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Wild caught cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) chilled in slurry or flake ice and its effect on product quality

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ABSTRACT

Chilling is an essential preservation technology in fish-processing. Slurry systems offer seafood preservation at sub-zero temperatures with advantages like faster chilling, reduced physical damage and prolonged shelf life. The study was conducted on wild caught cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in an industry setting. A seawater slurry at −2.0 ± 0.3°C was used, and cod and haddock were stored in ice or slurry for 8 days. The effect of chilling in seawater slurry compared to traditional flake ice, was evaluated by sensory evaluation (QIM) of whole fish, colour changes and texture of fillets, water content, water activity and water-holding capacity (WHC) in minced muscle. The results showed that chilling in slurry was faster, and gave lower temperatures compared to flake ice. However, slurry stored fish had worse QI-values and had yellower fillets compared to ice.

Keywords: chilling, flake ice, slurry ice, cod, haddock, fillet quality

1. INTRODUCTION

Wild caught cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are often frozen at sea, however a fraction of the fish is stored on flake ice and sold as fresh. Chilling is an essential operation in fish industry, and slurry systems are one of the refrigeration methods for preservation of seafood products at sub-zero temperatures (−0.5 to −3°C) (Huidobro and others 2002; Aubourg and others 2006). Fresh fish is easily perishable, and its shelf life is limited by oxidative, enzymatic and microbiological spoilage (Duarte et al., 2020). Adequate temperature control and handling practices during freezing, thawing and chilled storage of fish is thus especially important for food safety, shelf life and product quality.

Traditionally ice storage has been a common preservation technique to maintain freshness. However, ice storage using flake ice, crushed ice, cubed ice or tube ice can have a negative impact such as insufficient cooling (Li et al. 2012), external damages and logistical challenges (Kauffeld et al. 2010). Slurry systems provides opportunities for preservation of freshness in an ice-water suspension (Lan et al. 2021) at sub-zero temperatures (ranging from -0.5 to -1.5). The main advantages of slurry systems compared with flake ice or refrigerated seawater (RSW) are: (1) Faster cooling rate due to better heat exchange capacity, (2) reduced physical damage due to small spherical microscopic particles, (3) prolonged shelf life, and (4) their pumpability, which allows for more hygienic handling of the fish (Pi˜neiro and others 2004). With complete immersion in slurry ice, the fish could be isolated from contact with external oxygen, thus preventing decomposition caused by oxygen (Kilinc et al., 2007). Additionally, the inhibitory effect of slurry ice on microbial growth have been showed to provide increased shelf life for salmon (Rodriguez et al., 2018). The product quality benefits of using slurry systems compared to traditional ice storage are shown for several fish species such as European hake (Losada and others 2004), farmed turbot (Campos and others 2006), farmed perch (Lan et al. 2021), horse mackerel (Losada and others 2005), farmed salmon (Erikson et al. 2011, Chan et al. 2020) and cod (Digre et al. 2011, Eliasson et al. 2021).

There are however challenges related to use of slurry systems for chilling, like controlling ice-formation, avoiding excessive surface freezing and limited ice crystal growth, as these may lead to structural damage and negative texture and increased drip loss (Magnussen et al. 2008, Kaale et al., 2011, Duun and Rustad, 2007). Also, Huidobro and others (2001) reported that farmed seabream exhibited cloudy eyes, and Cakli et al. (2006) found a negative appearance of eyes and gills of sea bass when stored in slurry, which is considered negative for the commercialization of this fish species.

The main objective of this study was to compare the effects of slurry and flake ice storage on cod and haddock quality. The quality parameters included sensory assessment of whole fish (QIM), fillet colour, water content, water activity, water holding capacity (WHC) and texture. The experiments were carried out in both controlled environment and industrial processing onboard a trawler using the different chilling methods.

2. MATERIALS AND METHODS

2.1. Sample

Trawl caught cod or haddock were subjected to three different onboard treatments and subsequent storage in ice or slurry for 8 days (Figure 1). The fish were subjected to one of the following treatments before chilled storage: 1) direct onboard processing, where the fish were transferred directly from deck and down to the processing facilities, 2) traditional processing using dry bins which supply the processing line with fish until they are empty, or 3) kept in live holding tanks for ≤ 5 hours and then processed. All fish were killed, bled, had their heads removed and gutted before chilled storage in ice or slurry.

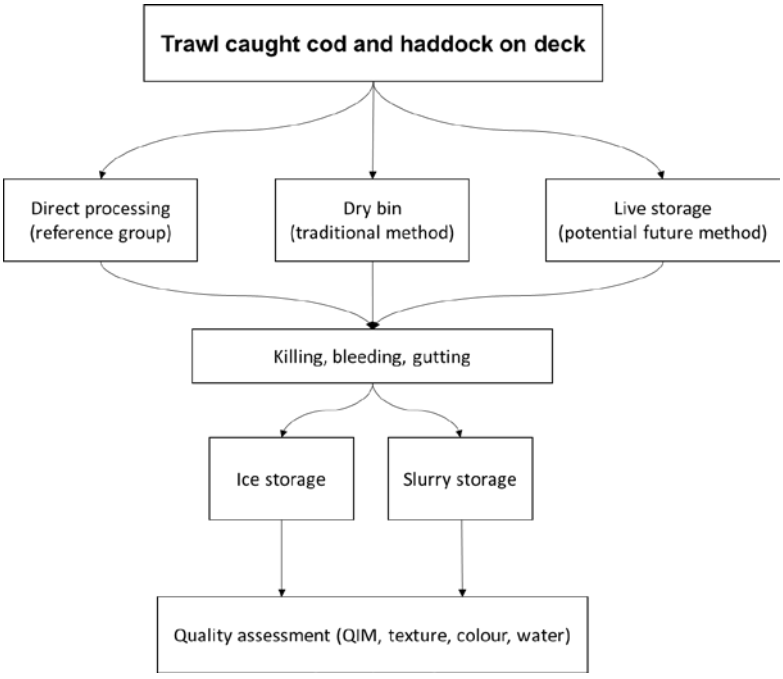

Figure 1: Experimental design. Trawl caught cod or haddock were either 1) sent direct from trawl on deck to the processing facility (direct processing), 2) kept in traditional dry bins for continuous supply of fish until empty, or 3) kept in live holding tanks, before subsequent killing, bleeding, gutting, head removal and chilled storage for 8 days in ice or slurry.

Round weight, total length, gonosomatic index (GSI), liver index and condition factor (mean ± STD, n = 58) for cod were 2.5 ± 0.7 kg (n = 65), 62 ± 6 cm, 5.2 ± 1.5 and 1.0 ± 0.1 respectively. Similarly, haddock had a round weigh of 1.2 ± 0.4 kg, total length of 45 ± 4 cm, liver index of 3.2 ± 1.2 and a condition factor of 1.2 ± 0.1. The cod consisted of 20 % females and 80 % males (n = 65), while the haddock were 62 % female and 38 % male (n = 60).

After processing, the different treatments of cod and haddock were split in two. Half of the fish were stored in flake ice in styrofoam boxes, while the other half were stored in plastic tanks (900L) with slurry ice. A 4.5 kW slurry machine (Skogland, Model S-1; Haugesund, Norway) was used for slurry ice production. The composition of the ice slurry mixture was about 40% ice and 60% water, prepared from filtered seawater (temperature: −2.0 ± 0.3°C). The salinity was 34‰ corresponding to a freezing point of −1.865°C at 1 atm air pressure (Fofonoff and Millard 1983). The texture of the slurry was made rather smooth (pumpable), and it did not have the typical snowy appearance when a major part of the liquid phase had been drained off. The wanted consistency was achieved by regulating the inlet water flowrate to the slurry machine. Two insulated polyethylene fish chilling tubs (900 L) were used for storage of slurry-chilled cod and haddock. At the bottom of each tank, the tap was removed for drainage of water. Fish and freshly made slurry was added in a batchwise manner, in layers. The resulting gutted fish density in the slurry was 151 kg m^{-3}. The system was completely closed with a lid and brought by refrigerated transportation to SINTEF Sealab in Trondheim. The tubs were stored in a cold room (4°) until analysis. Temperature was recorded during chilled storage with temperature loggers (IButton, Thermochron Data logger, UK) recording temperature at 1-minute intervals in the body cavity of the fish. Analyses were performed after chilled storage for 8 days according to Figure 1.

2.2. Assessment of whole fish

The QIM scheme for whole fresh cod as described in the QIM Eurofish manual (Martinsdottir et al., 2001) was used. The parameters for the evaluation were appearance of skin, eyes, gills, fillet and blood. A scoring system from 0 to 2 or 3 was used, where the lowest score indicates the best freshness. The scores are summarized to give an overall sensory score (0 – 23) referred to as the Quality Index (QI).

2.3. Computer vision evaluation of colour

Automated colour analysis of the fillets in the CIE L*a*b* colour space was conducted (Erikson and Misimi, 2008). The colour parameters were pixel-averaged over a selected region of interest (ROI) (Gonzales et al., 2004). Colour contributions from the peritoneum, backbone, cartilage, and residual blood in the neck region were excluded. The fillet images were colour-calibrated using the GretagMacbeth ColorChecker chart with 24 colour patches (Colour-Science AG, Hinwil, Switzerland). The hue angle (0° = red hue; 90° = yellow hue) and colour saturation (higher values mean more intense colour perception) were calculated as H°_{ab} = arctan (b*/a*) for a* > 0 or H°_{ab} = 180° + arctan (b*/a*) for a* < 0, and as $C^*_{ab} = (a^{*\,2} + b^{*\,2})^{1/2}$, respectively.

2.4. Textural properties

Hardness of the left fillets was measured after 8 days of cold storage with a TA.XT2 Texture Analyzer (Stable Micro Systems, Surrey, UK) equipped with load cell of 5 kg, as described by Einen and Thomassen (1998). A flattened cylindrical plunger (12 mm in diameter) was pressed into the fillets perpendicular to the muscle fibres at a constant speed of 5 mm/s until it reached 60% of the sample height. The measurements were performed in triplicate in the neck-, middle-, and tail region of the fish. The hardness (N) detected at 60% compression of the height was reported.

2.5. Water content

The water content of the dorsal muscle was determined by drying a minced 2 g sample to constant weight at 105°C for 24 h (AOAC, 1990). The difference in weight before and after drying was taken as the total water content of the sample. The mean of 3 parallels is reported.

2.6. Water activity (a_w)

The water activity was determined on minces samples by reading each sample twice by FAst lab (GBX Advanced Technologies, France) after calibration with saturated K_2SO_4 solution.

2.7. Water holding capacity (WHC)

A piece of the dorsal muscle was minced and subjected to the low-speed centrifugation method described by Eide et al. (1982). A centrifugal force of 230 x g was used (Hultmann and Rustad, 2002). The water holding

capacity is defined as the percentage of water retained in the mince after centrifugation for 5 min. Four parallel samples were run for each fish.

2.8. Statistical analyses

IBM SPSS 29 for Windows was used for the statistical analysis. The effects of treatment on the different parameters (fillet colour, texture, water binding capacity, water-activity and water-content) were analysed by a one-way analysis of variance (ANOVA). Where significance ($P<0.05$) was indicated, a Turkey's *post hoc* test was run. If not otherwise described the results are reported as mean values ± standard error of means (SEM).

3. RESULTS AND DISCUSSION

Fish represent one of our most perishable food products, and even under chilled storage the shelf life of the product is limited by oxidative, enzymatic and microbiological spoilage (Duarte et al., 2020). Adequate temperature control and handling practices during freezing, thawing and chilled storage of fish is thus especially important for food safety, shelf life and product quality.

Coming from the sea, the core temperature of cod (n=58) and haddock (n=60) were 7.2 ± 0.5°C and 6.5 ± 0.6°C (mean ± std) before handling and subsequent storage in ice or slurry. The temperatures in the body cavities of the fish were monitored during cold storage as shown in Figure 2 during the first 5 hours.

For fish stored in ice the initial body temperature was reduced from 8.1°C to 2.2°C during the first hour, while fish stored in slurry was reduced to 1.2°C. Correspondingly, after two hours the temperatures were reduced to 0.9 and -0.1 respectively. As expected, chilling in seawater slurry was found to be more rapid than chilling in ice. Additionally chilling in slurry gave lower temperatures compared to flake ice, stabilizing at around -0.6°C after 3 hours and 36 minutes for slurry, and at 0.2°C after 4 hours and 12 minutes for flake ice. The temperatures were stable around these temperatures until analysis on day 8.

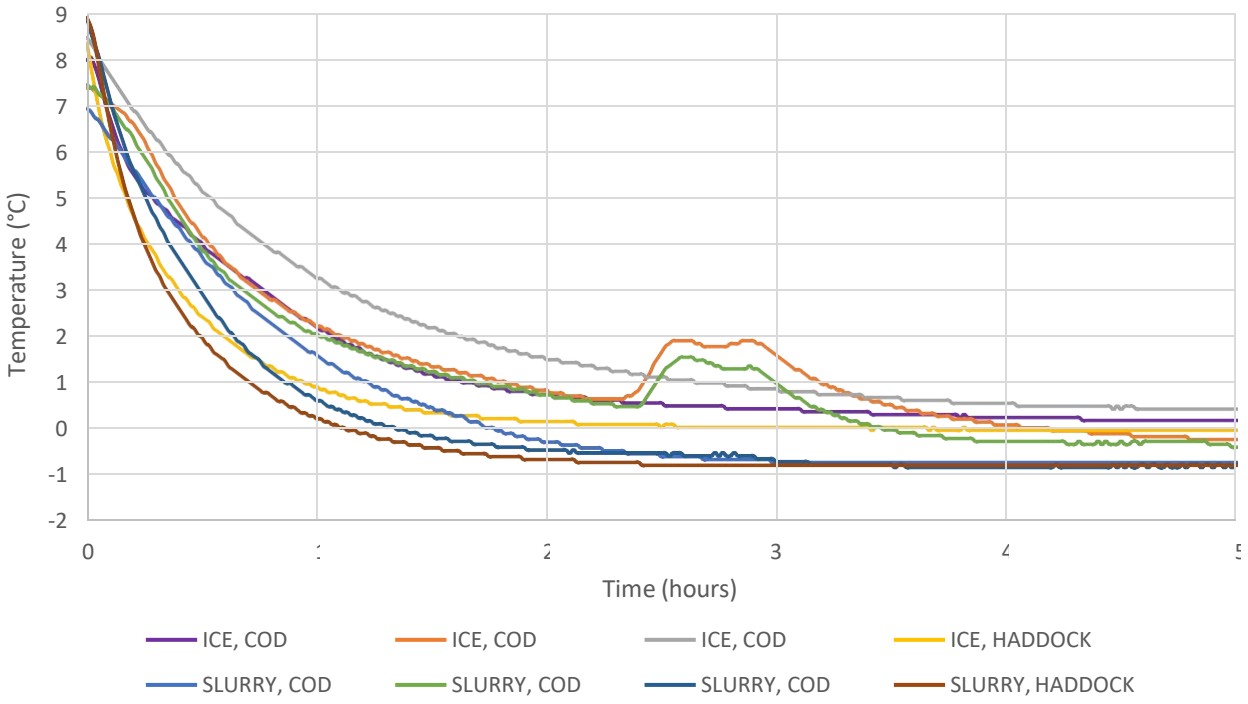

Figure 2: Temperature development for cod or haddock in tubs (900L) with flake ice or slurry for the first 5 hours.

A Similar study done on ice and slurry chilled farmed Atlantic cod (round weight 3.4 ± 0.6 kg) under the same conditions, found that the initial body temperature of 8.5°C was reduced to a core temperature of 1.4°C after 54 minutes stored in ice, and to 0°C after 24 minutes in slurry (Digre et al. 2011). Thus, the chilling in the current study was less effective in comparison. Overall, the results show that chilling in slurry improved chilling efficiency and might be a good chilling method for prechilling of fish to sub-zero temperatures in plants or onboard vessels.

The QI scores for the different treatments are shown in Table 1. Both cod and haddock stored in ice exhibited the lowest QI scores, indicating to have gotten the best scores when evaluating appearance of skin, eyes and gills. However, the difference was only significant for haddock ($p<0.05$). Similarly, slurry stored cod and haddock had the worst QI scores (highest QI scores), with only haddock showing a significant difference ($p<0.05$). Erikson et al. 2011 found similar QI values when examining salmon subjected to 4 different chilling regimes for 4 days post-mortem, with QI-values of 6.8 and 6.4 for ice storage and slurry storage respectively. We did not observe cloudy eyes as a result of chilling in slurry (data not shown), a phenomenon which has been reported when chilling gilthead seabream (*Sparus auratin*) in slurry at -2.2 °C (Huidobro et al. 2001), and for slurry-chilled famed Atlantic cod (Digre et al. 2011). Additionally, none of the treatments were similar to the suggested rejection score of 15 (Martinsdottir et al. 2001), indication overall good quality after 8 days of chilled storage in both slurry and ice.

The ability of the fish muscle to retain its natural water and thereby its juiciness is one of the quality criteria of fish. In the current study mean white muscle water content of cod was stable at around 82-83% independent of treatment methods. Similarly, for haddock the water content was stable at 81-82% (Table 1). This is in accordance with previous studies on cod reporting white muscle content of 79-80% after storage in ice or slurry of up to 14 days (Digre et al., 2011).

Water is an important constituent of all foods, and the activity of water as a medium is correlated with the deterioration of food stability due to the growth of microorganisms (Rahman et al., 2007). The minimum water activity is the limit below which a microorganism or group of microorganisms can no longer reproduce. In freshly caught fish the water activity is above 0.95 (Aberoumand, 2010). In this study the water activity was very high for both cod and haddock, with mean values around 1. However, there were no significant changes between treatments ($p>0.05$).

The WHC is regarded as an essential flesh-quality parameter, and it is especially important for fish texture (Fennema, 1996). The mean WHC for all treatments is shown in Table 1. No significant differences were found between the different treatments, and the mean values ranged between 88-92% for both cod and haddock.

Table 1: Fillet quality parameters (QI, water content, water activity and WBC) for cod and haddock after direct processing, storage in dry bins or live holding tanks before processing and subsequent chilled storage in slurry or ice for 8 days. Average ± SEM. Letters (A, B) denote significant difference between treatments, p<0.05.

			Direct processing		Dry bin		Live storage	
		n	**Slurry**	**Ice**	**Slurry**	**Ice**	**Slurry**	**Ice**
Cod	QI (score 0-23)	7-13	6.5±0.3	6.5±0.5	7.6±0.4	7.7±0.3	7.5±0.4	6.8±0.4
	Water content (%)	8-11	$82.0±0.2^{B}$	$82.4±0.2^{AB}$	$82.4±0.2^{AB}$	$83.2±0.3^{A}$	$82.0±0.3^{B}$	$82.1±0.2^{B}$
	Water activity (a_w)	8-11	1.0±0.0	1.0±0.0	1.0±0.0	1.0±0.0	1.0±0.0	1.0±0.0
	WHC (%)	8-11	89.2±1.0	92.1±0.7	91.2±0.6	88.5±1.4	90.9±1.0	92.0±1.0
Haddock	QI (score 0-23)	10-11	$9.3±0.5^{AB}$	$8.4±0.3^{A}$	$10.0±0.3^{B}$	$8.7±0.2^{AB}$	$9.9±0.3^{B}$	$8.9±0.3^{AB}$
	Water content (%)	10	81.9±0.3	82.3±0.3	81.6±0.4	81.5±0.4	81.2±0.2	81.9±0.3
	Water activity (%)	4-10	$1.0±0.0^{A}$	$1.0±0.0^{AB}$	$1.0±0.0^{B}$	$1.0±0.0^{AB}$	$1.0±0.0^{AB}$	$1.0±0.0^{AB}$
	WHC (%)	10	88.2±1.7	90.0±0.9	88.1±1.8	90.5±0.8	92.0±1.0	91.2±0.7

Fillet hardness, expressed as force at 60% compression is shown in Figure 3. For cod, no significant differences were found between the treatments ($P>0.05$). The highest hardness values were recorded in the neck region of the fillets for both cod and haddock. Among all treatments, slurry stored haddock after live storage had the highest hardness values, but only the tail showed a significant difference ($p<0.05$).

Overall, our data suggest that treatments did not affect the fillet hardness. Our results are in accordance with previous studies on salmon (Gallart-Jonert et al. (2007), Bahuaud et al. 2008, Erikson et al. (2011), concluding that hardness of superchilled salmon fillets were comparable to those of ice stored fish. Similarly, Digre et al. (2011) did not detect any significant changes in hardness between ice and slurry stored cod with hardness values in the range 10.4 - 12.5 after 7 days of chilled storage and 11.5 - 13.8 after 14 days. However, previous studies have reported superchilled (-2°C) mullet (*Mugil ssp*.) to have a significant softer texture compared to ice storage (Lee and Toledo, 1984). Overall, it could be noted that haddock had a softer texture compared to cod (lower hardness values).

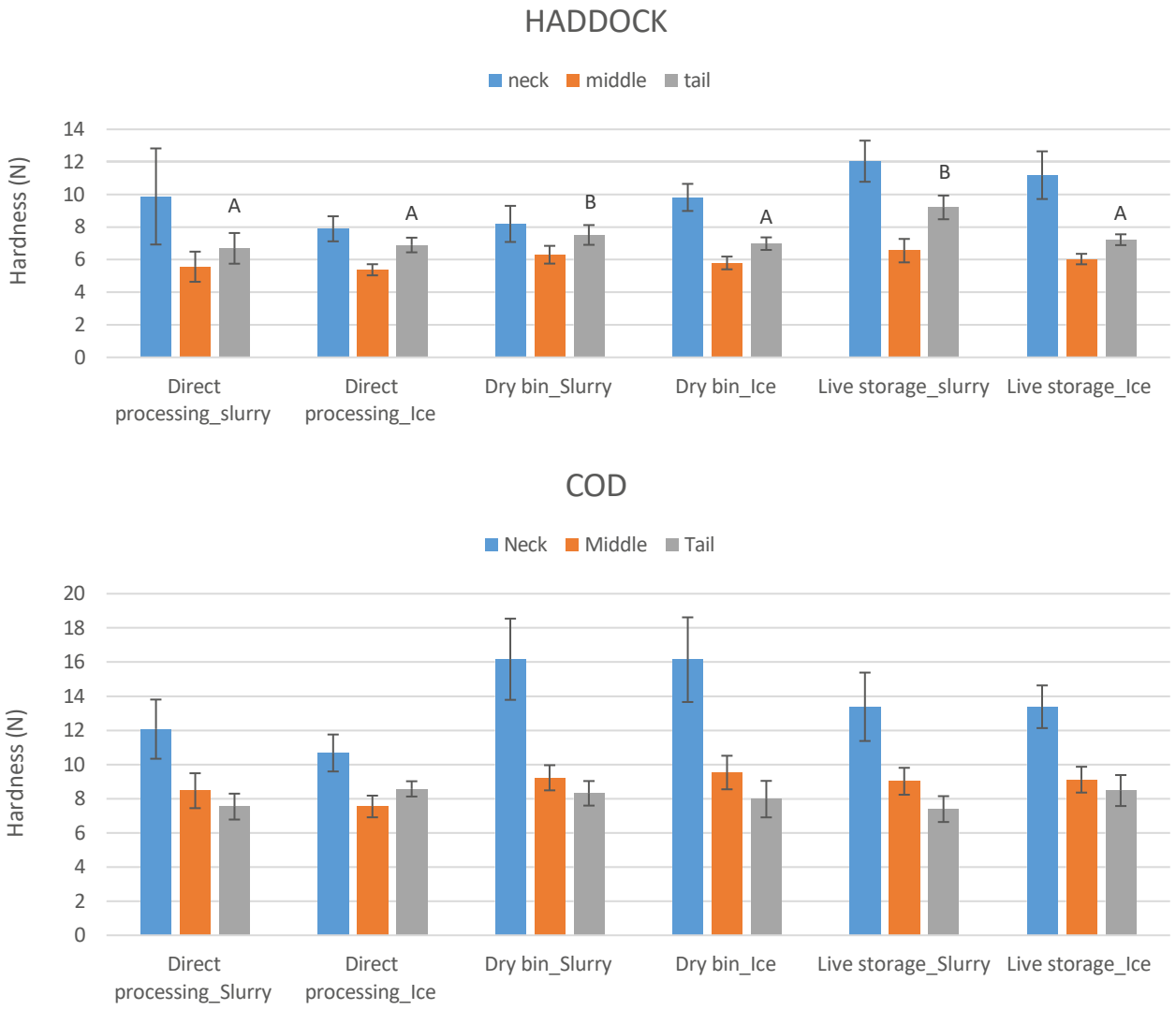

Figure 3: Fillet hardness (N) measured as the force at 60% compression of cod and haddock fillets after direct processing, storage in dry bins or live holding tanks before processing and subsequent chilled storage in slurry or ice for 8 days. Letters (A, B) denote significant difference between treatments, P<0.05. Mean ± SEM.

Fillet colour for the different treatments is shown in Table 2. The data represents averages of the entire filet as determined by computer vision. For cod no significant changes were found between the treatments for lightness (L*-value) or hue (H_{ab}°). For haddock no changes were detected in hue. Yellowness (b*) of the fillets were found to be more prominent for both cod and haddock stored in slurry ($p<0.05$) compared to storage in ice. Slurry stored haddock were found to have fillets with higher chroma values (colour saturation) compared to ice storage. Similarly, slurry stored cod fillets that had been subjected to live storage or direct processing had higher chroma values. Ice stored fillets from direct processing were found to have the lowest

chroma values for both cod and haddock ($p<0.05$). Additionally, ice stored fillets from direct processing were found to be the whitest ($p<0.05$). No large colour differences were found between cod and haddock fillets.

Digre at al. 2011 studied how rested and stressed farmed Atlantic cod chilled in ice or slurry effected fillet quality. They measured CIE-L*a*b*, hue and chroma values of cod fillets from 4 different treatments after 7 and 14 days of storage (L*: 74.5 - 80.3, a*: -1.8 - 2.5, b*: 9.5 - 18.6, hue: 75.3 - 95.7, chroma: 9.9 - 18.7). Fillets from the present study had higher values for lightness (L*) and redness (a*) and lower values for yellowness (b*), chroma and hue. Meaning that our fillets were lighter in colour and less yellow, but with higher colour saturation and more redness. After 14 days of chilled storage in ice or slurry they did observe fillets stored in slurry to be more yellowish in colour (higher b*- values), but the effect was not significant. In our study, slurry stored fillets were found to be significantly more yellow after 8 days of chilled storage in slurry compared to ice. Previous studies have summarized how freezing and thawing may result in negative impacts such as yellow discoloration of fillets (Svendsen et al. 2022). When comparing different treatments of cod straight after capture, live holding (3h or 6 h) or delayed bleeding (2h or 5h) Erikson et al. 2019 showed differences in yellowness between fresh fillets (b*: 1.7 - 2.4) and frozen-thawed fillets (b*: 6.6 – 7.4). Even though our yellowness-values (b*) where somewhat lower, the values for filets cut from fish stored in slurry were closer to their results after freezing and thawing, exhibiting higher yellowness. As shown in Table 2, objective machine vision analysis of slurry and ice stored fillets in CIE L*a*b* colour space resulted in some minor differences between treatments apart from the yellowness found in fillets after storage in slurry.

Table 2: CIE L* a* b*, hue, chroma and whiteness for cod and haddock fillets after 8 days of cold storage. The fish were subjected to different treatments onboard to minimize discoloration and presence of residual blood in fillets. Different letters, A, B or C, represent significant differences between treatments for either cod or haddock. Mean values mean ± SEM.

		Direct processing		Dry bin		Live storage	
	n	Slurry	Ice	Slurry	Ice	Slurry	Ice
				Cod			
L* (lightness)	6-11	83.6±0.4	85.3±0.4	84.8±0.7	84.1±0.8	83.1±0.6	84.6±0.6
a* (redness)	6-11	2.5 ± 0.3^{ABC}	1.6 ± 0.2^{A}	2.4 ± 0.4^{ABC}	3.2 ± 0.3^{C}	2.9 ± 0.4^{BC}	1.7 ± 0.3^{AB}
b* (yellowness)	6-11	5.6 ± 0.8^{BC}	3.7 ± 0.7^{A}	5.0 ± 1.1^{BC}	4.9 ± 0.7^{BC}	7.1 ± 0.7^{C}	6.4 ± 0.7^{BC}
C_{ab}* (chroma)	6-11	6.2 ± 0.7^{AB}	4.1 ± 0.7^{A}	5.8 ± 0.8^{AB}	6.0 ± 0.5^{AB}	7.7 ± 0.6^{B}	6.7 ± 0.8^{AB}
H_{ab}°(hue, °)	6-11	63.1±3.9	62.0±4.9	57.7±10.9	54.1±5.1	67.1±3.7	75.4±1.6
W (whiteness)	6-11	66.9 ± 2.6^{AB}	74.1 ± 2.5^{B}	70.0 ± 3.7^{AB}	69.4 ± 2.7^{AB}	61.8 ± 2.3^{A}	65.4 ± 2.7^{AB}
				Haddock			
L* (lightness)	9-10	84.8 ± 0.5^{AB}	85.5 ± 0.4^{B}	82.9 ± 0.5^{A}	84.6 ± 0.4^{AB}	84.3 ± 0.6^{AB}	85.1 ± 0.4^{AB}
a* (redness)	9-10	2.3 ± 0.4^{AB}	2.4 ± 0.2^{AB}	3.4 ± 0.3^{B}	2.8 ± 0.2^{AB}	2.2 ± 0.2^{AB}	2.0 ± 0.3^{A}
b* (yellowness)	9-10	3.4 ± 0.5^{AB}	2.8 ± 0.3^{A}	7.1 ± 0.5^{C}	6.1 ± 0.9^{BC}	5.4 ± 1.1^{ABC}	5.5 ± 0.7^{ABC}
C_{ab}* (chroma)	9-10	4.3 ± 0.5^{AB}	3.7 ± 0.3^{A}	8.0 ± 0.5^{C}	6.8 ± 0.8^{CD}	6.0 ± 1.0^{ABC}	6.0 ± 0.7^{ABC}
H_{ab}°(hue, °)	9-10	56.2±6.0	49.4±3.1	63.5±3.0	61.8±4.4	60.9±5.8	68.7±3.8
W (whiteness)	9-10	74.6 ± 1.7^{BC}	77.0 ± 1.0^{C}	61.6 ± 2.0^{A}	66.3 ± 2.9^{AB}	68.0 ± 3.8^{ABC}	68.6 ± 2.4^{ABC}

4. CONCLUSIONS

Slurry systems offer seafood preservation at sub-zero temperatures. In the current study the effects of slurry and flake ice storage on cod and haddock quality was conducted. Chilling cod and haddock in slurry was more rapid than chilling in ice. The time necessary to reach sub-zero temperature in slurry was about 2 hours, and there was only around 1 °C of difference between the two storage methods. When conducting sensory evaluation of whole fish (QIM), the worst scores were obtained for slurry stored fish. However, the highest QI-value was 10, which is much lower than the suggested rejection score of 15, which had been suggested as a maximum score before rejecting the fish. This indicates both slurry and ice stored fish to be of good quality after 8 days of chilled storage. In the current study all water parameters gave stable values for water content (81-83%), water activity (around 1) and WHC (88-92%) with no differences between treatment methods or

species. Similarly, fillet hardness showed little variation, but haddock had a softer texture compared to cod. Storage in slurry resulted in fillets with a more yellowish tint compared to storage in ice regardless of the onboard processing method. Overall, the results show that chilling in slurry improved chilling efficiency and might be a good method for prechilling of fish to sub-zero temperatures in plants or onboard vessels.

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