatant for the dark and 0.5 mL for the light muscle, respectively. The results were expressed as μmol malondialdehyde diethyl acetal per kg of wet muscle (μmol MDA/kg muscle).

3.6 pH, thawing loss and cooking yield

The muscle pH was measured by inserting the pH probe (Radiometer PHM80 Portable pH meter, Denmark) directly into the muscle samples.

Thawing losses were calculated as the ratio (%) of liquid lost during thawing to the weight of the individual frozen blocks.

Cooking yield (CY) was calculated as the ratio (%) of the sample weight after cooking to the weight of the sample before cooking. About 35 g of each fillet (n = 5 from each group) were weighed and heated in a steaming oven (Convotherm OGS 6.10 Combi convection steam oven, Elektrogeräte GmbH, Eglfing, Germany) at 100 °C for 10 minutes. Samples were drained for 10 minutes prior to being weighed again.

3.7 Statistical analysis

Data summaries and statistical analyses were carried out and figures were drawn using the STATISTICA software (Version 10.0, StatSoft, OK 74104 USA), and Microsoft Office Excel 2013 (Microsoft Inc. Redmond, WA, USA). One-way ANOVA, Tukey HSD's test and Student t test for independent samples were performed on the means of each variable. Pearson correlation analysis was performed to find the correlations between variables. Significance of difference

was defined at p<0.05 for all statistical analyses. Principal components analysis (PCA) was

performed using Unscrambler ® (Version 10.2, CAMO ASA, Trondheim, Norway) to identify

similarities and differences between samples. All variables were weighed with the inverse of

the standard deviation to correct for different scales of the variables.

4   RESULTS AND DISCUSSION

In present study, the effects of rigor state and storage conditions on the physicochemical stability of herring during frozen storage were investigated. The results have, as mentioned before, been published in reviewed scientific papers (Dang *et al.*, 2017 and Dang *et al.*, 2018). Hence, only the most relevant results and observations are summarized here.

The rigor state of the herring muscle when processed and frozen, significantly affected its physical and chemical properties during frozen storage. Pre-rigor freezing effectively reduced thawing loss and maintained the cooking yield of herring fillets throughout frozen storage (Figure 2). The differences observed between the pre- and post-rigor herring fillets regarding to thawing loss and cooking yield was most likely due to lower level of protein denaturation in the fish frozen pre-rigor than post-rigor. Previous study on frozen cod showed that the intracellular ice crystals in cod frozen pre-rigor were smaller than those in comparable post-rigor cod (Love, 2001). Hence, pre-rigor frozen cod were found to exhibit less denatured proteins than post-rigor material under the same storage conditions (fish were stored at temperature in the range from -35 to -14 °C) (Love, 1962). Furthermore, in present study, herring frozen pre-rigor on-board the vessel was only pumped once into the hold, while the herring frozen post-rigor on-land was pumped twice. Thus, the post-rigor fish were likely subjected to more physical strain during processing.
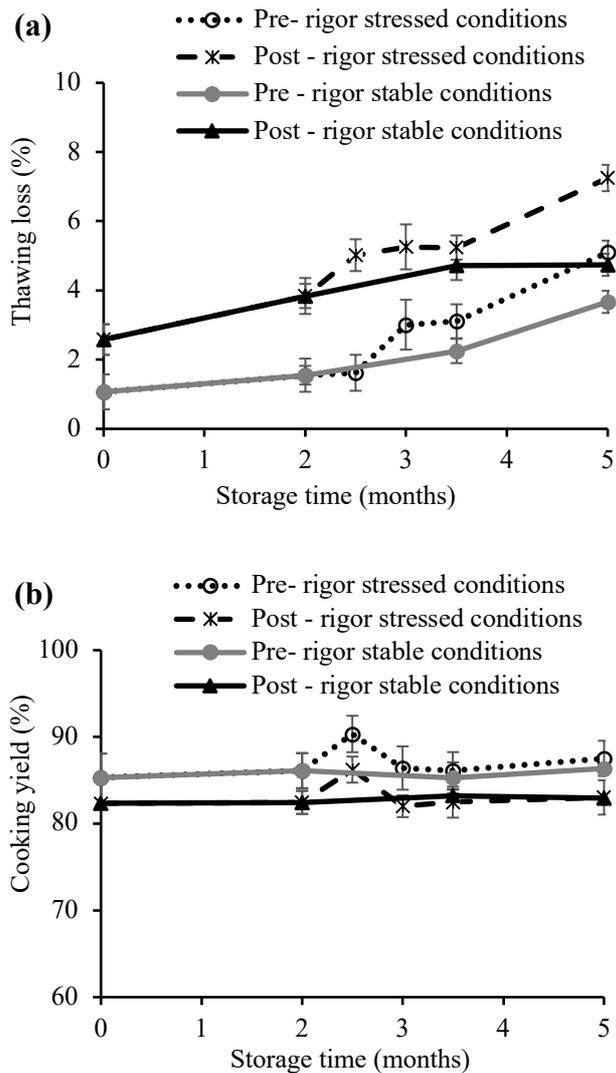
Figure 2. Thawing loss (%) (a), and cooking yield (%) (b) of herring fillets as affected by the state of rigor (pre-rigor or post-rigor) when frozen, at 0, 2, 2.5, 3, 3.5 and 5 months at stressed temperature conditions (samples were stored at -25 °C for 2 months, then stressed at -12 °C for one month, followed by storage at −25°C for the remaining storage duration) and at 0, 2, 3.5 and 5 months at stable conditions (-25 °C) (n = 3, mean ± SD). (Dang *et al.*, 2018).

Processing and freezing of the herring in pre-rigor state were shown to be beneficial in terms of preventing lipid oxidation since the PV and TBARS content in the pre-rigor frozen herring was generally lower than in the post-rigor frozen fillets (Figure 3). However, the state of rigor

did not seem to affect lipid hydrolysis since no difference was observed in the FFA content between the pre- and post-rigor frozen samples (data not shown). The lower lipid oxidation of the pre-rigor frozen fish compared to the post-rigor fish was in agreement with previous findings of Jacobsen and Timm (2001) which suggested that low pH promotes oxidation. Lower pH and higher oxidation were observed in the post-rigor frozen fish were observed in present study.
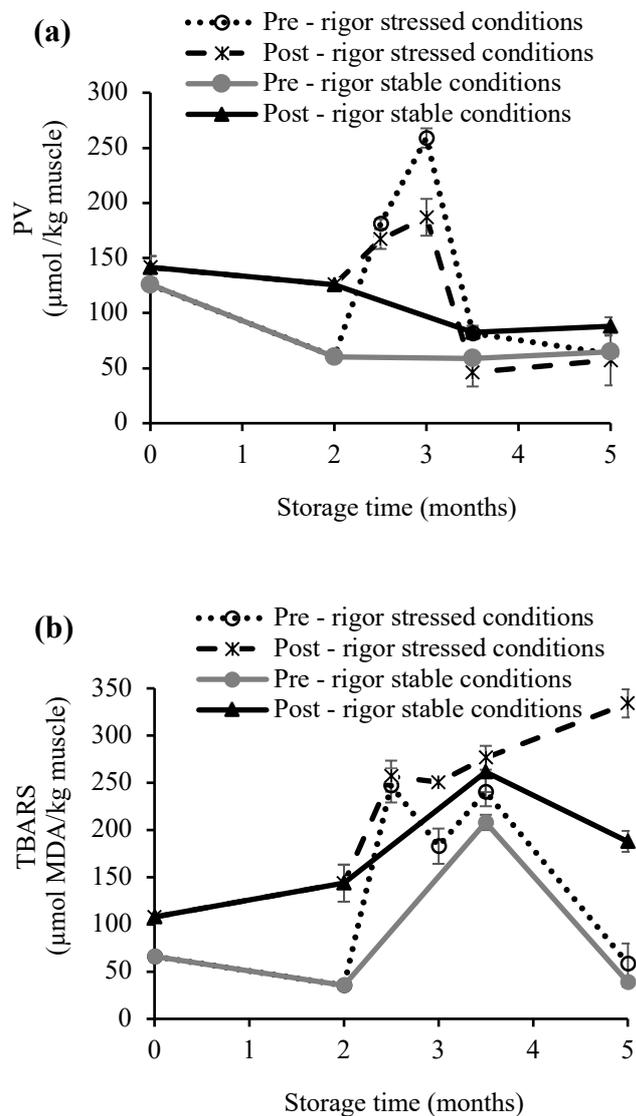
Figure 3. Peroxide value (PV; µmol/kg muscle) (a) and thiobarbituric reactive acid substances (TBARS; µmol MDA/kg muscle) (b) in the dark herring muscle as affected by state of rigor (pre-rigor or post-rigor) when frozen, at 0, 2, 2.5, 3, 3.5 and 5 months at stressed temperature conditions (samples were stored at -25 °C for 2 months, then stressed at -12 °C for

one month, followed by storage at -25 °C for the remaining storage duration) and at 0, 2, 3.5 and 5 months at stable conditions (-25 °C) (n = 3, mean ± SD). (Dang *et al.*, 2018).

Ensuring a stable and uniform temperature in a frozen storage facility or a container during transport are often challenging for the fisheries industry. In this study, herring were stored at abused conditions (-12 °C) for one month, and then restored at stable conditions (-25 °C) to simulate temperature abuses, which are common during loading and unloading processes during frozen storage and transportation. The temperature abuse and instability significantly affected the physicochemical properties of the herring muscle including thawing loss, cooking yield and lipid degradation.

Previous studies have demonstrated that unstable temperature can affect the muscle structure, causing recrystallization and an increase in size of ice crystals within the fish muscle (Pham and Mawson, 1997). Large crystals particularly needle shaped ones, rupture muscle cells, which in turn leads to increased liquid loss during thawing (Pham and Mawson, 1997; Delgado and Sun, 2001; Nesvadba, 2008). Furthermore, temperature abuse during frozen storage speeds up protein denaturation (Kadim and Mahgoub, 2007), leading to increased thawing and cooking loss.

The temperature stress accelerated lipid degradation in present study (Figure 4), but increased temperature is one of the main factors that accelerate lipid oxidation (Shahidi & Zhong, 2010; Karlsdottir *et a.,* 2014). Lipid hydrolysis was also accelerated by temperature abuse. It is known that the action of lipases and phospholipases cause hydrolysis of phospholipids and triglycerides, resulting in accumulation of FFA in the fish muscle (Sista *et*

al., 1997). Therefore, to avoid consequences of lipolysis, ice recrystallization should be minimized by keeping frozen products under stable conditions (Pham and Mawson, 1997).
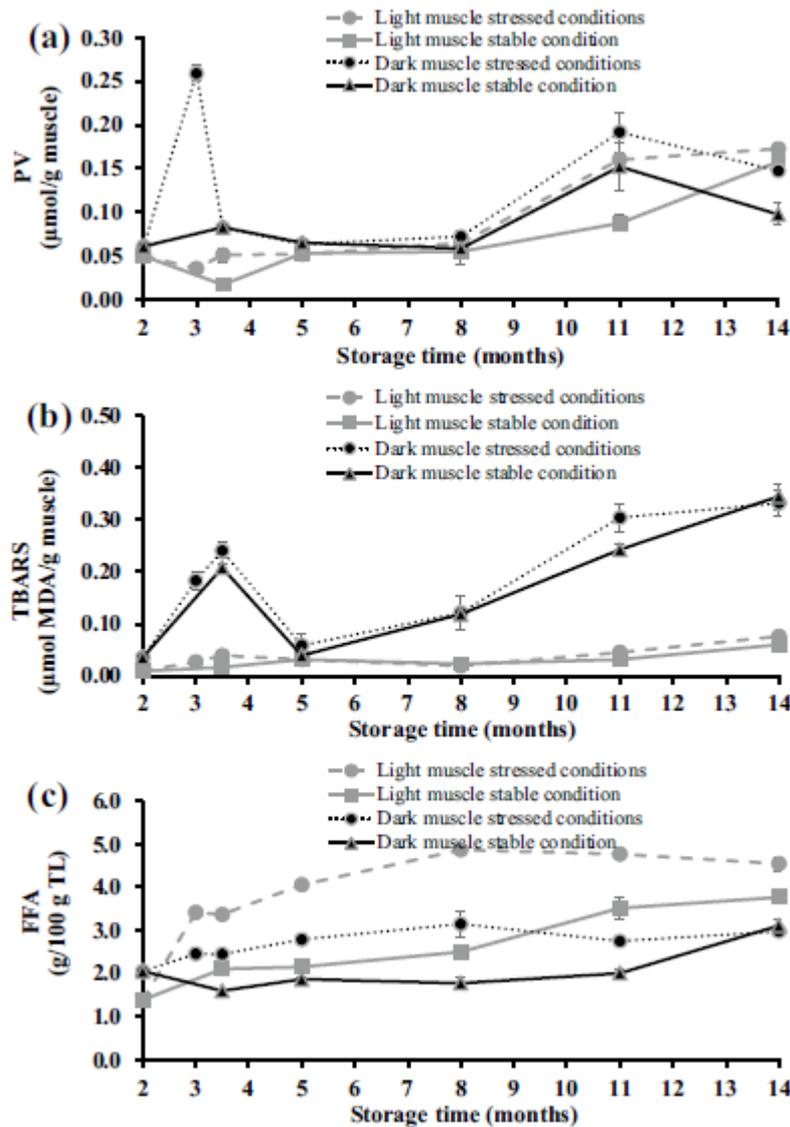
Figure 4. Changes in lipid hydroperoxide content (PV; µmol/g muscle) (a), thiobarbituric acid reactive substances content (TBARS; µmol MDA/g muscle) (b) and free fatty acids content (g FFA/100 g TL) (c) in the light and dark herring muscle after 2, 3, 3.5, 5, 8, 11 and 14 months at stressed temperature conditions (samples were stored at -25 °C for 2 months, then stressed at − 12 °C for 1 month, followed by storage at − 25 °C for the remaining storage duration) and after 2, 3.5, 5, 8, 11 and 14 months at stable conditions (samples were stored at a stable temperature of -25 °C for up to 14 months) (n = 3, mean ± standard deviation). (Dang *et al.*, 2017).

A principal component analysis (PCA) of the measured variables (water, total lipids and phospholipids content, fatty acid composition and lipid deterioration) revealed mainly the difference between the dark and the light muscle of the herring, as well as the effects of storage time and conditions (Figure 5). The light muscle was characterized by a higher water content and amount of PUFA, whereas the dark muscle had a higher lipid content and amount of MUFA. The highest quantity of PUFA in both muscle types was associated with n-3 fatty acids, with DHA being the most abundant, followed by EPA. The light muscle had a significantly higher amount of DHA and EPA compared to those of the dark muscle, indicating a high stability of the n-3 fatty acids in the light muscle of herring. The present work showed that Atlantic herring caught in Icelandic waters had high amount of MUFA and PUFA, and is a good source of DHA for human consumption.
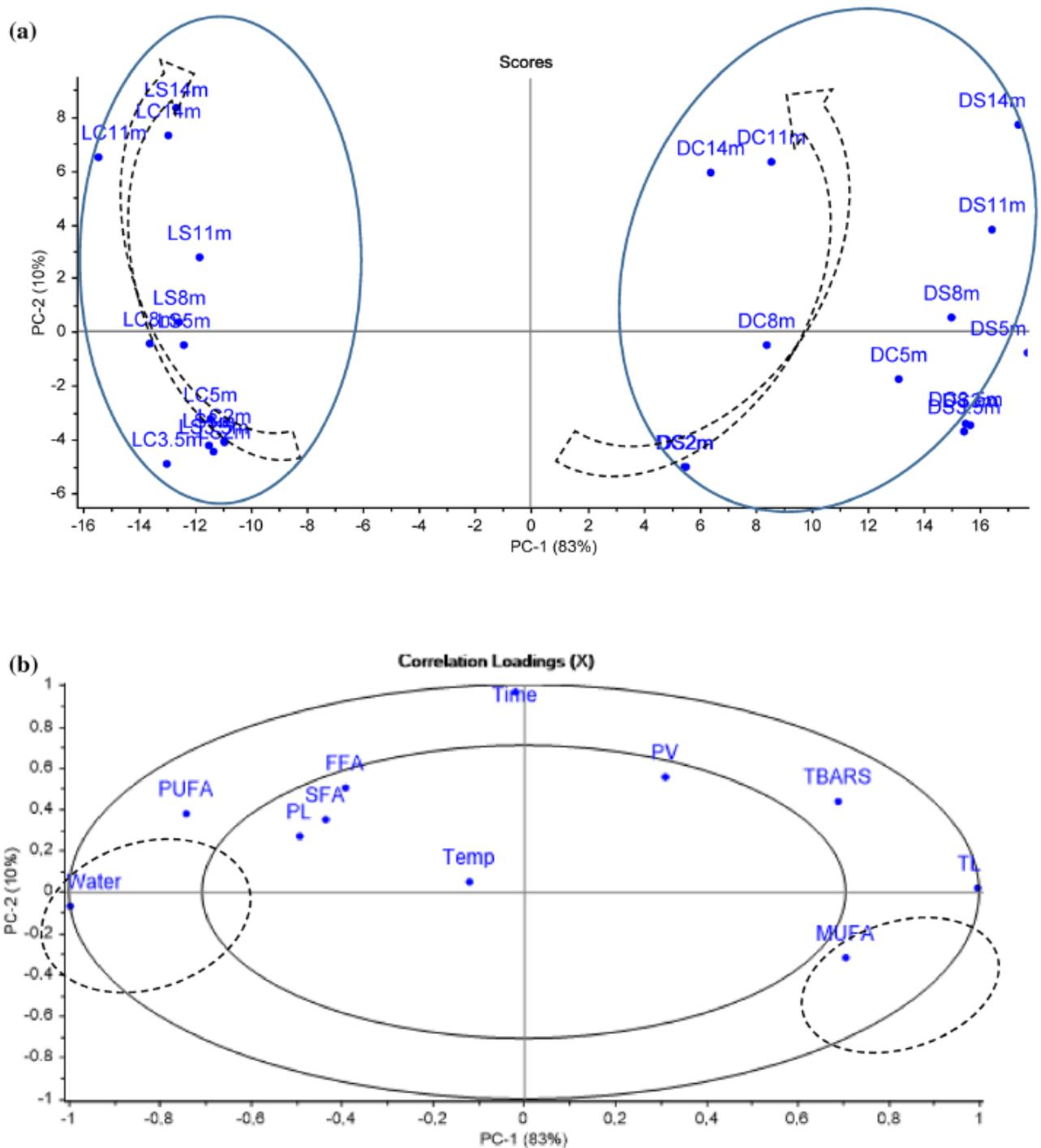
Figure 5. Scores (a) and correlation loadings (b) from PC1 and PC2 from the principal components analysis (PCA) of light and dark muscles of herring. All samples and analytical parameters were used. The first letter D or L indicates the dark and light muscle, respectively. The second letter S or C indicates the storage conditions (stressed and constant temperature, respectively). The number and the last letter (m) of the sample description indicate the storage time in months. (Dang *et al.*, 2017).

According to present study, storage conditions is a key factor regarding quality deterioration of herring fillets during prolonged frozen storage. Pre- and post-rigor processing and freezing, in combination with stable or unstable storage conditions significantly affected the physicochemical characteristics of herring fillets during frozen storage. Pre-rigor freezing effectively reduced thawing loss and maintained the cooking yield of herring fillets throughout frozen storage. Also, the pre-rigor frozen cod were found to exhibit less denatured proteins than post-rigor material under the same storage condition. There were also a different between the dark muscle and white muscle. The light muscle was characterized by a higher water content and amount of PUFA, whereas the dark muscle was associated with n-3 fatty acids, with DHA being the most abundant, followed by EPA. The light muscle had a higher amount of DHA and EPA compared to those of the dark muscle. Present results demonstrate that temperatures should be strictly controlled during storage and transportation of fatty fish. By reducing the temperature to a stable and low temperature of -25 °C, thawing loss was reduced, and lipid oxidation and hydrolysis were minimized. It is therefore important to prevent temperature fluctuation during frozen storage and transportation to extend the storage life of herring fillets. Furthermore, pre-rigor processing and freezing of herring was shown to be beneficial in terms of preventing lipid oxidation, as well as reducing thawing loss and maintaining the cooking yield of the herring fillets.

5 ACKNOWLEDGEMENTS

6 REFERENCES

Ackman, R. G. (1980). Fish lipids. Part 1. In J. Connell (Ed.), Advances in fish science and technology (pp. 86-103). Farnham, Surrey: Fishing News (Books) Ltd.

AOAC (2001). Official method Ce 996.06. Fat (total, saturated, and unsaturated) in food, hydrolytic extraction gas chromatographic method. In D. Firestone (Ed.), Official Methods and Recommended Practices of the AOCS. Champaign, IL: American Oil Chemists' Society.

AOCS (1998). Official method Ce 1b–89. Fatty acid composition by GLC: marine oils. In D. Firestone (Ed.), Official Methods and Recommended Practices of the AOCS. Champaign, IL: American Oil Chemists' Society.

Azam, K., Mackie, I. M., & Smith, J. (1989). The effect of slaughter method on the quality of rainbow trout (*Salmo salar*) during ice storage. International Journal of Food Science and Technology, 24, 69-79.

Bak, L., Andersen, A., Andersen, E., & Bertelsen, G. (1999). Effect of modified atmosphere packaging on oxidative changes in frozen stored cold water shrimp (*Pandalus borealis*). Food Chemistry, 64(2), 169–175.

Benjakul S, Bauer F. (2001) Biochemical and physicochemical changes in catfish (Silurus glanis Linne) muscle as influenced by different freeze–thaw cycles. Food Chemistry 72:207–217

Bernardez, M., Pastoriza, L., Sampedro, G., Herrera, J. J. R., & Cabo, M. L. (2005). Modified method for the analysis of free fatty acids in fish. Journal of Agricultural and Food Chemistry, 53, 1903–1906.

Bligh, E. G., & Dyer, W. J. (1959). A rapid method of total lipid extraction and purification. Canadian Journal of Biochemistry and Physiology, 37(8), 911–917.

Dang, H. T. T., Gudjónsdóttir, M., Karlsdóttir, M. G., Van Nguyen, M., Romotowska, P. E., Tómasson, T., & Arason, S. (2017). Influence of Temperature Stress on Lipid Stability of Atlantic Herring (Clupea harengus) Muscle During Frozen Storage. Journal of the American Oil Chemists' Society, 94(12), 1439-1449.

Dang, H. T. T., Gudjónsdóttir, M., Ren, D., Karlsdóttir, M. G., Minh, V. N., Tómasson, T., & Arason, S. (2018). Effects of pre and postrigor freezing and temperature stress during frozen storage on physicochemical stability of Atlantic herring (*Clupea harengus*) muscle. Journal of Food Processing and Preservation, 42(9), e13754.

Dawood, A. A., Roy, R. N., & Williams, C. S. (1986). Effects of delayed icing on the storage life of rainbow trout. Journal of Food Technology, 21(2), 15-166.

Delgado, A. E., & Sun, D. W. (2001) Heat and mass transfer models for predicting freezing processes - a review. Journal of Food Engineering, 47, 157–174.

Erikson, U. (2000). Rigor measurements. (K. C. S, & W. D. P, Eds.) Cornwall, UK: Fishing News Books.

Hagyard, C., Keiller, A., & Cu, T. (1993). Frozen storage conditions and rancid flavour development in lamb. Meat Science, 35(3), 305–312.

Hamre, K., Lie, Ø & Sandnes, K. (2003). Seasonal development of nutrient composition, lipid oxidation and colour of fillets from Norwegian springs pawning herring (*Clupea harengus L.*). Food Chemistry, 82, 441-446.

Hølmer, G. (1993). Mechanisms of oxidation. Autooxidation and enzymatic oxidation. In: Antioxidants, free radicals and polyunsaturated fatty acids in biology and medicine. Diplock, A.T., Gutteridge, J.M.C. and Shukla, V.K.S. (eds.) IFSC Centre A/S, Lystrup, Denmark.

Hultin, H. O. (1994). Oxidation of lipids in seafoods. In F. Shahidi & J. R. Botta (Eds.), Seafoods Chemistry, Processing, Technology and Quality (pp. 49-74). London: Blackie A&P.

ISO. (1999). Animal feeding stuffs. Determination of moisture and other volatile matter content (6496). Geneva, Switzerland: International Organization for Standardization.

Jacobsen, C., & Timm, M. (2001). Oxidation in fish oil enriched mayonnaise: Ascorbic acid and low pH increase oxidative deterioration. Journal Agriculture Food Chemistry, 49, 3947–3956.

Jerrett, A. R., Holland, A. J., & Cleaver, S. E. (1998). Rigor contractions in rested and partially exercised chinook salmon white muscle as affected by temperature. Journal of Food Science, 63(1), 53-56.

Kadim, I.T. & Mahgoub, O. (2007). Postharvest handling of red meat. In: Rahman, M.S. (Ed.), Handbook of Food Preservation, second ed. CRC Press, Boca Raton, FL, pp. 173–202

Karlsdottir, M., Sveinsdottir, K., Kristinsson, H., Villot, D., Craft, B., & Arason, S. (2014). Effects of temperature during frozen storage on lipid deterioration of saithe (*Pollachius virens*) and hoki (*Macruronus novaezelandiae*) muscles. Food Chemistry, 156(8), 234-242.

Kiessling, A., Stien, L. H., Torslett, Ø., Suontama, J., & Slinde, E. (2006). Effect of pre- and post-mortem temperature on rigor in Atlantic salmon muscle as measured by four different techniques. Aquaculture, 259, 390-402.

Lemon, D. W. (1975). An improved TBA test for rancidity. New Series Circular No. 51, Halifax Laboratory, Halifax, Nova Scotia.

Love, R. M. (1962). Protein denaturation in frozen fish. VII.—Effect of the onset and resolution of rigor mortis on denaturation. Journal of the Science of Food and Agriculture, 13(10), 534–545.

Love, R. M. (2001). Gaping of fillets. Ministry of Technology. Torry Research Station advisory note No. 61. Aberdeen.

Lowry, R. R., & Tinsley, I. J. (1976). Rapid colorimetric determination of free fatty acids. Journal of the American Oil Chemists' Society, 53(7), 470–472.

Moureh, J., & Derens, E. (2000). Numerical modelling of the temperature increases in frozen food packaged in pallets in the distribution chain. International Journal of Refrigeration, 23(7), 540–552.

Nesvadba, P. (2008) Thermal properties and ice crystal development in frozen foods. In J. A. Evans (Ed.). Frozen food science and technology. Oxford: Blackwell.

Nielsen, D., Hyldig, G., Nielsen, J., & Nielsen, H. H. (2005). Lipid content in herring (*Clupea harengus L.*)-influence of biological factors and comparison of different methods of analyses: solvent extraction, Fatmeter, NIR and NMR. LWT - Food Science and Technology, 38(5), 537-548.

Nielsen, M., & Jørgensen, B. (2004). Quantitative Relationship between Trimethylamine Oxide Aldolase Activity and Formaldehyde Accumulation in White Muscle from Gadiform Fish during Frozen Storage. Journal of Agricultural and Food Chemistry, 52(12), 3814–3822.

Ólafsdóttir, G. (2005). Volatile compounds as indicators in fish during chilled storage: Evaluation of microbial metabolites by an electronic nose. Reykjavik: University of Iceland.

Pham, Q.T. & Mawson, Q.F. (1997). Moisture migration and ice recrystallization in frozen foods. In: Erickson, M.C., Hung, Y.C. (Eds.), Quality in Frozen Food. Chapman & Hall, New York, US, pp. 67–91.

Rediers, H., Claes, M., Peeters, L., & Willems, K. (2009). Evaluation of the cold chain of fresh-cut endive from farmer to plate. Postharvest Biology and Technology, 51(2), 257-262.

Romotowska, P. E., Karlsdottir, M. G., Gudjonsdottir, M., Kristinsson, H. G., & Arason, S. (2016). Seasonal and geographical variation in chemical composition and lipid stability of Atlantic mackerel (*Scomber scombrus*) caught in Icelandic waters. Journal of Food Composition and Analysis, 49, 9–18.

Shahidi, F. & Zhong, Y. (2010). Lipid oxidation and improving the oxidative stability. Chem. Soc. Rev. 39, 4067–4079.

Shantha, N. C., & Decker, E. A. (1994). Rapid, sensitive, iron-based spectrophotometric methods for determination of peroxide value of food lipid. Journal of AOAC International, 77(2), 421–424.

Sista, R.V., Erickson, M.C. & Shewfelt, R.L. (1997). Quality deterioration in frozen foods associated with hydrolytic enzyme activities. In: Erickson, M., Hung, Y.C. (Eds.), Quality in Frozen Food. Chapman and Hall, New York, US, pp. 101–110.

Skjervold, P. O., Fjæra, S. O., Østby, P. B., & Einen, O. (2001). Livechilling and crowding stress before slaughter of Atlantic salmon (*Salmo salar*). Aquaculture, 192, 2-4.

Skjervold, P. O., Rørå, A. M., Fjæra, S. O., Vegusdal, A., Vorre, A., & Einen, O. (2001). Effects of pre-, in-, or post-rigor filleting of live chilled Atlantic salmon. Aquaculture, 194, 315-326.

Stewart, J. C. (1980). Colorimetric determination of phospholipids with ammonium ferrothiocyanate. Analytical Biochemistry, 104, 10–14.

Stien, L. H., Suontama, J., & Kiessling, A. (2006). Image analysis as a tool to quantify rigor contraction in pre-rigor-filleted fillets. Computers and Electronics in Agriculture, 50, 109-120.

Stroud, G. D. (2001). The Herring. FAO Fisheries technical paper - T57. Retrieved from www.fao.org/wairdocs/tan/x5933e/x5933e01.htm

Tornberg, E., Walgren, M., Brøndum, J., & Engelsen, S. B. (2000). Prerigor conditions in beef under varying temperature and pH falls studied with rigormeter NMR and NIR. Food Chemistry, 69, 407-418.

Undeland, I., Ekstrand, B., & Lingnert, H. (1998). Lipid oxidation in herring (*Clupea harengus*) light muscle, dark muscle, and skin, stored separately or as intact fillets. JAOC, 75(5), 581-590.

Undeland, I., Hall, G., & Lingnert, H. (1999). Lipid Oxidation in Fillets of Herring (*Clupea harengus*) during Ice Storage. Journal of Agricultural and Food Chemistry, 47(2), 524-532.

Undeland, I., Stading, M., & Lingnert, H. (1998). Influence of skinning on lipid oxidation in different horizontal layers of herring (*Clupea harengus*) during frozen storage. Journal of the Science of Food and Agriculture, 78, 441-450.

WFLO-World Food Logistics Organization. (2008). Frozen foods handling & storage. Retrieved March 8 2015, from https://www.gcca.org/wp-content/uploads/2012/09/FrozenFoodsHandling.pdf

Zaritzky NE (2008) Frozen storage. In: Evans JA (ed) Frozen food science and technology. Blackwell, Oxford