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Brief Report

Soft Fillets in a Sustainable Seafood Era: Assessing Texture, Yield Loss and Valorization Potential of 'Mushy' Greenland Halibut Fillets

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Abstract

'Mushy halibut syndrome' (MHS) is associated with inferior fillet quality in Greenland halibut and is reported to occur in commercial catches across the North Atlantic. MHS constitutes a quality issue in fisheries and leads to economic losses and food wastage. Despite the known challenges associated with MHS, quantitative data on product properties are lacking, and yet they are crucial to assess actual losses and value-adding processing potential. As part of a larger effort to document and characterize MHS in Greenland halibut, we investigated how thaw drip loss (TDL), cooked drip loss (CDL), cooked yield, and tissue compressibility and elasticity differ between normal and 'mushy' halibut fillets. The fillets were sorted into three categories: normal, intermediate MHS, and severe MHS. The mean TDL and CDL increased more than three-fold in both MHS categories compared to normal fillets, while cooked yield decreased by approximately 20%. Fillets severely affected by MHS demonstrated high tissue compressibility (56%) and poor elasticity (46%), while the elasticity of the fillets belonging to the intermediate MHS category did not differ significantly from that of normal ones. These findings provide new insights into the product attributes of fillets affected by MHS, which are important for developing utilization and valorization strategies.

Keywords: mushy halibut syndrome; seafood quality; sustainability; side streams

Key Contribution: In this article, we argue that MHS, while niche, represents a broader opportunity for sustainable seafood valorization. By integrating laboratory data on texture and yield differences between affected and unaffected fish, we exemplify the scale of losses and provide an incentive for commercial stakeholders to allocate more resources for the improved handling of inferior fish products, with the prospect of ensuring quality consistency, increasing customer satisfaction, and reducing food wastage.

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1. Introduction

The Greenland halibut (*Reinhardtius hippoglossoides*) is one of the few commercially fished oily white fishes. It is caught in the cold waters of the North Atlantic and Arctic Ocean and is widely appreciated for its delicate white flesh and sweet buttery flavor. Major global providers of Greenland halibut are anchored in Canada, Norway, Greenland, and Iceland. In Greenland, seafood constitutes more than 90% of the total exports, of which Greenland halibut accounts for approximately 30% [1].

With the emerging global focus on food wastage and sustainability in fisheries, 'mushy halibut syndrome' (MHS) is gaining increased attention. MHS affects Greenland halibut at an unknown frequency and results in food wastage and loss of revenue [2]. Affected fillets (henceforth MHS-fillets) appear jelly-like with a 'mushy' cooked texture, and different severities occur. Detection of MHS is difficult, and severely affected fillets can be unsaleable, leading to further losses even when they are detected in a timely manner [3,4]. A similar phenomenon known as 'jellied condition' occurs in American plaice (*Hippoglossoides platessoides*) and poses similar challenges [5].

According to the Food and Agriculture Organization of the United Nations (FAO), 35% of global harvested fisheries and aquaculture products are lost along the supply chain [6,7]. In commercial species, fillet yield ranges from 30 to 50%, while the remains are by-products [8]. Concerns related to discarded fish and by-products in fisheries have led to innovative solutions to promote efficient exploitation and preserve marine resources. Today, many by-products are repurposed, and even low-cost processing of raw materials, such as comminution, can reduce wastage and open up new markets [9].

To our knowledge, no studies have investigated the alternative utilization potential of MHS-fillets. However, a study on American plaice suggested that comminuting 'jellied' fillets could enhance product value and supplement the world's food supply [10]. The authors found that it was possible to produce fish sticks with consumer appeal by mincing combinations of normal, semi-jellied, and heavy-jellied fillets. The moisture content measured in the raw jellied fillets compares to the moisture content of MHS-fillets (see Table 1). It is possible that the same potential exists for MHS-fillets, but data on specific product attributes are needed.

Table 1. Moisture content range (%) previously reported in the literature for American plaice fillets affected by jellied condition and Greenland halibut fillets affected by MHS.

American Plaice				Greenland Halibut	
Templeman & Andrews (1956) [5] [a]	**% Moisture [Min–Max]**	**Rideout & Snow (1974) [10]** [b]	**% Moisture [Min–Max]**	**Severin et al. (2025) [11]**	**% Moisture [Min–Max]**
Normal	82.39–83.36%	*Normal*	80.5–83.13%	*Normal*	69.5–77.3%
Intermediate	84.31–85.40%	*Semi-jellied*	83.26–86.13%	*Mild-moderate MHS* [c]	71–84.6%
Jellied	86.14–87.45%	*Heavy jellied*	84.6–93.7%	*Severe MHS* [d]	80.0–87.35%

[a] Reflects values reported in Table 5 in Templeman & Andrews (1956) [5]; [b] reflects values reported for moisture in Table 2 in Rideout & Snow (1974) [10]; [c] reflects the combined range reported for MHS categories B and C in Severin et al. (2025) [11]; [d] reflects the combined range reported for MHS categories D and E in Severin et al. (2025) [11].

While MHS-fillets are considered to be of overall low quality, the actual effect of MHS on fillet yield and firmness has not been investigated. In a previous study, we defined organoleptic characteristic related to the visual and textural appearance of fillets exhibiting varying severities of MHS and documented a gradual decline in the dry matter and oil and protein content of Greenland halibut fillets with increasing MHS severity [11]. In the current study, we quantify and compare thaw drip loss (TDL), cooked drip loss (CDL), cooked yield, and texture of normal and 'mushy' fillets. Furthermore, we examine the influence of MHS severity and discuss the potential of utilizing MHS-fillets to prevent post-harvest losses. This paper fills a research gap by linking deviating physical fillet attributes to MHS. Our findings provide a preliminary baseline for future research into value-adding processing and product development, which can contribute to increased cost-effectiveness, optimized raw material utilization, and improved customer satisfaction.

2. Materials and Methods

2.1. Raw Material

2.1.1. Capture and Processing

Greenland halibut fillets were obtained from a land-based production site in Maniitsoq (Greenland). The fish were caught by commercial trawlers in West Greenland (NAFO divisions 1C and 1D) during November 2022. The fish were headed and gutted and stored frozen at −30 °C until February 2023, when the fish were thawed overnight in 8 °C water and processed by a BAADER 176 flatfish-filleting machine.

2.1.2. Fillet Categorization

On site, the fillets were sorted into categories based on sensory indicators of MHS, as described by Severin et al. [11]. The cited article describes five study categories. Due to the sensory and chemical similarities between overlapping MHS categories documented in the referenced study, these five categories were reduced to three in the current study.

Category A included normal fillets. Category B contained fillets mildly and moderately affected by MHS. Category C consisted of fillets severely affected by MHS.

The sensory attributes that determined fillet categorization related to flesh firmness, color, and moisture release. Fillets with firm flesh of a homogenous white to semi-translucent color, with no moisture release upon the application of manual pressure, were assigned to category A. Fillets with glistening and slightly gelatinous soft flesh of increased translucency, and limited to small moisture release during the application of manual pressure, were assigned to category B. Finally, fillets with a generalized gelatinous and flaccid appearance, with fragile, almost transparent, slippery flesh, and more pronounced moisture release upon the application of manual pressure, were assigned to category C [11].

All of the sampled fillets were quick-frozen to −35 °C and stored at −20 °C for transport.

2.2. Drip Loss and Yield Analysis

2.2.1. Thaw Drip Loss (TDL)

All frozen fillets were weighed immediately after being taken out of the freezer (initial sample weight) and then placed in sieves and enclosed in an outer plastic pouch to collect water and prevent vapor loss. The fillets were thawed in a refrigerator at 4 °C for 24 h and then reweighed after water loss to determine drip loss during chilled storage. The thawing method was used to mimic a kitchen situation, where seafood is thawed in the fridge over the course of 24 h. TDL was calculated and expressed as the percentage of fluid lost during thawing [12]:

$$\mathrm{TDL}(\%) = \left[\frac{W_0 - W_F}{W_0}\right] \times 100$$

where W_0 is the initial sample weight in grams and W_F is the final sample weight.

2.2.2. Cooked Drip Loss (CDL)

A subsample of loin meat was weighed from each fillet. For fillets with a weight of 150 g or less, a 75 g subsample was excised. For fillets with a weight above 150 g, the subsample weight was 100 g. CDL was determined using a modified protocol based on the one used by Karinen et al. (2010) [13]: Thawed subsamples were placed in plastic cook-in-the-bag pouches with perforated bottoms, covered by larger bags. Water was brought to 90–95 °C, and the packaged subsamples were submerged and cooked for 5 min. After cooking, the subsamples were cooled at room temperature (24 °C) for 5 min and reweighed. CDL was calculated for all fillets corresponding to the TDL formula presented in Section 2.2.1.

2.2.3. Cooked Yield

Yield was determined by the observed change in weight after cooking, relative to the weight of the raw material. Yield was calculated and expressed as a percentage [14]:

$$\text{Yield}(\%) = \left[\frac{W_F}{W_0}\right] \times 100$$

where W_0 is the subsample weight in grams before cooking, and W_F is the final subsample weight after cooking and cooling.

2.3. Tissue Compressibility and Elasticity

Product firmness relates to its ability to resist deformation and is inversely related to compressibility [15]. Punch-biopsies from the loin part of each thawed fillet were used to assess tissue compressibility and elasticity using a stainless-steel biopsy cylinder with a height of 10 cm and an internal diameter of 29 mm. A 12 cm long plastic piston was used for gentle removal of the muscle biopsy. Each subsample had an initial height of 6 mm.

2.3.1. Tissue Compressibility

Compressibility was assessed by exposing the subsamples to mechanical compression using cylindrical steel weights of different hefts (35–230 g). The subsamples were placed in a plastic cylinder and exposed to a compression of 35 to 230 g for 1 min. After each compression, subsample height was measured (see Figure 1). Total compression was defined as the reduction in subsample height in mm after exposure to a series of compressions with all steel weights, and Compressibility was calculated as a percentage:

$$\text{Compressibility}(\%) = \left[\frac{C_T}{H_0}\right] \times 100$$

where H_0 is the subsample height in mm prior to compression (6 mm) and C_T is the measured total compression in mm as measured immediately after compression with the last steel weight.



Figure 1. (**a**) Experimental set-up with cylindrical steel weights organized according to heft and stainless-steel punch-biopsy cylinder equipped with plastic piston and transparent measurement cylinder. (**b**) Measurement of subsample height.

2.3.2. Tissue Elasticity

Elasticity refers to the ability of a product to regain its original shape and size after compression. In this study, Elasticity was assessed by comparing the initial subsample height with the final subsample height, and it was expressed as a percentage [16]:

$$\text{Elasticity}(\%) = \left[\frac{H_F}{H_0}\right] \times 100$$

where H_0 is the initial subsample height in mm prior to compression (6 mm) and H_F is the final subsample height in mm, as measured at 3 min, after the last compression.

2.4. Histology

To confirm MHS in small tissue subsamples, the fillets were processed for paraffin embedding and sectioning according to the standard protocol [17]. All subsamples were excised from the anterior part of the dorsal epaxial musculature to ensure consistency. Sections of 4 µm were mounted on slides and stained with hematoxylin–eosin using Mayer's hematoxylin (Mayer's Hematoxylin Solution, cat. no. MHS1, Merck Life Science ApS, Copenhagen, Denmark) counter-stained with eosin (Eosin Y for microscopy Certistain®, cat. no. 1.15935, Merck Life Science ApS, Denmark). DPX (DPX Mountant for histology, cat. no. 06522, Merck Life Science ApS, Denmark) was used as the mounting media. All sections were studied and photographed under a Leica DMLB microscope.

2.5. Statistical Analysis

We used GraphPad Prism for Windows (GraphPad Software, Version 10.2.3 (403), Boston, MA, USA, www.graphpad.com) for all of the statistical analyses. The normality and lognormality of the data were assessed using the Shapiro–Wilk normality test. Statistical significance of the parametric data was verified by a one-way ANOVA with Tukey's multiple comparisons test for post hoc analysis at a confidence level of 95%. Non-parametric data were analyzed using the two-tailed Kruskal–Wallis test and Dunn's correction for multiple comparisons post hoc test. Correlation analysis was assessed using Spearman's correlation coefficient (ρ). Differences were considered significant at $p < 0.05$.

3. Results

3.1. Histology

Histological examination confirmed myofiber degeneration in the absence of microbial infection, as previously described [11]. Myofibers from normal fillets were evenly spaced in close apposition but became increasingly disorganized and necrotized in both MHS categories. The level of tissue distortion varied in category B, which contained both normal and degenerated tissue. Figure 2 shows the histoarchitecture of muscle tissue from fillets belonging to the three study categories.

3.2. Thaw Drip Loss, Cooked Drip Loss, and Cooked Yield

TDL and CDL differed significantly between the normal fillets and fillets belonging to both MHS categories (Figure 3a,b). The mean TDL was 8.3% in category A, 30.4% in category B, and 24.5% in category C. The higher TDL in category B may be attributed to two fillets with above-average TDLs of 40% and 63%. The mean CDL was 9% in category A, 33.9% in category B, and 27.2% in category C.

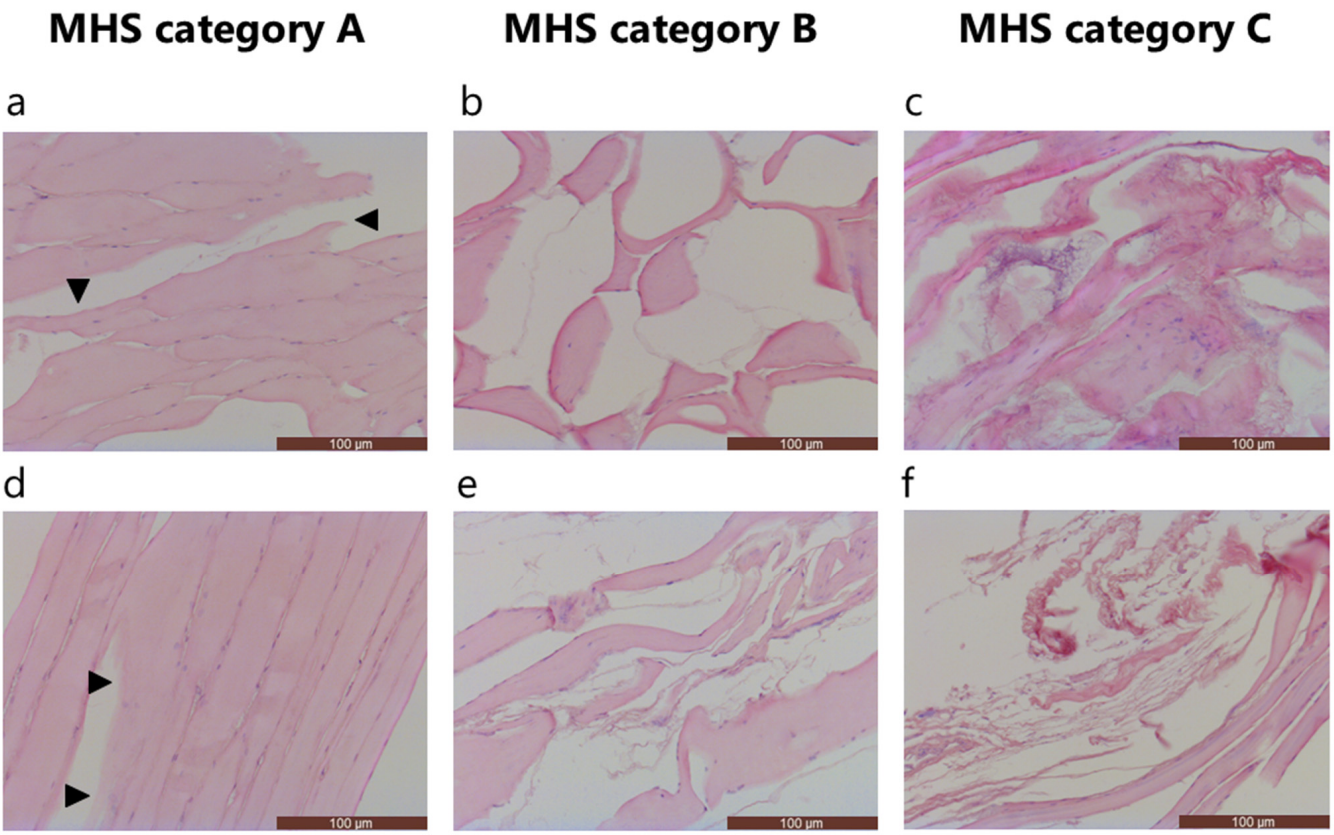


Figure 2. Histological sections of muscle tissue from fillets belonging to study categories A (normal fillets), B (mild–moderate MHS), and C (severe MHS). (**a**) Transverse section of normal myofibers (category A). Some freezing damage is visible (black arrowheads). (**b**) Transverse section showing mild to moderate myofiber atrophy and necrosis, with widening of the intermyofibrillar space (category B). (**c**) Transverse section showing severe myofiber necrosis with hypereosinophilia and myophagocytosis (category C). (**d**) Longitudinal section of normal myofibers with uniform thickness and nuclei placement (category A). Some freezing damage is visible (black arrowheads). (**e**) Longitudinal section showing mild to moderate myofiber detachment, necrosis, and nuclear atypia (category B). (**f**) Longitudinal section showing severe myofiber degeneration and nuclear dissolution (category C).

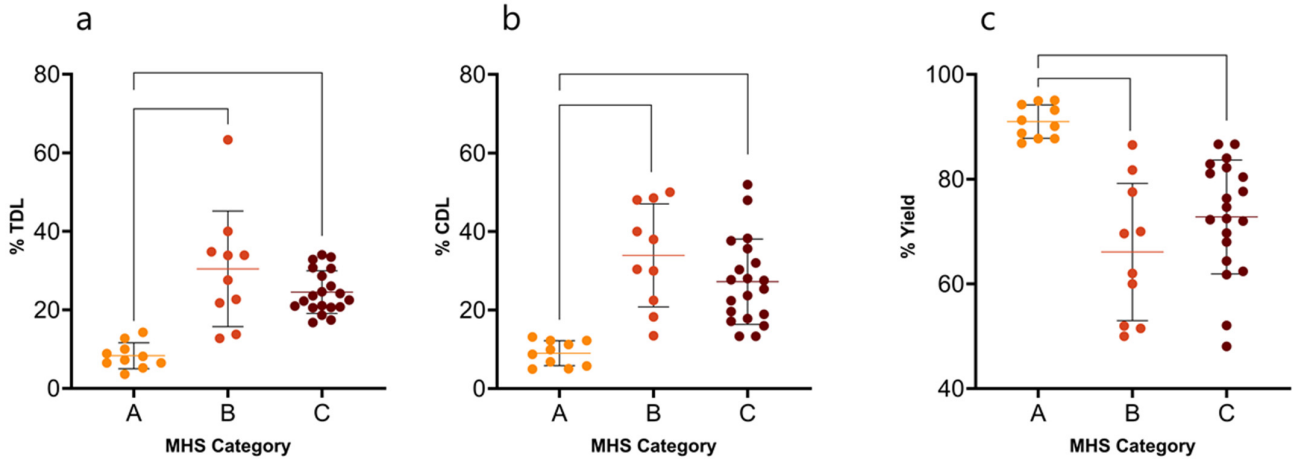


Figure 3. Scatter plots of TDL (**a**), CDL (**b**), and cooked yield (**c**) of fillets belonging to study categories A (normal fillets), B (mild–moderate MHS), and C (severe MHS). Results are displayed with mean and standard deviation, and each dot represents a fillet sample. Significant differences between the categories were identified using one-way ANOVA followed by Tukey's multiple comparisons test ($p < 0.05$, CI = 95%), and they are marked with brackets.

The mean yield for category A was 91% compared to 66% and 73% for categories B and C, respectively (Figure 3c). The yield peak for category A was 95%, while a yield as low as 48% was measured in category C (see Supplementary Material S1 for details).

3.3. Tissue Compressibility and Elasticity

Increased tissue compressibility and reduced elasticity were most pronounced in category C. The mean total compressibility was 1.6 mm in category A, compared to 2.65 mm in category B and 3.35 mm in category C (see Figure 4a). Generally, it required a compression of at least 155 g to induce a measurable effect on category A subsamples, while the compression of category B and C subsamples was evident at 115 g (see Supplementary Material S2 for more details).

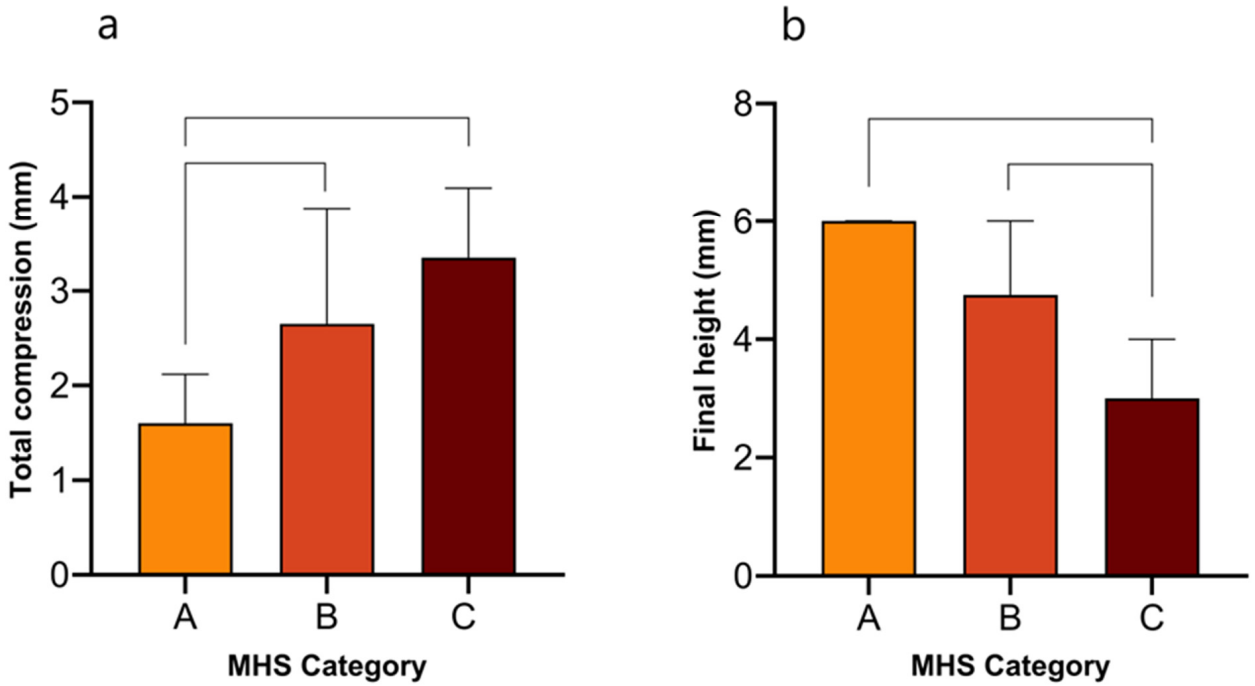


Figure 4. Column diagrams of tissue compressibility and elasticity of fillets belonging to study categories A (normal fillets), B (mild–moderate MHS), and C (severe MHS). Significant differences between categories are marked with brackets in both graphs. (**a**) Mean total compressibility after a full series of compression by all stainless-steel weights. The variation in total tissue compressibility (total compression in mm) was assessed using one-way ANOVA followed by Tukey's multiple comparisons test ($p < 0.05$, CI = 95%). The results are depicted with mean and standard deviation. Category B and C fillets displayed significantly higher compressibility compared to category A fillets. (**b**) The variation in tissue elasticity (final height in mm) was assessed using a two-tailed Kruskal–Wallis test ($p < 0.05$, CI = 95%), and the groups were compared using Dunn's multiple comparison test. The results are presented with median and range. Category A and B subsamples were significantly better at regaining their original shape and height compared to those in category C.

We found a statistically significant difference in tissue elasticity between categories A and C, and between B and C. After compression by all steel weights, the subsamples from categories A and B had a mean final height of 5.8 and 4.65 mm, respectively, while the subsamples in category C displayed a mean final height of 2.75 mm. This is illustrated in Figure 4b.

3.4. Correlations

Fillets assigned to the MHS categories by organoleptic characteristics exhibited significant deviations in the texture measurements, drip loss, cook loss, and product yield compared to normal fillets. Spearman's correlation coefficient confirmed a strong inverse relationship between tissue compressibility and tissue elasticity across all of the categories. We found a strong negative correlation between MHS severity and tissue elasticity. When only the results for categories A and C were taken into account, we also found a strong positive correlation between MHS severity and tissue compressibility, TDL, and CDL and a strong negative correlation with tissue elasticity and yield. These results demonstrate that the visual and tactile traits used for classification correspond to measurable changes in fillet quality, although greater variability was observed within the intermediate MHS category (see Supplementary Material S3 for details).

4. Discussion

The current study demonstrated a three-fold increase in TDL and CDL for MHS-fillets compared to normal fillets, while yield was averagely reduced by 20%. MHS-fillets also showed increased compressibility and reduced elasticity. The mean total tissue compressibility was 56% in category C. For category A, the total compression was only 27%. Similarly, tissue elasticity was reduced by more than 50% in category C: while the normal tissue regained its original shape and size to a degree of 97%, merely 46% tissue restoration was achieved for category C fillets. This poor elasticity can be explained by the low structural integrity of the muscle tissue, as demonstrated in Figure 2. Category B displayed a lower level of compressibility and greater elasticity, indicating that the deformation induced by compression was temporary.

Fillets severely affected by MHS not only differed visually and texturally at the surface level but also showed significantly altered quality traits, including increased drip and cook losses, reduced product yield, higher compressibility, and less elasticity. The correlations between MHS severity and TDL, CDL, and yield were strongest when only the results from categories A and C were analyzed. Category B displayed the largest variance in TDL and CDL, which ranged at 12.8–63.3% and 13.5–50%, respectively, while the yield ranged at 50–86.5%. This observation is similar to the one made in our previous study, where the variation in the measured dry matter and oil content was rather wide for intermediate MHS-fillets [11]. This could be due to intermediate fillets being more difficult to accurately categorize based on sensory characteristics, relate to differences in water-holding capacity (WHC) and the degree of the degeneration of muscle fibers and collagen bonds, or be attributed to sample size and natural variation [18]. These findings suggest that organoleptic categorization may serve as a useful proxy for predicting sensory quality, and they may also reflect deeper structural or compositional changes within the muscle tissue, warranting further research, in particular for MHS-fillets belonging to the intermediate category.

Although sensory attributes such as juiciness, tenderness, and overall mouthfeel were not directly assessed, several of the measured physicochemical properties are well-established determinants of these important sensory experiences. For example, higher drip and cook losses typically result in drier, less juicy fillets, while less elasticity may correspond to a softer or mushier mouthfeel. Additionally, fillet firmness and juiciness are directly affected by drip loss and WHC. WHC describes the ability of muscle meat to retain moisture and is associated with protein and tissue properties, and a high WHC is considered advantageous, as it results in lower drip and greater yield [19,20]. While WHC was not measured in this study, the increased drip loss of fish products generally indicates a corresponding decline in WHC [21]. In addition, the widening of the intermyofibrillar space, as observed during the histological examination, is linked to low WHC [22]. These

inferences point to a likely decline in perceived eating quality as MHS severity increases, emphasizing the importance of early detection and classification.

Due to raw material and equipment availability, our study had a small sample size with an overweight of category C fillets, and our texture assessment was limited to mechanical compression. Although this limits the generalizability of our results, our findings highlight that MHS-fillets fail to meet the quality standard for Greenland halibut.

While the meat of Greenland halibut is considered softer and more delicate than, for example, Atlantic halibut (*Hippoglossus hippoglossus*), it is a savory, oily fish. We have previously demonstrated a low fat content in MHS-fillets [11]. Combined with the high drip and low firmness documented in the current study, the result is a watery mouthfeel with less flavor and chewing resistance than expected [23–25]. Factoring in the significantly decreased yield of MHS-fillets, there is a clear commercial incentive to investigate alternative processing options. While high fillet yield can be a breeding criterion in farmed fish, selective breeding is not an option for wild-caught fish. Therefore, strategies aimed at mitigating the effects of MHS need to focus on improved detection and utilization.

Comminution is a low-cost processing method widely used in commercial fish processing, as it enables the utilization of products which would otherwise be rejected by consumers. Rideout and Snow (1974) investigated the possibility of utilizing jellied plaice fillets for human consumption. Though yield declined with increasing percentages of heavy jellied fillets, it did not markedly affect the sensory product experience, and batches consisting of 100% heavy jellied fillets still resulted in a yield above 70% [10].

The similarities in chemical and physical properties between jellied plaice and MHS-fillets suggest that comminuting MHS-fillets for alternative utilization as fish sticks could be a feasible processing strategy. The low fat content and pH level of MHS-fillets might even make them suitable for processing as fish paste or surimi, although mixing with higher-protein fish products or the adding of binding agents may be necessary for optimal gel formation and texture [11,26].

The effect of freezing and thawing was evident in the histological sections of both normal and MHS-fillets (Figure 2). Freezing affects the textural properties of muscle tissue, and the high moisture content and fragile muscle structure of MHS-fillets may make them more susceptible to physicochemical changes during freezing and thawing processes [27]. This is especially important in the context of inferior or underutilized fish, as proper handling and freezing protocols could either enhance, preserve, or further degrade the quality of MHS products. Future studies into this area should include the impact of freezing and packaging on product appearance and quality [28] and test the effect of different processing and preservation techniques such as draining, salt washing, or the addition of binders [29].

When looking into utilization strategies, it is important to take into account economic and regulatory hurdles. Utilizing inferior fish products often requires specialized equipment and additional processing steps, and some facilities may face challenges with logistics or labor availability. This is particularly relevant for remote North Atlantic and Arctic processing locations. To ensure that the strategy is economically viable, the costs of reprocessing equipment, product development, quality control, distribution, and marketing potential should be carefully considered. Another challenge with MHS is securing raw material supply, and consistent, reliable detection is vital to ensuring a successful utilization strategy. Lastly, details on the microbial safety and stability of MHS products are required to uphold food safety and quality standards, and obtaining permits for processing may be relevant [30].

5. Conclusions

Physicochemical product characterization is central for assessing quality and processing options. In this study, we used low-technological methods to characterize and quantify differences in the product properties of Greenland halibut fillets affected and unaffected by MHS. Compared to normal fillets (category A), TDL and CDL were significantly higher in both MHS categories (B and C), while yield was significantly lower. Decreased elasticity and firmness was evident in both MHS categories but most pronounced in category C.

Our preliminary results suggest that MHS severity influences physical parameters; category B displayed a wider range in TDL, CDL, and yield compared to categories A and C. This could be due to sensory classification errors, sample size, natural variation, or relation to WHC. More data are needed for fillets belonging to the intermediate category.

Only manual compression was used in the current study, and sample size was limited to 40 fillets. While the applied manual method can be considered objective and offers a low-cost solution for quick assessments in the field, the interpretation may be subject to some variability. To verify the trends observed here and further explore the variations between MHS severities, we recommend applying instrumental texture analysis on a larger, more diverse sample to increase the objectivity and reproducibility of the data, preferably paired with expanded sensory panel testing, including more organoleptic criteria [31]. Future investigations should also include the measurement of proteins, vitamins, and minerals in the drip to quantify the nutritional loss during the processing of MHS-fillets.

The growing demand for sustainable seafood requires the optimal utilization of all harvested fish products, not only to reduce losses in the fisheries but also to ensure food availability and security [32]. This merits further investigation into issues like MHS, where there is potential for increasing raw material usage and decreasing economic and material losses. The physicochemical properties for MHS-fillets appear similar to those of jellied plaice fillets, suggesting that comminution could be a value-adding processing option [10]. Additionally, preservation techniques such as salting might be able to enhance the raw product value [33]. Due to the logistic circumstances of many North Atlantic and Arctic processing plants, careful consideration should be paid to equipment and processing costs when determining an alternative utilization strategy.

With improved detection, classification, and strategic processing, MHS could become a case study in circular economy practices within marine harvesting sectors. We propose a shift in perspective, from viewing mushy fillets as waste to exploring their potential in alternative product streams. It is our hope that this brief report will encourage more research into the valorization of fish products currently considered unmarketable due to inferior sensory properties.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fishes10080367/s1, Supplementary Material S1: Raw data for all fillet samples as well as calculated TDL, CDL, and yield. The file also contains capture information. Supplementary Material S2: Raw data and calculations concerning compressibility and elasticity. Supplementary Material S3: Data related to statistical correlation analysis, including *p*-values and heatmaps.

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Abbreviations

The following abbreviations are used in this manuscript:

MHS	Mushy halibut syndrome
TDL	Thaw drip loss
CDL	Cooked drip loss
WHC	Water holding capacity

References

1. Naatsorsueqqissaartarfik. *Greenland in Figures 2024*; Statistics Greenland: Nuuk, Greenland, 2024.
2. Ortega, S.; Lindberg, S.-K.; Olsen, S.H.; Anderssen, K.E.; Heia, K. Early identification of mushy Halibut syndrome with hyperspectral image analysis. *LWT* **2023**, *176*, 114559. [CrossRef]
3. Ortega, S.; Ofstad, R.; Syed, S.; Kranz, M.; Heia, K.; Anderssen, K.E. Characterization of vasskveite (water halibut) syndrome for automated detection. *Appl. Food Res.* **2023**, *3*, 100250. [CrossRef]
4. Severin, N.L.; Buchmann, K. The 'jellied' or 'mushy' condition of fish in the North Atlantic and North Pacific fisheries: Characteristics, causes and consequences. *Heliyon* **2024**, *10*, e27130. [CrossRef] [PubMed]
5. Templeman, W.; Andrews, G.L. Jellied Condition in the American Plaice *Hippoglossoides platessoides* (Fabricius). *J. Biol. Board Can.* **1956**, *13*, 147–182. [CrossRef]
6. FAO. *The State of the World Fisheries and Aquaculture 2020. Sustainability in Action*; FAO: Rome, Italy, 2020. [CrossRef]
7. FAO. *The State of World Fisheries and Aquaculture 2022—Towards Blue Transformation*; The State of the World Series; Food and Agriculture Organization of the United States: Rome, Italy, 2022.
8. Olsen, R.L.; Toppe, J.; Karunasagar, I. Challenges and realistic opportunities in the use of by-products from processing of fish and shellfish. *Trends Food Sci. Technol.* **2014**, *36*, 144–151. [CrossRef]
9. Nawaz, A.; Li, E.; Irshad, S.; Xiong, Z.; Xiong, H.; Shahbaz, H.M.; Siddique, F. Valorization of fisheries by-products: Challenges and technical concerns to food industry. *Trends Food Sci. Technol.* **2020**, *99*, 34–43. [CrossRef]
10. Rideout, S.G.; Snow, G.W. *A Study into the Possible Utilization of "Jellied" Flounder of the Species Hippoglossoides platessoides by Commuting the Fillets*; Fisheries and Oceans Canada: Ottawa, ON, Canda, 1974.
11. Severin, N.L.; Ortega, S.; Romeyn, R.; Olsen, S.H.; Heia, K.; Jacobsen, C.; Boeknaes, N.; Hauptmann, A.L.; Boje, J.; Kania, P.W.; et al. An Interdisciplinary Approach to Detect and Grade 'Mushy Halibut Syndrome' in fillets of Greenland halibut (*Reinhardtius hippoglossoides*). *J. Food Meas. Charact.* **2025**, *19*, 3444–3461. [CrossRef]
12. Bigelow, W.; Lee, C.M. Evaluation of Various Infused Cryoprotective Ingredients for Their Freeze–Thaw Stabilizing and Texture Improving Properties in Frozen Red Hake Muscle. *J. Food Sci.* **2007**, *72*, C056–C064. [CrossRef]

13. Karinen, J.F.; Barnett, H.J.; Masuda, M. Soft flesh in sablefish, Anoplopoma fimbria, of southeastern Alaska: Relationships with depth, season, and biochemistry. *Mar. Fish. Rev.* **2010**, *72*, 26–35.
14. Murmu, P.; Chowdhury, S.; Sarkar, S.; Dora, K.C.; Nath, S.; Pal, D. Utilisation of filleting wastes in improving yield of Asian Sea Bass fillet. *J. Ecol. Environ.* **2016**, *34*, 2404–2408.
15. Cheng, J.-H.; Sun, D.-W.; Han, Z.; Zeng, X.-A. Texture and Structure Measurements and Analyses for Evaluation of Fish and Fillet Freshness Quality: A Review. *Compr. Rev. Food Sci. Food Saf.* **2014**, *13*, 52–61. [CrossRef]
16. Montgomery, J.L. Compression Measurements. In *Handbook of Meat, Poultry and Seafood Quality*; Nollet, L.M.L., Ed.; Blackwell Publishing: Oxford, UK, 2007; pp. 71–88.
17. Buchmann, K.; Skovgaard, A.; Kania, P. *Myxobolus groenlandicus n.* sp. (Myxozoa) distorting skeletal structures and musculature of Greenland halibut *Reinhardtius hippoglossoides* (Teleostei: Pleuronectidae). *Dis. Aquat. Org.* **2012**, *98*, 133–141. [CrossRef]
18. Love, R.M. Variability in Atlantic Cod (*Gadus morhua*) from the Northeast Atlantic: A Review of Seasonal and Environmental Influences on Various Attributes of the Flesh. *J. Biol. Board Can.* **1975**, *32*, 2333–2342. [CrossRef]
19. Olsson, G.B.; Olsen, R.L.; Ofstad, R. Post-mortem structural characteristics and water-holding capacity in Atlantic halibut muscle. *LWT Food Sci. Technol.* **2003**, *36*, 125–133. [CrossRef]
20. Hughes, J.M.; Oiseth, S.K.; Purslow, P.P.; Warner, R.D. A structural approach to understanding the interactions between colour, water-holding capacity and tenderness. *Meat Sci.* **2014**, *98*, 520–532. [CrossRef]
21. Chan, S.S.; Roth, B.; Jessen, F.; Jakobsen, A.N.; Lerfall, J. Water holding properties of Atlantic salmon. *Compr. Rev. Food Sci. Food Saf.* **2022**, *21*, 477–498. [CrossRef]
22. Liu, Y.; Sun, Q.; Pan, Y.; Wei, S.; Xia, Q.; Liu, S.; Ji, H.; Deng, C.; Hao, J. Investigation on the correlation between changes in water and texture properties during the processing of surimi from golden pompano (*Trachinotus ovatus*). *J. Food Sci.* **2021**, *86*, 376–384. [CrossRef] [PubMed]
23. Havforskningsinstituttet. Ønsker Blåkveiteprøver fra Fiskere og Importører. Available online: https://www.hi.no/hi/nyheter/2019/mars/onsker-blakveiteprover-fra-fiskere-og-importorer (accessed on 10 October 2024).
24. Karl, H.; Numata, J.; Lahrssen-Wiederholt, M. Variability of fat, water and protein content in the flesh of beaked redfish (*Sebastes mentella*) and Greenland halibut (*Reinhardtius hippoglossoides*) from artic fishing grounds. *J. Consum. Prot. Food Saf.* **2018**, *13*, 383–389. [CrossRef]
25. Severin, N.L. (University of Copenhagen, Frederiksberg, Denmark). Unpublished work and personal communication, 2023.
26. Bashir, K.M.I.; Kim, J.-S.; An, J.H.; Sohn, J.H.; Choi, J.-S. Natural Food Additives and Preservatives for Fish-Paste Products: A Review of the Past, Present, and Future States of Research. *J. Food Qual.* **2017**, *2017*, 9675469. [CrossRef]
27. Erikson, U.; Uglem, S.; Greiff, K. Freeze-Chilling of Whitefish: Effects of Capture, On-Board Processing, Freezing, Frozen Storage, Thawing, and Subsequent Chilled Storage—A Review. *Foods* **2021**, *10*, 2661. [CrossRef]
28. Cropotova, J.; Mozuraityte, R.; Standal, I.B.; Grøvlen, M.S.; Rustad, T. Superchilled, chilled and frozen storage of Atlantic mackerel (Scomber scombrus) fillets—Changes in texture, drip loss, protein solubility and oxidation. *Int. J. Food Sci. Technol.* **2019**, *54*, 2228–2235. [CrossRef]
29. Gonçalves, A.; Souza, M.; Regis, R. Effects of different levels of food additives on weight gain, cook-related yield loss, physico-chemical and sensorial quality of Nile tilapia fillets (*Oreochromis niloticus*). *Int. Food Res. J.* **2018**, *25*, 2068–2080.
30. Ghosh, P.R.; Fawcett, D.; Sharma, S.B.; Poinern, G.E.J. Progress towards Sustainable Utilisation and Management of Food Wastes in the Global Economy. *Int. J. Food Sci.* **2016**, *2016*, 3563478. [CrossRef] [PubMed]
31. Hyldig, G.; Nielsen, D. A Review of Sensory and Instrumental Methods used to Evaluate the Texture of Fish Muscle. *J. Texture Stud.* **2001**, *32*, 219–242. [CrossRef]
32. UN. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations Publishing: New York, NY, USA, 2015.
33. Jiang, Q.; Nakazawa, N.; Hu, Y.; Osako, K.; Okazaki, E. Microstructural modification and its effect on the quality attributes of frozen-thawed bigeye tuna (*Thunnus obesus*) meat during salting. *LWT* **2019**, *100*, 213–219. [CrossRef]

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