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Overview on fish quality research. Impact of fish handling, processing, storage and logistics on fish quality deterioration

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Report summary

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Titill / Title	**Overview on fish quality research - Impact of fish handling, processing, storage and logistics on fish quality deterioration**
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Ágrip á íslensku:	Stutt geymsluþol fisks er takmarkandi þáttur í útflutningi ferskra fiskafurða frá Íslandi. Fjallað er um upphafsgæði hráefnis, aðferðir við kælingu, vinnslu, pökkun og aðstæður við geymslu og flutning ásamt áhrifum allra þessara þátta á ferskleika og geymsluþol fiskafurða. Hitastigsstýring er mjög mikilvæg til að viðhalda gæðum fisks. Forkæling flaka í vinnslu hefur verið notuð til að lækka hitastig fyrir pökkun. Samt sem áður verður að gæta þess að tæknin við forkælingu stofni ekki örveruástandi vörunnar í hættu og verði þar með til að hún skemmist fyrr eftir pökkun. Samverkandi áhrif sem verða af ofurkælingu og loftskiptri pökkun (MAP) geta lengt ferskleikatímabil og geymsluþol fiskafurða verulega. Ennfremur eru pökkunaraðferðir skoðaðar þar á meðal nýjar umhverfisvænni pakkningar. Að lokum er rætt um áhrif flutningaleiða ferskra fiskafurða á lokagæði þeirra til neytenda á markaði. Skýrsla þessi veitir yfirsýn yfir rannsóknir Rannsóknastofnunar fiskiðnaðarins og Matís ohf síðastliðna þrjá áratugi á viðfangsefninu. Ennfremur er rætt um hvernig þessar niðurstöður geti nýst fiskiðnaðinum.
Lykilorð á íslensku:	*Fiskur – Ferskleiki – Geymsluþol - Gæði - Kæling - Undirkæling - Vinnsla – Pökkun - Flutningsferlar – Hitastigsstýring – Virðisauki*
Summary in English:	The limited shelf life of fresh fish products is a large hurdle for the export of fresh products from Iceland. The influence of raw material quality, cooling methods, processing, packaging and storage conditions on freshness and shelf life extension is discussed. Temperature control is important to maintain fish quality. Pre-cooling of fillets in process has been used to lower the temperature prior to packaging. However, the cooling technique applied should not compromise the microbiological quality of the product and render it vulnerable to faster spoilage post-packaging. Synergism of combined superchilling and modified atmosphere packaging (MAP) can lead to a considerable extension of the freshness period and shelf life of fish products. Further, alternative and environmentally-friendly packaging methods are considered. Finally, the impact of transportation mode of fresh fish products on their resulting quality is examined. This report provides an overview of the findings on fish research carried out at Matís (Icelandic Fisheries Laboratories) over the last three decades and further discusses their practicality for the fish processing industry.
English keywords:	*Fish - Freshness – Shelf life - Quality - Cooling - Superchilling - Processing - Packaging - Logistics - Temperature control – Added value*

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Summary

Fresh fish has a short shelf life even at refrigeration temperatures. The limited shelf life is a large hurdle for the export of fresh fish products from Iceland to mainland Europe or USA. The influence of raw material quality, cooling methods, processing, packaging and storage conditions on freshness and shelf life extension is discussed. Terms, like **freshness period** and **remaining shelf life**, are introduced. They provide a comprehensive and useful insight to understand better the effects of different cooling, processing, storage techniques and other parameters on the quality deterioration of fresh fish products.

Whole fish storage at subzero temperatures may extend shelf life. Modified atmosphere (MA) bulk storage of whole fish under chilled conditions also generally contributes to longer shelf life, but the extent and textural defects resulting may differ among fish species. Selection of proper gas mixture and fish to volume ratio is the key to success to minimise textural defects and depends on the fish species. Much work is still needed in that area to optimise the conditions that lead to high quality products in all aspects. Faster cooling of whole fish in liquid ice has been achieved compared to ice, while further storage has led to different outcomes with respect to product quality. Based on the cold- and warmwater fish trials conducted in Iceland, long-term application of liquid ice upon catch/slaughter may be more beneficial to warmwater/freshwater than coldwater marine fish. However, the use of liquid ice as an efficient cooling medium to quickly lower whole fish temperature prior to iced storage on board should be further investigated, to evaluate its effect on freshness maintenance and shelf life extension of resulting fish products. Temperature control is important to maintain fish quality. Freshness loss in iced, whole fish depends on the species and ambient temperature, being shortest for cod (7-9 days) in comparison to American plaice (10 days) and redfish (14 days). This should be carefully considered during the selection of raw material for processing of fresh products to be exported to foreign markets.

Liquid cooling of fillets has been used to lower the temperature in process prior to packaging. Microbiological quality of the cooling medium, its renewal and temperature control are necessary for success. Otherwise, high microbial load of specific spoilage organisms (SSO, namely *Photobacterium phosphoreum*, pseudomonads and H_2S-producing

bacteria) in the cooling medium will lead to a contamination of the fillets and rapid growth of SSO during storage of the products, especially under temperature abuse. However, the impact of CBC (Combined Blast and Contact) cooling on the temperature maintenance of abused fillets has been found to be considerable when compared to liquid cooling (LC) in process or untreated fillets. CBC cooling can lead to freshness and shelf life extension and is therefore an advantageous method to process fillets to be shipped as fresh products. It provides an additional protection during product shipping where breakage of the cold chain is common. Further, a bacterial growth-retarding effect of CBC processing on some SSO has been observed.

The use of modified atmosphere packaging (MAP) generally resulted in an increased sensory shelf life when compared with traditional ice storage, but the magnitude of the increase depended on various factors such as the composition of the gas mixture, storage temperature, raw material quality and pack size. Lower levels of carbon dioxide are generally used to reduce water loss and textural defects. The use of nitrogen to replace oxygen or vacuum packaging does not lead to as much freshness extension in marine fresh fish products. Vacuum packaging of marine fish products was not found to be a better alternative to MAP. Temperature considerably influenced the efficacy of MAP as a means to extend sensory shelf life of fish fillets. Generally, a 4-5 °C increase in product temperature led to about 50% decrease in freshness period and shelf life. At 7 °C, added value provided by MA-packaging was totally lost. However, synergism of superchilling and MA can lead to a considerable shelf life increase for loins/fillets. Brining (48 h) of cod loins led to a much shorter shelf life for MA-packed loins stored at -2 °C compared to unbrined loins stored under the same conditions. Finally, the effect of freezer storage on the keeping quality and storage life of thawed sea-frozen cod fillets stored at 0-1 °C in air and under MA was evaluated. MA packaging of sea-frozen fillets prolonged shelf life of the thawed fillets compared to air-packed fillets for up to 7 days. With longer freezer storage, the development of *P. phosphoreum,* considered as an important spoilage organism in MA-packaged fish, was delayed during chilled storage upon thawing and the formation of TMA was slower.

Alternative, environmentally-friendly packaging methods are being sought to decrease processing cost. In our study, the use of corrugated plastic (CP) boxes during storage of cod fillets lead to a similar shelf life as for fish packaged in styrofoam boxes. This is explained by the similar average product temperature measured. This implies that export of fish under rather steady conditions, like those encountered in overseas shipping of containers under superchilled temperature, could be done in CP boxes, especially if CBC fillets are involved.

The impact of transportation mode of fresh fish products on their resulting quality is a relevant topic for discussion. Deviations in optimal storage temperature will inevitably lead to decreasing product quality and shortening of shelf life, resulting in a depreciated product value. Temperature control in fresh fish distribution chains is actually mainly a problem for air freight, but not sea freight. This is caused by the fact that more interfaces, where ambient conditions are not well controlled, are found in air logistic chains. The most hazardous parts of this chain are found during the un-chilled storage prior to airplane loading and after unloading at destination. Inevitably, prolonged temperature abuse will affect the product temperature and quality. Indeed, in a trial comparing air and sea freight transportation, the temperature increase in the superchilled fish was greater when transported by air than by sea freight, resulting in a similar microbiological quality of the products at delivery despite the 98-h time difference from processing.

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1. Introduction

Fresh fish fillets have a short shelf life even at refrigeration temperatures. The limited shelf life is a large hurdle for the export of fresh fillets from Iceland to mainland Europe or USA. Transport by sea to major cities in Europe takes about 4-6 days and even longer to the States. For this reason the transport of choice has been air freight. Recent work has shown that storage of superchilled fillets can extend the freshness period (Martinsdóttir *et al*., 2005). Further, combined use of modified atmosphere packaging (MAP) and superchilling can provide further freshness and shelf life extension for both bulk (Lauzon and Martinsdóttir, 2005) and retail (Wang *et al*., 2008) cod products. These findings may contribute to changes required for fish transportation to foreign markets as lower costs, increased stability of the cold chain, environmentally-friendly packaging and shipping methods are among the main driving forces for improvement in the field of logistics. It is also anticipated that these changes may lead to decreased losses of fresh food products.

The use of modified atmosphere (MA) to affect the shelf life of fresh fish is well documented (Tiffney & Mills, 1982; Farber, 1991, Lampila, 1991; Reddy *et al*., 1992; Davis, 1993). Most of the research has focused on MAP of fish products for the retail market. Considerable research has also been carried out on MA storage of whole white fish (Stansby & Griffiths, 1935; Villemure *et al*., 1986; Einarsson & Valdimarsson, 1990) and salmon (Veranth & Robe, 1979; Barnett *et al*., 1982; Trondsen, 1989; Sörensen *et al*., 1990; Bergslien & Meling, 1991). Retail and bulk packaging ("bag in box" system) of fish fillets in modified atmosphere was the subject of several trials at the Icelandic Fisheries Laboratories (IFL) and Matís since 1980.

Other parameters affecting freshness and shelf life are related to raw material handling and storage as well as processing and storage conditions of fresh products. Proper utilization of ice both for lowering the temperature of the catch below 0 °C and maintaining low temperature has proved to be one of the most important factors regarding raw material handling. Well insulated fish tubs and temperature controlled ship holds and raw material reception/storage at the processing plant are also of significance. Since immediate chilling after pre-processing onboard the fishing vessel is of significant importance, slurry ice machines of different types have been developed in the recent years. Some of the currently existing slurry ice brands include e.g. Liquid Ice, Flow Ice, Optim-Ice, Fluid Ice and Bubble Slurry Ice. The thermal and rheological properties along with other characteristics of ice slurries have been thoroughly described (Kauffeld *et al*., 2005).

CBC is a new cooling technique developed by Skaginn hf for fish processing and is called Combined Blast and Contact cooling. The technique involves superchilling the skin side of fillets through a freezer tunnel on a Teflon coated aluminium conveyor belt at a temperature of approximately -8 °C and simultaneously blasting cold air over the fillets, allowing for a rapid lowering of fillet temperature down to -1 °C. Prior to CBC cooling, the fillet goes through a pre-cooler/fluid-ice (about 2.5% salt) to avoid freezing of the flesh in the tunnel. This superchilling process facilitates further handling of the fillets, in particular deskinning and effective cooling prior to packaging. CBC treatment of fillets has been shown to contribute to a slower quality degradation rate at early stage, leading to the extension of the freshness period (Martinsdóttir *et al*., 2005; Olafsdottir *et al*., 2006b).

Currently the main export of fresh fillets from Iceland is in bulk (3-5 kg) rather than in retail. When reaching foreign markets a large part of the fresh fish fillets are packed for retail and sold by supermarkets or distributed to the catering industry. Temperature mapping of chilled supply chains has revealed the importance of thermal protection of wholesale packaging during transport and storage, especially for air transportation chains (Mai *et al*., 2010; Margeirsson *et al*., 2008; Giannakourou *et al*., 2005). Traditionally, rather well insulated expanded polystyrene (EPS) boxes have been utilised for export of Icelandic fresh fish products up to this date. EPS boxes are usually white, manufactured from moulded polystyrene beads and up to 98% of the boxes consist of air pores. The air decreases the density and increases the insulation performance but decreases strength and increases the required storage volume for the boxes. Another type of wholesale fresh fish packaging has been receiving increased international attention because of environmental and economic reasons, i.e. corrugated plastic (CP) boxes. These boxes are produced from extruded corrugated plastic (polypropylene) sheets which are 2 - 3.5 mm in thickness. The CP boxes can be flat packaged, which can save valuable storage space but they have poor strength and studies have indicated that the insulation is worse than for EPS boxes (Anyadiegwu and Archer, 2002; Margeirsson *et al*., 2009). In the United Kingdom, usage of EPS and CP boxes as wholesale fresh fish boxes has been estimated at 14 and 0.6 million boxes, respectively (Seafish Industry Authority, 2009) but the ratio between these two box types may change in the future, bearing the aforementioned environmental and economic reasons in mind.

In this report, an overview will be given on several studies carried out at the Icelandic Fisheries Laboratories (IFL) and Matís ohf over the last three decennies. The report will discuss how the fish processing industry may use the findings obtained as well as provide recommendations to succeed in exporting fresh fishery products from Iceland with added value.

2. Methods for assessing product freshness and shelf life

In this compiled report, the effects of different cooling, processing, storage techniques and other parameters on the quality deterioration of fresh fish products are discussed, mainly for cod products. Many methods have been tested for evaluating fish quality. Sensory methods are still the most satisfactorily way of assessing fish freshness and quality deterioration (Connell, 1975; Howgate, 1982; Ólafsdóttir *et al*., 1997). Freshness evaluation of cooked fillets has been performed using a scheme based on the previous work of Shewan *et al*. (1953), the Torry scheme (Martinsdóttir *et al*., 2001) which implies the assessment of the fish flavour and odour. Quality deterioration of fish is first characterised by the initial loss of the fresh fish flavour (sweet, seaweedy) which is followed by the development of a neutral odour/flavour (Torry score 7 out of 10), leading to the detection of off-odours and -flavours (Torry score 5 out of 10). End of shelf life is usually determined when sensory attributes related to spoilage such as sour, pungent, TMA odour and/or flavour become evident. When the average Torry score is around 5.5, most panellists detect those attributes, which indicates that the sample is approaching the end of shelf life (Martinsdóttir *et al*., 2001).

The initial quality loss is mainly explained by autolytic changes, such as degradation of nucleotides (ATP-related compounds) by autolytic enzymes. The loss of the intermediate nucleotide, inosine monophosphate (IMP), is responsible for the loss of fresh fish flavour. These autolytic changes make catabolites available for bacterial growth (Huss, 1995).

Microorganisms are found in substantial numbers on the skin, gill surfaces and in the intestines of live fish. The numbers and types of microbes present are related to the environment in which the fish are caught (Shewan, 1971). The spoilage pattern of fish may be influenced by various parameters, such as the microbiota acquired during handling and processing, the conditions to which the fish has been subjected during storage and processing, and on the actual chemical composition of the fish. Non-bacterial spoilage is more important in fatty fish where oxidation of the lipids produces off-odours and off-flavours (Shewan and Hobbs, 1967). The deteriorative changes occurring in fish result in the gradual accumulation of certain compounds in the flesh. Quantification of these compounds can provide a measure of the progress of deterioration (Connell, 1975).

Among the chemical indices of spoilage assessed are trimethylamine (TMA), total volatile bases (TVB) and hypoxanthine contents of the flesh. TMA is the best known compound produced during fish spoilage and it is mainly derived from bacterial breakdown of trimethylamine oxide (TMAO) which is an osmolyte naturally found in marine fish (Pedraso-Menabrito and Regenstein, 1990). TMA does not increase much during the early stages of spoilage. It is therefore not considered suitable for discriminating fish stored less than 6 days in ice (Howgate, 1982). TVB content is an alternative to measuring TMA, and includes ammonia, dimethylamine (DMA) and TMA. In coldwater marine fish, reported spoilage bacteria include mainly pseudomonads, *Shewanella putrefaciens* and *Photobacterium phosphoreum* (Gram & Huss, 1996; Olafsdottir *et al*., 2006a,b). *S. putrefaciens* and *P. phosphoreum* both reduce TMAO to TMA, causing the fishy odour but the latter is also CO_2-tolerant (Dalgaard, 1995). *P. phosphoreum* is widespread in the marine environment (Dalgaard *et al*., 1997; Emborg *et al*., 2002). Amino acids are important bacterial substrates for the formation of sulphides and ammonia (Herbert and Shewan, 1975, 1976; Ringø *et al*., 1984). Lerke *et al*. (1967) demonstrated that proteolysis was not of major importance in spoilage of fresh fish. Proteolysis becomes evident in the later stages of spoilage, which appears to be due to derepression as the amino acids are utilised. The increased supply of amino acids to the non-protein nitrogen (NPN) pool resulting from proteolysis supports greater production of ammonia and volatile acids in the later stages of spoilage (Liston, 1982).

Descriptive profiling methods such as generic descriptive analysis (DA) and quantitative descriptive analysis (QDA®), described by Stone and Sidel (2004), are now commonly used at Matís to describe the sensory characteristics of products. These methods may be used to provide a detailed quantitative description of product's sensory characteristics, i.e. appearance, odour, flavour and texture. Each attribute is evaluated on an unstructured scale (left end = 0%, increasing intensity to the right end = 100 %). Most of the attributes used in our sensory evaluation of fish products have been defined and described by the sensory panel during several projects (Sveinsdottir *et al.,* 2003; Ginés *et al.,* 2004; Magnússon *et al*., 2006; Bonilla *et al*., 2007; Wang *et al*., 2008; Martinsdóttir *et al.,* 2009; Sveinsdóttir *et al*., 2010). During the first few days after catch, the average QDA score for sweet flavour of cod is usually above 40 (Wang *et al*., 2008; Lauzon *et al*., 2009). When the sensory score referred to as QDA score is around 30, the sweet flavour is still characteristic for the fish, but when the score has decreased to 25 or below, it indicates that the sweet flavour is no longer evident and the freshness period terminated. When the average QDA score for spoilage related attributes such as sour and TMA odour and/or flavour is above 20 (on the scale 0 to 100), most panellists detect them, which indicates that the sample is approaching the end of shelf life. These limits have been used in determination of maximum shelf life of desalted cod (Magnússon *et al*., 2006), farmed Atlantic salmon (Sveinsdottir *et al*., 2002), Arctic char (Cyprian *et al*., 2008) and cod fillets (Bonilla *et al*., 2007; Lauzon *et al*., 2009).

In this report, the **freshness period** (FP) is therefore defined by the time from processing/packaging until the product loses its freshness characteristics (Torry score of 7 or QDA score ≤ 25 for sweet flavour), while the **remaining shelf life** (RSL) is the time left to reach sensory rejection, as described above. The sum of FP and RSL gives the **sensory shelf life** (SL) of the products. **Total shelf life** (TSL) includes the number of days post-catch prior to processing/packaging and the sensory shelf life of the finished product. This terminology is valuable in the assessment of the effects of different methods on the freshness and quality deterioration of fish products.

3. Main research results

3.1 Freshness deterioration and sensory shelf life of whole, wild and farmed fish

Several storage trials of whole fish have been conducted in the past years. **Table 1** shows the main data for whole, wild fish and **Table 2** for farmed fish stored under different conditions.

Superchilling has been used to cool down whole, gutted fish rapidly but it may provide desirable conditions during fish storage to further slow down bacterial growth and extend shelf life. However, the subzero temperature zone may influence enzymatic reactions, as substrate concentration increases following partial freezing of the water phase, which may lead to an altered spoilage process. In fact, a faster spoilage process was observed for cod when stored at -1.8 °C in air than in ice at 0.6 °C (Einarsson and Lauzon, 1996). Conversely, whole and gutted plaice (*Hippoglossoides platessoides*) had an extended shelf life when stored at -1.7 °C in air (14 days) compared to ice storage at 0.6 °C (12 days) (Lauzon 1997, 2000). Therefore, it appears that fish species variability exists in relation to their sensitivity to superchilling. This may be explained by differences in fish water content and their respective freezing point which has been reported to range from -0.6 to -2.0 °C according to fish species (http://www.msstate.edu/org/silvalab/FREEZING%20.pdf; retrieved 15.09.2010). Indeed, according to Rha (1975), a lean fish fillet containing 80% moisture will have about 10% of its water frozen at -1 °C while a higher moisture content (85%) will result in about 35% frozen water at the same temperature.

Further, temperature fluctuations during superchilled storage may be undesirable as it can lead to alternative slow freezing and melting of ice crystals, and cause muscle cell damage. Upon refreezing, water melted from small ice crystals tends to bathe unmelted crystals, causing them to grow in size (Potter, 1986). Protein denaturation will also result from slow freezing, leading to inferior quality products. Denaturation depends on the concentration of enzymes and other compounds present. Likewise, additional salt may increase acidity and enhance protein denaturation. Thus, as the water is frozen out as pure ice crystals, the higher concentration of compounds in the unfrozen portion will result in an increase in the rate of denaturation. It has been demonstrated that the temperature of maximum activity is in the region of -1 to -2 °C (Johnston *et al.*, 1994). Other quality changes at subzero conditions include flavour and odour deterioration, pigment degradation, enzymatic browning and lipid oxidation.

Table 1. Experimental data of whole fish stored under different conditions

Fish species	Month-year	Known history	Raw mat. age[1] (days)	Packaging type	Packaging conditions	Storage temp. (°C)	Shelf life[2] (days)	Freshness period[3] (days)	Reference
Redfish	**11-00**	**in rigor, ungutted**	**2**	70L box	air, iced	1.9	19	14	Lauzon *et al*. 2001 (Rf 06-01) and Lauzon *et al*. 2002
				6 x 70L box in 2.2 m^3 container	MA= CO_2/N_2: 60/40, iced		21	14	
				6 x 70L box in 2.2 m^3 container (5d)	CO_2/N_2: 60/40, iced, air from d5		21	12	
				6 x 70L box in 2.2 m^3 container (14d)	CO_2/N_2: 60/40, iced, air from d14		22	15	
				70L box	air to d5, iced; MA from d5		21	**16**	
Saithe				plastic boxes for all	air, iced for all	0 °C for all	18		Martins-dóttir *et al*. 2001
Haddock							15		
Plaice							13-14		
Brill							14		
Cod							15		
Shrimp							6		
Herring							8		
Redfish							18		
Sole							15		
Turbot							13		
Plaice	**11-95**	**gutted**	**2.5**	70L box	air	-1.7	14	12	Lauzon 1997 and 2000
				460L tub	air, iced	0.6	12	10	
				stainless steel tub	ice water (1:1)	0.7	14	12	
				70L box	air	9.9	6	5	
Cod	**03-95**	**gutted**	**1**	70L box	air, iced	-1.8±0.2	11.5	(QIM)	Einarsson & Lauzon 1996
						0.6±0.2	14+		
						9.3±0.3	4+		
Cod	**01-90**	**gutted**	**2**	90L box	air, iced	0±1	15	9	Einarsson & Valdimarsson 1990
				3 x 90L box in 2.2 m^3 container	CO_2/N_2: 25/75 and iced	0±1	**23**	**15**	
Cod		**gutted**	4	90L boxes	Iced	0-1	15-16		Magnússon & Martins-dóttir 1995
				thawed, stored in 90L boxes	-25°C, 8 wks	0-1	15-16		
Cod	**11-09**	**gutted**	0	460 L tubs (300 kg fish stored for 10 days)	Iced (0.5 ± 0.8)	3.2 ± 1.0	>10 (11-12*)	7	Magnússon *et al*., 2010
					Liquid ice pre-cooling and re-iced (0.1 ± 0.7)		10	7	
					Liquid ice (insufficient icing) (1.9 ± 0.9)		9-10	7	

1: time in days from catch to trial

2: time in days from catch, based on sensory assessment of cooked fish (Torry score = 5.5) or whole fish (QIM, Quality Index Method)
3: time in days from catch, based on sensory assessment of cooked fish (Torry score = 7)
* Estimated value based on sensory data available

The effects of MA bulk storage on whole, chilled fish were studied for redfish and cod, where extension of the freshness period by 1-2 and 6 days, respectively, was evidenced (**Table 1**). Shelf life extension compared to air-stored fish was also less for MA-stored redfish (2 days) than cod (8 days), probably due to the higher storage temperature used for redfish. This redfish study also evaluated the effects of MA (CO_2/N_2: 60/40) in bulk storage with subsequent modified atmosphere packaging (MAP) of fillets (Lauzon *et al*., 2002). MA bulk storage of whole fish for more than 5 to 10 days did not significantly increase shelf life, and negative effects were observed in texture and overall appearance. MAP of fillets processed from 10-day MA bulk stored fish showed a modest increase in shelf life, but negatively affected their texture. However, texture parameters negatively affected by MA, like tenderness, were improved upon aerobic storage after MA storage for 5 to 10 days but not 14 days (data not shown). Lower microbial levels were found in MA bulk stored fish and MAP fillets compared to traditionally iced fish, while higher trimethylamine (TMA) levels were found in MAP fillets.

Textural defects could be expected as dissolution of CO_2 into the surface of fresh muscle foods reduces their pH sufficiently to weaken the water-holding capacity of the protein (Parry, 1993). The reduction of bound water leads to excessive exudate along with a coarsening of the texture, which has been described by panellists as an increase in toughness and dryness (Tiffney and Mills, 1982), as well as a grainy (Wang and Brown, 1983) or powdery effect (Haard and Lee, 1982). The severity of these effects depends on the level of CO_2 used. Layrisse and Matches (1984) reported that drip loss in shrimp was a function of CO_2 concentration. Selection of proper gas mixture and fish to volume ratio is the key to success to minimise textural defects and apparently depends on the fish species. MA-bulk storage of whole salmon may be advantageous as extended shelf life was observed under high CO_2 levels (**Table 2**). Much work is still needed in that area to optimise the conditions that lead to high quality products in all aspects.

Recently, an 8-day storage trial of whole and gutted haddock demonstrated that liquid ice cooled faster (<1 h to 0 °C) than ice (4.5 h to 0 °C) and reached a lower average temperature (-0.4 to 0.-0.6 °C compared to -0.1 °C for ice). Despite these differences, an apparently more rapid spoilage process had started to develop in the fish stored in liquid ice, as evidenced by a more rapid growth of spoilage bacteria and earlier production of TVB-N. This was believed to be attributed to the salt uptake measured in the flesh of liquid iced fish after 8 days, creating a different environment favouring TMA-producing bacteria like *P. phosphoreum* and *S. putrefaciens* (H_2S-producing bacteria) as supported by bacterial data (Þorvaldsson *et al*., 2010; Reynisson *et al.,* 2010). Moreover, TMA production is known to be readily increased under low oxygen tension, a condition possibly established with the use of liquid ice in tubs. However, adding a top layer of ice retarded this process. Another trial involving whole, gutted cod differently cooled and stored on board was conducted in November 2009 following the quality deterioration of the fish for 10 days (**Table 1**). The liquid ice treatment was not properly applied (insufficient cooling medium used) and will not be discussed further. Comparison of direct icing vs 30-min liquid cooling prior to re-icing showed that, despite a more rapid cooling rate for liquid cooling treatment (reaching 0 °C in about 5 h compared to 10 h for iced fish), no difference was observed in freshness preservation while slightly longer shelf life was seen for iced fish. The shelf life in this study was considerably shorter compared to previous studies with whole cod, which may be explained by the fluctuating (2 to 5 °C) ambient temperature in the cold room where the tubs were stored (Magnússon *et al*., 2010).

Storage of whole and gutted seabass in liquid ice extended the sensory shelf life by two days, as assessed by the evaluation of cooked fish (**Table 2**). However, assessment of whole fish by the Quality Index Method (QIM) showed that no difference was found during the first 20 days of storage between the iced fish and that stored in liquid ice (data not shown). However, whole gutted cod stored in liquid ice prior to processing was found to have a better (lower) overall quality index due to better appearance in comparison to ice-stored fish. Despite this fact and a much faster cooling rate, fish stored in liquid ice and further processed to become salted products did not lead to higher yield or better quality (Jónsson and Arason, 1999). Therefore based on the cold- and warmwater fish trials conducted, long-term application of liquid ice upon catch/slaughter may be more beneficial to warmwater/freshwater fish than coldwater marine fish.

Finally, the use of liquid ice as an efficient cooling medium to quickly lower whole fish temperature prior to iced storage on board should be further investigated as to evaluate its effect on freshness maintenance and shelf life extension of resulting fish products. Overall, it is found that the length of the freshness period for whole, iced fish depends on the species and ambient temperature, being shortest for cod (7-9 days) in comparison to American plaice (10 days) and redfish (14 days). This information is relevant to fish processors.

Table 2. Experimental data of whole farmed fish stored under different conditions

Fish species	Year	Known history	Raw mat. age[1] (days)	Packaging type	Packaging conditions (for MAP: $CO_2/O_2/N_2$)	Storage temp. (°C)	Shelf life[2] (days)	Freshness period[3] (days)	Reference
Arctic char	**2006**		**0**	EPS	air, iced	0-1	17		Cyprian *et al.* 2008
		T abused on d1 (24h, 18 °C)				0-1	15		
European seabass	**2001**	**ungutted**	**0-1**	EPS	air, iced	0-2	22		Ólafsdóttir 2001 (Rf 22-01)
					liquid ice	0-2	24		
Salmon	**1999**	**2d-unfed, gutted**	**0**	plastic boxes	air, iced	0-2	20		Sveinsdottir *et al*. 2002
Salmon	**1991**	**gutted**		bulk	air, iced	1.4	13	12	Á. Þorkelsdóttir & G. Stefánsson 1994 (Rf 63-94)
				4 fish/bag	air, bag	1.4	15.5	14-14.5	
					80/0/20	1.4	17	14-14.5	

1: time in days from catch to trial
2: time in days from catch, based on sensory assessment of cooked fish (Torry score = 5.5 or QDA value =20) or whole fish (QIM, Quality Index Method)
3: time in days from catch, based on sensory assessment of cooked fish (Torry score = 7)

3.2 Freshness deterioration and sensory shelf life of fish fillets

In this chapter, the influence of raw material quality and age, cooling methods, processing, packaging and storage conditions on freshness and shelf life extension of fish fillets will be discussed. For more details and references, please consult **Tables 4 to 7** in the Appendix section summarising all data presented.

3.2.1 Raw material age of processed fresh products

Shelf life of fresh cod fillets (processed from gutted, iced cod) and stored under chilling conditions (0-1 °C) usually ranges between 10-13 days. Generally, the fresher the raw material, the longer will the freshness period last, as shown in **Figures 1** and **2**. However, deviations have been observed, most likely due to raw material history and storage conditions. Delaying processing will reduce the raw material freshness, found to be lost 8 days post-catch for cod in the fillet trial in 1990. Another trial with whole, gutted cod (1990, **Table 1**) involving aerobic iced storage resulted in a freshness period of 9 days. This should be carefully considered during the selection of raw material for processing of fresh products to be exported to foreign markets.

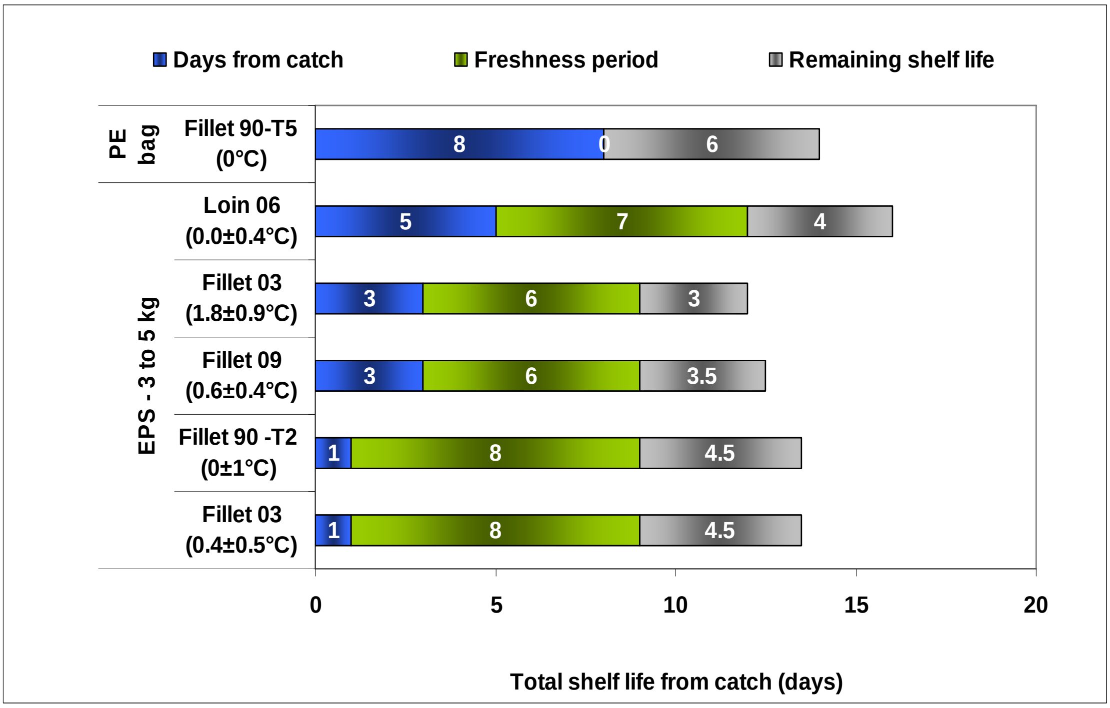


Figure 1. Effect of raw material age at processing on freshness period and shelf life of cod products (average product temperature ± SD). Product type along with trial year indicated (Fillet 90, 1990).

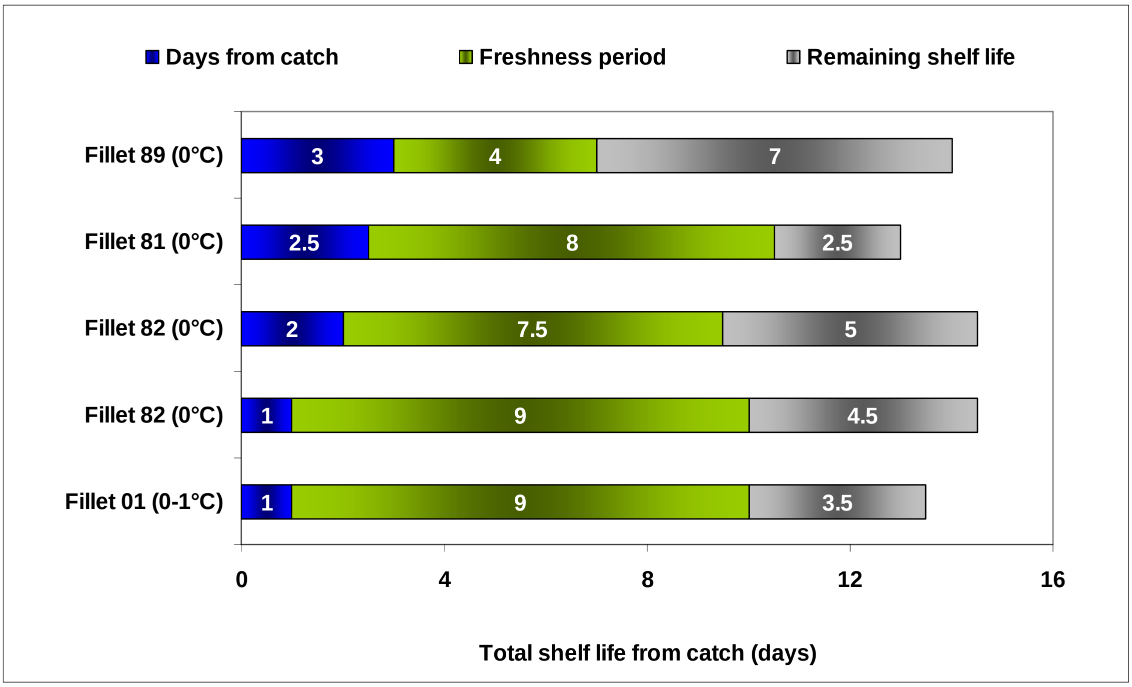


Figure 2. Effect of raw material age at processing on freshness period and shelf life of haddock products. Product type along with trial year and average product temperature (Fillet 89 (0°C), etc) are given.

3.2.2. Cooling methods of raw material on board and in process

It has been found that superchilling of processed products can extend the freshness period as well as the shelf life (Olafsdottir *et al*., 2006b). Though the effect of superchilling of raw material effected by subzero storage temperature and/or cooling methods on delaying quality deterioration of resulting products is not as well known. Liquid ice has been shown to rapidly reduce the fish temperature compared to ice storage. As discussed earlier (under 3.1 and **Table 2**), sensory shelf life extension was obtained using liquid ice storage for a warmwater fish, European seabass, while no significant quality improvement of the flesh was seen for cod compared to ice storage. Positive impact of liquid ice on the raw material has mainly been related to its overall appearance, with less skin bruises (Jónsson and Arason, 1999). Its negative impact seems to be related to salt uptake in the fish flesh, faster growth of spoilage bacteria and TVB-N production, as seen in whole, gutted haddock (see above discussion).

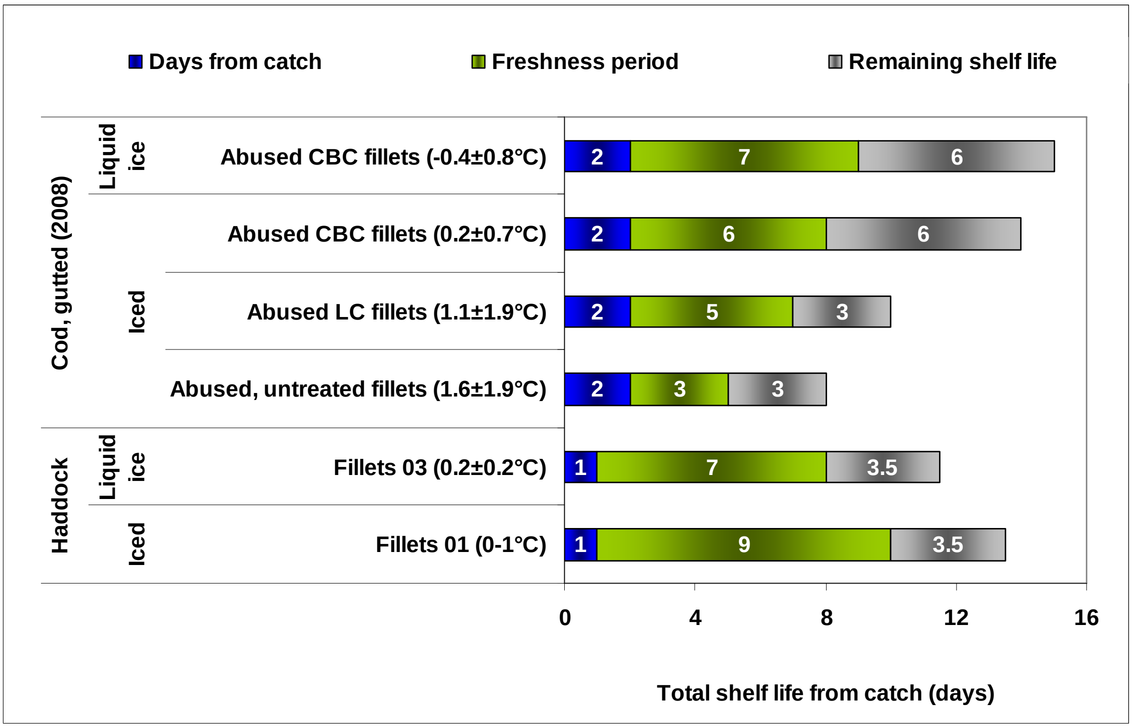
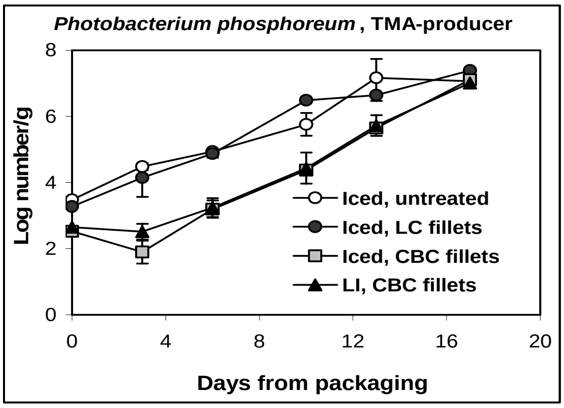


Figure 3. Effect of cooling methods applied to raw material on freshness period and shelf life of resulting fish products (average product temperature ± SD). Iced, whole and gutted fish stored in ice on board; LI, liquid ice; Abused, implied storage of EPS boxes at 10 °C for 7.5 h (day 0 post-packaging) and 10 °C for 16 h (day 2); LC, liquid cooling of fillets for few minutes; CBC, superchilling treatment.

Improper storage or temperature abuse of whole fish will reduce its shelf life. A temperature abuse of 24 h at 18 °C resulted in an increase from 3 to 12 °C in Arctic char product stored in EPS boxes before proper icing (**Table 2**), leading to a 2-day shelf life reduction or 12% of the product shelf life at 0-1 °C (Cyprian *et al*., 2008). **Figure 3** shows that overnight storage of whole, ungutted haddock in slurry ice at a processing plant led to a reduced freshness period compared to gutted haddock iced on board. Delayed handling and cooling of whole haddock clearly have a negative impact on the freshness maintenance of the product, resulting to a shorter shelf life (Olafsdottir *et al*., 2006a). Application of liquid ice (LI) cooling to whole, gutted cod was compared to ice storage. The 2-day old raw material was then processed and not found to be significantly different (p>0.05) with respect to all sensory attributes tested (QDA). The products prepared from the two batches stored differently on board were CBC fillets, superchilled with the skin on, to which a temperature abuse profile was applied (Magnússon *et al.,* 2009a). Despite the same temperature treatment applied to both groups, the LI-CBC fillets had an overall temperature of -0.4 °C compared to 0.2 °C for the iced-CBC fillets. The superchilled state of LI-CBC fillets may have influenced the resulting extended freshness period observed in that group. Otherwise, little difference was observed among the two groups, as shown in **Fig. 4.**

Liquid cooling of newly processed fillets in brine has been used in industry to lower fillet temperature before packaging. However, the impact of CBC cooling on the temperature maintenance of abused fillets has been found to be considerable when compared to liquid cooling (LC) in process or untreated fillets (Magnússon *et al.,* 2009a). In a trial conducted in 2008, LC lengthened the freshness period by almost 67% compared to untreated, abused fillets while CBC doubled (100% increase) the freshness period and the remaining shelf life time (**Fig. 3**). CBC therefore resulted in a shelf life of 12 days compared to 8 days for LC, abused fillets and 6 days for untreated, abused fillets. CBC cooling is therefore an advantageous method to process fillets to be shipped as fresh products since it will help in maintaining freshness and shelf life despite breakage in the cold chain. Further, a bacterial growth-retarding effect of CBC processing on specific spoilage organisms (SSO) has been observed in cod fillets as illustrated in **Fig. 4.** *P. phosphoreum* (Pp) is known to be negatively affected by superchilling but triggered under abused temperature (Olafsdottir *et al*., 2006a,b).



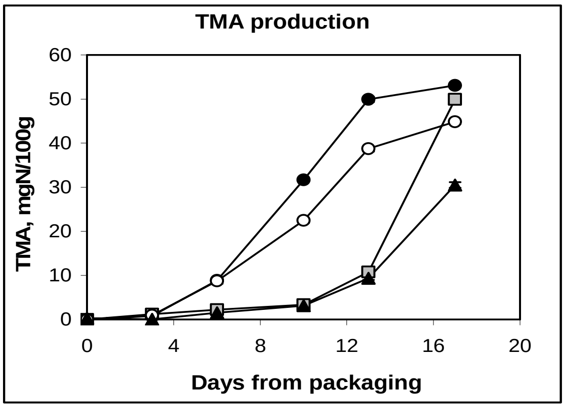


Figure 4. Effect of raw material storage and fillet treatment in process on growth of *P. phosphoreum* and trimethylamine (TMA) production during storage in 3-kg EPS boxes under abusive conditions (10 °C for 7.5 h day 0 post-packaging and 10 °C for 16 h on day 2). Iced, refers to whole, gutted cod stored in ice for 2 days on board; LI, liquid ice used to store cod for 2 days on board; LC, liquid cooling of fillets for few minutes; CBC, superchilling treatment. Error bars show SD (n=2).

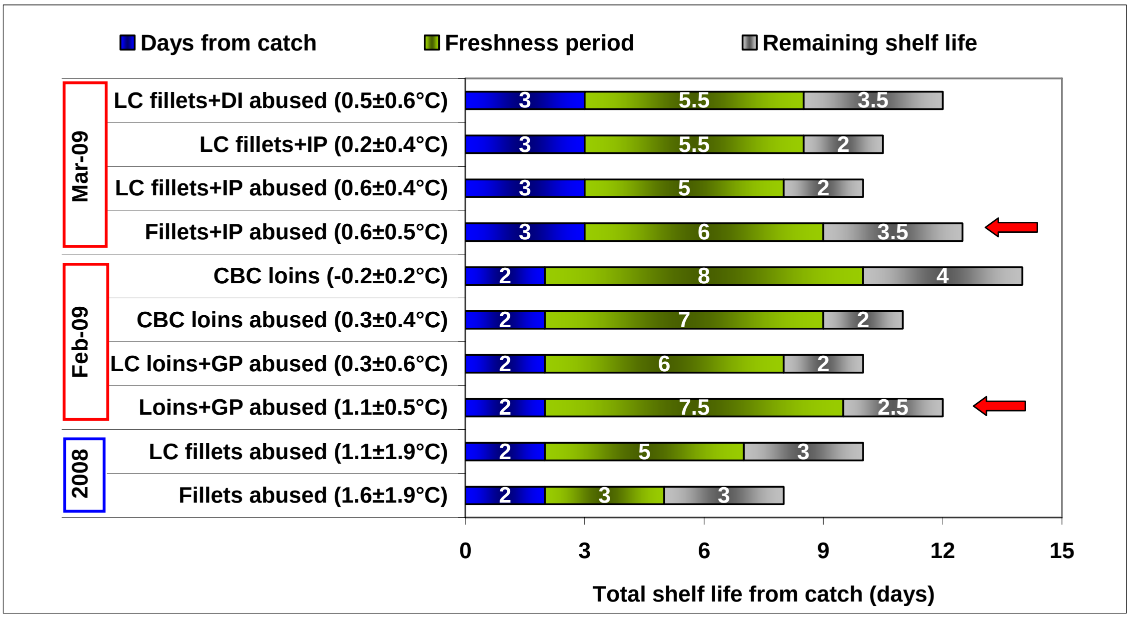


Figure 5. Effect of cooling methods in process on fillet freshness period and shelf life (average product temperature ± SD). Abused 2008, implied storage of EPS boxes at 10 °C for 7.5 h (day 0 post-packaging) and 10 °C for 16 h (day 2); Abused 2009, implied storage of EPS boxes at 4-5 °C for 12 h (day 1 post-packaging) and 10 °C for 6 h (day 2); LC, liquid cooling of fillets for few minutes; CBC, superchilling treatment; GP, gel pack put on top of fillets in EPS boxes; IP, ice pack put on top of fillets in EPS boxes; DI, dry ice put on top of fillets in EPS boxes.

Usefulness of liquid cooling of fillets in process using slurry ice was demonstrated in the 2008-trial discussed above. However, in two successive experiments (Feb. and March 09), the microbial load of the cooling media (brine) used contained high levels of SSO (Pp, pseudomonads and H_2S-producing bacteria) which led to a contamination of the loins/fillets and rapid growth of SSO during storage of the products, especially those temperature abused. This resulted in decreased shelf life for treated loins (20% less for LC loins and 10% for CBC loins) compared to untreated ones (10 days) under abused condition, despite a lower initial temperature of treated loins (**Fig. 5,** Feb-09). The freshness period was also shorter for abused treated loins. Non-abused CBC loins had the longest freshness period and shelf life (12 days) (Martinsdottir *et al*., 2010). Similarly, a reduction in shelf life was seen for LC fillets in March 09, both abused and not, compared to abused untreated fillets with a shelf life of 9.5 days. Use of dry ice (DI) contributed to a slower deterioration process in LC fillets, gaining two days in shelf life compared to LC fillets packaged with an ice pack (IP)

(**Fig. 5**, Mar-09) (Magnússon *et al.*, 2009b). This was due to slower SSO growth than seen in other LC fillets, especially for Pp which is sensitive to subzero condition (data not shown). The red arrows on **Fig. 5** indicate the longer shelf life obtained for untreated products following temperature abuse compared to treated ones of each respective trial.

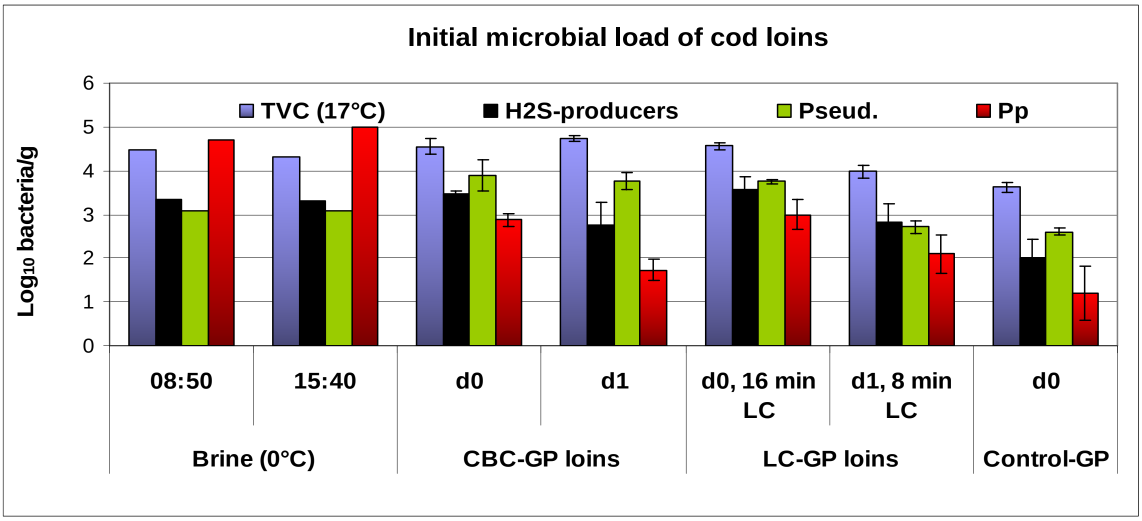


Figure 6. Effect of brine microbial load on fillet contamination (Feb. 2009). TVC, total viable psychrotrophic counts at 17 °C; H_2S-producers, pseudomonads and *Photobacterium phosphoreum* (Pp) are SSO of fresh cod products. Error bars show SD (n=3).

Figure 6 shows how contaminated brine affected the fillets cooled in the medium in February 2009 (Martinsdottir *et al.*, 2010). Brine temperature in the liquid cooler was controlled (0 °C) and little SSO increase occurred, mainly Pp growth noticed at the end of processing. Older raw material (5-d old) was processed prior to the 2-d old cod, inevitably contaminating the processing line and brine due to generally higher bacterial contamination found on the skin of older fish. Renewal of the brine occurred daily, but since skin-on fillets were introduced to the brine, the established microbial load (2.9 x 10^4/g brine) could not be lowered. For instance, doubling the liquid cooler volume with as much fresh brine would only bring about a 50% decrease in bacterial load (1.45 x 10^4/g brine). The cross-contamination that occurred on newly prepared fillets upon liquid cooling is clearly seen in **Fig. 6.** Filleting of 2-d old fish resulted in products (Control-GP) with low microbial load (log 3.6/g or $10^{3.6}$/g) while liquid cooling (LC-GP and CBC-GP loins on d0) led to a tenfold increase. The most significant increase was observed for Pp, almost 100-fold in LC and

CBC loins. It is noteworthy that LC products sampled on day 0 had been twice longer in the liquid cooler than the ones used for the rest of the experiment and therefore contained significantly higher microbial load. Also CBC loins analysed one day post-packaging had tenfold lower Pp counts compared to those sampled on day 0 (CBC-GP). This can be explained by Pp sensitivity to superchilled conditions, as mentioned earlier, like those encountered following CBC cooling.

Figure 7 provides similar findings on the contamination of fillets following liquid cooling (Magnússon *et al*., 2009b). To be emphasised here is the effect of poor temperature control in the liquid cooler on the brine microbial load over time. When poor temperature control occurred in the liquid cooler (T1: brine around 4-5 °C over a 3-h period), the levels of the main SSO (Pp) increased almost tenfold during that short period. However, under better controlled conditions (T2: brine at 1 °C) no SSO growth was observed. Nevertheless, high microbial load was seen in both experiments in the brine, only few hours from process initiation. The effect of the raw material age on the resulting microbiological quality of untreated fillets (control) is clearly illustrated in **Fig. 7**. T1 fillets were processed from 4-5 days old cod while T2 fillets from 3-4 days old fish. TVC and pseudomonad counts were tenfold higher in T1 fillets, while Pp counts were 100-fold higher than in T2 fillets. This considerable microbial load increase in processing older raw material is critical to the final quality of the processed product and will inevitably influence its freshness period and resulting shelf life, making them vulnerable to temperature abuse post-packaging. Further, it should be pointed out that greater differences in microbial load were observed in LC fillets prepared from fresher than older raw material when compared to untreated fillets. Cross-contamination of high quality fillets via liquid cooling is disadvantageous.

Another trial was performed in February 2010 to evaluate two cooling media, liquid cooling brine (1.5-2.2% NaCl) vs slurry ice (0.7% NaCl), during precooling at a cod processing line (Margeirsson *et al*., 2010). Again, recycled brine was found to contain a high microbial load (almost 10^5 CFU/ml) which led to higher initial microbial counts (10^4 CFU/g) of fillets treated in it compared to almost tenfold lower counts on fillets treated in slurry ice. Storage of the fillets showed a similar freshness loss rate while negative sensory attributes, bacterial growth and amine products (TVB-N and TMA) were detected earlier in liquid brine-cooled than slurry ice-cooled fillets.

Therefore, in order to maintain low bacterial levels in the liquid cooler, it is necessary to ensure proper skin cleaning of whole fish to reduce initial load, followed by rinsing of the fillets prior to liquid cooling to minimise the bacterial load brought to the brine. It should also be kept in mind that it is crucial to first process younger raw material with proper cooling history prior to that of lower quality/older age on each processing day. This should be done to minimise cross-contamination.

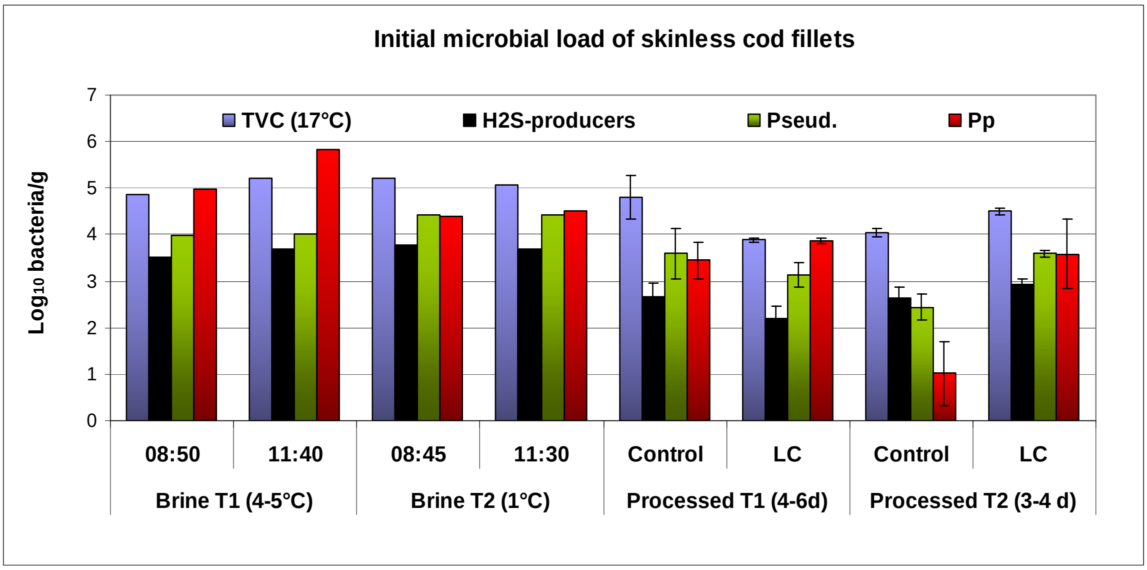


Figure 7. Effect of brine microbial load on fillet contamination (March 2009). TVC, total viable psychrotrophic counts at 17 °C; H_2S-producers, pseudomonads and *P. phosphoreum* (Pp) are SSO of fresh cod products. Error bars show SD (n=3).

Quality deterioration of superchilled redfish fillets (about 4% fat), accomplished by brine cooling, slurry ice cooling and/or storage at -1 °C in EPS boxes for 6 days followed by chilled storage (2 °C), was more pronounced in products with higher mean temperature. Lowering the oxygen tension by vacuum packaging of redfish fillets prior to slurry ice cooling effectively reduced lipid oxidation and delayed growth of spoilage bacteria compared to air-stored fillets, being either brine-cooled or untreated prior to packaging in EPS boxes (H.L. Lauzon and M.G. Karlsdóttir, unpublished data).

3.2.3 Brining of fillets and different processing/storage methods

An experiment was conducted to evaluate the effect of brining, modified atmosphere packaging (MAP) and superchilling on the quality changes and shelf life of cod loins as measured by microbial, sensory and chemical analysis (Magnusson *et al.*, 2007; Lauzon *et al.*, 2009). Brining of processed fillets was not shown to increase product shelf life compared to unbrined fillets processed two days later (**Fig. 8**). Temperature of treatment, microbiological quality of brine and age of raw material are expected to be influencing factors. Unbrined and brined (2.5 ± 1.0 % NaCl) cod loins were kept in styrofoam boxes (air) and under modified atmosphere (MA, $CO_2/O_2/N_2$:50/5/45) at 0 and -2 °C, sampled over a 4-week period.

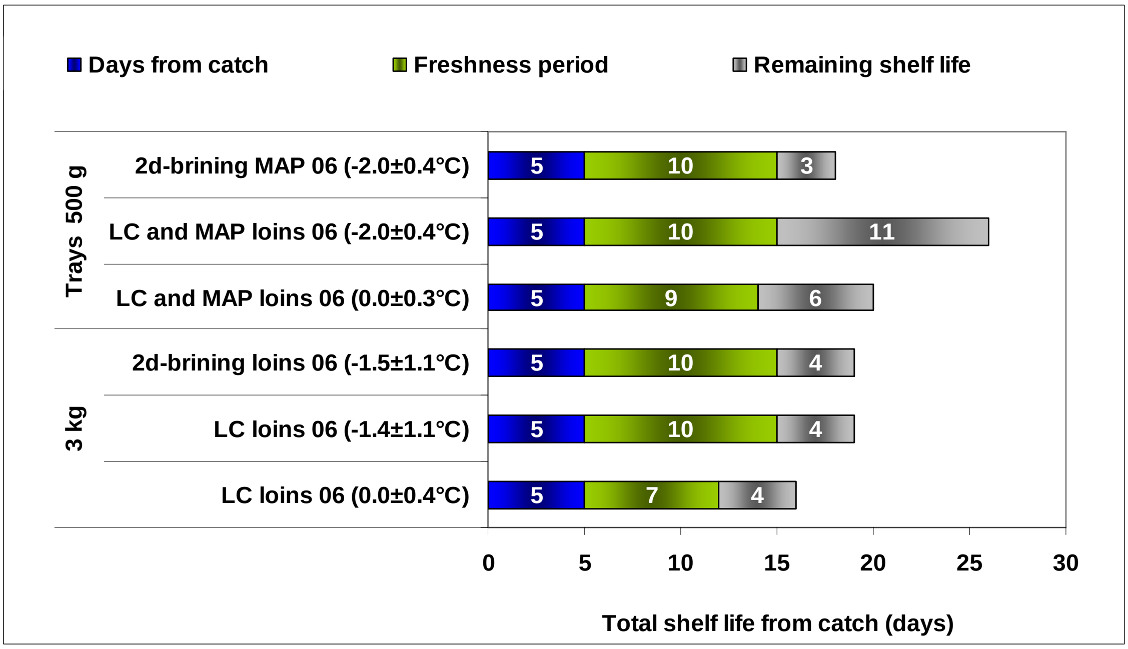


Figure 8. Effect of brining, modified atmosphere packaging (MAP) and superchilling on product freshness period and shelf life (average product temperature ± SD). LC, liquid cooled for few minutes before packaging.

According to sensory analysis, the shelf life of unbrined air-packed loins was about 11 days at 0 °C and 14-15 days at -2 °C. The shelf life of MA-packed unbrined loins was about 14-15 days at 0 °C but 21 days at -2 °C. Thus, synergism of combined superchilling (-2 °C) and MA led to a considerable shelf life increase for unbrined loins despite the fact that processing and packaging took place 5 days post-catch. The shelf life of air-packed brined loins at -2 °C was 12-15 days (estimated to 14 d) but only 13 days under MA. Further, brining led to a much shorter shelf life for MA-packed loins (-2 °C) compared to unbrined loins under the same conditions (21 days), likely due to the initial sensory quality differences of these loin products at packaging. Therefore, the same synergistic effect did not apply to brined loins as with unbrined ones. Modified atmosphere (MA) packaging of fillets processed from 5-day old cod was only found to extend the freshness period in chilled products, but did contribute to the shelf life extension of lower quality products under chilled and superchilled conditions. Superchilling (-1.5 to -2 °C) alone maximised the freshness period, reaching 10 days in all products.

3.2.4 Effect of product temperature on quality deterioration and shelf life

Improper chilling or temperature abuse will shorten the freshness period of a product, while superchilling will extend it. For instance, the freshness period of 2 °C-fillets has been found to be 6 days (processed from 3-day old cod) while that of CBC fillets (-0.9 °C) was 7.5 days, but both resulting in a similar shelf life (SL=9-9.5 days) (**Fig. 9**). On the other hand, CBC fillets prepared from 3-day old cod and maintained at -1.3 °C had an increased freshness period (10 days) and SL (16 days). In fresher raw material (1-day old cod), processed fillets maintained at 0.4 °C had a freshness period of 8 days and a SL of 12.5 days, while CBC fillets maintained at -0.3 °C had a similar freshness period and a SL of 13 days. Lowering the average fillet temperature to -0.8 °C or -1.3 °C increased freshness period by 1.5 day (9.5 days) but SL by only one day (14 days). Temperature abuse of chilled, fresh fillets (1.9 ± 2.3 °C in 3 kg EPS, processed from 1-day old cod) 3 days post-packaging (16 h at room temperature, RT) reduced the freshness period by 2.5 days and the SL by 3 days Temperature abuse of products at early storage time, processed from older raw material (3-day old), may have less influence on the freshness period due to its shorter length compared to fresher raw material but will certainly influence the resulting SL. In a trial of CBC fillets comparing their storage at superchilled and chilled conditions, temperature abuse two days post-packaging led to a decrease in the freshness period from 10 days (EPS boxes) to 8 days (superchilled storage at -1.2 ± 1.4 °C in Polimon trays, HDPE with PET/LDPE film) and 7 days (chilled storage at 1.3 ± 1.1 °C in Polimon trays). Their shelf life was reduced by 2 and 8 days, respectively (Martinsdottir *et al.*, 2004 and 2005).

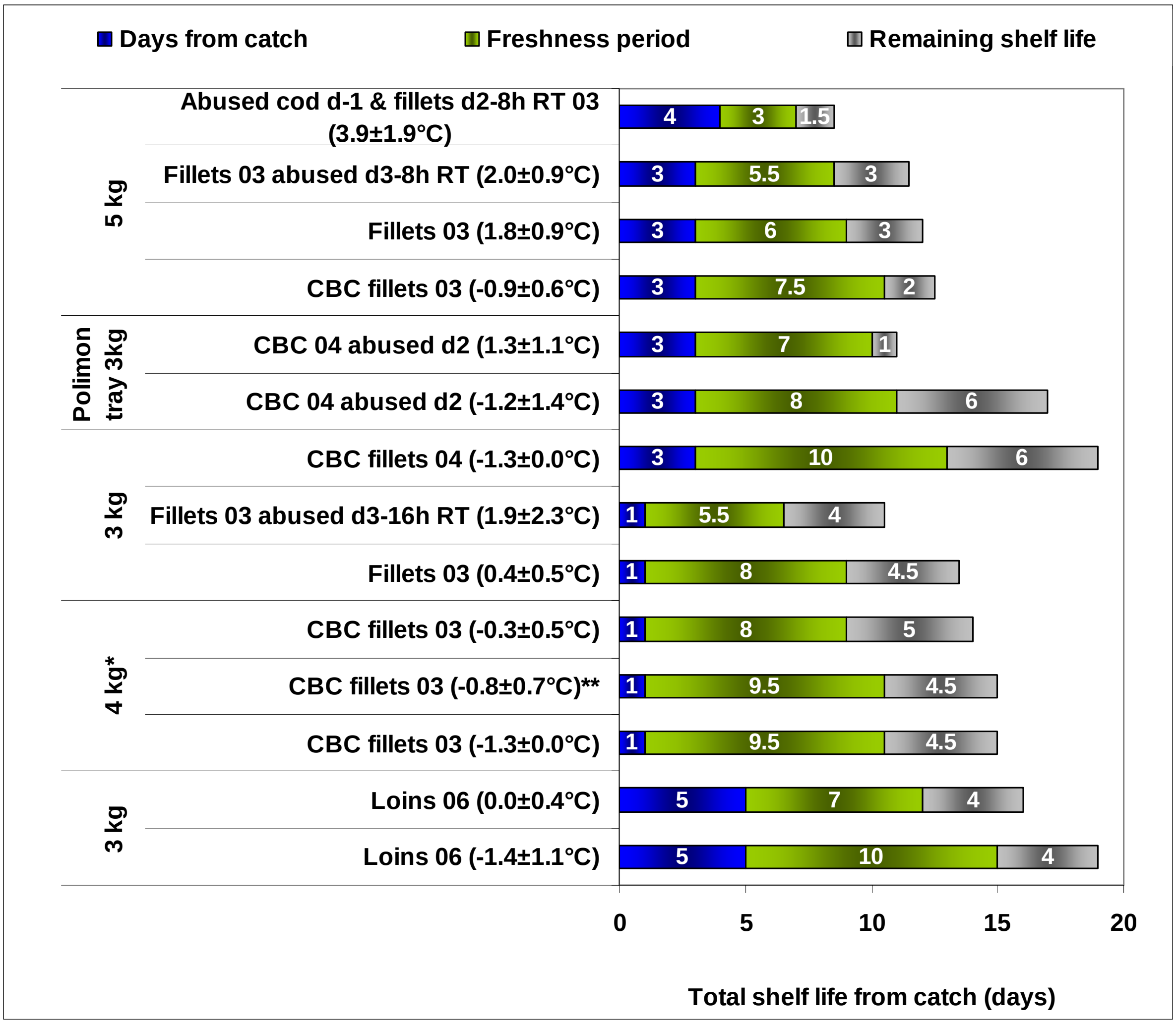


Figure 9. Effect of temperature on product freshness period and shelf life (average product temperature ± SD). CBC, superchilling treatment; * Fresh raw material processed after older fish; ** Products stored at -1.5 °C for 7 days after which EPS boxes were transferred to 0.5 °C storage room; RT, room temperature (18-20 °C).

Overall, superchilled storage is advantageous to extend the freshness period, while comparison of abused products, either CBC processed, liquid cooled (LC) or uncooled in process (**Fig. 3**), showed the greater benefit of CBC cooling. The freshness period was extended by 100% for abused CBC fillets but 67% for abused LC fillets compared to untreated fillets. Temperature abuse can be extremely detrimental in "unprotected" or uncooled fish products or in those cooled but produced with poor hygienic conditions and leading to high microbial contamination.

Bacterial spoilage of lean fish is the main cause of quality deterioration. SSO tolerate well chilling conditions and cause off-odours and off-flavours, and some are capable of producing TMA, the fishy smell. SSO are differently influenced by temperature as shown in **Fig. 10**. Pp is the most temperature-influenced SSO in cod products. This was found by gathering SSO growth data under isothermal conditions for cod fillets. Maximum specific growth rates (μ_{max}) for all SSO were plotted against temperature (T) using the square root model. Therefore, Pp can be expected to be found at high levels in temperature abused cod products. Pp produces TMA, which has been observed to reach higher levels at higher temperature in a fish model system (Ólafsdóttir *et al.*, 2003).

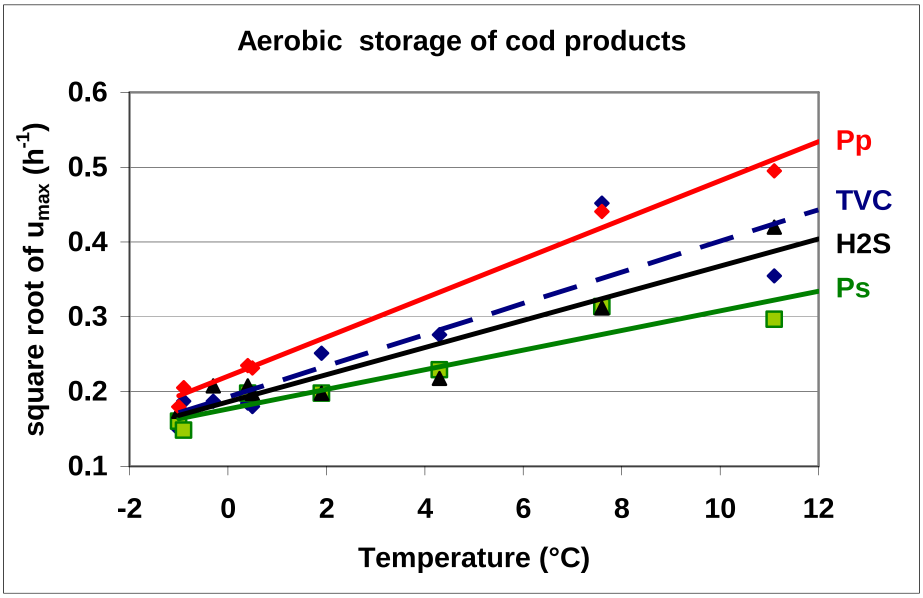


Figure 10. Effect of temperature on maximum specific growth rate of SSO in cod fillets. Pp, *Photobacterium phosphoreum*; TVC, total psychrotrophic viable counts; H_2S-producing bacteria; Ps, pseudomonads; μ_{max}, maximum specific growth rate (h^{-1}) determined by DMFit (Baranyi and Roberts, 1994).

3.2.5 Effect of MAP on quality deterioration and shelf life of fillets

The use of modified atmosphere packaging (MAP) usually leads to an increase in sensory shelf life when compared with traditional ice storage in air, but the magnitude of the increase depends on various factors such as the composition of the gas mixture, storage temperature, raw material quality and pack size. The results presented are based on several studies conducted between 1980 and 2007 (see **Tables 4-7** in the Appendix). Generally, fillets stored under higher concentration of CO_2 have a prolonged shelf life. These findings agree with other MAP storage trials found in the literature (Molin *et al*., 1983; Dalgaard *et al*., 1993). Also, the use of O_2 with CO_2 is preferable to N_2 as a filling gas when packaging lean fish, since it usually provides a slightly longer shelf life. Despite the advantage of using 100% CO_2 to prolong shelf life by slowing down the bacterial activity occurring in the fish products, it has been observed to result in greater weight losses due to increased drip (data not shown). During the trials of gadoid fillets, it was found that 100% CO_2 caused a weight loss of 9-15%, whereas 75% CO_2 resulted in 3-5% weight reduction in retail packs and 2-4% in bulk packs. Using 90% CO_2 resulted in about 2-4% weight reduction in bulk packs. On the other hand, there were no apparent weight losses when 50% CO_2 was used. High CO_2 concentrations at low temperature (0 °C) imply a greater pH reduction in fish as CO_2 dissolves readily under such conditions (Umbreit *et al*., 1972), affecting the water holding capacity of the muscle and leading to water leaking out of the muscle. Moreover, toughness of the muscle generally increases with increasing CO_2. Therefore, the proper CO_2 concentration must be determined for each fish species to reduce drip and textural defect as much as possible without significantly reducing shelf life extension.

Figures 11 and **12** present the effect of gas composition on the freshness period and shelf life extension of haddock, cod and redfish fillets, respectively, stored at 0 °C. The gas mixture tested with least 50% CO_2 and including 50% O_2 was still efficient at extending the freshness period of fillets prepared from 2- or 3-day old haddock, .i.e. by 5-10 days. Use of nitrogen to replace oxygen or vacuum packaging did not lead to as much freshness extension. Processing of MAP fillets under high hygienic standard (extra care) prolonged the freshness period considerably in combination with 75% CO_2 and 25% O_2. It was also interesting to see that storing a bulk quantity of fillets under MA was feasible and led to much freshness maintenance (**Fig. 11**). Earlier work by Stansby and Griffiths (1935) showed that shelf life of haddock fillets stored in bulk at 0 °C was increased in an atmosphere rich in CO_2 in comparison with fillets stored in air. For redfish, a medium fat fish, use of oxygen as a filling gas is not recommended as it caused much freshness reduction (**Fig. 12**). For MAP cod fillets, the gas mixture $CO_2/N_2/O_2$: 60/30/10 extended the freshness period by 5 days and shelf life by a week. Though, it was not found to be optimal as some textural defects were reported due to the CO_2 level used (Martinsdóttir *et al*., 2003).

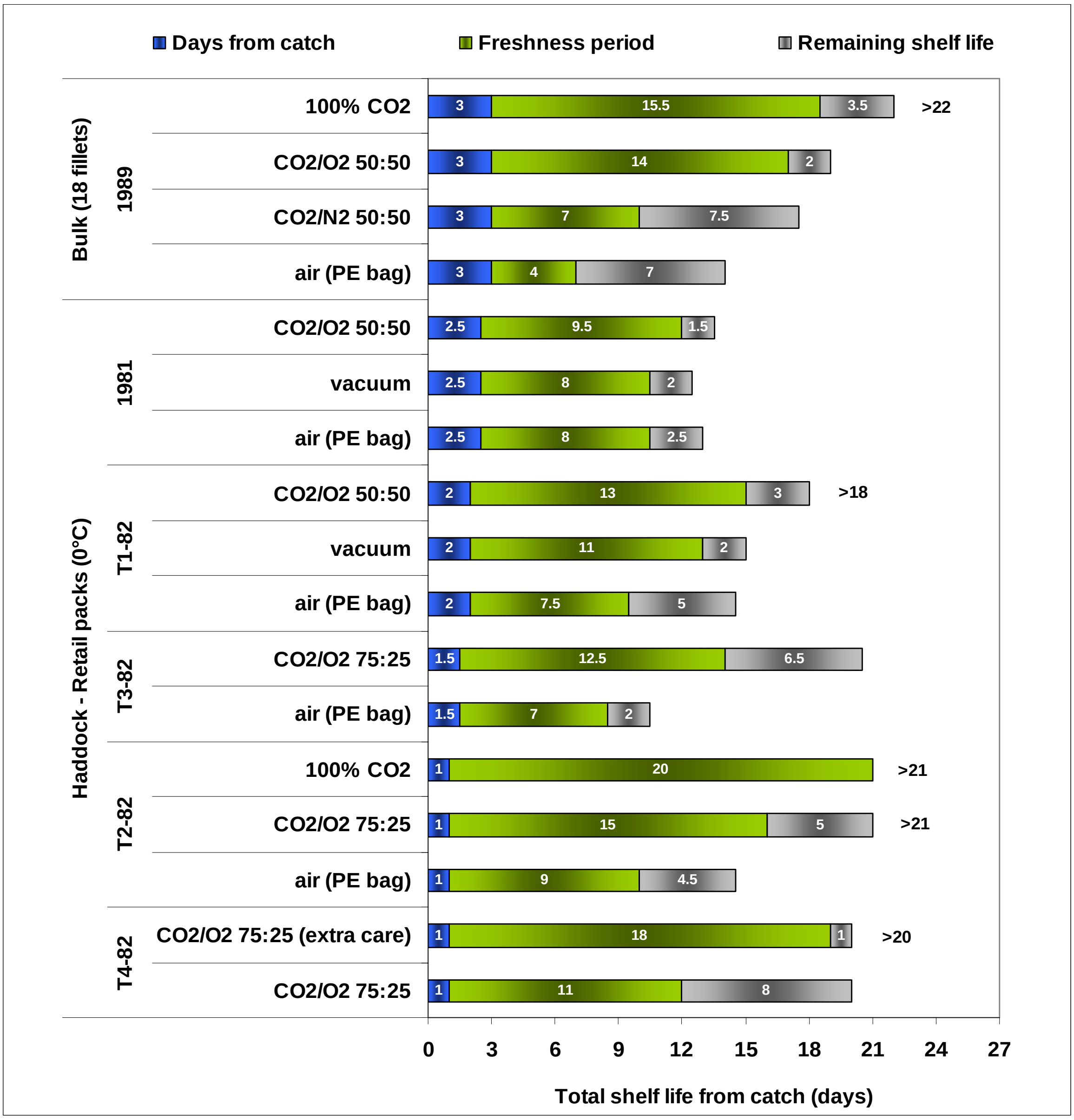


Figure 11. Effect of atmosphere composition on the freshness period and shelf life of haddock fillets stored at 0 °C

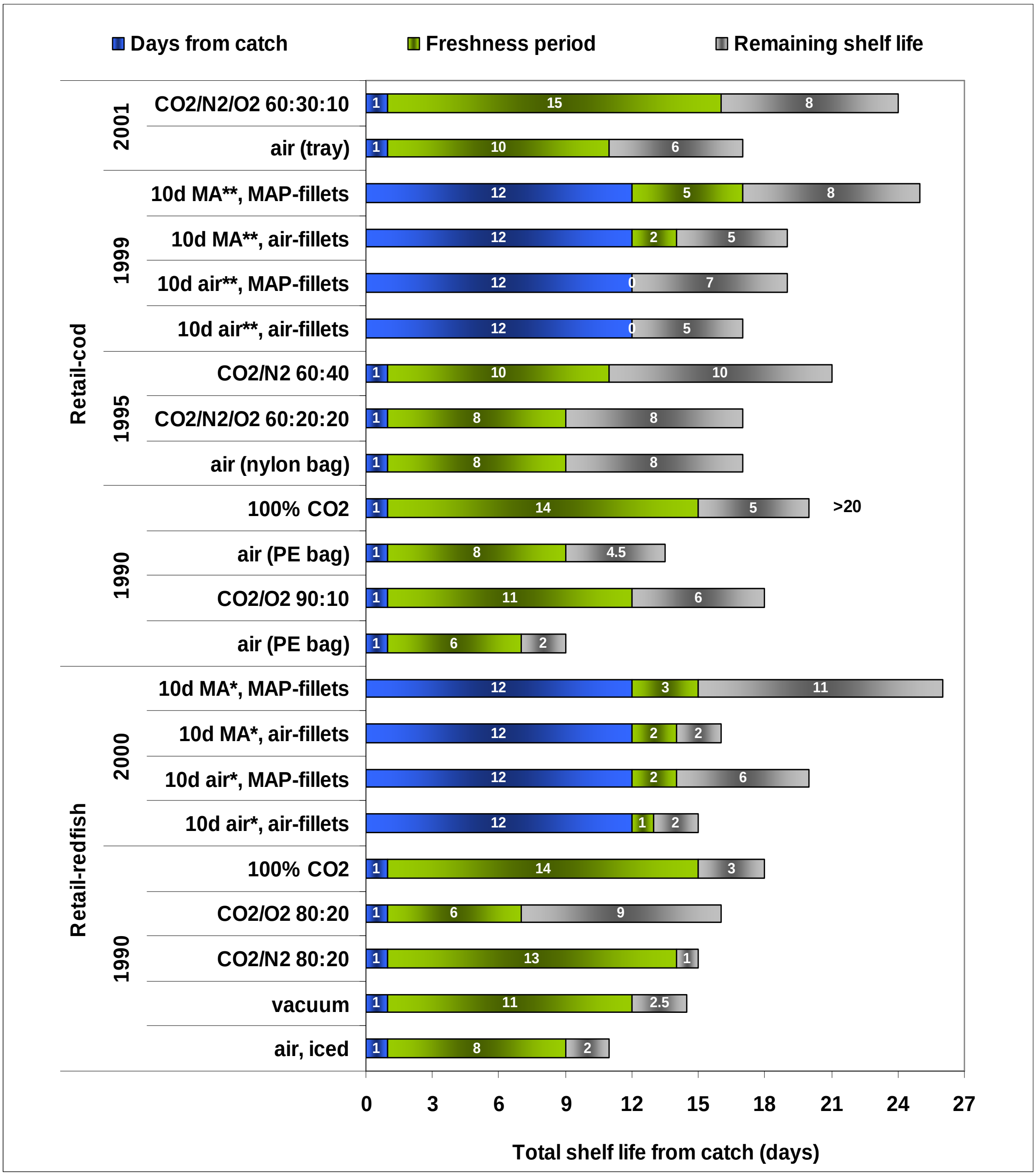


Figure 12. Effect of atmosphere composition on the freshness period and shelf life of fish fillets stored at 0 °C. * Storage of whole, ungutted redfish (2 days old) in bulk under air or MA (CO_2/N_2: 60/40) for 10 days in May 2000 prior to filleting and further packaging; ** Storage of whole, gutted cod (2 days old) in bulk under air or MA ($CO_2/O_2/N_2$: 50/30/20) for 10 days in November 1999 prior to filleting and further packaging.

Vacuum packaging of marine fish products has not been found to be a better alternative to MAP. Previous work at our lab has shown that at 0 °C, vacuum packing of haddock fillets (Stefánsson & Valdimarsson, 1982) and vacuum packing with or without N_2 flushing of cod fillets (Magnússon, 1980) do not markedly increase shelf life in comparison with air storage. It has been reported that vacuum packaging can extend the shelf life of some fish species such as rainbow trout (Hansen, 1972) and plaice (Huss, 1972) whereas little or no beneficial effect has been found for others, such as haddock (Huss, 1972) and hake (Lamprecht *et al*., 1984). These apparent conflicting results have been attributed to the presence of TMAO acting as an alternative electron acceptor for bacterial metabolism (Jensen *et al*., 1980). Rainbow trout and plaice contain low amounts of TMAO whereas haddock, cod and hake contain high amounts (Hebard *et al*., 1982). Some spoilage bacteria use TMAO, leading to an increased TMA production. The bacterial reduction of TMAO to TMA proceeds at a faster rate at conditions of low oxygen tension (Huss, 1972).

A bulk experiment was conducted in May 2000 to assess the effect of MA (CO_2/N_2: 60/40) on whole, ungutted redfish followed by filleting and further packaging in air or MA. Redfish was 12 days old when filleted and it was found that the freshness period lasted for 1-2 days for air-stored fillets, but 2-3 days for MAP-fillets. Shelf life was extended by 5 days for MAP-fillets processed from air-stored redfish, but by 10 days when processed from MA-stored redfish. However, textural defects were noticed in MAP-fillets (Lauzon *et al*., 2001; Lauzon *et al*., 2002). A similar bulk trial was performed with cod in November 1999, using $CO_2/O_2/N_2$: 50/30/20 and followed by filleting and further packaging (Lauzon *et al*., 2001). As shown in **Fig. 12**, the freshness period of air-stored cod was over upon filleting 12 days post-catch while MA-stored fish further processed and packed had a 2- or 5-day freshness period in fillets either air-stored or MAP, respectively. Shelf life was extended by two days for MAP-fillets processed from air-stored cod, but by 6 days when processed from MA-stored cod. Again, textural defects and loss in tenderness were still noticed in MAP-fillets. Interestingly, some of the tenderness was apparently recovered for air-stored fillets processed from MA-stored fish, indicating the reversibility of the textural changes after a 10-day MA storage period for whole fish.

Temperature considerably influences the efficacy of MAP as a means to extend sensory shelf life of fish fillets. Under temperature abuse (>2-3 °C), the value of MA-packaging is generally lost since CO_2 dissolution into the water phase of fish muscle is considerably decreased leading to decreased microbial inhibitory action. Distribution and storage of MAP-fish should therefore only be attempted through a secure cold chain. Otherwise, the value of the process will be lost and even unsafe products may result in packs with low oxygen tension (*Clostridium botulinum* growth risk >3 °C). Some trials clearly show the rapid loss in freshness of MAP products as temperature increases (**Fig. 13**). Generally, a 4-5 °C increase in product temperature leads to about 50% decrease in freshness period and shelf life. At 7 °C, added value provided by MA-packaging was totally lost. Bulk storage (3 kg) of CBC cod fillets was evaluated under air and MA in Polimon trays (HDPE, see on the right) sealed with a PET/LDPE film using a 900 VG XL semi automatic packaging machine (Polimoon, Kristiansand, Norway) supplied by courtesy of VGÍ hf in 2004 (Martinsdottir *et al*., 2005).

Superchilling has been shown to extend the freshness period of fish products, while MAP often leads to the extension of the "neutral flavour" period. Some trials have shown that MAP products processed from 1- to 5-day old raw material can extend the freshness period of MAP chilled products by 4-5 days (1 or 2-day old raw material) down to two days (5-day old). The shelf life extension can reach up to 7 days for fresh raw material, but only 4 days for 5-day old raw material. Superchilling combined with MAP led to slightly more extension of the freshness than shelf life period in products processed from fresh raw material: a freshness extension of 4-13 days was observed compared to a SL extension of 3-10 days for 1-day old raw material (**Fig. 13**); 5 vs 3 days for 3-day old fish (**Fig. 13**); 1 vs 6 days for 5-day old fish (**Fig. 8**). Therefore, further freshness extension using MAP under superchilled conditions can only be achieved using fresh raw material. MA-packaging of CBC-processed fillets is convenient, as the product temperature is optimal for rapid CO_2 dissolution and gas equilibrium in packs.

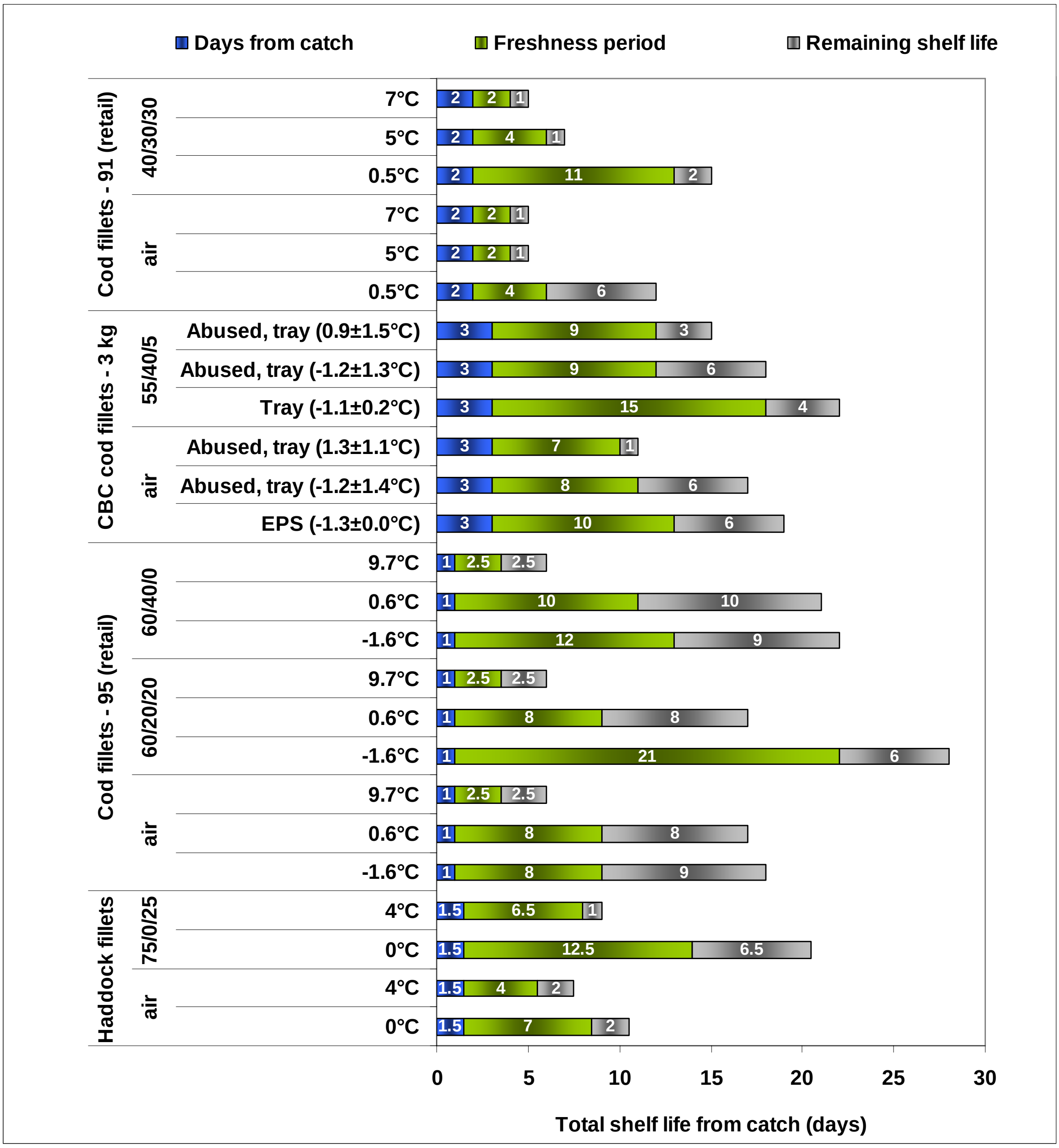


Figure 13. Effect of temperature on the freshness period and shelf life of MAP fish fillets compared to air-stored products. Gas mixtures are composed of $CO_2/N_2/O_2$. CBC, superchilling treatment.

Based on these findings, the raw material age is another important criterion for added value of MAP-fish, especially if the freshness period is to be maintained longer. The length of the freshness period and shelf life depended on the time from catch as shown in **Fig. 14**. Generally, the freshness period of MAP fillets processed from 1-3 days old raw material ranged between 10-15 days while a restricted freshness period was observed in fish processed 5-7 days post-catch. After 8 days storage of whole, gutted cod, freshness attributes were lost when evaluated in filleted products. Our results therefore indicate that proper handling and processing of fresh raw material (3-day old or less) into MAP products could be advantageous to Icelandic fish exporters.

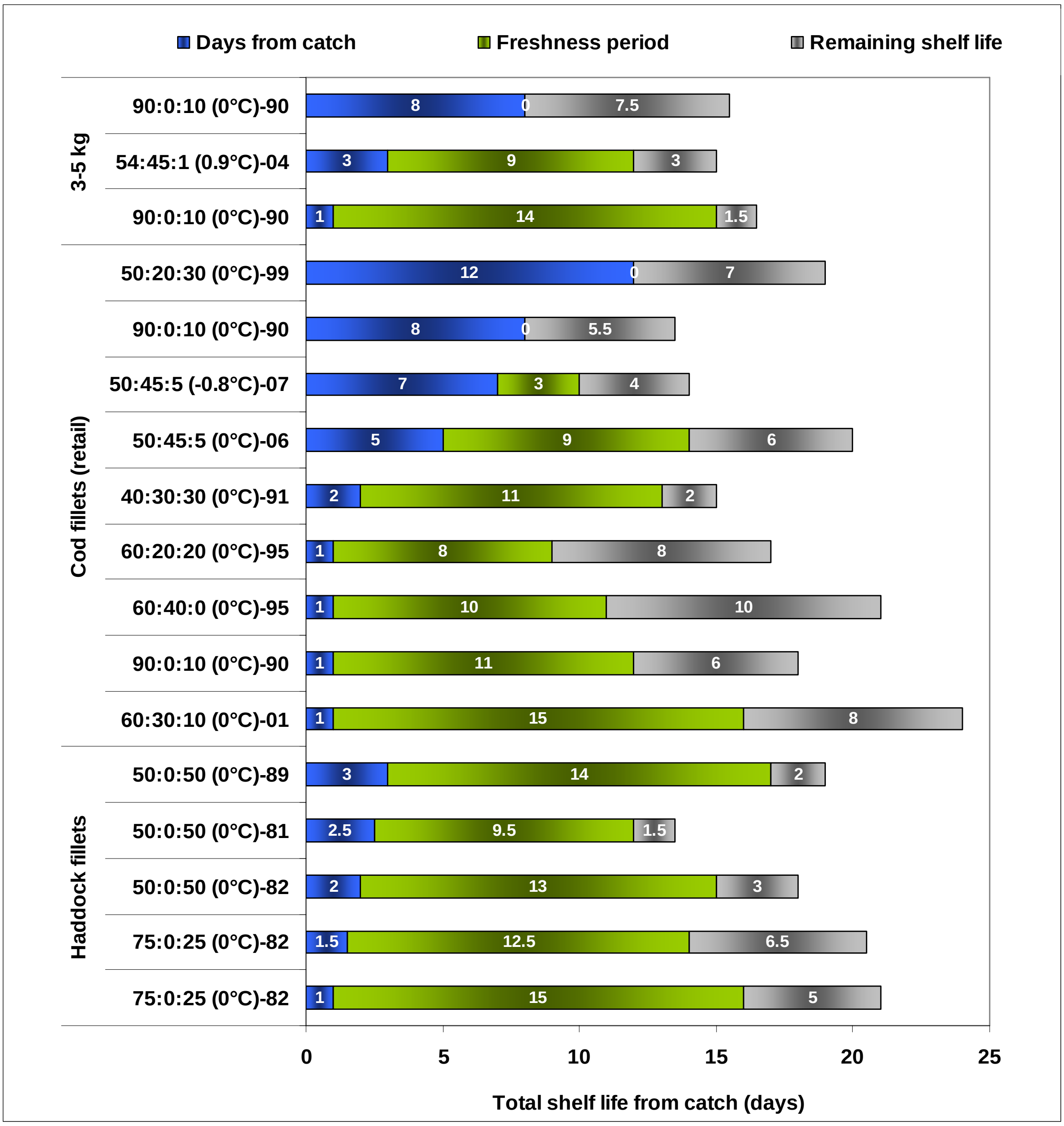


Figure 14. Effect of raw material age on the freshness period and shelf life of MAP fish fillets. Gas mixtures are composed of $CO_2/N_2/O_2$. Approximate product temperature (°C) and trial year given.

Based on the fact that MAP products require a steady distribution cold chain and that superchilling can provide additional freshness extension, it can be foreseen that containerised sea transport under superchilled conditions may be a good alternative to air freight. Following a 5-day shipping and distribution time period to the nearest markets, the freshness period left should be appropriate to allow for a 5- to 7-day life time for high quality products at market place, which is convenient for retail fish products.

However, non-bacterial deteriorative changes may occur at this subzero temperature under fluctuating storage conditions. Preliminary results of a recent study dealing with MA-packaging of superchilled (CBC) cod loins in bulk (2.75 kg) and sea freight transport simulations indicate that lipid hydrolysis, as evaluated by levels of free fatty acids (FFAs), occurs at a faster rate under air than MA storage, as well as being positively related to temperature (data not shown). FFAs are important not only because of their susceptibility to oxidation but also because, by themselves, they cause taste deterioration (Refsgaard et al., 2000). Accumulation of FFAs has been related to some extent to lack of acceptability, because FFAs are known to have detrimental effects on ATPase activity, protein solubility and relative viscosity (Careche and Tejada, 1994), to cause texture deterioration by interacting with proteins (Mackie, 1993) and to be interrelated with lipid oxidation development (Han and Liston, 1987). Because of their relatively small size and greater accessibility (lower steric hindrance) to oxygen and pro-oxidant molecules, FFAs undergo a faster oxidation rate than higher-molecular weight lipid classes (triglycerides and phospholipids) (Labuza and Dugan, 1971; Miyashita and Takagi, 1986).

Development of primary and secondary lipid oxidation compounds was also studied in the light and dark cod muscle as well. As expected, TBARS values were considerably higher for the dark muscle compared with the light muscle (data not shown). This difference is related to the fatty acid composition of these two muscle types, but studies have indicated that the polyunsaturated fatty acids in the dark muscle are more easily destroyed. Thus, it can be expected that the fatty acid oxidation occur mainly in the dark muscle. Further, there was a trend for higher TBARS levels attained in MAP than air-stored fish, reaching a maximum level after 6 days of MAP superchilled storage, with meaningful levels (35-40 μmol MDA/kg fish) detected in the dark muscle. The results show that the packaging method influences the formation of secondary lipid oxidation compounds. Overall, a different oxidation pattern develops in fish products stored in air than under MA (M.G. Karlsdóttir, unpublished data).

Retail and small bulk-packs (5 kg) of fish fillets extended sensory shelf life satisfactorily, but larger bulk-packs (20 kg) were less successful. The shelf life increase of small MA bulk packs of cod fillets ranged from 43-65% in comparison with air-stored fillets and from no increase up to 36% for large packs (20 kg). **Figure 15** summarises these results. MA bulk-packaging was done by inserting icemats between layers of fillets to ensure proper cooling. This probably contributed to a better dispersion of CO_2 to all fish. Two icemats were used for 5-kg bulk and 5 icemats for 20-kg units. Despite this measure, larger bulk units did not keep as long as the smaller ones, possibly due to a proportionally lower number of icemats, which should have been 8 instead of 5 for 20-kg units, resulting in a less direct contact of CO_2 with the fillets. In order to obtain the best results with modified atmosphere all fish surfaces should be exposed to CO_2. However, this may be commercially difficult when using bulk packaging of fillets.

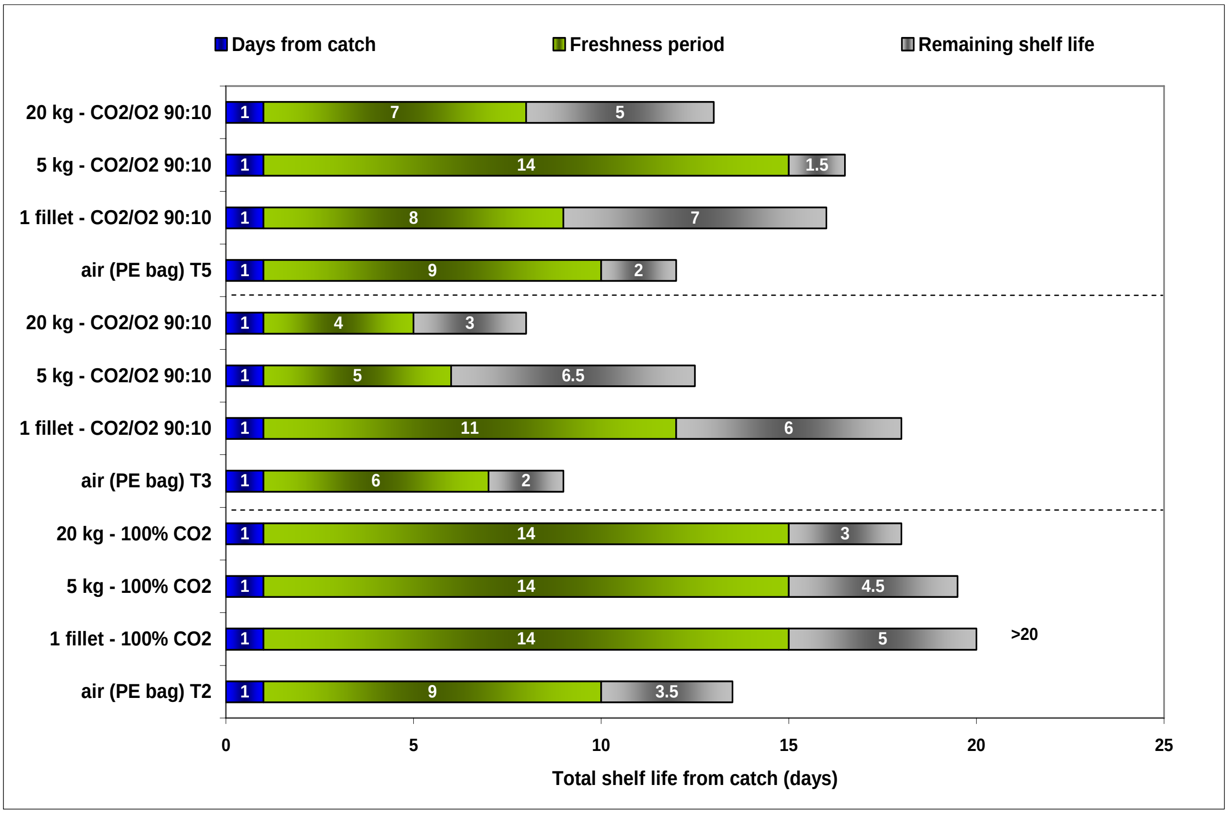


Figure 15. Effect of pack size on the freshness period and shelf life of MAP fish fillets

Figure 16 compares the different levels of TMA found in haddock fillets at sensory rejection. TMA content of air-stored fillets at 0 °C was within the expected range, 10-15 mg N/100 g, at sensory rejection. However, at higher storage temperature (4 °C) considerably more TMA was produced. This agrees with other research work on air-packaged and MAP cod fillets stored from 0 to 10 °C (Einarsson & Lauzon, 1996; Davis, 1990). Based on what was previously mentioned, production of TMA in MAP fish should be expected to be lower when high levels of O_2 are included in the gas mixture, but higher under low oxygen tension. This trend is clearly seen from **Fig. 16**. Higher TMA contents were observed in fillets with decreasing levels of O_2, and with higher storage temperatures. It follows that replacing O_2 by N_2 led to a higher TMA content. However, 100% CO_2 did not favour TMA production, probably due to its high inhibitory effect towards the spoilage microflora.

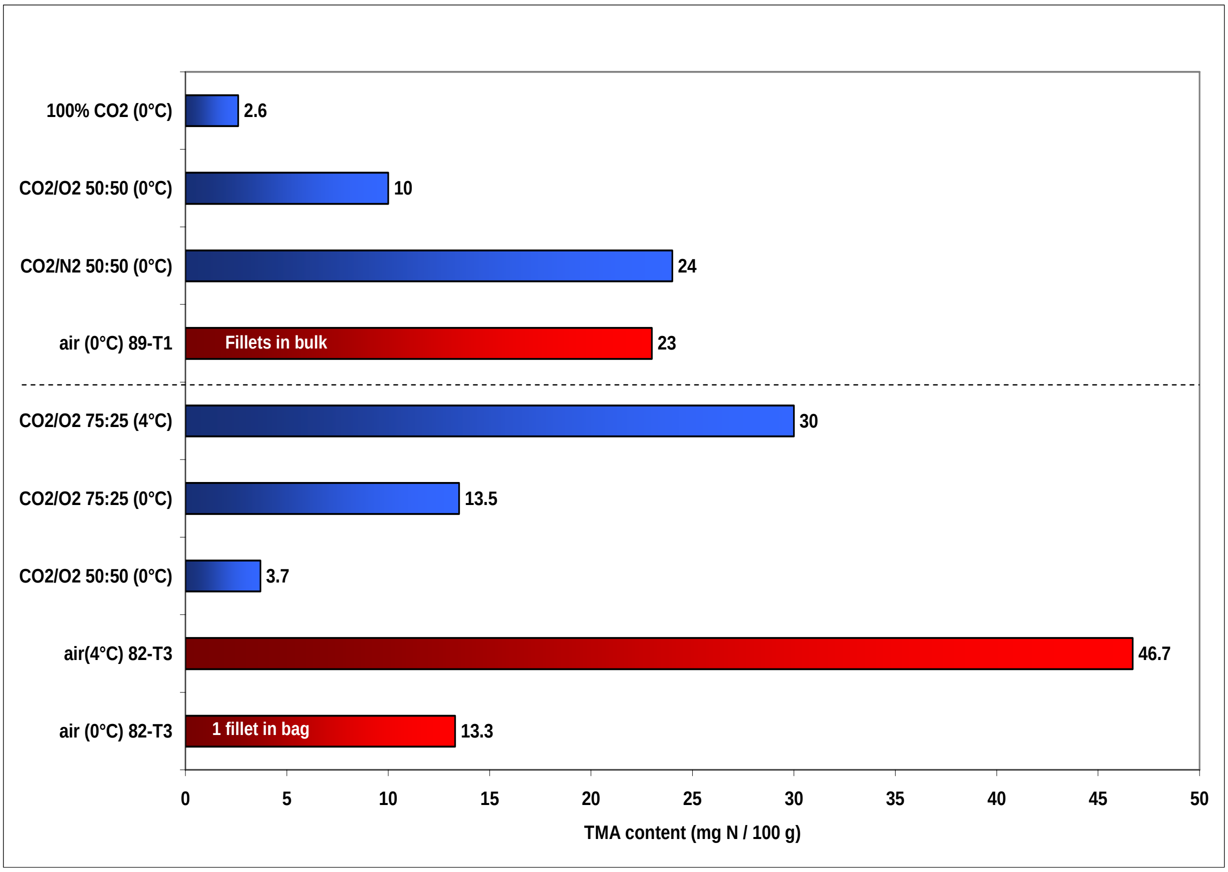


Figure 16. Effect of modified atmosphere and temperature on TMA content in haddock fillets at sensory rejection

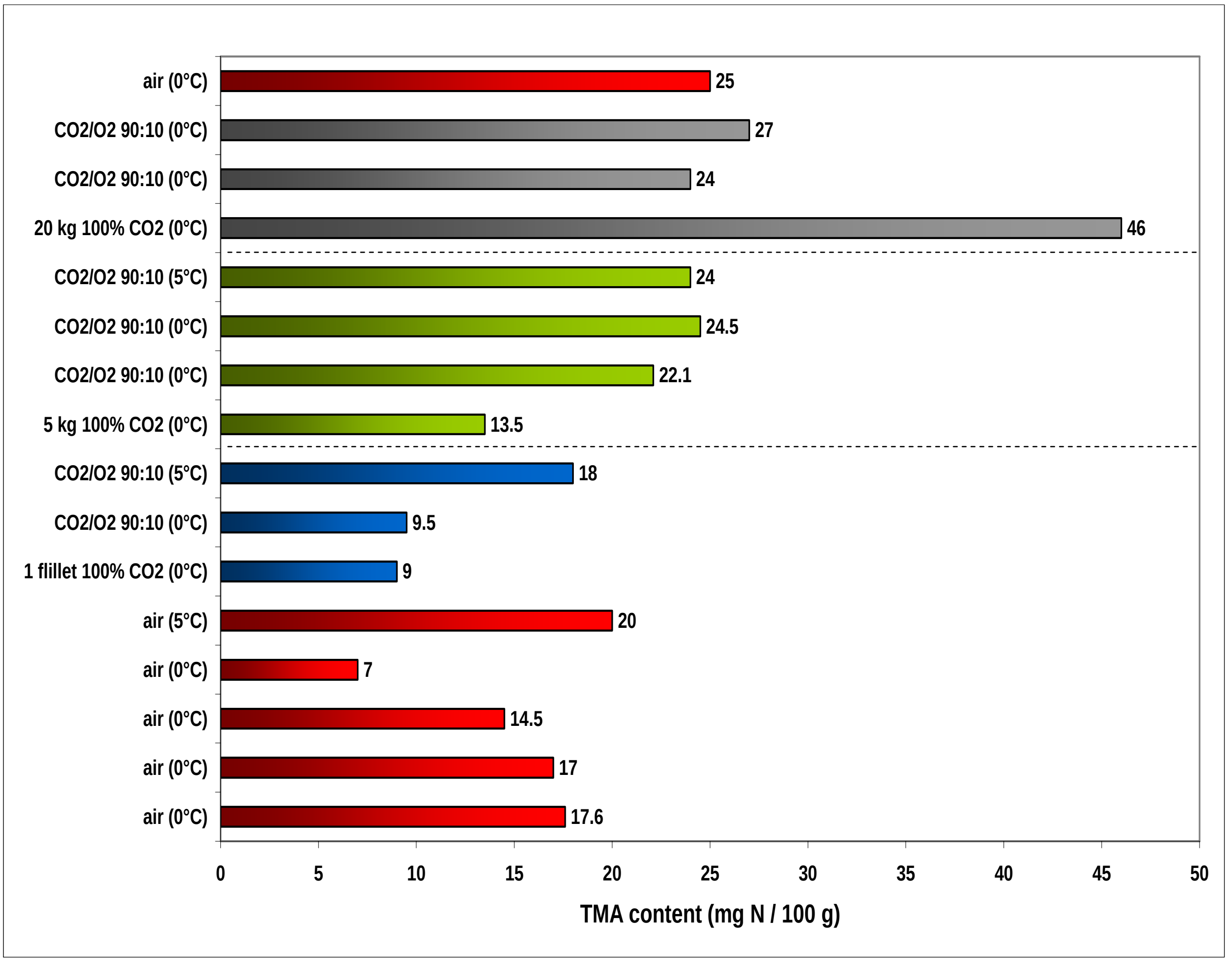


Figure 17. Effect of modified atmosphere, pack size and temperature on TMA content in cod fillets at sensory rejection

Similarly, **Figure 17** demonstrates the effect of gas composition, pack size and storage temperature on TMA production of cod fillets. The effect of higher storage temperature was not as evident as for haddock. On the other hand, TMA production was less in MAP retail-packs than in traditional air-stored fillets as previously seen with haddock fillets, whereas MAP fillets stored in bulk generally had a greater TMA content. Interestingly, a lower TMA content was observed in smaller bulk units flushed with 100% CO_2, as opposed to higher levels in larger bulk units. This difference could be due to the decreased accessibility of CO_2 to the fillets in larger bulk units, leading to lower levels of dissolved CO_2 in the muscle and lower oxygen tension, hence favouring the development of potential spoilage bacteria and the production of TMA. In general the variation in TMA content observed in the trials, ranging from 3 to 46 mg TMA /100 g, at sensory rejection, suggests that TMA is not a good indicator of spoilage in MAP fish fillets nor useful to evaluate shelf life of MAP fish fillets.

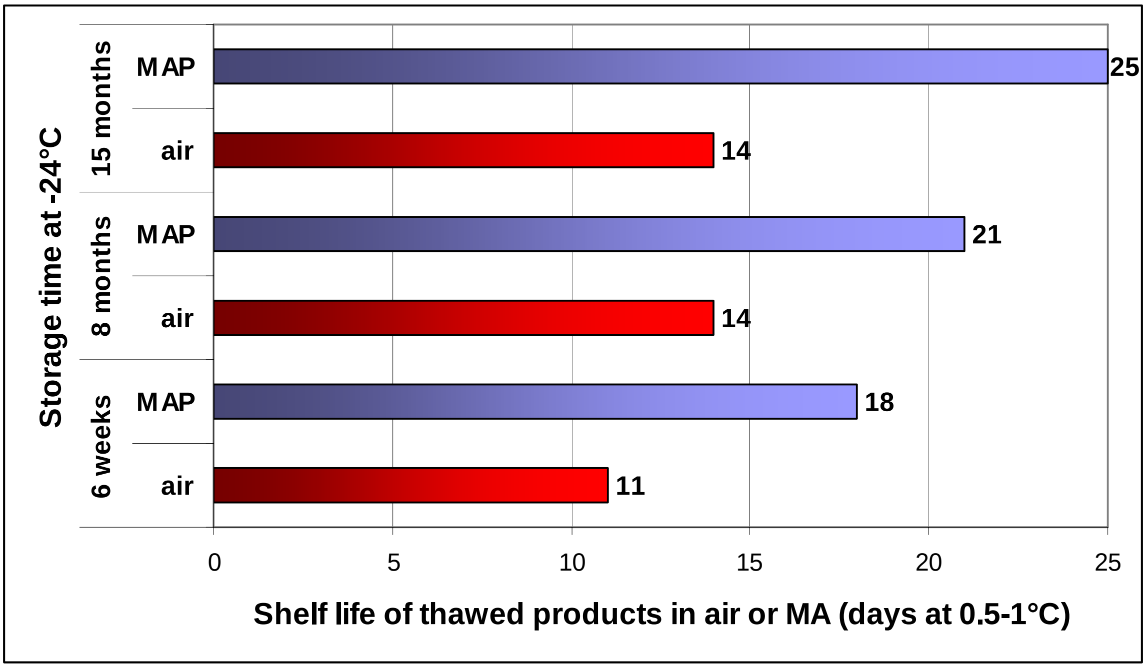


Figure 18. Effect of freezer storage on the keeping quality and storage life of thawed sea-frozen cod fillets stored in air and under MAP

Finally, the effects of freezer storage on the keeping quality and storage life of thawed sea-frozen cod fillets stored in air and under MA were evaluated (Martinsdóttir *et al*., 2003). This was based on findings reported by Danish scientists that *P. phosphoreum*, considered as an important spoilage organism in MA-packaged fish (Dalgaard *et al*., 1997), is sensitive towards freezing and freezer storage (Boknæs *et al*., 2001, 2002). Storage studies on thawed sea-frozen fillets packed under MA ($CO_2/O_2/N_2$:60/10/30) were conducted at 0-1 °C and compared to air storage. Sea-frozen fillets had been kept for 6 weeks, 8 months and 15 months in freezer storage (–24 °C), then retail-packed, thawed and kept for up to 25 days (0.5-1 °C). Sensory, microbiological and chemical analyses were performed. MA packaging of sea-frozen fillets prolonged shelf life of the thawed fillets compared to air-packed fillets for up to 7 days (**Fig. 18**). With longer freezer storage, the development of *P. phosphoreum* was delayed during chilled storage upon thawing and the formation of TMA was slower.

3.2.6 Influence of packaging type on quality deterioration and resulting shelf life following temperature abuses

The use of insulated box for fresh fish export has been a common practice. Expanded polystyrene (EPS) boxes, in 3-and 5-kg sizes are mostly used. However, environmental concerns have led to the evaluation of alternative packaging solutions. Corrugated plastic (CP) boxes have a much lower insulation capacity than EPS boxes but they can be useful in supply chains where temperature abuses are minimised. A trial was conducted to compare the effect of temperature abuse early (day 0) or late (day 4) post-packaging (3 kg) to simulate conditions at the start and end of shipment to the retailer, respectively (Margeirsson & Lauzon, unpublished data). The same temperature load was applied for 6 h, removing the boxes from the cooler and dispersing them on a pallet at room temperature (18-20 °C).

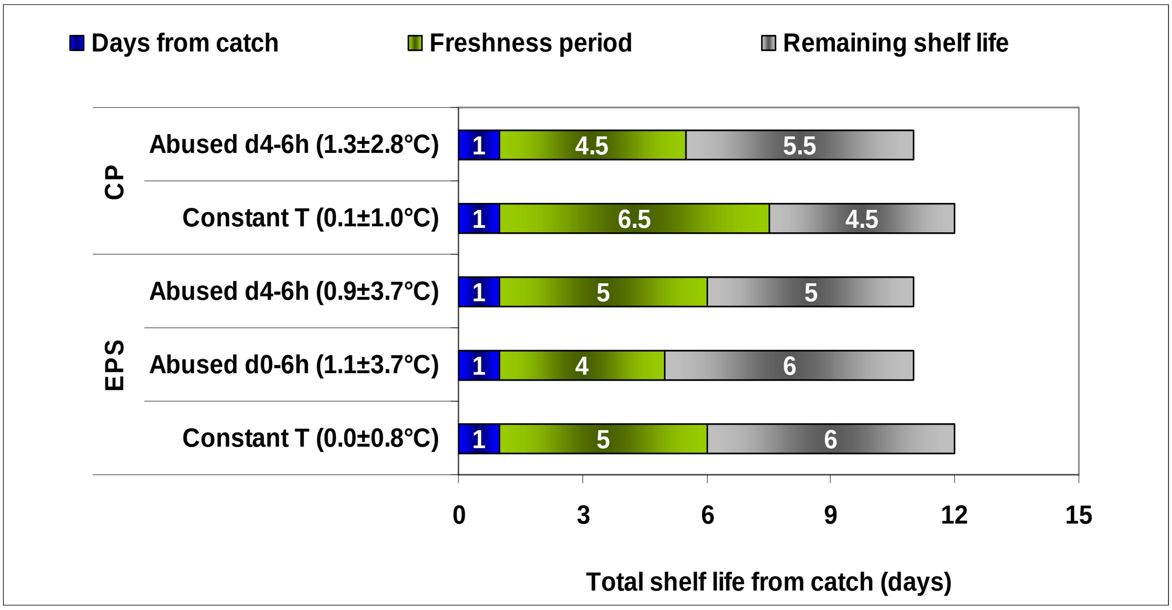


Figure 19. Effect of packaging type on freshness period and resulting shelf life of cod fillets stored in bulk (3 kg) following temperature abuse (average product temperature ± SD). EPS, expanded polystyrene box; CP, corrugated plastic boxes. Temperature abuse at day 0 or 4 post-packaging for 6 h at room temperature (18-20 °C).

Figure 19 shows that for EPS storage, the freshness period of fillets abused on day 0 was reduced by one day, resulting in a corresponding shorter shelf life compared to non-abused fillets. The shelf life of non-abused fillets, either EPS or CP packed, was found to be 11 days. CP-fillets abused on d4 had a similar deterioration pattern as that observed for their EPS counterpart. Therefore, based on the temperature profile evaluated, CP boxes performed similarly to EPS boxes. This is explained by the similar average product temperature measured. This implies that export of fish under rather steady conditions, like those encountered in overseas shipping of containers under superchilled temperature, could be done in CP boxes, especially if CBC fillets are involved.

3.3 The effect of salt content, superchilling and MAP on water properties and distribution of fresh fish

Most studies on superchilling have been focusing on increased shelf life and quality changes of food during storage (Lauzon and Martinsdóttir, 2005; Olafsdottir *et al*., 2006b; Sivertsvik *et al*., 2003; Wang *et al*., 2008; Lauzon *et al*., 2009). However, recently increased effort has been put into studies for monitoring and process control of physicochemical properties during handling of superchilled products (Stevik *et al*., 2010; Gudjónsdóttir *et al*., 2010). Optimization of physicochemical properties during processing and relating these properties to quality features of the final product is important in the search for optimum superchilling of each product.

Water is the most abundant component in fish muscle and can generally be divided into three populations according to its position in the muscle. Firstly, approximately 10% of the water in fish muscle is tightly bound to proteins. This group is very stable and does not exchange with the other water populations to any extent. Secondly, the majority of the water is so called entrapped water, i.e. the water found in the muscle cells, etc. And finally, a small population of free water can be found in the muscle. Continuous osmosis occurs between the entrapped and free water populations and the amount of water in each population is highly susceptible to different processing and storage treatments. The following passage will discuss the effect of salting, superchilling and modified atmosphere packaging on water distribution, water binding and drip of fish muscle.

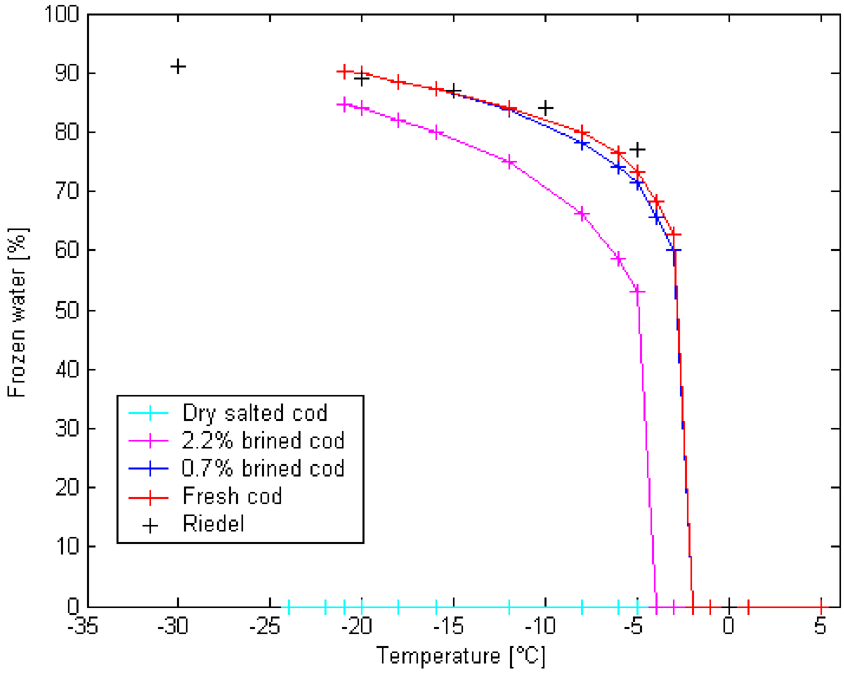


Figure 20. Percentage of frozen water in cod mince as affected by salt concentrations in the muscle and evaluated by relative free induction decay (FIDR) measurements. Reference measurements from calorimetric analysis are also shown (Riedel, 1978). Figure from Gudjónsdóttir (2006).

The temperature during storage and transportation has a large effect not only on the quality and storage life of food but also on the water properties and distribution throughout the muscle. The superchilling temperature range depends on the initial freezing point, where the first ice crystal formation occurs in the product. This initial freezing point depends on the substances and contents of the product, especially the muscle salt concentration (Chen, 1985a,b). Gudjónsdóttir (2006) also showed how the freezing processes and amount of unfreezable water of cod mince were affected by increased salt concentrations as evaluated by Relative Free Induction Decay (FIDR) measurements using low field Nuclear Magnetic Resonance (NMR) (**Fig. 20**). The figure illustrates how the initial freezing point in fish muscle with a salt concentration of 2.2% occurred at -4 to -5 °C, while unsalted cod initiated ice crystal formation at -2 to -3 °C. Fish muscle with higher salt concentration can therefore be stored at a lower superchilling temperature than unsalted muscle without freezing. As mentioned earlier, temperature fluctuations during superchilled storage may be undesirable as it may lead to deteriorative changes. As the water is frozen out as pure ice crystals, the higher concentration of compounds in the unfrozen portion will result in an increased rate of protein denaturation. Lowering the storage temperature of lightly salted products too much is therefore risky since the storage quality is dependent on the temperature stability.

By adding up to 6% (w/w) sodium chloride salt to a muscle tissue, the chloride ions in the salt bind to the actin and myosin filaments, increasing the negative charges of the proteins and hence amplifying the electro-repulsive forces between filaments. This leads to muscle swelling and more water is retained in the muscle and the water holding capacity of the muscle is increased (Offer and Trinick, 1983; Offer and Knight, 1988; Erikson *et al*., 2004; Gudjónsdóttir *et al*., 2010). Because of this, light salting can be a good method to decrease water drip during storage. It is therefore commonly used prior to freezing with the aim of working against the negative effects of freezing. The combination of salt content and superchilling in fish muscle is however also dependent on the salting method. Brine injection has shown to lead to more storage drip than brine immersed fish fillets when stored at superchilling temperatures (Guðjónsdóttir *et al*., 2010). This can be explained by the fact that during brine injection there is an increased risk of puncturing cells with the needles, as well as other destruction of the muscle due to too high injection pressure. This possible destruction of the muscle can lead to reduced water holding properties and thus increased drip. It is also possible that the water added by brine injection is more susceptible to drip than water already present in the muscle, leading to increased drip in the injected fillets. Measurements on the water distribution in cod loins using low field NMR relaxation time analysis support this statement, since a higher fraction of free water was observed in brine injected than brine immersed loins (Guðjónsdóttir *et al*., 2010). The amount of free water is generally described as water lost from the muscle by storage drip. More tightly bound water is only lost if the muscle undergoes further degradation or denaturation, which affects the water binding ability of the proteins in the muscle. Brine immersion can, on the other hand, lead to protein gelation if the salt content is too high, leading to a less attractive product. Therefore many factors must be kept in mind during the production of lightly salted products, with regard to salt concentration, salting method and storage temperature.

Changing the packaging atmosphere does not only affect the bacterial growth but studies have shown that dissolution of carbon dioxide, CO_2, in MA-packed fish can affect both the texture and taste of the fish (Davis, 1993; Lauzon *et al*., 2009). In the above mentioned studies by Lauzon *et al.* (2009) and Gudjónsdóttir *et al.* (2010), MA-packed loins showed a higher drip at the end of shelf life than air-packed loins, with approximately 9% and 5-6% drip, respectively. However, the shelf life was extended significantly by using MAP instead of air packaging. The storage temperature is also of importance here, but partial freezing of samples leads to increased drip. Although up to 9% of the loin weight is lost during MAP storage, the relative water content and water holding capacity were fairly stable during storage. Loins stored at -3.6 °C showed a decrease in WHC during storage, due to partial freezing of these loins, while loins at higher superchilling temperatures (i.e. closer to 0 °C) had a stable WHC during storage. This indicates that temperatures below -2°C should be avoided for fresh or lightly salted cod products, to prevent partial freezing and the muscle destruction accompanying it.

3.4 Impact of transportation mode of fresh fish products on their resulting quality and expected shelf life

Because of the importance of storage and transport temperature, almost all countries in Europe, USA and many other countries have signed the ATP - Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage (ATP, 1970). Some studies have revealed that temperature control in fresh fish cold chains is quite often far from what is described in the ATP (Margeirsson *et al*., 2008; Giannakourou *et al*., 2005), i.e. fish temperature should be as close to 0 °C as possible without freezing the products. Thereby such deviations will inevitably lead to decreasing product quality, shortening of shelf life and decreasing product value. According to Mai *et al*. (2010), the temperature control in fresh fish distribution chains is mainly a problem for air freight, but not sea freight. This is caused by more interfaces, where ambient conditions are not well controlled, as found in air logistic chains. Temperature control can in fact be improved in chilled distribution chains for other perishable products such as beef (Gill *et al*., 1996), poultry (Raab *et al*., 2008) and vegetables (Rieders *et al*., 2009).

The risk of a commonly experienced temperature abuse at various interfaces in the chill chain should be minimised. This can be done with technical solutions such as well designed docking stations with door sealing cushions to minimise air flow and heat transfer to the packaged products. Satisfactory information flow, both upstream and downstream the chain, is also essential in order to minimise unnecessary delays at the interfaces.

An important issue regarding certain handover points in certain chill chains is that master packaging is commonly broken up, often in order to maximise volume utilization. This is the way large part of chilled fish products are handled before being loaded on board airplanes and the processor should prepare his product with adequate precooling before packaging and insulation of the packaging.

3.4.1 Air freight transport and relevant temperature profile

An example of the temperature profile observed in an air logistic chain of 36.5 h is presented in **Figure 21** (Margeirsson *et al*., 2008). It reveals some few hazardous parts of the chain considering the temperature abuse that the packaging experiences. The two most eye-catching steps are the flight followed by un-chilled storage at Humberside airport and the un-chilled storage at Keflavík airport. Un-chilled storage (reloading) in Reykjavík is also notable but since the duration of this step is only approximately 2 h, the temperature abuse is not significant. Relevant events in the chain are tabulated in **Table 3**. Inevitably, prolonged temperature abuse affects the product temperature as can be seen in **Figure 22**.

The consignor/shipper can follow the following recommendations in order to minimise the risk of undesirable thermal loads on the perishable freight:

- Apply precooling before packaging as one step of the processing. Fish products packaged at -0.5 °C simply can withstand more temperature abuse than products at 4 °C when packaged.
- Use well insulated packaging solutions and pack as densely as possible, given the products requirements.
- Check product temperature before shipping.
- Ship products to the departing airport as late as possible, especially if refrigerated storage is unavailable there. Still, the products must be in time at the airport according to the freight forwarder‘s/transporter‘s specification. It follows that temperature-controlled transport to the airport should be used.

- Protect the products from challenging climatic conditions such as rain and direct sunlight. Thin polyethylene films protect against rain but not sunshine.

- Select a direct flight to minimise the number of thermally hazardous interfaces in the chill chain.

- Make sure that all necessary documentation is sent beforehand to the collector of the cargo at the destination airport. Furthermore, make sure that the freight is collected as soon as possible in a temperature-controlled vehicle and that no delays occur in the transport to the client/market.

- When a new freight forwarder/airline is taking care of the air transport, the temperature control in the chill chain should be investigated in at least three separate shipments with the help of ca. 4 – 6 temperature loggers. The cost related to such tests is minimal compared to the value of the goods and this can give valuable information on room for improvements in the chill chain.

Table 3. Relevant events in the supply chain from Icelandic fish processor to Carlisle

No	Date	Time	In link	Event	From	To	Responsible party after event
1	20.09	18:45		Handover	Producer	Transporter	Transporter
2	21.09	3:05	Reykjavík	Heating of surrounding	Refrigerated truck	Unloading area	Transporter
3	21.09	6:25	Keflavík airport	Handover + heating of surrounding	Chilled truck	Unloading area	Transporter
4	21.09	17:45	Keflavík airport	Heating of surrounding	Chilled storage at airport	Loading area at airport, then airplane and unchilled storage at Humberside airport	Transporter
5	22.09	7:15	Carlisle	Heating of surrounding	Chilled truck	Loading area at wholesaler in Carlisle	Wholesaler

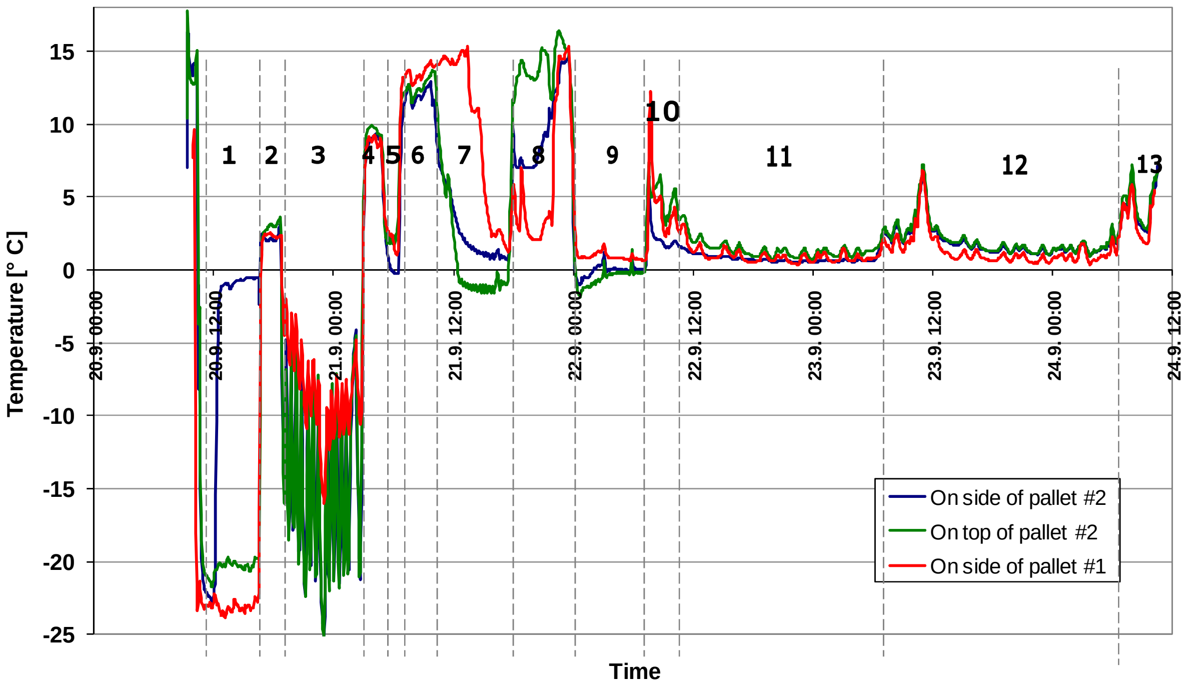


Figure 21. Ambient temperature during transport in September 2007 from processor in Iceland to wholesaler in Carlisle (UK). Numbers 1 to 13 refer to the different steps of the chill chain: 1, cold storage at processor after packaging; 2, chilled storage at processor; 3, transportation (ca. 400 km) from processing plant to Reykjavik in a refrigerated truck; 4, unloading and loading in a chilled truck in Reykjavik; 5, transportation (ca. 50 km) from Reykjavik to Keflavik airport in a chilled truck; 6, unchilled storage at Keflavik airport; 7, chilled storage at Keflavik airport; 8, flight (ca. 1800 km) to Humberside airport (UK) and unchilled storage at Humberside; 9, storage at Humberside and transportation (ca. 280 km) to Carlisle (UK); 10, unloading/unchilled storage at wholesaler in Carlisle; 11 and 12, storage in Carlisle; 13, distribution to retailers.

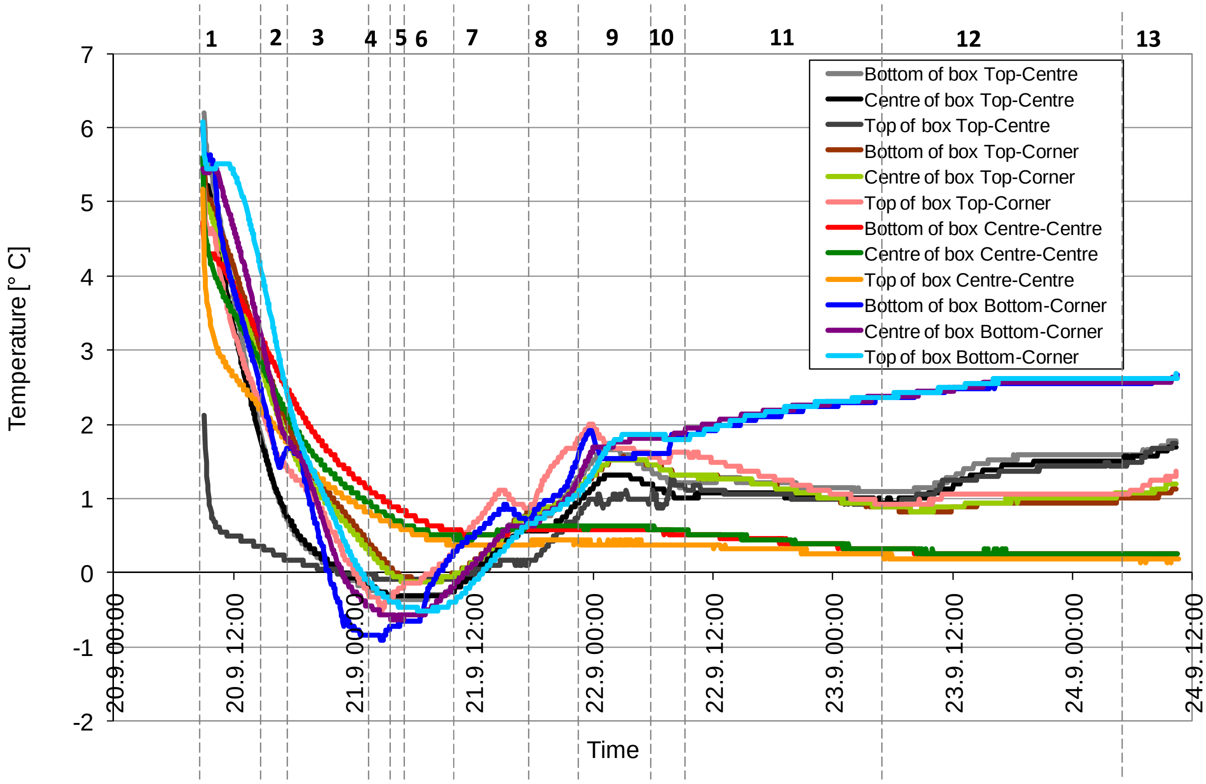


Figure 22. Temperature inside four EPS boxes on one pallet in chilled fish supply chain from Iceland to UK in September 2007. Numbers 1 to 13 refer to the different steps of the chill chain: 1, cold storage at processor after packaging; 2, chilled storage at processor; 3, transportation (ca. 400 km) from processing plant to Reykjavik in a refrigerated truck; 4, unloading and loading in a chilled truck in Reykjavik; 5, transportation (ca. 50 km) from Reykjavik to Keflavik airport in a chilled truck; 6, unchilled storage at Keflavik airport; 7, chilled storage at Keflavik airport; 8, flight (ca. 1800 km) to Humberside airport (UK) and unchilled storage at Humberside; 9, storage at Humberside and transportation (ca. 280 km) to Carlisle (UK); 10, unloading/unchilled storage at wholesaler in Carlisle; 11 and 12, storage in Carlisle; 13, distribution to retailers.

3.4.2 Overseas shipping and relevant temperature profile

The big advantage that sea transport has compared to air transport is continuity in the transport, i.e. the chain has few and relatively secure handover points regarding temperature control. Containers (refrigerated and non-refrigerated) are multimodal equipment, which generally allow goods to be transferred between land and sea transport without the need of breaking up the cargo. An example of air temperature profile in sea transport chain is presented in **Figure 23.** (Mai *et al.*, 2010).

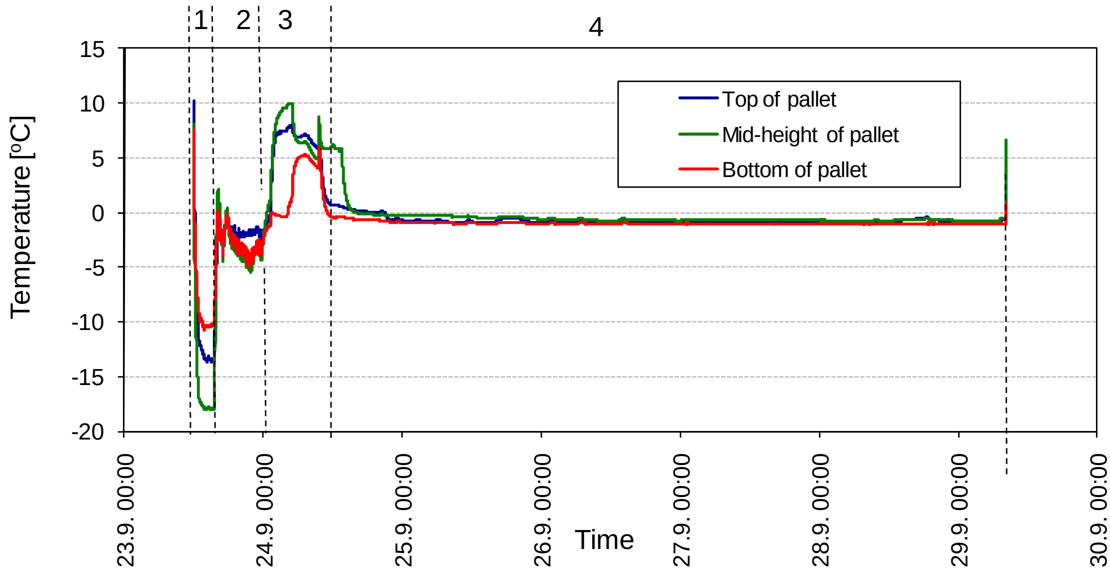


Figure 24. Ambient temperature during containerised sea transport from processor in Iceland to Grimsby (UK) in September 2008. Numbers 1 to 4 refer to the different steps of the chill chain: 1, cold storage at the producer; 2, loading into container and transport to Reykjavík; 3, partly chilled hold in Reykjavík; 4, transportation and handling in refrigerated container trucked from producer to Reykjavík, followed by shipment to Immingham (UK) and land transportation to final destination (Grimsby, UK).

Some general recommendations for sea transport include:

- Check product temperature before loading the container.
- Permit free flow of cooling air around the cargo by not overloading the container.
- Air temperature should be kept between -1 and 0 °C for optimal storage of superchilled fish products. The superchilled storage conditions during sea transport are in general more important than during road transport since normally, sea transport lasts longer.
- Ice on top of fresh fish fillets when transported in containers with proper temperature control may not be required. If used then make sure melted ice water does not stay in contact with the products or that cross contamination is not caused by melted ice from one fish box to another.

3.4.3 Comparison of transportation modes: Bremerhaven trial

A trial was carried out in February 2009 to study temperature changes during transport via air and sea freight and to evaluate their effect on the quality of the fish products following repackaging during chilled storage (Martinsdottir *et al*., 2010). For this purpose, CBC cooled cod loins packed in EPS boxes, with and without a gel pack, were transported via air and sea freight to Bremerhaven, Germany. After the transport, the samples were retail-packed in air and MA, stored at 1.1 ± 0.6 °C, and analysed with microbial and chemical methods. The temperature history of the groups was studied using temperature loggers.

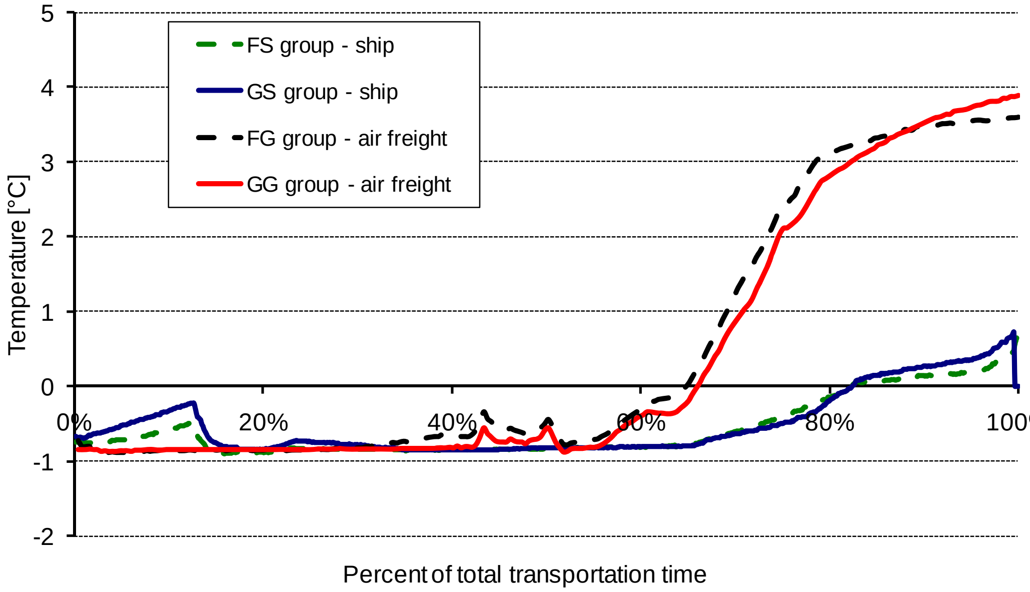


Figure 25. Average temperature inside EPS boxes with or without gel pack. EPS boxes with a gel pack on top of the fillets (FS and FG, dashed lines) or none (GS and GG, full lines). Average temperature of four loggers is shown for each box. Total transportation time by air and sea freight was 42 and 140 h, respectively.

Figure 25 shows how temperature evolved throughout the two shipments. Overall temperature increase was greater in the superchilled fish transported by air than by sea freight. In fact, the product temperature started to fluctuate after about 42% of the total transportation time (42 h) and had reached above 0 °C after about 64% of the time. By ship, product temperature started to rise after about 66% of total transportation time (140 h) and reached 0 °C after 81% of the journey time. At the end point, the average product temperature was 3 degrees lower when transported by sea than by air freight. Little difference was noticed between the mean product temperature with and without a gel pack during the whole transportation time for both air and sea freight. However, the gel packs seem to have contributed to better temperature control for both transport modes with regard to the mean product temperature at final destination (Bremerhaven): 0.5 °C and 0.7 °C with and without gel pack, respectively, for sea transport and 3.6 °C and 3.9 °C with and without gel pack, respectively for air-shipped fish. The effect of the gel packs can also be noted by comparing the lower product temperature in the upper part of the boxes to the higher product temperature in the bottom corners of boxes shipped by air. This temperature difference in boxes with a gel pack was 1.3 °C compared to 0.8 °C in boxes without a gel pack.

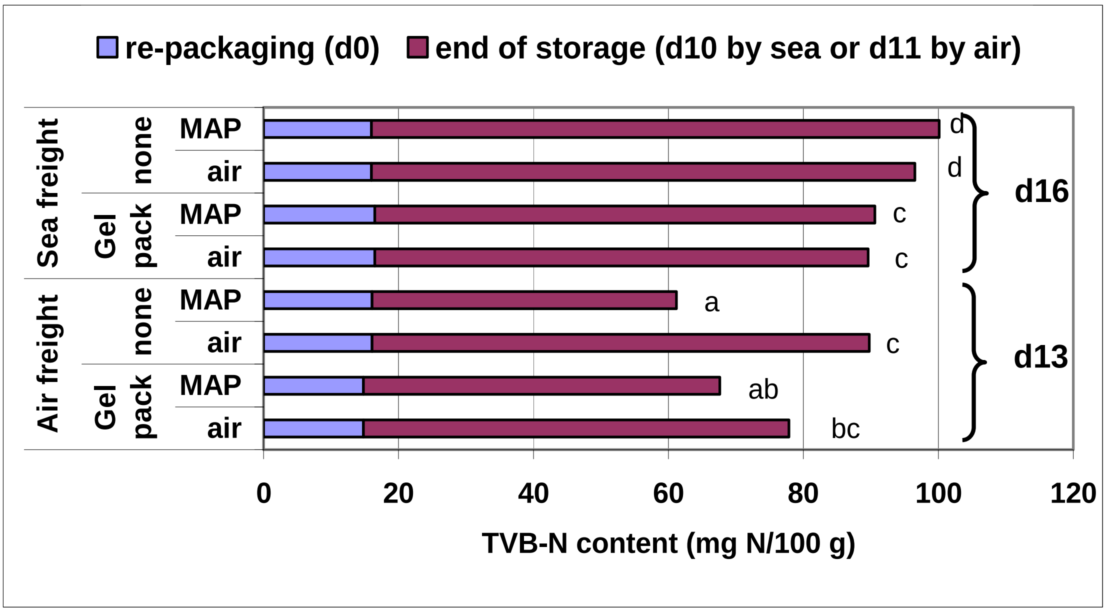


Figure 26. Effect of transportation modes and packaging methods on TVB-N formation in cod loins. TVB-N content prior to transportation was 12.5 ± 0.5 mg N/100 g. Total time from processing in Iceland including transport is designated by d13 and d16 (13 and 16 days). Different letters indicate significant difference between groups after 10 (sea freight) and 11 (air freight) days from re-packaging ($p<0.05$).

Further, the main results show that the temperature fluctuations were larger and more frequent for product transported by air than by sea. Ambient air temperature fluctuations led to a higher temperature (3.3-3.6 °C) in air freight shipped cod loins upon arrival in Bremerhaven. For some fillets, the temperature exceeded 4 °C. It follows that this difference in fish quality will result in products of different shelf life expectations upon re-packaging into retail portions. Since sensory evaluation was not conducted in Bremerhaven, comparison of quality deterioration among differently treated products is based on chemical and microbial spoilage indices, TVB-N content and counts of *Photobacterium phosphoreum*, respectively.

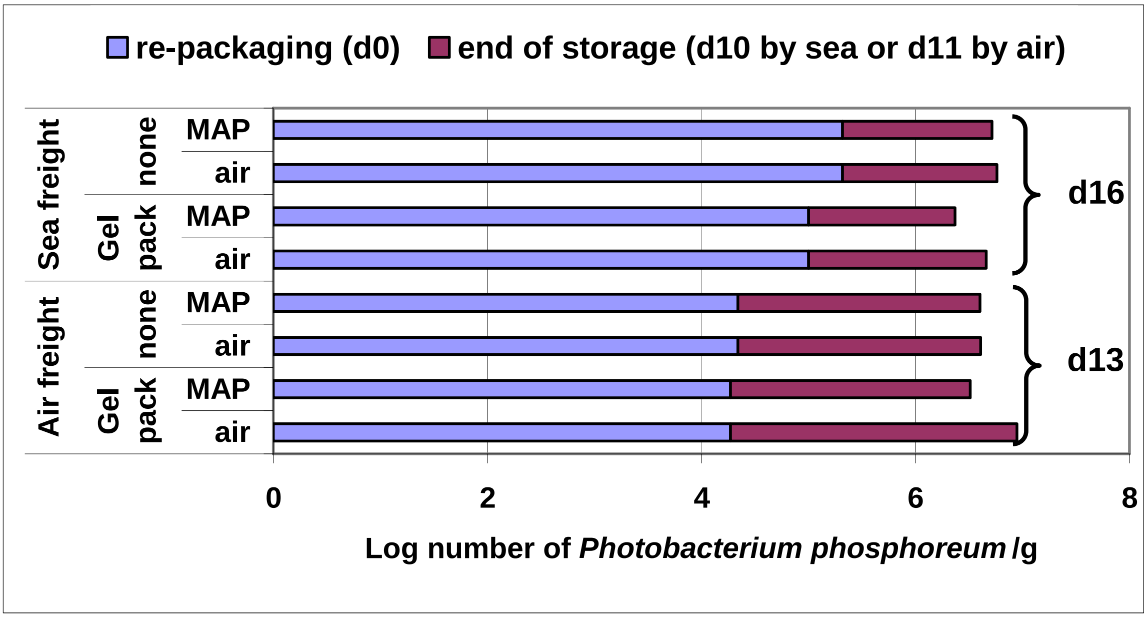


Figure 27. Effect of transportation mode and packaging method on *P. phosphoreum* (Pp) growth in cod loins. Pp level prior to transportation was log 2.9 ± 0.2/g. Total time from processing in Iceland including transport is designated by d13 and d16 (13 and 16 days). No significant difference (p>0.05) in Pp counts between groups at re-packaging time (d0) or end of storage (d10 or 11).

Figures 25 and **26** present TVB-N and Pp levels measured on the re-packaging day and after 10 or 11 days storage for the different groups. At re-packaging, similar TVB-N levels (p=0.31) were observed in air and sea freight transported fish in spite of the 4-day difference in time from processing. Slightly higher Pp levels were found in sea freight fish compared to air-transported fish, but this difference was statistically insignificant (p=0.08). At the end of storage, similar Pp levels (log 6.4-6.9/g) were detected among the differently treated groups after 10 (sea freight) or 11 (air freight) days from re-packaging independently of the atmospheric condition used, i.e. 16 or 13 days respectively from processing. This implies that an overall longer microbiological shelf life was obtained for sea-transported fish.

Based on the EC regulation No 2074 from 2005, a TVB-N content exceeding 35 mg N/100 g flesh of a gadoid species indicates that an unprocessed fishery product is unfit for human consumption, when supported by sensory evaluation. TVB-N content at the end of storage in all groups surpassed this value, but indicated though that significantly lower levels were found in MAP products (11 days after re-packaging) prepared from air-transported fish compared to all products (10 days after re-packaging) derived from sea-transported fish. The use of gel packs during sea freight shipping was advantageous to slow down TVB-N formation after re-packaging. To the contrary, the use of gel packs during air freight transportation did not significantly influence the development of chemical and microbial indices in air- or MA-packed products. This is probably explained by the high thermal load applied to the air freight fish during transportation as indicated by the short time elapsed from processing until the fish temperature had reached 0 °C (27 h) compared to sea freight fish (113 h). In other words, the early "melting" of the gel packs did not allow for any increased protection of the air-transported CBC loins over those packaged with no gel pack. However, MA re-packaging of air-transported fish led to significantly slower TVB-N formation than re-packaging in normal atmosphere, as evaluated after 11 days of storage. Such a difference was not observed upon storage of re-packaged sea-transported fish. This may be because the spoilage microbiota was already actively growing at re-packaging, with Pp levels just at or above log 5/g in contrast to a tenfold lower level in air freight fish.

Overall, it was found that the temperature increase in the superchilled fish was greater when transported by air than by sea freight, resulting in a similar microbiological quality of the products at delivery despite the 98 h time difference from processing. Gel packs contributed to a better temperature control in the upper part of the boxes, generally leading to a slower TVB-N formation after re-packaging. The results further suggest that the retail shelf life of re-packaged sea-transported fish was shorter than 10 days, but probably 10-11 days for retail packs prepared from air-transported fish. Use of MA did not apparently increase the retail life of products prepared from sea-transported fish, while MA re-packaging of air-transported fish led to a slower spoilage process than re-packaging in normal atmosphere.

4. Conclusion

Fresh fish products have a limited shelf life which is an important hurdle for the export of fresh products. Handling, cooling, processing, packaging and storage methods greatly influence the quality maintenance and successive deterioration process of such products. Raw material quality and other intrinsic/extrinsic parameters related to the fish influence the freshness and shelf life extension that can possibly be achieved. Temperature control is important to maintain fish quality. Pre-cooling of fillets in process is being used to lower the temperature prior to packaging. However, the cooling technique applied should not compromise the microbiological quality of the product and render it vulnerable to faster spoilage post-packaging. Synergism of combined superchilling and MAP can lead to a considerable extension of the freshness period and shelf life of fish products. Nevertheless, stable storage conditions are required to slow down deteriorative changes of both microbial and chemical nature. Further, environmentally-friendly packaging methods (CP boxes) may become an interesting alternative to export fish under rather steady conditions, like those encountered in overseas shipping of containers under superchilled temperature, especially if CBC fillets are involved. Finally, the impact of transportation mode of fresh fish products on their resulting quality was examined. This report provided an overview of the findings on fish research carried out at Matís (Icelandic Fisheries Laboratories) over the last three decades.

The practicality of this information for the fish processing industry will be considered. A simple way to summarise some of the information is to present processing, packaging and storage alternatives in a graphical manner, as illustrated in **Tables 4** and **5**. Fishing trip at sea may last from one to several days. Taking into account the 9-day freshness period of cod (from catch) stored at about 0 °C, the age of fish at processing will indicate the time period left for the distribution and retailing of high value products. Raw material age at processing and product temperature post-packaging are important parameters affecting the fish freshness and quality deterioration. The examples presented in **Tables 4** and **5** for various products and chill chain situations may lead to different outcomes in freshness period (high value) and shelf life (SL) left for fish products at delivery. These estimations are based on cod trials discussed in this report. It should be mentioned that few data is available for superchilled cod processed from 1-day and 5-day old raw material.

Table 4. Estimated duration of the freshness period and shelf life of air-stored cod products as influenced by raw material age at processing, mean product temperature post-packaging and transportation mode

Age at processing	1 day old from catch			3 days old from catch			5 days old from catch	
Storage conditions after fillet processing (mean product temperature)	superchilled (-1 °C)	chilled 0.5 °C	abused 2 °C	superchilled (-1 °C)	chilled 0.5 °C	abused 2 °C	superchilled (-1 °C)	chilled 0.5 °C
Estimated freshness period (days)	10+	8	6	10	6	5-6	10	4
Estimated shelf life (days)	15-17	12-13	10	15-16	10-12	8-9	14	9-11
Sea freight -6 d SL at delivery Freshness period	SC 9-11 4+	C 6-7 2	AB 4 0	SC 9-10 4	C 4-6 0	AB 2-3 0	SC 8 4	C 3-5 0
Air freight -2 d SL at delivery Freshness period	NA	C 10-11 6	AB 8 4	NA	C 8-10 4	AB 6-7 3-4	NA	C 7-9 2

SL, shelf life in days; SC, superchilled; C, chilled; AB, abused; NA, not available

Table 5. Estimated duration of the freshness period and shelf life of MAP cod products as influenced by raw material age at processing, mean product temperature post-packaging and transportation mode

Age at processing	1 day old from catch		3 days old from catch	
Packaging conditions ($CO_2/N_2/O_2$)	Retail pack (60:20:20)		3-kg pack (45:40:5)	
Storage conditions after fillet processing (mean product temperature)	superchilled (-1.6 °C)	chilled (+0.5 °C)	superchilled (-1 °C)	abused (+1 °C)
Estimated freshness period (days)	21	8-15	15	9
Estimated shelf life (days)	27	16-23	19	12
Sea freight of 6 days Shelf life at delivery (days) Freshness period (days)	SC 21 15	C 10-17 2-9	SC 13 9	AB 6 3
Air freight of 2 days Shelf life at delivery (days) Freshness period (days)	NA	C 14-21 6-13	NA	AB 10 7

SC, superchilled; C, chilled; AB, abused; NA, not available

Table 4 clearly demonstrates that the raw material age at processing will reflect the possible shipping conditions to result in valuable products. For instance, refrigerated (0.5 °C) sea shipping of cod processed 5 days post catch can not be expected to deliver products with any freshness characteristics. Based on these estimations, it is observed that superchilling of fish products at processing prior to packaging will result in an extended freshness period and shelf life. Product superchilling will also result in built-in refrigeration in the fillets which will, in turn, ensure a better temperature control during shipping and distribution to foreign markets. Because of the insulation properties of EPS boxes generally used, superchilling conducted before packaging is more efficient and will lead to a homogeneous product temperature once packaged in the box. Stability of the superchilled product once packaged is critical to maintain its freshness and to avoid undesirable quality defects. **Table 5** further indicates similar trends on the importance of proper storage conditions to maintain freshness of MAP fish products and reduce the deterioration rate. The raw material age at processing is also emphasised. These are the two main criteria for successful MA packaging.

Finally, the terms "freshness period" and "remaining shelf life" were introduced and found to be useful since they led to a better understanding of the effects of different cooling, processing, storage techniques and other parameters on the quality deterioration of fresh fish products. Fish processors must consider the value of their raw material, the processing and storage methods available and the drawbacks of their chill chain in order to take proper decisions and attain the highest product value at any given time.

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Appendix I: Data summary of several fillet trials

Table 4. Fish fillets (research in earlier years)

Fish species	Year	Known history	Raw mat. age[1] (d)	Packaging type	Packaging conditions (for MAP: $CO_2/O_2/N_2$)	Storage temp. (°C)	Shelf life[2] (d)	Freshness period[3] (d)	Reference
Haddock	**1981**	**gutted**	**2-3**	PE bag	air (open)	0	10.5	8	G. Valdimarsson & G. Stefánsson, 1981 (TT#129)
				N/PE (90 µm)	vacuum	0	10	7.5-8	
					~ 50/50/0	0	11	9-9.5	
	02-82	**ungutted**	**2**	PE bag (T1)	air	0	12.5	7.5	Stefánsson & Valdimarsson 1982 (Rf 3. Rit)
				N/PE 20/70µm	vacuum	0	13	11	
				N/PE 60/100	50/50/0	0	**>16**	**13**	
	1982	**ungutted**	**1**	PE bag (T2)	air (open)	0	13.5	9	
				N-PVDC/PE (25/50 µm)	75/25/0	0	>20	**15**	
					100/0/0	0	>20	**>20**	
	04-82	**ungutted**	**1-2**	PE bag (T3)	air (open)	0	9	7	
						4	6	~4	
				N-PVDC/PE (25/50 µm)	75/25/0	0	19	12.5	
						4	7.5	6.5	
	04-82	**ungutted**	**1**	N-PVDC/PE (25/50 µm) (T4)	75/25/0	0	19	11	
		ungutted, extra care			75/25/0	0	**>19**	**18**	
	02-89	**line caught, gutted**	**3**	PE bag (T1)	air (open)	0	11	4	Stefánsson & Blomsterberg 1991 (Rf 29. Rit, T1)
				PAE 85	50/0/50	0	14.5	7	
				(18 fillets)	50/50/0	0	**16**	5-14	
					100/0/0	0	**>19**	**15.5**	
Redfish	**11-90**	**deskinned**	**1**		air, iced	0	10	8	Blomsterberg & Stefánsson 1994 (Rf 67-94)
				Vacuum bag	80/20/0	0	**15**	**6**	
					80/0/20	0	**14**	**13**	
					100/0/0	0	**17**	**14**	
					vacuum	0	13.5	11	
	08-95	**long-line**	**1**	Retail skin pack	air-packed	0	11	9.5	Stefánsson & Halldórsson 1995 (Rf 95-95)
						5	8	6.5	
	03-00		**2**	10 d in air (0.9°C), then filleted, packed	air (open)	0-2	5	1	Lauzon *et al.* 2001 (Rf 06-01);
					60/0/40		9	3	
				10 d in 60/0/40 (0.9°C), then filleted, packed	air (open)		5.5	2	Lauzon *et al.* 2002
					60/0/40		11	2	
	05-00		**2**	10 d in air (1.8°C), then filleted, packed	air (open)	0-2	3	1	Lauzon *et al.* 2001 (Rf 06-01);
					60/0/40		8	2	
				10 d in 60/0/40 (1.8°C), then filleted, packed	air (open)		4	2	Lauzon *et al.* 2002
					60/0/40		14	3	

1: time in days from catch to trial
2: time in days from processing/packaging, based on sensory asssessment of cooked fish (Torry score = 5.5)
3: time in days from processing/packaging, based on sensory asssessment of cooked fish (Torry score = 7)

Table 5. Cod fillets (research in earlier years)

Year mo-yr	Known history	Raw mat. age[1] (d)	Packaging type	Packaging conditions (for MAP: $CO_2/O_2/N_2$)	Storage temp. (°C)	Shelf life[2] (d)	Freshness period[3] (d)	Reference
1980		**3**	air (iced)		0-1	11		Magnússon H.
			Vacuum			8		1980
			vacuum + N_2			7		(unpublished)
1990	**gutted**	**1**	PE bag (T2)	air (open)	0	12.5	8	Stefánsson &
			N/PE 20/70µm	100/0/0		>19	14	Blomsterberg
			PAE 85 (5 kg)	100/0/0		18.5	14	1991
			PAE 85 (20kg)	100/0/0		17	14	(Rf 29. Rit, T2)
			PE bag (T3)	air (open)	0	8	6	Stefánsson &
			N/PE 20/70µm	90/10/0		17	6.5-11	Blomsterberg
			PAE 85 (5 kg)	90/10/0		11-11.5	5	1991
			PAE 85 (20kg)	90/10/0		7	4	(Rf 29. Rit, T3)
			PE bag (T4)	air (open)	0	9	5.5	Stefánsson &
					5	4	2.5	Blomsterberg
			PAE 85 (5 kg)	90/10/0	0	>14	7	1991
					5	7.5	5	(Rf 29. Rit, T4)
			N/PE 20/70µm	90/10/0	5	7	5	
		1	PE bag (T5)	air (open)	0	11	9	Stefánsson &
		8				6	0	Blomsterberg
		1	N/PE 20/70µm	90/10/0		15	8	1991
		8				5.5	0	(Rf 29. Rit, T5)
		1	PAE 85 (5 kg)	90/10/0		15.5	14	
		8				7.5	0	
		1	PAE 85 (20kg)	90/10/0		12	7	
02-91	**line caught**	**2**	300 g; 960 cm^3	air	16	2	1	Einarsson 1992
					7	3	2	
					5	3	2	
					0.5	10	4	
					-2.5	15	7	
					-4.5	35	8	
				40/30/30	16	2	1	
					7	3	2	
					5	5	4	
					0,5	13	8	
					-2.5	31	10	
					-4.5	36	11	
1993	**T abused**	**1-2**	5 kg EPS +ice pack (on top)	air (open)	Abused early/ late	8.5	5.5	Á. Þorkelsdóttir *et al.* 1993 (Rf 24-93)
					0°C for 6d; then 2-3°C abused late	9	6.5	
			vacuum bag in EPS box + ice pack (bottom)	90/10/0	Abused early/late	11.5	9	
					0°C for 6d; then 2-3°C abused late	12.5	10	
08-95	**long-line**	**1**	Retail skin pack	air-packed	0	12	10.5	Stefánsson &
					5	8.5	7.5	Halldórsson
								1995
								(Rf 95-95)
1995		**1**	Nylon bag	air (open)	-1.6	17	8	Einarsson &
				60/20/20		27	21	Lauzon 1996
				60/0/40		21	12	
				air (open)	0.6	16	8	
				60/20/20		16	8	
				60/0/40		20	10	

				air (open)	9.7	5	2.2	
				60/20/20		5	2.5	
				60/0/40		5	2.5	
05-99	**gutted**	**2**	10 d in air, then filleted, packed	air (open)	0-2	4	1	Lauzon *et al*. 2001 (Rf 06-01)
				70/30/0		6	3	
			10 d in 60/0/40, then filleted, packed	air (open)		6.5	2	
				70/30/0		7	1	
11-99	**gutted**	**2**	10 d in air, then filleted, packed	air (open)	0-2	5	0	
				50/30/20		7	0	
			10 d in 60/0/40, then filleted, packed	air (open)		7	2	
				50/30/20		13	5	

1: time in days from catch to trial
2: time in days from processing/packaging, based on sensory asssessment of cooked fish (Torry score = 5.5)
3: time in days from processing/packaging, based on sensory asssessment of cooked fish (Torry score = 7)

Table 6. Cod fillets (research in recent years)

Year mo-yr	**Known history**	**Raw mat. age[1] (d)**	**Packaging type**	**Packaging conditions (for MAP: $CO_2/O_2/N_2$)**	**Storage temp. (°C)**	**Shelf life[2] (d)**	**Freshness period[3] (d)**	**Reference**
09-01	**Whole, filleted**	**1**	**Tray (400 g) + bag: 115µ**	air (open)	0.5±0.1	15-17	10	Martinsdóttir *et al*. 2003 (Rf 22-03)
				60/10/30	0.5±0.1	22-24	**15**	
2001	**Thawed fillet**	**Freezing time: 6w**	**Tray (400 g) + bag: 115µ**	air (open)	0.9±0.3	11	6	Martinsdóttir *et al*. 2003 (Rf 22-03)
				60/10/30	0.9±0.3	18	6	
		Freezing time: 8m		air (open)	0.9±0.1	14	12	
				60/10/30	0.9±0.1	21	**14**	
		Freezing time: 15 m		air (open)	0.8±0.2	14	6	
				60/10/30	0.8±0.2	25	6	
10-03	**Trad. process**	**3**	EPS (5kg)	air T_p=1.8±0.9°C	0.8±1.9	9	6	Martinsdóttir *et al*. 2004 (Rf 03-04); Olafsdottir *et al.* 2006b
	Trad. process, 1x T abuse		Abused d3-8h @ RT	air T_p=2.0±0.9°C	1.4±3.4	8.5	5.5	
	Trad. process, 2x T abuse	**4 (abused pre/post process)**	Abused d3-8h @ RT	air T_p = 3.9°C	1.9±3.8	4.5	3	
	CBC	**3**		air -0.9±0.6°C	0.7±1.6	9.5	**7.5**	
11-03	**Trad. process**	**1**	EPS (3kg)	air T_p=0.4±0.5°C	0.3±0.1	12.5	8	Martinsdóttir *et al*. 2004 (Rf 03-04); Olafsdottir *et al.* 2006b
			Abused d3-16h @ RT	air T_p=1.9±2.3°C	1.7±4.8	9.5	5.5	
12-03	**CBC**	**1**	EPS (4kg)	air -0.3±0.5°C	0.4±1.1	13	**8**	Martinsdóttir *et al*. 2004 (Rf 03-04); Olafsdottir *et al.* 2006b
				air -1.3±0.0°C	-1.2±1.3	14+	**9.5**	
				air -0.8±0.7°C	-0.2±1.3	14	**9.5**	
10-04	**CBC, 2x T abuse**	**3**	Polimon tray (~9L, 3kg fish)	air T_p=1.3±1.1°C	1.1±1.9	8	7	Martinsdóttir *et al*. 2005 (Rf 10-05)
				air -1.2±1.4°C	-1.2±1.9	14	8	
				54/1/45 T_p=0.9±1.5°C	0.9±1.6	12	**9**	
				54/1/45 T_p=-1.2±1.3	-1.2±1.8	15	**9**	
11-04	**CBC**	**3**	EPS (3kg)	air -1.3±0.0°C	-1.0±0.4	16	10	Martinsdóttir *et al*. 2005 (Rf 10-05)
			Polimon tray (~9L, 3kg fish)	air -1.3±0.0°C		14?	11	
				56/7/37 -1.1±0.2°C		19	**15**	
2005	**Farmed, iced**	**1**	5 fillets/box	T_p=0.4±0.4°C	0.8±0.2	**17**	**14**	Tryggvadóttir *et al*. 2005 (Rf 26-05)
	Wild, iced					~16	10	
11-05	**2d whole +gutted; filleted**	**2 + 1**	EPS (5 kg)	air	1.5	7	6	Wang *et al*. 2008
			Tray (500 g) + bag: 115µ	50.7/4.6/44.7		11	9	
			EPS (5 kg)	air	-1	13	10	
			Tray + bag	50.7/4.6/44.7		21	**15**	

1: time in days from catch to packaging
2: time in days from processing/packaging, based on sensory asssessment of cooked fish (Torry score = 5.5)
3: time in days from processing/packaging, based on sensory asssessment of cooked fish (Torry score = 7)

Table 7. Fish fillets (research in recent years)

Fish species	Year mo-yr	Known history	Raw mat. age[1] (d)	Packaging type	Packaging conditions (for MAP: $CO_2/O_2/N_2$)	Storage temp. (°C)	Shelf life[2] (d)	Fresh-ness period[3] (d)	Reference
Cod	**10-06**	**3d whole filleted, brined 2d**	**3 + 2 2.5% salt**	EPS (5 kg)	air -1.5±1.1°C	-2	14	**10**	H. Magnússon *et al*. 2007 (Matís 12-07); Lauzon *et al*. 2009
				tray + film (350-550 g)	49.0/7.4/43.7	-2	13	**10**	
		whole	**5**	EPS (5 kg)	air 0.0±0.4°C	0	11	7	
				tray + film	49.0/7.4/43.7	0	15	9	
				EPS (5 kg)	air -1.4±1.1°C	-2	14	**10**	
				tray + film	49.0/7.4/43.7	-2	21	**10**	
	10-07	**whole, gutted** -0.2±0.1°C	**2**	tray + film (350-550 g)	50/5/45 -0.8±1.2°C	-0.6±1.4	19	13	M. Guðjóns-dóttir *et al*. 2008 (Matís 22-08)
		-0.2±0.2°C	**7**				7	3	
	10-08	**whole, gutted, flake ice**	**2**	EPS (3 kg), liquid cooling of fillets	1.1±1.9°C	-0.6±2.5°C Dynamic storage: RTS @ 10°C d0 = 7.5 h d2 = 16 h	7-10	4-5	H. Magnússon *et al*. 2009a (Matís 23-09)
				no cooling	1.6±1.9°C		6-9	3-6	
				CBC fillets	0.2±0.7°C		12-13	4-6	
		liquid ice	**2**	CBC fillets	-0.4±0.8°C		13-14	6-7	
	12-08	**whole, gutted**	**1**	EPS (3 kg)	T_p = 0.0±0.8°C	-0.4±2.1	11	5	Chill-on project, unpublished data (Margeirsson & Lauzon)
				Abused d0-6h	1.1±3.7°C	0.2±3.6	10	4	
				Abused d4-6h	0.9±3.7°C	0.2±3.8	10	5	
				CP (3 kg)	0.1±1.0°C	-0.4±2.1	11	6.5	
				Abused d4-6h	1.3±2.8°C	0.2±3.6	10	4.5	
	02-09	**whole, gutted**	**2**	EPS (5 kg) CBC+ice pack	T_p = -0.2±0.3°C	$T_{ambient}$ = -1.0±0.4°C	12	7	Martinsdóttir *et al*. 2010 (Matís 18-10)
					0.0±0.2°C	0.0±1.7°C	9	7	
				CBC	-0.2±0.2°C	-1.2±0.2°C	12	8	
					0.3±0.4°C	-0.1±1.8°C	9	7	
				LIC + ice pack	0.3±0.6°C	0.0±2.0°C	8	6	
				control + IP	1.1±0.5°C	0.2±1.8°C	10	7.5	
	03-09	**whole/gutted, slurry ice**	**3**	EPS (5 kg) control + IP	T_p = 0.6±0.4°C	$T_{ambient}$ = -0.4±2.3°C	9-10	6-7	H. Magnússon *et al*. 2009b (Matís 34-09)
				LIC + ice pack	0.6±0.5°C	-0.1±2.4°C	7	5	
				LIC + dry ice	0.5±0.6°C	-0.3±2.2°C	8-9	5-8	
				LIC + ice pack	0.2±0.4°C	-1.0±2.2°C	7-8	5-7	
Haddock	**10-01**	**Trad., gutted**	**1**	EPS (11 fillets)	air	0	12.5	9	Olafsdottir *et al*. 2006a
						7	5.5	4	
						15	3.5	2.5	
	11-03	**Trad., gutted**	**1**	EPS (3kg)	air	0.3±0.3	10.5	7	Martinsdóttir *et al*. 2003, Rf 03-04
				Abused d3-16h		2.0±5.4	8	6	
Tilapia	**02-09**	**Filleted post-rigor**	**1**	tray + film	air	1 ± 0.5	13-15		Martinsdóttir *et al*. 2008 (Matís 38-09)
						-1 ± 0.5	20		

1: time in days from catch to packaging
2: time in days from packaging, based on sensory asssessment of cooked fish (Torry score = 5.5 or QDA value)
3: time in days from packaging, based on sensory asssessment of cooked fish (Torry score = 7 or QDA value)