Water holding properties of Atlantic salmon

Chan, Sherry Stephanie; Roth, Bjørn; Jessen, Flemming; Jakobsen, Anita Nordeng; Lerfall, Jørgen

Published in:
Comprehensive Reviews in Food Science and Food Safety

Link to article, DOI:
10.1111/1541-4337.12871

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Received: 2 July 2021 | Revised: 8 October 2021 | Accepted: 21 October 2021

DOI: 10.1111/1541-4337.12871

COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Comprehensive REVIEWS in Food Science and Food Safety WILEY

Water holding properties of Atlantic salmon

Sherry Stephanie Chan[1] | **Bjørn Roth**[2] | **Flemming Jessen**[3] | **Anita Nordeng Jakobsen**[1] | **Jørgen Lerfall**[1]

[1] Department of Biotechnology and Food Science, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

[2] Department of Processing Technology, Nofima AS, Stavanger, Norway

[3] National Food Institute, Technical University of Denmark, Kgs. Lyngby, Denmark

Correspondence
Sherry Stephanie Chan, Department of Biotechnology and Food Science, Norwegian University of Science and Technology (NTNU), NO-7491, Trondheim, Norway.
Email: sherry.s.chan@ntnu.no

Funding information
Norges Teknisk-Naturvitenskapelige Universitet

Abstract

With global seafood production increasing to feed the rising population, there is a need to produce fish and fishery products of high quality and freshness. Water holding properties, including drip loss (DL) and water holding capacity (WHC), are important parameters in determining fish quality as they affect functional properties of muscles such as juiciness and texture. This review focuses on the water holding properties of Atlantic salmon and evaluates the methods used to measure them. The pre- and postmortem factors and how processing and preservation methods influence water holding properties and their correlations to other quality parameters are reviewed. In addition, the possibility of using modelling is explained. Several methods are available to measure WHC. The most prevalent method is the centrifugation method, but other non-invasive and cost-effective approaches are increasingly preferred. The advantages and disadvantages of these methods and future trends are evaluated. Due to the diversity of methods, results from previous research are relative and cannot be directly compared unless the same method is used with the same conditions.

1 | INTRODUCTION

The quality of seafood is increasingly important and influences the production cost and consumer preference. Salmon is a dominating species in aquaculture with a worldwide total production of 2.5 million tonnes and is also an important seafood commodity with a high value (Ernst & Young, 2019). Norway is currently the world's largest producer of Atlantic salmon, with a total production of 1.4 million tonnes in 2019 (SSB, 2020). As an export commodity, Atlantic salmon represents around 93% of the Norwegian aquaculture production, and these fish are exported for further processing. They have a high calorie and protein retention of 25% and 28%, respectively (Fry et al., 2018). As salmon production becomes more lucrative, more countries are using innovative technologies to explore the possibilities of producing salmon on sea-based and land-based farms. Therefore, as one of the leading countries with a proven aquaculture industry, Norway is in a good position to strengthen its standing in the globally competitive aquaculture market and produce fish of high quality. This applies throughout the entire value chain, from production, harvesting, primary and secondary processing and finally storage and consumption.

Water is the predominant component in fish. It supports a series of biochemical, microbiological and physical reactions that affect the sensory, nutritional and functional properties during fish processing and storage (Jepsen et al., 1999). Water holding properties include drip loss (DL) and water holding capacity (WHC), two representative indicators for freshness considering the affinity between fish muscle and water. WHC, the ability of muscle protein to prevent water from being released from their three-dimensional structure against external forces, is a

property that contributes significantly to both meat and fish quality (Duun, 2008; Huff-Lonergan & Lonergan, 2005; Kaale et al., 2014; Warner, 2014). WHC is also defined as the ability to retain inherent water within the muscle (Bowker, 2017; Cheng & Sun, 2008; Zhang et al., 1995). Water released without any additional force is referred to DL, sometimes called purge or weep. This is the extrusion of tissue juices from the muscle protein networks and is closely related to WHC (Huff-Lonergan & Lonergan, 2005; Szmańko et al., 2021).

A high DL is undesirable due to oxidative and hydrolytic processes from microorganisms and is intensified by the purge, resulting in lower quality. Improved WHC as a reflection of limited DL became more desired by the producers for higher net weight and better acceptable appearance to the consumers. It affects weight changes during storage and transport, DL during thawing, weight loss during cooking as muscle texture changes, and thereby consumer preferences and costs (Duun, 2008; Kaale et al., 2014). For producers, a high WHC results in lower DL and greater protein functionality, influencing profitability. It also reflects a better appearance and improved juiciness and texture. Some reports refer to liquid holding capacity (LHC) as an interchangeable term for WHC (Ofstad et al., 1996). Others differentiate the LHC into water and lipid lost during processing, especially for fatty fish (Løje, 2007; Rørå & Regost, 2003). Ofstad et al. (1995) reported that the primary liquid loss in fatty fish such as salmon and rainbow trout is mostly water, and fat loss can be considered negligible. A better understanding of WHC in salmonid species could help prevent fluid loss, potentially nutrient loss and increase product yield through the whole value chain, leading to better quality.

The composition and muscle structure can differ between mammalian and avian meat and fish. In contrast to meat, fish has less connective tissues with shorter muscle fibers. In salmon, these muscle fibers are separated into distinct red and white muscles (Kiessling et al., 2006; Listrat et al., 2016). Two of the quality defects faced by the meat industry are pale, soft, exudative (PSE) and dark, firm and dry (DFD) meat. PSE meat results in a loss of WHC while DFD meat has a high WHC, but both give visual defects rejected by consumers (Listrat et al., 2016; Strasburg et al., 2007). Consumer research indicated a preference for tenderness for meat when making purchasing decisions, while the preferred quality for fish is a firm texture with a good WHC (Listrat et al., 2016; Maltin et al., 2003).

Several reviews have described WHC in food. So far, the focus has been mainly on meat products such as beef, pork and lamb (Cheng & Sun, 2008; Fennema, 1990; Forrest et al., 2000; Huff-Lonergan & Lonergan, 2005; Oswell et al., 2021) and rarely on aquaculture species. This article follows the majority of research referring to WHC as the ability of the muscle to hold water and DL as weight loss mainly from water and includes other minor constituents such as the loss of water-soluble vitamins, minerals and proteins (Kamruzzaman et al., 2012; Ofstad et al., 1995; Strasburg et al., 2007). By understanding the mechanisms and processes that influence water holding properties, products can aim to have a good WHC or lessen DL. Therefore, this review presents an overview of water holding properties and how this affects the Atlantic salmon in the value chain.

2 | MEASURING WATER HOLDING PROPERTIES

Water is an essential constitution that, together with lipids, make up 80% of fish muscle (Murray & Burt, 2001). Water is closely correlated with physical and chemical changes within the fish, including pH, textural properties, protein denaturation, enzyme activity, fatty acid hydrolysis and rheological property (Dawson et al., 2018; Wang et al., 2018). The three primary states of water are bound, immobilized and free water. These are located in different compartments within the muscle. Immobilized and free water are mainly responsible for DL, accounting for up to 90% of the total water (Aursand et al., 2009). Furthermore, the immobilized water, which accounts for most of the water (up to 80%), is correlated with texture (Bowker, 2017). This is explained by the microstructural observations of the protein–water interactions, which shows that the decrease in immobilized water content is related to quality deterioration over time (Sun et al., 2018).

The lack of a standardized method to measure WHC makes it challenging to compare the same parameters with previous literatures (Oswell et al., 2021; Szmańko et al., 2021). Moreover, WHC could differ after a product is processed or cooked. Therefore, the choice of the measurement method and its calculation is distinguished based on the experimental purpose (Hamm, 1986). It is also impossible to measure the same sampling point at different times, resulting in a certain degree of uncertainty. Therefore, it is essential to acknowledge the differences between the methods and choose one that suits the objective best. A summary of the methods is shown in Figure 1.

2.1 | Conventional approaches

Established methods based on the amount of force applied to remove loosely bound or unbound water have been reported in determining the WHC of muscle. These are "no force," "applied external mechanical force" or "applied thermal force" (Fennema, 1990; Honikel & Hamm, 1995). Applying no force is equivalent to measuring DL, where the only force involved is the gravitational force (Cheng & Sun, 2008; Fennema, 1990; Honikel & Hamm, 1995). This is a simple but often more time-consuming technique as

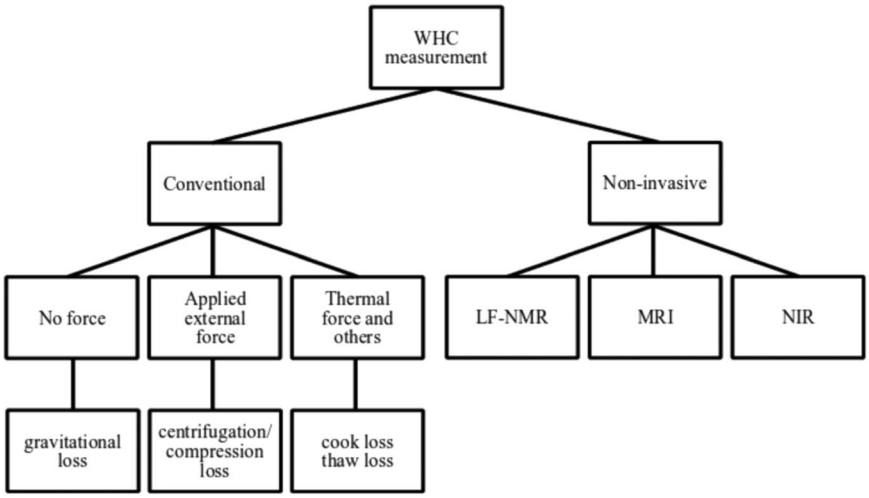

FIGURE 1 A summary of various methods used in measuring water holding capacity (WHC) in Atlantic salmon. "Conventional" represents methods involving force where WHC is calculated from the water loss. "Noninvasive" represent methods that are rapid and noninvasive. LF-NMR, MRI, and NIR represent low field-nuclear magnetic resonance, magnetic resonance imaging, and near-infrared spectroscopy, respectively

the samples are hung and left sitting for days while drip is collected. The amount of time is also another variable. The DL is then calculated as the percentage of the collected drip against the original weight.

Applying an external mechanical force includes centrifugation and compression, where pressure is applied to remove the liquid. The filter paper wetness (FPW) involves pressing the sample between filter papers and is one of the simplest and quickest methods that highly correlates with DL (Mallikarjunan, 2016). The centrifugation method involves applying centrifugal force either low-speed (200–800 × g) using 2–15 g of samples, or high-speed centrifugation (5000–40,000 × g) using 1–20 g of samples to measure the ability of the sample to retain water by measuring the liquid lost after centrifugation (Varmbo et al., 2000). Applying a thermal force involves cooking and measuring the cook loss of the sample. This primarily represents the loss of intra- and extracellular water from the muscle due to protein denaturation and cell membrane disintegration. Finally, other methods also include measuring thaw loss after freezing (Bowker, 2017).

The centrifugation method, especially the low-speed centrifugation method that largely retains the microstructure of the muscle, is the most preferred way to measure WHC in fish species (Varmbo et al., 2000). A summary of selected literatures that used the centrifugation method on Atlantic salmon is shown in Table 1. WHC is calculated from liquid loss and can be expressed in %. Most studies present it in % and calculate WHC by measuring the differences in weight from the sample as the liquid is collected through a filter after centrifugation, as shown in Equation 1 (Aursand et al., 2009; Erikson et al., 2011; Gomez-Guillen et al., 2000; Kaale et al., 2014; Løje, 2007; Ofstad et al., 1996, 1995; Rørå & Regost, 2003; Sun et al., 2018; Thorarinsdottir et al., 2004):

$$\text{WHC}\,(\%) = \frac{W_T - \text{LL}}{W_T} \times 100\% \tag{1}$$

where w_T refers to the total sample weight, and LL refers to the liquid loss.

These results, however, only give the relative WHC values, and such results can only be compared with those that use the exact same method (Skipnes et al., 2007; Varmbo et al., 2000). Since most frozen foods are usually cooked and consumed after thawing, to incorporate cooking loss, Skipnes et al. (2007) developed a method that includes water content and cook loss to determine WHC of whole and comminuted samples in both raw and cooked fish (Equations 2–4). This method calculates the dry matter, where liquid is lost by drying the sample gravimetrically at 105°C, representing the moisture that includes the loss of bound water and has been used by several studies with Atlantic salmon and Atlantic cod (Blikra et al., 2019; Chan, Roth, Jessen, et al., 2020; Chan, Roth, Skare, et al., 2020; Chan, Skare, et al., 2021; Fidalgo et al., 2020; Lerfall & Rotabakk, 2016; Rotabakk et al., 2017). In addition, the total WHC changes from raw to cooked product can also be determined.

Raw samples:

$$\text{WHC}\ (\%) = \frac{W_0 - \triangle W}{W_0} \times 100\% \tag{2}$$

where:

$$W_0 = \frac{V_0}{m_0} \times 100\% \tag{2a}$$

$$\triangle W = \frac{\triangle V_0}{m_0} \times 100\% \tag{2b}$$

where V_0 represents the initial water content, m_0 is the initial sample weight and ΔV_0 is the liquid separated after centrifugation of the raw material.

TABLE 1 Selected literatures on centrifugation parameters and calculation methods for measuring water holding capacity (WHC) of raw Atlantic salmon

Salmon storage	Fillets storage conditions	Centrifugation parameters	Calculation method[1]	Reference
Raw	Iced storage, 3 days	210 g, 5 min	Equation 1	Aursand et al. (2010)
	Superchilling in seawater slurry (−1.9°C) or iced, 11 days	230 g, 5 min	Equation 1	Erikson et al. (2011)
	Iced storage, 11 days	210 g, 5 min	Equation 1	Hultmann and Rustad (2002)
	Superchilled storage (−1.4 or −3.6°C), 34 days	210 g, 5 min	Equation 1	Duun and Rustad (2008)
	Superchilled storage (−1.7°C), 28 days	270 g, 5 min	Equation 1	Kaale et al. (2014)
	1 day	1500 g, 5 min, 10°C	Equation 1	Løje et al. (2017)
	Iced storage, 4 days	500 g, 10 min, 10°C	Equation 1	Røra et al. (2003)
	Iced storage, 22 days	530 g, 15 min, 4°C	Equation 2	Chan, Roth, Jessen, et al. (2020)
	Superchilled in N_2 (−1°C) or iced storage, 23 days	530 g, 15 min, 4°C	Equation 2	Chan, Roth, Skare, et al. (2020)
	Vacuum skin vs. modified atmospheric packaging (60% CO_2:40% N_2), 4°C, 20 days	530 g, 15 min, 4°C	Equation 2	Chan, Skare, et al. (2021)
	Vacuum skin vs. traditional vacuum packaging, 4°C, 20 days	530 g, 15 min, 4°C	Equation 2	Chan, Rotabakk, et al. (2021)
	Vacuum storage, 60 MPa/10°C, 30 days	530 g, 15 min, 4°C	Equation 2	Fidalgo et al. (2020)
	Iced storage, 19 days	530 g, 15 min, 4°C	Equation 2	Lerfall et al. (2015)
	Iced storage, 14 days	530 g, 15 min, 4°C	Equation 2	Lerfall and Rotabakk (2016)
	Iced storage, 18 days	530 g, 15 min, 4°C	Equation 2	Rotabakk et al. (2017)

[1]Equations 1 and 2 are different calculations of WHC based on the centrifugation method. Equation 1 calculates WHC from the liquid lost after centrifugation relative to the initial sample weight, while Equation 2 includes the water content of the initial sample (Skipnes et al., 2007).

Cooked samples:

$$\mathrm{WHC}_1\,(\%) = \frac{V_1 - \triangle V_1}{V_1} \times 100\% \qquad (3)$$

where V_1 represents the water content and ΔV_1 the liquid separated after centrifugation of the cooked material.

The equation describing the total changes in WHC from raw to cooked samples is:

$$\mathrm{WHC}_{\mathrm{TOT}}\ \ (\%) = \frac{V_0 - \left(\triangle V_1 - C_1\right)}{V_0} \times 100\% \qquad (4)$$

where C_1 represents the cook loss.

To compare samples with different water contents before centrifugation, WHC can also be expressed relative to the fat-free dry matter content as the amount of water retained based on the mass fraction of final to initial weight (Løje, 2007):

$$\mathrm{WHC}\,(\%) = \frac{100 - t - \Delta r}{100 - t} \times 100\% \qquad (5)$$

where:

$$\Delta r = \frac{m_0 - m_1}{m_0} \times 100\% \qquad (5a)$$

where m_0 and m_1 refer to the initial sample weight and sample weight after centrifugation, respectively. t refers to the % of initial dry matter.

The methods mentioned above are considered conventional approaches involving a certain extent of sample destruction. The centrifugal force and duration both affect water extrusion. The rotor geometry and centrifuge also need to be considered as this can affect the centrifugal force. Zhang et al. (1995) evaluated the impact of centrifugal force (959, 8630 and 34,500 × g), duration (7.5, 15 and 22.5 min), sample temperature (2, 10 and 20°C) and salt concentration (0, 0.3, 0.6 mol/l) on lean beef muscle. WHC decreased when the centrifugal duration increased from 7.5 to 15 min, but the decrease was minimal afterwards. Likewise, the WHC decreased with a higher centrifugal force and temperature since more water was expelled. It is, therefore, crucial to measure WHC with the same test conditions to prevent misinterpretation of results.

The increasing demand for quality assurance in fish also led to the introduction of rapid, nondestructive and cost-efficient techniques for measuring WHC in fish. These include low field nuclear magnetic resonance (LF-NMR), magnetic resonance imaging (MRI) and near-infrared (NIR) spectroscopy, which can be used to measure water properties in both processed and unprocessed fish (Aursand et al., 2010, 2009; Gallart-Jornet et al., 2007a; Gudjonsdottir et al., 2010; Jepsen et al., 1999; Løje, 2007).

2.2 | Noninvasive approaches

LF-NMR uses a proton resonance frequency as low as 60 MHz using pulse sequences such as the Carr–Purcell–Meiboom–Gill (CPMG) sequence and has been successfully implemented to study different water populations or "pools" in fish (Aursand et al., 2010; Gallart-Jornet et al., 2007b; Jepsen et al., 1999). This rapid, noninvasive method is based on T_1 (longitudinal) and T_2 (transverse) constant relaxation times and provides valuable information regarding the state of water, compartmentalization and changes in water location, and by extension the WHC in the fish muscle. Aursand et al. (2010) found that T_2 relaxation analysis can distinguish differences in water distribution in salmon muscle according to antemortem handling, fillet location and brine salting. From the exponential fitting of transversal relaxation (T_2) measurements, the three water components can be separated based on their location within the myofibrillar protein structures. T_{2b} represents strongly bound water with the shortest relaxation time at 1–10 ms relaxation, T_{21} and T_{22} have relaxation times at 10–100 and 100–400 ms, representing immobilized and free water between the muscle fibers, respectively (Aursand et al., 2008; Wang et al., 2018). LF-NMR can also be combined with other analytical methods such as ^{23}Na NMR and MRI to optimize processing methods such as fish salting by analyzing water and salt distributions (Gudjónsdóttir et al., 2015; Veliyulin & Aursand, 2007). T_{21} relaxation times correlate with WHC during salting. A longer relaxation time indicates increased water mobility due to salt-induced muscle swelling, thereby increasing WHC (Aursand et al., 2008; Gudjónsdóttir et al., 2015). As storage time increases, the greater protein denaturation causes water to flow more freely. Some bound water then becomes immobilized, while some immobilized water becomes free water, increasing DL (Sun et al., 2018). LF-NMR can therefore describe the water pools and predict WHC in fish muscle (Andersen & Jørgensen, 2004; Jepsen et al., 1999).

MRI can be considered an extension of NMR and gives the spatial and morphological observations of the molecular water, salt and fat distribution within the muscle. This system can be applied to different processing methods such as salting, freezing and thawing, and allows for time-related analysis of water mobility (Aursand et al., 2009; Wang et al., 2018). Only a few studies have been conducted using MRI as a tool to analyze water properties in fish (Aursand et al., 2010; Nott et al., 1999; Veliyulin et al., 2006; Wang et al., 2018). Due to high equipment costs, this method is more suited for laboratory research. It is also advantageous to measure salt content in muscle directly instead of chemical methods to prevent sample destruction (Aursand et al., 2010).

Chemical compositions are heterogeneous in the salmon fillet. For example, fat content decreases from head to tail and belly to back (Katikou et al., 2001; Zhu et al., 2014). Conventional approaches to measuring WHC can be challenging to account for the overall spatial distribution and variation of WHC in the fillet (Wu & Sun, 2013). NIR spectroscopy can be used alone or combined with imaging. Hyperspectral imaging is a promising online quality detection tool increasingly used industrially (Cheng & Sun, 2014; He et al., 2013). This online, noninvasive, rapid method integrates spectroscopy and computer imaging into one technique. It collects images at varying wavelengths in the same spatial area, providing detailed information simultaneously of the spectral and spatial assessment for quality analysis and food control. This includes physicochemical attributes, microbial quality and contamination in fish and seafood products (Cheng & Sun, 2014, 2015). The major constituents of fish such as fat, water and protein have absorption peaks in the NIR region of 760–1100 nm (Heia et al., 2016). Hyperspectral imaging has been used for several quality measurements related to water holding properties in Atlantic salmon. These include ice fraction after superchilling (Stevik et al., 2010), water content (He et al., 2014), WHC (Wu & Sun, 2013), DL and pH (He et al., 2014). Therefore, hyperspectral imaging can determine DL and WHC and provide a spatial distribution of WHC within salmon fillets at the pixel level (He et al., 2014; Wu & Sun, 2013). With the wide range of traits that this imaging technique can measure, individual and multiple rapid quality assessments can be obtained.

3 | FACTORS INFLUENCING WATER HOLDING PROPERTIES

3.1 | pH

Postmortem pH and protein denaturation are critical determinants of DL and WHC in fish and meat (Duun, 2008; Huff-Lonergan & Lonergan, 2007; Kaale et al., 2014; Rotabakk et al., 2017). Other pre- and postmortem factors that influence DL and WHC in Atlantic salmon have also been reported (Figure 2), such as premortem stress (Lerfall et al., 2015; Roth et al., 2006), starvation (Mørkøre et al., 2008) and the state of rigor mortis (Ofstad et al., 1996; Rotabakk et al., 2017).

There are three main proteins in fish muscle classified according to solubility, that is, sarcoplasmic, stromal and myofibrillar proteins. The latter accounts for >50% of muscle proteins (Kijowski, 2001). Myosin and actin comprise the major share of the total myofibrillar protein content at ~65% of myofibrillar protein (Strasburg et al., 2007).

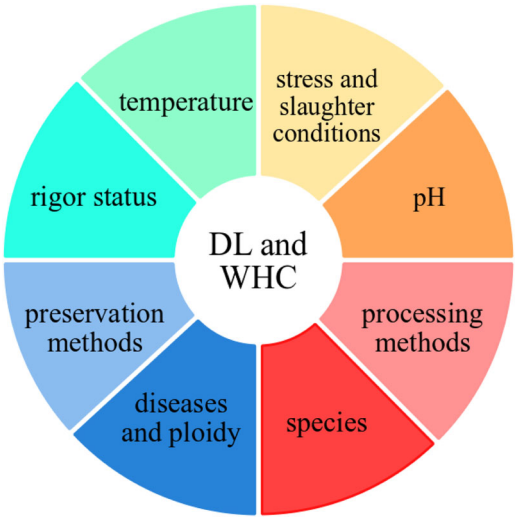

FIGURE 2 An overview of pre- and postmortem factors reported affecting drip loss (DL) and water holding capacity (WHC) of Atlantic salmon

Postmortem glycolysis leads to the accumulation of lactic acid and the decline of muscle pH. At the overall isoelectric point (pI) of myofibrillar proteins (~5.5), the strong protein–protein attraction destabilizes the protein matrix and limits the space between the peptide chains for water to penetrate (Ofstad et al., 1995; Strasburg et al., 2007). The protein–water interaction is at its minimal, resulting in the shrinkage of myofibrils and loss of WHC. At pH below or above the global pI, the overall charge becomes positive or negative, causing the peptide chains to repel and create more space to bind with water molecules. Ofstad et al. (1995) studied the effects of pH, salt and temperature on WHC in comminuted salmon. A combination of low pH (6.0), low NaCl concentration (0.17 mol/l) and high temperature (70°C) gave the most significant interaction effect on liquid loss (i.e., lowest WHC), as compared to high pH (7.0), high NaCl concentration (0.34 mol/l) and low temperature (30°C). More mincing of salmon muscle with NaCl (0.34 mol/l) led to microstructural changes and gave a higher WHC. The higher DL seen at low salt concentrations (0.17 mol/l) may indicate inadequate swelling of the protein matrix. As more salt is added to the salmon mince, the myofibrillar proteins solubilize with salt and become a homogeneous paste in the matrix, thus holding water (Ofstad et al., 1995).

3.2 | Rigor status

The prerigor period of salmon varies and can range from 2 h to over a day postmortem. The immobilized water is the water most affected by the structural changes within the sarcomere. During the conversion of muscle to meat, the muscle goes into rigor as the myosin and actin filaments become bound. The shortening of the sarcomere without changing the filament length causes water to be lost within the myofibrils and relocated to the extracellular space, eventually released as drip (Huff-Lonergan & Lonergan, 2005; Hughes et al., 2014; Wong, 2018).

Rotabakk et al. (2017) reported that the season (spring and autumn) or locality (northern, southern Norway) on the Norwegian coast did not affect the WHC of Atlantic salmon after slaughter. Moreover, salmon slaughtered in spring (May) had a higher DL by 0.3% than in autumn (November). The difference in sea temperature and photoperiod along the coastline explained this observation, where the temperature is lower, but daylight is longer in the north. In addition, the filleting method and state of rigor had a significant effect. Fish that were filleted, instead of kept as head-on gutted (HOG), had a lower WHC, while prerigor salmon after slaughter had better water holding properties than postrigor salmon kept in ice for 4 days. Therefore, the study described the potentiality of filleting fish prerigor. As DL is a time- and temperature-dependent phenomenon, chilled products should be stored at low temperatures (e.g., −1 to 4°C) with short storage duration. It is also important to minimize the quick onset of rigor through controllable methods such as gentle handling and proper chilling processes immediately after slaughter (Chan, Roth, Skare, et al., 2020).

3.3 | Temperature and species

WHC of fresh and cold-smoked salmon fillets does not seem to be affected by the muscle temperature at the point of filleting (Lerfall & Rotabakk, 2016). The pH and chemical composition in fish muscle differ among individuals, and there are also chemical variations depending on where the analysis is done on the fillet (Ofstad et al., 1993).

It was mentioned that DL increases in the cranial-caudal direction for fresh and frozen rainbow trout, but after ice storage, these variations became minimal among the fillet portions (Mørkøre et al., 2002). The species of interest and killing process also influence WHC. Farmed salmon was shown to have a higher WHC than lean species such as wild and farmed cod, which was related to species-specific features and the higher stability of their actin and myosin (Duun, 2008; Ofstad et al., 1996). This was also consistent with the results of Duun (2008), who concluded that Atlantic salmon has better WHC than cod with a similar muscle pH. Interestingly, the comparison of WHC in farmed salmon and rainbow trout by Løje et al. (2017) found that the species with the higher fat content (salmon) was less able to hold water in the muscle, thereby lowering the WHC.

3.4 | Diseases and ploidy

Diseases and ploidy can influence DL and WHC. Salmon containing the salmonid alphavirus (SAV) and those from a fish farm with repeated pancreatic disease (PD) outbreaks showed a higher DL than salmon with no records of PD and from farms diagnosed with PD 5–7 and 11–12 months before slaughter (Lerfall, 2011). In fish farms, triploid salmons were introduced to prevent breeding between wild and farmed fish that might escape from a cage. Lerfall et al. (2017) conducted a study to distinguish the quality differences between diploid and triploid salmon farmed at 5, 10 and 15°C. DL was significantly affected by the rearing temperature and ploidy, whereas ploidy did not influence WHC. Increasing the rearing temperature from 5 to 15°C also led to a larger increase in DL for both ploidies. DL was generally higher in triploid salmon, with the most significant differences observed at 10°C. This was related to the larger cellular volume to accommodate the extra chromosome (Benfey, 1999; Bjørnevik et al., 2004).

3.5 | Stress and slaughter conditions

Roth et al. (2008) showed that fillets exposed to electrical stunning after a percussive blow to the head during slaughter led to a higher DL than fillets without electrical stimulation. In a follow-up study, Roth et al. (2010) further observed that fillets exposed to 12 or 180 s of electrical stunning had a higher DL and lowered WHC than those exposed for 6 s after 16 days of storage at 3.8°C. The pre-slaughter crowding method, where fish are crowded in net pens before slaughter, induces significant stress responses, accelerates rigor mortis in fish and negatively affects the quality (Bahuaud et al., 2010). Few studies, however, have analyzed the crowding effect on water holding properties in salmonid species. Gatica et al. (2010) concluded that crowding and reduced oxygen levels increased the DL of salmon fillets. Disparities may be observed among various species attributed to the different crowding densities and the duration to which they were confined.

4 | EFFECTS OF PROCESSING AND PRESERVATION METHODS

4.1 | Salting and smoking

Various processing and preservation methods are available to prolong fish shelf life. In Europe, a substantial amount of the fish produced for human consumption are smoked (Birkeland & Akse, 2010; Cardinal et al., 2004; European Commission, 2016). The smoking process involves either soaking in brine, injection or dry salting, then smoking and drying. During lightly processed procedures such as gentle salting and cold-smoking, protein denaturation in the muscle shifts the water distribution within the salmon. As measured using NMR, the population of water with the relaxation time T_{21} (immobilized water) decreases while the T_{22} population (free water) increases (Aursand et al., 2008; Gudjónsdóttir et al., 2015; Løje, 2007). This indicates an increase in water mobility (Aursand et al., 2008). As a result, the water that remained in the muscle would be more tightly bound (Gudjónsdóttir et al., 2015; Wang et al., 2018), resulting in a higher WHC as observed in previous studies with cold-smoked salmon (Chan, Roth, Skare, et al., 2020; Gomez-Guillen et al., 2000; Lakshmanan et al., 2007; Løje, 2007). An overview of previous research done on DL and WHC for the standard salting techniques combined with cold-smoking is shown in Table 2.

Rørå et al. (2003) studied the effect of diets containing fish oil (control) or soybean oil on WHC in salmon after dry salting and cold-smoking. Neither diet influenced the WHC. However, the rigor status before secondary processing and temperature during cold-smoking affected the WHC. After vacuum storage, prerigor brine injected (25% brine (w/w)) fillets had a slightly higher exudate of 0.3% than those processed postrigor (Birkeland & Akse, 2010). This was explained by the osmotic pressure that forces moisture out of the muscle during the vacuum packaging of prerigor fillets. Rørå and Regost (2003) studied the effect of WHC on smoking salmon packed in plastic bags from 5 to 40°C in a water bath or heating chamber. WHC was better for those cold-smoked below 30°C, but there was no difference between heating methods.

The degree of muscle swelling and WHC are dependent on factors such as salting procedure, salt concentration and smoking conditions. Salt and smoking temperatures denature actin and myosin, as confirmed using differential scanning calorimetry (DSC) (Schubring, 2006). Myosin is typically sensitive and undergoes structural denaturation quickly during basic procedures such as processing involving salt. When fish is immersed in lower brine concentrations, a lower degree of protein denaturation occurs (Gallart-Jornet et al. 2007b). The Cl^- ions from salt weakly attach to the protein. These repulsive electrostatic forces cause the protein to entrap water and induce swelling of muscle fibers, thereby increasing WHC (Offer & Trinick, 1983; Thorarinsdottir et al., 2004). This is also known as the "salting in" effect and was observed by Chan, Roth, Jessen, et al. (2020) on the immersion of whole salmon in refrigerated seawater (salinity 3.5%).

Better processing yields were obtained for brine and injection salting than dry salting of salmon fillets (Birkeland et al., 2004, 2003; Bjørnevik et al., 2018; Cardinal et al., 2001). Compared to injection salting, dry salting

TABLE 2 Research overview on obtained drip loss (DL) and water holding capacity (WHC) from standard salting procedures (dry, injection and brine) combined with cold-smoking of Atlantic salmon

Salting and smoking method	Process parameters	Storage conditions	Days post-mortem	DL after smoking	WHC condition	WHC calculation	WHC after storage	Conclusion	Reference
Dry salting and cold-smoking	99.8% NaCl, 68% humidity, smoked at 23°C	Vacuum packaged and put in ice	4 and 5	−12%	500 g, 10 min, 10°C	Equation 1	95%	Compared to injection salting, dry salting had a lower yield.	Birkeland et al. (2004)
	Pre- vs. postrigor, 5 or 12 h salting, 2.5 vs. 4% final NaCl content, smoked at 15 vs. 25°C	Vacuum packaged stored for 6 weeks, 4°C	Pre: 0 Post: 5	−7%	-	-	-	A 2.5% NaCl target gave 1% better yield than 4% NaCl.	Bjørnevik et al. (2018)
	Fresh vs. frozen fish, refined salt, smoked at 65% (20°C) or 50% (30°C) humidity	Vacuum packaged, 2°C	7	−7 to −9%	-	-	-	Freezing influences DL smoked at 20°C, but not 30°C. Drying at 20°C gives a greater DL than 30°C.	Cardinal et al. (2001)
	Ice vs. RSW stored fish, ice vs. superchilled fillets, salted at 99.8% NaCl, 75% humidity, smoked at 22°C	Vacuum packaged until 31 days postmortem, 4°C	9 and 10	−7% to −8%	530 g, 15 min, 4°C	Equation 2	84%–87%	Whole fish stored in RSW then ice storage after filleting had the least DL when kept raw (1.5%), but was insignificant to other groups after smoking.	Chan, Roth, Skare, et al. (2020)
	Ice vs. RSW stored fish, salted at 99.8% NaCl, 75% humidity, smoked at 22°C	Vacuum packaged until 29 days postmortem, 4°C	7 and 8	−7%	530 g, 15 min, 4°C	Equation 2	85%–88%	No difference in DL was observed after smoking.	Chan, Roth, Jessen, et al. (2020)
	Sea caged vs. land-based diploid and triploid salmon, starved vs. not starved, salted at pure refined NaCl, 65% humidity smoked at 20°C	Vacuum packaged, stored at frozen storage at −80°C	-	-	4000 g, 10 min, rt	Equation 1	99.8%–100%	WHC increased after smoking due to the added salt. There were no differences between starvation and stress.	Gomez-Guillen et al. (2000)

(Continues)

TABLE 2 (Continued)

Salting and smoking method	Process parameters	Storage conditions	Days post-mortem	DL after smoking	WHC condition	WHC calculation	WHC after storage	Conclusion	Reference
	salted at 99.8% NaCl, 68%–73% humidity varying smoking temperatures from 20°C to 30°C	Vacuum packaged until day 16, 0–4°C	5	-	500 g, 10 min, 10°C	Equation 1	96%–97%	No difference was seen on WHC at varying smoking temperatures.	Hultmann et al. (2004)
	Muscle temperature upon filleting at 2, 9 and 14°C, salted in 99.8% NaCl, smoked at 22°C	Vacuum packaged and stored for 28 days, 5°C	6 and 7	−10%	-	Equation 2	-	DL was not affected by the muscle temperature upon filleting.	Lerfall and Rotabakk (2016)
	Small vs. large salmon size, salted (60 g salt/kg fillet), 75% humidity, smoked at 26°C	Vacuum packaged and stored for 20 days, 2°C	-	-	1500 g, 5 min, 10°C	Equation 1, Equation 5	81%–94%, 2.0%–2.6%	WHC decreasing during storage and is related to lipid loss.	Løje (2007)
	Varying diets, salted (70:30 salt/sugar), smoked at 22°C	Stored for 5 days or 15 days, 4°C or 14°C	4	−12% to −13%	500 g, 10 min, 10°C	Equation 1	96%–99%	WHC was not influenced by dietary oil.	Rørå et al. (2003)
Injection salting and cold-smoking	Test on various parameter settings, 20 and 26% brine (w/w), 70% humidity, smoked at 23°C	Vacuum packaged, 4°C	1 and 2	+5%	-	-	-	Constant injections and increasing brine injection pressure gave better yields.	Birkeland et al. (2003)

(Continues)

TABLE 2 (Continued)

Salting and smoking method	Process parameters	Storage conditions	Days post-mortem	DL after smoking	WHC condition	WHC calculation	WHC after storage	Conclusion	Reference
	25% (w/w) brine, 68% humidity, smoked at 23°C	Vacuum packaged and put on ice	4 and 5	+4%	500 g, 10 min, 10°C	Equation 1	96%	WHC were similar for both dry salted and injection salted salmon.	Birkeland et al. (2004)
	Pre- vs. postrigor processing. 25% (w/w) brine, 45% humidity, smoked at 27°C	Vacuum packaged and stored for 14 days, 2–4°C	Pre: 0 and 1 Post: 4 and 5	−2% to −3%	-	-	-	No difference in processing yield was observed from pre- or postrigor injection salted fillets.	Birkeland and Akse (2010)
	Pre- vs. postrigor 2.5 vs .4% final NaCl content, 160 or 300 g/l brine, smoked at 15 vs. 25°C	Vacuum packaged and stored for 6 weeks, 4°C	Pre: 0 Post: 5	+6% to +7%	-	-	-	Injection salting gave a 14%–15% better yield than dry salting.	Bjørnevik et al. (2018)
Brine salting and cold-smoking	Saturated brine (50% w/v), smoked at 65% (20°C) or 50% (30°C) humidity	Vacuum packaged, 2°C	7	−5% to −6 %	-	-	-	There was a better yield using brine salting than dry salting.	Cardinal et al. (2001)
	Saturated brine (360 g/l), 65% humidity, smoked at 20 vs. 30°C	Vacuum packaged, 2°C	6	−5% to −6%	-	-	-	There was a better yield for smoking at 30°C than 20°C.	Sigurgisladottir et al. (2000)

Abbreviation: RSW, refrigerated seawater.

induces a lower WHC (Birkeland et al., 2004; Bjørnevik et al., 2018). Maximum swelling and maximum WHC are usually obtained at 1 M (5.8% NaCl) (Fennema, 1990; Gallart-Jornet et al., 2007b; Thorarinsdottir et al., 2004). Gallart-Jornet et al. (2007b) found that the weight of salmon fillets increased as brine concentration decreased, and brine concentrations with <18% NaCl (w/w) decreased protein denaturation and increased WHC. The maximum weight increase was at 4% NaCl (w/w). When salt concentration increases (e.g., 25% NaCl (w/w) and dry salting), proteins denature and the myofibrils dehydrate, leading to muscle shrinkage, lower WHC and higher yield loss (Gallart-Jornet et al., 2007b; Thorarinsdottir et al., 2004).

A higher fat content gives greater resistance to salt uptake. The relevance of fat content and fillet shape on WHC of raw and cold-smoked fillets was studied by Mørkøre et al. (2001). A decrease in weight loss (i.e., greater yield) with increasing fat content was observed during the salting and smoking process, as less water is available for osmotic dehydration. The WHC in cold-smoked salmon was reduced as fat content increased, measured by centrifugation and expressed as water loss. A significant amount of the fat in the white muscle is found in the connective tissue surrounding the muscle fibers (Stien et al., 2007). Ofstad et al. (1993) explained that myofibers severely shrinks at 45°C, likely due to myosin denaturation. Therefore, this facilitates the fluid release and may explain the correlation between WHC and fat content.

4.1.1 | Salt and smoke replacers

High consumption of NaCl is associated with hypertension and cardiovascular diseases. In Norway, a salt content of 3 g NaCl/100 g product for cold-smoked salmon is voluntarily encouraged by permitting the display of "The Keyhole" label on food packages, representing healthier products (Ministry of Health and Care Services, 2015). Alternatives have been introduced to replace NaCl, but the salt replacers should have similar functional properties and not compromise the overall sensory profile, safety and quality of the food. KCl is considered a good substitute for NaCl based on its similar physical and chemical properties. The comparison of using 50% KCl/50% NaCl with 100% NaCl on vacuum packaged smoked salmon after 42 days of storage, using water vapor permeable bags during the salting-smoking process, showed no differences in weight loss nor the formation of exudates (Rizo et al., 2018). Lerfall (2011) studied the influence on quality using nitrite salt (99.4% NaCl, 0.6% $NaNO_2$) on cold-smoked salmon and found no difference in weight loss compared to 100% NaCl. Nevertheless, the food industry remains skeptical about using KCl as a replacement due to the undesirable after-taste and possibility of health risks such as hyperkalemia (Cepanec et al., 2017). More research needs to be done to identify the quality changes using salt replacers on smoked salmon.

The use of liquid smoke can be a healthier alternative than the traditional smoking method of using wood chips. It contains lesser amounts of polycyclic aromatic hydrocarbons (PAH), which are undesirable for human health. Birkeland and Skåra (2008) indicated no difference in DL between the application of smoke condensate or wood chips after vacuum packaged storage. Valø et al. (2020) used purified condensed smoke (PCS) and found that smoke from the atomization of PCS successfully inhibited microbial growth in salmon. Throughout storage, DL was significantly higher for PCS processed salmon.

4.2 | Chilling

Temperature is a critical factor in food preservation, and this should be lowered as early as possible. The internal temperature of fish is usually aimed to be 0–2°C (Bantle et al., 2015). The most common method of fish chilling is by using ice, but other methods, such as superchilling and ice slurry, are also used. These various chilling methods could influence the amount of DL and WHC. However, industrial and laboratory chilling may vary due to the more significant variations and process differences with large scale industrial chilling.

4.2.1 | Superchilling

Superchilling is a preservation method where the core temperature of the fish is lowered between conventional chilling and freezing (Banerjee & Maheswarappa, 2019). As Magnussen et al. (2008) described, superchilling is also defined as where a thin layer of ice forms on the fillet surface. This ice eventually absorbs heat from the internal reservoir to achieve equilibrium. The use of fish as a cooling medium eliminates the need for external ice, which usually takes up to 30% of space during transportation (Bahuaud et al., 2008; Magnussen et al., 2008). Extensive research has shown that superchilled Atlantic salmon introduces several benefits, including reducing enzymatic reactions and microbiological growth, improving quality and extended shelf life compared to traditional chilling (Claussen et al., 2017; Duun, 2008; Kaale et al., 2011; Magnussen et al., 2008).

Determining the freezing time and temperature measurement during superchilling remains challenging (Banerjee & Maheswarappa, 2019; Magnussen et al., 2008). The freezing time, and thereby the amounts and distribution of the ice fraction, significantly affect the

water holding properties and processing yield (Magnussen et al., 2008; Stevik et al., 2010). Kaale et al. (2013) studied the effect of cooling rates (153 and 227 W m^{-2} K^{-1}) and superchilling temperature (−20 and −30°C) on salmon fillets. A faster freezing rate (227 W m^{-2} K^{-1}) with a low temperature (−30°C) produced small crystals evenly distributed in and out of muscle cells and can reduce DL during thawing more than larger crystals formed at slow freezing rates. However, this advantage can be diminished during superchilled storage as the small crystals can collectively form large crystals. Consequently, cell membranes rupture and cell components are disrupted, leading to negative consequences for texture, DL and WHC (Bahuaud et al., 2008; Kaale et al., 2013). An earlier study by Duun and Rustad (2008) showed that salmon fillets stored superchilled at −1.4°C had a significantly higher DL (1.6%) than those at −3.6°C (0.3%). Nonetheless, a DL of <2% is considered low. The WHC, as measured by liquid loss, was similar for both groups and increased until 16 days of storage. Kaale et al. (2014) also stated that WHC increased with 21 days of superchilled storage at −1.7°C for salmon fillets, while a decrease in WHC was observed for chilled fillets at 4°C during the first 7 days, followed by an increase.

The optimal degree of superchilling was suggested to be freezing 5%–30% of the free water (Kaale & Eikevik, 2014). This range of ice fractions was investigated on salmon by Stevik et al. (2010), where superchilled salmon with 30% ice level gave a consistently lower WHC than 10 and 15% ice levels and chilled samples stored at 0 and 2°C. Claussen et al. (2017) further found that superchilled storage of organic salmon at −1.5°C (with about 15% ice fraction) led to a slightly greater DL during the first 7 days than those chilled at 3°C, which may be due to damage from partial freezing. These differences disappeared afterwards. Therefore, attention must be given to the temperature fluctuations and development of ice crystals within the muscle during the superchilling process.

A practical superchilling approach beneficial for storing large volumes of fish is using refrigerated seawater (RSW) tanks, which are often used with pelagic fish. Chan, Roth, Skare, et al. (2020) studied the effect of superchilling of salmon in RSW at subzero temperatures with a new slaughtering method in a fishing vessel against the conventional ice storage method. This concept slaughters fish by the sea cage immediately onboard the vessel, where fish are pumped, electrically stunned, bled and gutted. Then, the gutted whole fish is superchilled in RSW tanks during transportation (Chan Roth, Skare, et al., 2020). Fish stored in RSW and then on ice after filleting had the lowest DL, but those stored in RSW and then superchilled in liquid N_2 after filleting gave the lowest WHC. However, these differences disappeared after smoking. Another similar study showed that whole gutted salmon in RSW had a significantly better WHC than those on ice (Chan, Roth, Jessen, et al., 2020). This difference also disappeared after filleting and cold-smoking. Immersing whole fish in RSW is a brining method that leads to weight gain from the concentration gradient differences. Chan, Roth, Jessen, et al. (2020) and Chan, Feyissa, et al. (2021) found an overall weight gain of 0.7% and 0.9%, respectively, for salmon stored in −1°C RSW for 4 days followed by 3 days on ice. Erikson et al. (2011) also showed that salmon stored at −2°C seawater (SW) slurry led to a weight gain of 6% at 11 days. On the other hand, storing fish for a day in slurry then 3 days on ice brought about a loss in weight, like traditional ice storage, yet the WHC was better than only storing on ice during the 4-day storage. This was likely because the fish were stored for only a day in slurry, so the observable differences were minor. Therefore, storage in RSW could be advantageous in water retention and may improve cook loss. The RSW tanks also provide a high heat transfer coefficient that allows the fish's internal temperature to cool to the desired temperature in a relatively shorter time.

4.3 | Freezing and thawing

Freezing and frozen fish storage is a food preservation method that significantly prolongs the product's shelf life. However, biochemical reactions such as myofibrillar protein denaturation may still occur, negatively affecting functional properties, including WHC, juiciness and texture. This leads to a dry texture, reduced quality, and impacts DL. In terms of water mobility, freezing can change the immobilized water in intracellular locations of muscle tissues into free water that can be easily lost as drip (Dawson et al., 2018). Like superchilling, the freezing rate also affects the sizes and uniformity of crystals formed at the intra- and extracellular muscle structures. Faster freezing rates are better at maintaining the physical and chemical attributes of products, as ice nucleation within the intracellular tissues forms smaller and more uniform ice crystals within the structure. Einen et al. (2002) studied the effect of freezing on both pre- and postrigor fillets of Atlantic salmon. They observed that the frozen-thawed fillets had considerably higher DL than the unfrozen counterparts, and those postrigor had the highest DL after 10 days of cold storage. Muscle fiber shrinkage and cell damage occur during freezing, especially at slow freezing rates. This led to an increase in DL, lowering fish quality.

Decreasing the frozen storage temperature from −22 to −40°C was found to greatly improve the quality and shelf life of salmon (Haugland, 2002). All free water is frozen at −40°C, so only bound water remains in the muscle, reducing water mobility and inhibiting biochemical reactions

(Bøgh-Sørensen, 2006). Indergård et al. (2014) tested various quality parameters during long-term frozen storage of salmon at −25, −45 and −60°C for up to 375 days. Storage at −60°C had the lowest DL of 2%, calculated by the weight difference between the raw material before frozen storage and after thawing. At ultra-low temperatures (<–45°C), the freezing rate increases due to the high heat transfer and low temperature (Wu et al., 2017). Therefore, smaller ice crystals may be formed within the tissue, preventing tissue damage and reducing DL during thawing. The study of Zhu et al. (2004) further showed that plate freezing of salmon at −38°C resulted in a lower DL than conventional air freezing. On the other hand, an ultra-rapid freezing process in liquid nitrogen (−195°C) had the highest DL, probably due to mechanical cracking.

The thawing method after frozen storage also greatly influences water holding properties. For example, thawing in heated air at 25°C led to a significantly higher DL than in a 5°C water bath regardless of storage duration and temperature (Haugland, 2002). Thawing should be done quickly to prevent water in the muscle from shifting its position, which leads to increased DL (Cai et al., 2019). A low temperature is also recommended to prevent the acceleration of microbial and enzymatic reactions. Various food thawing technologies can assist the thawing process, such as high pressure, ultrasound, high voltage electrostatic field and radiofrequency (Wu et al., 2017). Studies of ohmic heating of beef (Llave et al., 2018) and high pressure thawing of chicken breast (Li et al., 2014) showed a reduced thawing loss. So far, few studies have focused on the effect of innovative technologies on freezing and thawing salmon (Li et al., 2020). This introduces a knowledge gap for further research and process optimization.

4.4 | Thermal processes

Various cooking methods commonly used in food production, including boiling, baking, frying, steaming, sous-vide and broiling, result in a change in quality attributes. Thermal processing applies time and temperature to inactivate microorganisms and enzymes, ensuring safe consumption of the product. Fresh fish can rapidly undergo chemical, biochemical and microbial processes. Hence, thermal processing should take place before these processes deteriorate the quality (Skipnes, 2014). Since the chemical and morphological composition differs within the fish muscle, this can affect the cook loss. For example, Kong, Tang, Rasco, Crapo, et al. (2007) described that the cook loss with pink salmon was significantly lower from the middle section close to the dorsal fin than those closer to the head and tail. So, it can be assumed that location can affect Atlantic salmon as well. When comparing oven baking and pan-frying to an internal temperature of 45–63°C, Brookmire et al. (2013) reported that pressed juice for the oven-baked and pan-fried salmon was reduced to 27% at 55°C and 25% at 60°C, respectively.

During thermal processing, the shrinkage of myofibrillar proteins caused by protein denaturation and aggregation decreases the WHC and leads to a firmer and harder texture (Ofstad et al., 1993; Skipnes, 2014; Sun et al., 2018). Also, the lightness of the muscle increases while its distinct red color is lost. For Atlantic salmon, proteins denature around 45, 65 and 78°C for myosin, sarcoplasmic protein and actin, respectively (Ofstad et al., 1996). Cook loss increases with temperature and storage time. The majority of cook loss occurs within the first few minutes and reaches a maximum at 50°C in salmon due to the denaturation of myosin. Above 50°C, DL is probably reduced because of sarcoplasmic protein aggregation (Ofstad et al., 1993). The rate of quality deterioration can be expressed using an integration of the kinetic equation $\frac{dC}{dt} = -k(C)^n$, where k is the rate constant, C is the quantitative indicator of a quality parameter at time t and n is the reaction order (Kong, Kong, Tang, Rasco, & Crapo, 2007). Ovissipour et al. (2017) examined the cook loss and kinetics of protein denaturation during heat pasteurization of salmon from 55 to 95°C. They found that cook loss follows a first-order reaction, where most cook losses occurred during the first few minutes in heating and eventually slowed down. Area shrinkage also occurs from the decrease in the sarcomere length which shrunk along with the muscle fibers.

Sous-vide is a cooking method popular with ready-to-eat foods. The product is sealed in vacuum pouches, treated at a controlled time and temperature, and then rapidly cooled. A mild temperature of 60–80°C for 20–40 min is recommended for fish (González-Fandos et al., 2005), but in reality, 40–60°C is often used for optimal texture and flavor (Głuchowski et al., 2019). Lerfall et al. (2018) combined different CO_2 treatments and microwave or conventional pasteurization (62°C/12 min). They found that DL was not affected by the pasteurization method. Salmon packaged with CO_2 emitters, that allowed CO_2 to be released after pasteurization, had the lowest DL compared to the control group (unexposed to CO_2) or those that underwent soluble gas stabilization (SGS). SGS is a technology that can improve shelf-life where CO_2 is driven into the flesh before pasteurization (Abel et al., 2019; Lerfall et al., 2018). Abel et al. (2019) found no correlation between DL and WHC with packaging technology when modified atmosphere (MA) and SGS packaged salmon fillets were compared after mild heat treatment. Głuchowski et al. (2019) compared the effect of sous-vide (57°C/20 min, 63°C/80 min) with roasting (180°C/23 min) and steaming (100°C/16 min) on salmon fillet portions. The highest (94%) and lowest

yield obtained (84%) were salmon treated at 57°C/20 min and roasted, respectively. The salmon treated at 63°C/80 min had the best overall sensory scores, which were the recommended conditions for sous-vide treatment without significantly affecting yield (91%).

4.5 | Nonthermal treatments

Conventional food processing technologies often use thermal methods, but this could impact nutritional values, texture and freshness. High-pressure processing (HPP) is an innovative preservation technique that extends the microbiological shelf life of seafood without incorporating heat nor loss of the organoleptic and nutritional characteristics (Campus, 2010; Christensen et al., 2017; Yagiz et al., 2009). With HPP, the packaged product is placed inside a pressure vessel, water pressure (100–900 MPa) is applied, and the adiabatic heating is ~3°C/100 MPa (Aymerich et al., 2008). An advantage of this technology is that it is a mild process done at room temperature, eliminating the need for heat and subsequent cooling processes. Thus, this could be an alternative to conventional heating processes in preparing ready-to-eat food with minimal change in sensory attributes while inactivating microorganisms.

The effect of HPP on the quality parameters of raw, cold-smoked or sous-vide treated salmon (Christensen et al., 2017; Lakshmanan et al., 2005, 2007; Ojagh et al., 2011; Yagiz et al., 2009) has been studied. The hydrostatic pressure is important to control and reduce the DL. Hedges and Goodband (2003) found that HPP in frozen cod fillets could selectively denature the structure of myosin molecules and was correlated with WHC. An application of a pressure of up to 100 MPa before freezing seemed to reduce cook loss significantly. Simultaneously, structural denaturation of actin occurs at 200 MPa, which impairs the myofibrillar structure and decreases the WHC. Lakshmanan et al. (2007) reported that HPP decreases the WHC of raw salmon regardless of processing time and pressure, while there was a 2% increase in WHC for cold-smoked salmon exposed to 150 MPa for 10 min. Increasing the pressure to higher levels also seemed to give a lighter product (Lakshmanan et al., 2005).

Similarly, Christensen et al. (2017) observed that the WHC of salmon fillets decreased when exposed to 200 MPa, followed by storage for 18 days. The storage method, pressure and processing time are essential factors to optimize for the HPP method. It is also important to avoid severe treatment as high pressure may cause gaping (Gudmundsson & Hafsteinsson, 2001). Nevertheless, there is a potential value to exploring this technique further.

Another alternative for nonthermal treatment in food is the use of pulsed electric field (PEF). This is a method where short electric pulses with a high electrical field strength are applied to food between two electrodes to induce cell electroporation (i.e., holes in the cell membrane), making it accessible for the next processing step. The application of PEF could enhance heat and mass transfer processes (Toepfl et al., 2014). As muscle cells are partially disrupted, absorption rates could be improved, and the concentration of common preservatives used in food such as salt, nitrate and spices could be reduced (Gómez et al., 2019). Although PEF is being used in the food industry for various plant and meat-based products, there are currently only a few studies regarding the effect of PEF on the quality attributes of fish products. A recent study of PEF treatment on the freeze-thaw quality of Atlantic salmon showed that applying PEF decreased the thawing time with better preservation of muscle fiber, leading to a lower DL and better WHC (Li et al., 2020). Klonowski et al. (2006) also showed that fish muscle becomes more porous. There is a potential to use PEF technology to increase water uptake and water holding properties, but more research needs to be done. On the other hand, Gudmundsson and Hafsteinsson (2001) found that mild PEF treatment is unsuitable for preservation as it impacted the microstructure and texture and induced gaping. Therefore, it is important to consider factors that might affect quality, such as electric potential and pulse duration.

4.6 | Packaging

Various modern packaging technologies such as gas packaging, traditional vacuum and vacuum skin packaging are available to prolong the shelf life of fish. A comparison of water holding properties by Chan, Skare, et al. (2021) showed that salmon fillet portions kept in refrigerated storage in modified atmospheric packaging (MAP) with 60% CO_2:40% N_2 had similar DL, WHC and microbial shelf-life duration as with vacuum skin packaging. Interestingly, vacuum skin packaged salmon produced a significantly greater DL yet similar WHC than traditional vacuum packaged fillets (Chan, Rotabakk, et al., 2021).

The effect of combining superchilling and MAP extends the shelf life of salmon (Fernández et al., 2009; Hansen et al., 2009; Sivertsvik et al., 2003). Sivertsvik et al. (2003) found that DL was about the same in fillets stored in MAP (60% CO_2:40% N_2), either superchilled at −2°C or chilled at 4°C. On the other hand, Hansen et al. (2009) found DL for fillets superchilled in a freezing tunnel, then packaged in MAP (60% CO_2:40% N_2) and stored at 0.1°C, was significantly higher than the chilled samples. The differences observed from both studies could be attributed to the different storage temperatures. Therefore, the synergistic effect of superchilling combined with MAP can increase shelf

life, but this method needs to be optimized to minimize DL. Rotabakk and Skuland (2017) established that portion size, freezing regime and packaging method influenced DL of cold-smoked salmon after freezing and thawing. Sliced salmon in vacuum packaging produced more drip than whole fillets since muscle integrity is disintegrated and more surface area is exposed. Freezing in bulk also increased DL as the freezing time is lengthened. Smoked fillets in MAP also had a significantly lower amount of DL after thawing than those vacuum packaged, as explained by the cushioning effect of the headspace gas. However, during thawed storage, DL in MAP fillets was significantly higher.

An additional step that can be introduced before packaging in MAP is SGS. As mentioned, SGS is a process that adds CO_2 into the product. This allows CO_2 to dissolve into the product before packaging and prevents package collapse (Abel et al., 2019). Hurdle technology explains how several combinations of fish preservation and packaging methods can ensure good quality and extended shelf life (Leistner, 2000). Since SGS has only been implemented on a laboratory scale, following this with a scale-up would be interesting. In addition, future research may consider combining this technology with other packaging and processing methods such as vacuum packaging and HPP to observe how the quality would be affected.

Hyperbaric storage of food products has been attracting interest in the food preservation field. This method stores the product above atmospheric pressure at moderate pressures (<100 MPa) and gives a better shelf life and comparable quality to conventional refrigeration (Fidalgo et al., 2020). Fidalgo et al. (2019) conducted a study that optimized the conditions using different pressures and storage temperatures for the shelf-life extension of Atlantic salmon. The optimal condition was found to be 60 MPa/10°C. Following up, Fidalgo et al. (2020) found that DL was relatively stable with 3–4% for hyperbaric storage/low temperature (HS/LT 60 MPa/10°C) of vacuum packaged salmon throughout 30 days of storage. On the other hand, those stored under normal atmospheric pressure (0.1 MPa) at 5 and 10°C gave a DL of 7% at 30 days and 15 days of storage, respectively. WHC decreased after the first 5 days before increasing after 30 days for all samples. This latter increase in WHC was probably due to the remaining water being tightly retained within the muscle. The latest study with 75 MPa/25°C at room temperature showed that DL gradually increased for 30 days until 13% and was consistently higher than those at 0.1 MPa/5°C, reaching 7% (Fidalgo et al., 2021). Note that 0.1MPa/25°C had the highest DL after 5 days at 10%. This suggests that temperature could be a critical factor in quantifying DL although several advantages have been suggested using hyperbaric storage, such as better energy efficiency.

The usage of water vapor permeable (WP) bags was introduced to reduce the processing steps during salting and smoking (Rizo et al., 2015). Salmon portions were sprayed with liquid smoke with a specified salt dosage, then packed in WP bags for 24 h in a cold room with fixed relative humidity. These bags allowed drying simultaneously with salting and smoking and gave similar sensory quality to the commercial smoked salmon. Weight loss was higher for salmon in WP than high barrier vacuum bags due to the higher dehydration rate (Rizo et al., 2015). The use of these bags presents interesting opportunities to reduce processing steps and brine wastes produced during salting. More studies could be conducted to optimize the conditions and possibilities to reduce weight loss.

5 | MODELLING WATER HOLDING PROPERTIES

Quality measurements can often be costly and labor intensive. Mathematical modelling has been gaining popularity and can serve as an alternative for many purposes in the food industry, reducing experimental needs. Adequate validations must be done to check the accuracy of the model. Numerical models have been proposed based on the first principles of heat and mass transfer that studies the salting kinetics of salmon to predict state variables as a function of time and space (Martínez-López et al., 2019; Wang et al., 1998, 2000). Empirical models, such as Peleg's or Zugarramurdi and Lupin's models, can also be applied to predict salt and water concentrations based on mathematical equations obtained from experimental data. Besides, reaction rates for quality degradation of physical properties, such as color and texture, during thermal processing can be expressed using kinetic order equations (Kong, Tang, Rasco, & Crapo et al., 2007; Ovissipour et al., 2017).

Modelling WHC in Atlantic salmon during raw fillet storage has not been extensively studied. This is possibly due to the high variations and different methods that are available to measure WHC. Predicting WHC can be possible during thermal processing through the correlation of other related quality parameters. Multivariate analysis has shown that WHC is highly correlated with heating temperature, pH, heating time and salt, in decreasing order (Varmbo et al., 2000). Heat treatment causes more destructive changes to the muscle structure, thereby affecting WHC, as shown by Ofstad et al. (1995). When the salmon muscle is heat-treated, a rapid water loss (i.e., WHC decreases) is observed at temperatures >30°C. With the reduction in myofibrillar space, a transverse shrinkage occurred between 45 and 50°C. This eventually leads to protein denaturation and more water loss. Between 60 and 70°C, WHC slightly increased, probably due to protein aggregation that holds water (Varmbo et al., 2000).

The numerical modelling of WHC as a function of temperature has been formulated by van der Sman (2007) as follows:

$$C_{eq}(T) = C_{eq,0} - \frac{a_1}{1 + a_2 e^{(-a_3(T-T_\sigma))}} \quad (6)$$

where $C_{eq,0}$ is the initial WHC of the sample, T is the temperature in °C, T_σ is the center of the sigmoid curve, and a_1, a_2 and a_3 are fitting parameters. This model has yet to be used on salmon. The model was used by Blikra et al. (2019) with farmed cod after cooking from 0 to 100°C. It was found that WHC follows a negative sigmoidal curve when the sample is heated, inducing a pressure gradient inside the muscle that led to an expulsion of water. The decrease in WHC from 25 to 40°C to a minimum value signifies the loss of free water during heating. Heating further from 40 to 90°C gave no differences in WHC.

DL and WHC can have a high degree of uncertainly as affected by several postmortem and processing conditions. For this reason, it can be challenging to create a one-size-fits-all model with minor errors. Vibrational spectroscopy methods such as NIR have been used for early prediction of WHC in fresh pork (Forrest et al., 2000). A study to predict WHC using Raman spectroscopy in pork was a promising technique compared to NIR or fluorescence spectroscopy (Andersen et al., 2020, 2018). The broad range of this application makes it a suitable method to characterize the macro-components of food, including carbohydrates, protein, fat and water (Li-Chan, 1996). Using multivariate analysis, Pedersen et al. (2003) reported a good correlation between DL and WHC and the Raman spectra. The spectral regions between 951–876 and 3128–3071 cm^{-1} can provide information about WHC, where 940 cm^{-1} is assigned to the peptide α-helix conformation. The latter region is attributed to the N-H stretching band of the amide group in the protein structure, which provides details on proteolysis and protein denaturation. However, as spectroscopy methods measure the potential DL formation, the real DL obtained may differ from the predictions (Andersen et al., 2018). The possibility of using this noninvasive technique in predicting water holding properties calls for more studies to be done and its applicability in industrial settings.

6 | CONCLUSION

Water holding properties (WHC and DL) are essential attributes that can influence the entire value chain, from whole fish to filleting to further processing and storage. A common challenge for the fish industry in maintaining food quality is to obtain a low DL and good WHC, in other words, a high amount of immobilized water in the muscle. Various methods are available to measure WHC, and the demand for a rapid and low-cost approach introduces noninvasive techniques. Nevertheless, it must be noted that results obtained from various measurements are relative and should be compared with studies including many of the same technical details and calculation methods. Several methods, including pre- and postslaughter conditions, and processing and preservation technology combinations, can extend the product's shelf life and improve water holding properties. In addition, innovative technologies might be introduced and determining their potential needs more research to optimize the parameters in maximizing water holding properties without compromising quality.

ACKNOWLEDGMENT

The OPTiMAT project from the Norwegian University of Science and Technology (NTNU) financed this research.

AUTHOR CONTRIBUTIONS

Investigation, methodology and writing-original draft: Sherry Stephanie Chan. Supervision, validation and writing-review & editing: Bjørn Roth. Supervision, validation, and writing-review & editing: Flemming Jessen. Supervision, validation and writing-review & editing: Anita Nordeng Jakobsen. Project administration, supervision, validation and writing-review & editing: Jørgen Lerfall.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Sherry Stephanie Chan https://orcid.org/0000-0003-1367-9289

Anita Nordeng Jakobsen https://orcid.org/0000-0003-1114-0175

Jørgen Lerfall https://orcid.org/0000-0001-6243-0880

REFERENCES

Abel, N., Rotabakk, B. T., Rustad, T., Ahlsen, V. B., & Lerfall, J. (2019). Physiochemical and microbiological quality of lightly processed salmon (*Salmo salar* L.) stored under modified atmosphere. *Journal of Food Science*, *84*(12), 3364–3372. https://doi.org/10.1111/1750-3841.14852

Andersen, C. M., & Jørgensen, B. M. (2004). On the relation between water pools and water holding capacity in cod muscle. *Journal of Aquatic Food Product Technology*, *13*(1), 13–23. https://doi.org/10.1300/J030v13n01_03

Andersen, P. V., Afseth, N. K., Gjerlaug-Enger, E., & Wold, J. P. (2020). Prediction of water holding capacity and pH in porcine *longissimus lumborum* using Raman spectroscopy. *Meat Science*, *172*, 108357. https://doi.org/10.1016/j.meatsci.2020.108357

Andersen, P. V., Wold, J. P., Gjerlaug-Enger, E., & Veiseth-Kent, E. (2018). Predicting post-mortem meat quality in porcine *longissimus lumborum* using Raman, near infrared and fluorescence spectroscopy. *Meat Science*, *145*, 94–100. https://doi.org/10.1016/j.meatsci.2018.06.016

Aursand, I. G., Erikson, U., & Veliyulin, E. (2010). Water properties and salt uptake in Atlantic salmon fillets as affected by antemortem stress, rigor mortis, and brine salting: A low-field 1H NMR and 1H/23Na MRI study. *Food Chemistry*, *120*(2), 482–489. https://doi.org/10.1016/j.foodchem.2009.10.041

Aursand, I. G., Gallart-Jornet, L., Erikson, U., Axelson, D. E., & Rustad, T. (2008). Water distribution in brine salted cod (*Gadus morhua*) and salmon (*Salmo salar*): A low-field 1H NMR study. *Journal of Agricultural and Food Chemistry*, *56*(15), 6252–6260. https://doi.org/10.1021/jf800369n

Aursand, I. G., Veliyulin, E., Böcker, U., Ofstad, R., Rustad, T., & Erikson, U. (2009). Water and salt distribution in Atlantic salmon (*Salmo salar*) studied by low-field 1H NMR, 1H and 23Na MRI and light microscopy: Effects of raw material quality and brine salting. *Journal of Agricultural and Food Chemistry*, *57*(1), 46–54. https://doi.org/10.1021/jf802158u

Aymerich, T., Picouet, P. A., & Monfort, J. M. (2008). Decontamination technologies for meat products. *Meat Science*, *78*(1), 114–129. https://doi.org/10.1016/j.meatsci.2007.07.007

Bahuaud, D., Mørkøre, T., Langsrud, Ø., Sinnes, K., Veiseth, E., Ofstad, R., & Thomassen, M. S. (2008). Effects of -1.5°C superchilling on quality of Atlantic salmon *(Salmo salar)* pre-rigor fillets: Cathepsin activity, muscle histology, texture and liquid leakage. *Food Chemistry*, *111*, 329–339. https://doi.org/10.1016/j.foodchem.2008.03.075

Bahuaud, D., Mørkøre, T., Østbye, T. K., Veiseth-Kent, E., Thomassen, M. S., & Ofstad, R. (2010). Muscle structure responses and lysosomal cathepsins B and L in farmed Atlantic salmon (*Salmo salar* L.) pre- and post-rigor fillets exposed to short and long-term crowding stress. *Food Chemistry*, *118*(3), 602–615. https://doi.org/10.1016/j.foodchem.2009.05.028

Banerjee, R., & Maheswarappa, N. B. (2019). Superchilling of muscle foods: Potential alternative for chilling and freezing. *Critical Reviews in Food Science and Nutrition*, *59*(8), 1256–1263. https://doi.org/10.1080/10408398.2017.1401975

Bantle, M., Stavset, O., Nordtvedt, T. S., Gullsvåg, P. E., Eikevik, T. M., & Tolstorebrov, I. (2015). *Chilling of Salmon in Refrigerated Sea Water*. Proceedings of the 24th International Congress of Refrigeration, Yokohama, Japan.

Benfey, T. J. (1999). The physiology and behavior of triploid fishes. *Reviews in Fisheries Science*, *7*(1), 39–67. https://doi.org/10.1080/10641269991319162

Birkeland, S., & Akse, L. (2010). Study of the quality characteristics in cold-smoked salmon (*Salmo Salar*) originating from pre- or post-rigor raw material. *Journal of Food Science*, *75*(9), E580–E587. https://doi.org/10.1111/j.1750-3841.2010.01836.x

Birkeland, S., Rørå, A. M. B., Skåra, T., & Bjerkeng, B. (2004). Effects of cold smoking procedures and raw material characteristics on product yield and quality parameters of cold smoked Atlantic salmon (*Salmo salar* L.) fillets. *Food Research International*, *37*, 273–286. https://doi.org/10.1016/j.foodres.2003.12.004

Birkeland, S., & Skåra, T. (2008). Cold smoking of Atlantic salmon (*Salmo salar*) fillets with smoke condensate—An alternative processing technology for the production of smoked salmon. *Journal of Food Science*, *73*(6), 326–332. https://doi.org/10.1111/j.1750-3841.2008.00850.x

Birkeland, S., Skåra, T., Bjerkeng, B., & Rørå, A. M. B. (2003). Product yield and gaping in cold-smoked Atlantic salmon (*Salmo salar*) fillets as influenced by different injection-salting techniques. *Journal of Food Science*, *68*(5), 1743–1748. https://doi.org/10.1111/j.1365-2621.2003.tb12322.x

Bjørnevik, M., Cardinal, M., Vallet, J.-L., Nicolaisen, O., & Arnarson, G. Ö. (2018). Effect of salting and cold-smoking procedures on Atlantic salmon originating from pre-or post-rigor filleted raw material. Based on the measurement of physiochemical characteristics. *LWT - Food Science and Technology*, *91*, 431–438. https://doi.org/10.1016/j.lwt.2018.01.047

Bjørnevik, M., Espe, M., Beattie, C., Nortvedt, R., & Kiessling, A. (2004). Temporal variation in muscle fibre area, gaping, texture, colour and collagen in triploid and diploid Atlantic salmon *(Salmo salar* L). *Journal of the Science of Food and Agriculture*, *84*(6), 530–540. https://doi.org/10.1002/jsfa.1656

Blikra, M. J., Skipnes, D., & Feyissa, A. H. (2019). Model for heat and mass transport during cooking of cod loin in a convection oven. *Food Control*, *102*, 29–37. https://doi.org/10.1016/j.foodcont.2019.03.001

Bøgh-Sørensen, L. (2006). *Recommendations for the processing and handling of frozen foods* (4th ed.). International Institute of Refrigeration.

Bowker, B. (2017). Developments in our understanding of water holding capacity. In *Poultry quality evaluation* (pp. 77–113). Woodhead Publishing Series in Food Science, Technology and Nutrition.

Brookmire, L., Mallikarjunan, P., Jahncke, M., & Grisso, R. (2013). Optimum cooking conditions for shrimp and Atlantic salmon. *Journal of Food Science*, *78*(2), 303–313. https://doi.org/10.1111/1750-3841.12011

Cai, L., Cao, M., Regenstein, J., & Cao, A. (2019). Recent advances in food thawing technologies. *Comprehensive Reviews in Food Science and Food Safety*, *18*(4), 953–970. https://doi.org/10.1111/1541-4337.12458

Campus, M. (2010). High pressure processing of meat, meat products and seafood. *Food Engineering Reviews*, *2*(4), 256–273. https://doi.org/10.1007/s12393-010-9028-y

Cardinal, M., Gunnlaugsdottir, H., Bjoernevik, M., Ouisse, A., Luc Vallet, J., & Leroi, F. (2004). Sensory characteristics of cold-smoked Atlantic salmon (*Salmo salar*) from European market and relationships with chemical, physical and microbiological measurements. *Food Research International*, *37*(2), 181–193. https://doi.org/10.1016/j.foodres.2003.12.006

Cardinal, M., Knockaert, C., Torrissen, O., Sigurgisladottir, S., Mørkøre, T., Thomassen, M., & Luc Vallet, J. (2001). Relation of smoking parameters to the yield, colour and sensory quality of smoked Atlantic salmon (*Salmo salar*). *Food Research International*, *34*(6), 537–550. https://doi.org/10.1016/S0963-9969(01)00069-2

Cepanec, K., Vugrinec, S., Cvetković, T., & Ranilović, J. (2017). Potassium chloride-based salt substitutes: A critical review with a focus on the patent literature. *Comprehensive Reviews in Food Science and Food Safety*, *16*(5), 881–894. https://doi.org/10.1111/1541-4337.12291

Chan, S. S., Feyissa, A. H., Jessen, F., Roth, B., Jakobsen, A. N., & Lerfall, J. (2021). Modelling water and salt diffusion of cold-smoked Atlantic salmon initially immersed in refrigerated seawater versus

on ice *Journal of Food Engineering*, *312*, 110747. https://doi.org/10.1016/j.jfoodeng.2021.110747

Chan, S. S., Rotabakk, B. T., Løvdal, T., Lerfall, J., & Roth, B. (2021). Skin and vacuum packaging of portioned Atlantic salmon originating from refrigerated seawater or traditional ice storage. *Journal of Food Packaging and Shelf Life*, *30*, 100767.

Chan, S. S., Roth, B., Jessen, F., Løvdal, T., Jakobsen, A. N., & Lerfall, J. (2020). A comparative study of Atlantic salmon chilled in refrigerated seawater versus on ice: From whole fish to cold-smoked fillets. *Scientific Reports*, *10*, 17160. https://doi.org/10.1038/s41598-020-73302-x

Chan, S. S., Roth, B., Skare, M., Hernar, M., Jessen, F., Løvdal, T., Jakobsen, A. N., & Lerfall, J. (2020). Effect of chilling technologies on water holding properties and other quality parameters throughout the whole value chain: From whole fish to cold-smoked fillets of Atlantic salmon (*Salmo salar*). *Aquaculture*, *526*, 735381. https://doi.org/10.1016/j.aquaculture.2020.735381

Chan, S. S., Skare, M., Rotabakk, B. T., Sivertsvik, M., Lerfall, J., Løvdal, T., & Roth, B. (2021). Evaluation of physical and instrumentally determined sensory attributes of Atlantic salmon portions packaged in modified atmosphere and vacuum skin. *LWT*, *146*, 111404. https://doi.org/10.1016/j.lwt.2021.111404

Cheng, J. H., & Sun, D. W. (2014). Hyperspectral imaging as an effective tool for quality analysis and control of fish and other seafoods: Current research and potential applications. *Trends in Food Science & Technology*, *37*(2), 78–91. https://doi.org/10.1016/j.tifs.2014.03.006

Cheng, J. H., & Sun, D. W. (2015). Recent applications of spectroscopic and hyperspectral imaging techniques with chemometric analysis for rapid inspection of microbial spoilage in muscle foods. *Comprehensive Reviews in Food Science and Food Safety*, *14*(4), 478–490. https://doi.org/10.1111/1541-4337.12141

Cheng, Q., & Sun, D.-W. (2008). Factors affecting the water holding capacity of red meat products: A review of recent research advances. *Critical Reviews in Food Science and Nutrition*, *48*(2), 137–159. https://doi.org/10.1080/10408390601177647

Christensen, L. B., Hovda, M. B., & Rode, T. M. (2017). Quality changes in high pressure processed cod, salmon and mackerel during storage. *Food Control*, *72*, 90–96. https://doi.org/10.1016/j.foodcont.2016.07.037

Claussen, I. C., Gullsvåg, P. E., Bantle, M., Tolstorebrov, I., & Kvalsvik, K. (2017). *Superchilling of organic food. Part 2: Storage test with superchilled organic salmon and pork chops*. http://hdl.handle.net/11250/2488509/

Dawson, P., Al-Jeddawi, W., & Remington, N. (2018). Effect of freezing on the shelf life of salmon. *International Journal of Food Science*, *2018*, 1–12. https://doi.org/10.1155/2018/1686121

Duun, A. S. (2008). *Superchilling of muscle food. Storage stability and quality aspects of salmon (Salmo salar), cod (Gadus morhua) and pork* [PhD Thesis, Norwegian University of Science and Technology]. Trondheim, Norway.

Duun, A. S., & Rustad, T. (2008). Quality of superchilled vacuum packed Atlantic salmon (*Salmo salar*) fillets stored at -1.4 and -3.6°C. *Food Chemistry*, *106*(1), 122–131. https://doi.org/10.1016/j.foodchem.2007.05.051

Einen, O., Guerin, T., Fjæra, S. O., & Skjervold, P. O. (2002). Freezing of pre-rigor fillets of Atlantic salmon. *Aquaculture*, *212*(1), 129–140. https://doi.org/10.1016/S0044-8486(01)00874-2

Erikson, U., Misimi, E., & Gallart-Jornet, L. (2011). Superchilling of rested Atlantic salmon: Different chilling strategies and effects of fish and fillet quality. *Food Chemistry*, *127*(4), 1427–1437. https://doi.org/10.1016/j.foodchem.2011.01.036

Ernst & Young. (2019). *The Norwegian Aquaculture Analysis 2019*. https://www.ey.com/Publication/vwLUAssets/Norwegian_Aquaculture_Analysis_2019/>FILE/The%20Norwegian%20Aquaculture%20Analysis_2019.pdf

European Commission. (2016). *Case study- smoked salmon in France. Price structure in the supply chain*. http://www.eumofa.eu

Fennema, O. R. (1990). Comparative water holding properties of various muscle foods. *Journal of Muscle Foods*, *1*(4), 363–381. https://doi.org/10.1111/j.1745-4573.1990.tb00373.x

Fernández, K., Aspe, E., & Roeckel, M. (2009). Shelf-life extension on fillets of Atlantic Salmon (*Salmo salar*) using natural additives, superchilling and modified atmosphere packaging. *Food Control*, *20*(11), 1036–1042. https://doi.org/10.1016/j.foodcont.2008.12.010

Fidalgo, L. G., Castro, R., Trigo, M., Aubourg, S. P., Delgadillo, I., & Saraiva, J. A. (2019). Quality of fresh Atlantic salmon (*Salmo salar*) under hyperbaric storage at low temperature by evaluation of microbial and physicochemical quality indicators. *Food and Bioprocess Technology*, *12*(11), 1895–1906. https://doi.org/10.1007/s11947-019-02346-3

Fidalgo, L. G., Simões, M. M. Q., Casal, S., Lopes-da-Silva, J. A., Carta, A. M. S., Delgadillo, I., & Saraiva, J. A. (2020). Physicochemical parameters, lipids stability, and volatiles profile of vacuum-packaged fresh Atlantic salmon (*Salmo salar*) loins preserved by hyperbaric storage at 10 °C. *Food Research International*, *127*, 108740. https://doi.org/10.1016/j.foodres.2019.108740

Fidalgo, L. G., Simões, M. M. Q., Casal, S., Lopes-da-Silva, J. A., Delgadillo, I., & Saraiva, J. A. (2021). Enhanced preservation of vacuum-packaged Atlantic salmon by hyperbaric storage at room temperature versus refrigeration. *Scientific Reports*, *11*(1), 1668. https://doi.org/10.1038/s41598-021-81047-4

Forrest, J. C., Morgan, M. T., Borggaard, C., Rasmussen, A. J., Jespersen, B. L., & Andersen, J. R. (2000). Development of technology for the early post mortem prediction of water holding capacity and drip loss in fresh pork. *Meat Science*, *55*(1), 115–122. https://doi.org/10.1016/S0309-1740(99)00133-3

Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C., & Cao, L. (2018). Feed conversion efficiency in aquaculture: Do we measure it correctly? *Environmental Research Letters*, *13*(2), 024017. https://doi.org/10.1088/1748-9326/aaa273

Gallart-Jornet, L., Barat, J. M., Rustad, T., Erikson, U., Escriche, I., & Fito, P. (2007a). A comparative study of brine salting of Atlantic cod (*Gadus morhua*) and Atlantic salmon (*Salmo salar*). *Journal of Food Engineering*, *79*(1), 261–270. https://doi.org/10.1016/j.jfoodeng.2006.01.053

Gallart-Jornet, L., Barat, J. M., Rustad, T., Erikson, U., Escriche, I., & Fito, P. (2007b). Influence of brine concentration on Atlantic salmon fillet salting. *Journal of Food Engineering*, *80*(1), 267–275. https://doi.org/10.1016/j.jfoodeng.2006.05.018

Gatica, M., Monti, G., Knowles, T., & Gallo, C. (2010). Effects of crowding on blood constituents and flesh quality variables in Atlantic salmon (*Salmo salar* L.). *Archivos de medicina veterinaria*, *42*, 187–193. https://doi.org/10.4067/S0301-732İ2010000300010

Głuchowski, A., Czarniecka-Skubina, E., Wasiak-Zys, G., & Nowak, D. (2019). Effect of various cooking methods on technological and

sensory quality of Atlantic salmon (*Salmo salar*). *Foods (Basel, Switzerland)*, *8*(8), 323. https://doi.org/10.3390/foods8080323

Gomez-Guillen, M. C., Montero, P., Hurtado, O., & Borderias, A. J. (2000). Biological characteristics affect the quality of farmed Atlantic salmon and smoked muscle. *Journal of Food Science*, *65*(1), 53–60. https://doi.org/10.1111/j.1365-2621.2000.tb15955.x

Gómez, B., Munekata, P. E. S., Gavahian, M., Barba, F. J., Martí-Quijal, F. J., Bolumar, T., Campagnol, P. C. B., Tomasevic, I., & Lorenzo, J. M. (2019). Application of pulsed electric fields in meat and fish processing industries: An overview. *Food Research International*, *123*, 95–105. https://doi.org/10.1016/j.foodres.2019.04.047

González-Fandos, E., Villarino-Rodrıǵuez, A., Garcıá-Linares, M. C., Garcıá-Arias, M. T., & Garcıá-Fernández, M. C. (2005). Microbiological safety and sensory characteristics of salmon slices processed by the sous vide method. *Food Control*, *16*(1), 77–85. https://doi.org/10.1016/j.foodcont.2003.11.011

Gudjonsdottir, M., Gunnlaugsson, V. N., Finnbogadottir, G. A., Sveinsdottir, K., Magnusson, H., Arason, S., & Rustad, T. (2010). Process control of lightly salted wild and farmed Atlantic cod (*Gadus morhua*) by brine injection, brining, and freezing—A low field NMR study. *Journal of Food Science*, *75*(8), 527–536. https://doi.org/10.1111/j.1750-3841.2010.01808.x

Gudjónsdóttir, M., Traoré, A., Jónsson, Á., Karlsdóttir, M. G., & Arason, S. (2015). The effects of pre-salting methods on salt and water distribution of heavily salted cod, as analyzed by 1H and 23Na MRI, 23Na NMR, low-field NMR and physicochemical analysis. *Food Chemistry*, *188*, 664–672. https://doi.org/10.1016/j.foodchem.2015.05.060

Gudmundsson, M., & Hafsteinsson, H. (2001). Effect of electric field pulses on microstructure of muscle foods and roes. *Trends in Food Science & Technology*, *12*(3), 122–128. https://doi.org/10.1016/S0924-2244(01)00068-1

Hamm, R. (1986). Functional properties of the myofibrillar system and their measurements. In P. J. Bechtel (Ed.), *Muscle as food* (pp. 135–199). Academic Press.

Hansen, A. Å., Mørkøre, T., Rudi, K., Langsruda, Ø., & Eiea, T. (2009). The combined effect of superchilling and modified atmosphere packaging using CO2 emitter on quality during chilled storage of pre-rigor salmon fillets *(Salmo salar)*. *Journal of Science Food and Agriculture*, *89*(10), 1625–1633. https://doi.org/10.1002/jsfa.3599

Haugland, A. (2002). *Industrial thawing of Fish: To improve quality, yield and capacity.*. Norwegian University of Science and Technology. Norway.

He, H.-J., Wu, D., & Sun, D.-W. (2013). Non-destructive and rapid analysis of moisture distribution in farmed Atlantic salmon (*Salmo salar*) fillets using visible and near-infrared hyperspectral imaging. *Innovative Food Science & Emerging Technologies*, *18*, 237–245. https://doi.org/10.1016/j.ifset.2013.02.009

He, H.-J., Wu, D., & Sun, D.-W. (2014). Rapid and non-destructive determination of drip loss and pH distribution in farmed Atlantic salmon (*Salmo salar*) fillets using visible and near-infrared (Vis–NIR) hyperspectral imaging. *Food Chemistry*, *156*, 394–401. https://doi.org/10.1016/j.foodchem.2014.01.118

Hedges, N. D., & Goodband, R. M. (2003). *The influence of high hydrostatic pressure on the water-holding capacity of fish muscle*. First joint Trans-Atlantic Fisheries Technology Conference (TAFT), 33rd WEFTA and 48th AFTC meetings Iceland: Reykjavik, Iceland.

Heia, K., Wold, J. P., & Skjelvareid, M. H. (2016). Metoder for kvalitetsmåling på hel laks (Norwegian). *Nofima AS*, *7*, 1–17.

Honikel, K. O., & Hamm, R. (1995). Measurement of water-holding capacity and juiciness. In A. M. Pearson & T. R. Dutson (Eds.), *Quality attributes and their measurement in meat, poultry and fish products* (pp. 125–161). Springer.

Huff-Lonergan, E., & Lonergan, S. M. (2005). Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. *Meat Science*, *71*, 194–204. https://doi.org/10.1016/j.meatsci.2005.04.022

Huff-Lonergan, E., & Lonergan, S. M. (2007). New frontiers in understanding drip loss in pork: Recent insights on the role of postmortem muscle biochemistry. *Journal of Animal Breeding and Genetics*, *124*, 19–26. https://doi.org/10.1111/j.1439-0388.2007.00683.x

Hughes, J. M., Oiseth, S. K., Purslow, P. P., & Warner, R. D. (2014). A structural approach to understanding the interactions between colour, water-holding capacity and tenderness. *Meat Science*, *98*(3), 520–532. https://doi.org/10.1016/j.meatsci.2014.05.022

Hultmann, L., Bencze Rørå, A. M., Steinsland, I., Skåra, T., & Rustad, T. (2004). Proteolytic activity and properties of proteins in smoked salmon (*Salmo salar*)—Effects of smoking temperature. *Food Chemistry*, *85*(3), 377–387. https://doi.org/10.1016/j.foodchem.2003.07.014

Hultmann, L., & Rustad, T. (2002). Textural changes during iced storage of salmon (*Salmo salar*) and cod (*Gadus morhua*). *Journal of Aquatic Food Product Technology*, *11*(3–4), 105–123. https://doi.org/10.1300/J030v11n03_09

Indergård, E., Tolstorebrov, I., Larsen, H., & Eikevik, T. M. (2014). The influence of long-term storage, temperature and type of packaging materials on the quality characteristics of frozen farmed Atlantic Salmon (*Salmo Salar*). *International Journal of Refrigeration*, *41*, 27–36. https://doi.org/10.1016/j.ijrefrig.2013.05.011

Jepsen, S. M., Pedersen, H. T., & Engelsen, S. B. (1999). Application of chemometrics to low-field 1H NMR relaxation data of intact fish flesh. *Journal of the Science of Food and Agriculture*, *79*(13), 1793–1802. https://doi.org/10.1002/(SICI)1097-0010(199910)79:13⟨1793::AID-JSFA437⟩3.0.CO;2-S

Kaale, L. D., & Eikevik, T. M. (2014). The development of ice crystals in food products during the superchilling process and following storage: A review. *Trends in Food Science & Technology*, *39*, 91–103. https://doi.org/10.1016/j.tifs.2014.07.004

Kaale, L. D., Eikevik, T. M., Bardal, T., Kjorsvik, E., & Nordtvedt, T. S. (2013). The effect of cooling rates on the ice crystal growth in air-packed salmon fillets during superchilling and superchilled storage. *International Journal of Refrigeration*, *36*(1), 110–119. https://doi.org/10.1016/j.ijrefrig.2012.09.006

Kaale, L. D., Eikevik, T. M., Rustad, T., & Kolsaker, K. (2011). Superchilling of food: A review. *Journal of Food Engineering*, *107*, 141–146. https://doi.org/10.1016/j.jfoodeng.2011.06.004

Kaale, L. D., Eikevik, T. M., Rustad, T., & Nordtvedt, T. S. (2014). Changes in water holding capacity and drip loss of Atlantic salmon *(Salmo salar)* muscle during superchilled storage. *LWT - Food Science and Technology*, *55*(2), 528–535. https://doi.org/10.1016/j.lwt.2013.10.021

Kamruzzaman, M., ElMasry, G., Sun, D.-W., & Allen, P. (2012). Prediction of some quality attributes of lamb meat using near-infrared hyperspectral imaging and multivariate analysis. *Analytica Chimica Acta*, *714*, 57–67. https://doi.org/10.1016/j.aca.2011.11.037

Katikou, P., Hughes, S. I., & Robb, D. H. F. (2001). Lipid distribution within Atlantic salmon (*Salmo salar*) fillets. *Aquaculture*, *202*(1), 89–99. https://doi.org/10.1016/S0044-8486(01)00562-2

Kiessling, A., Ruohonen, K., & Bjørnevik, M. (2006). Muscle fibre growth and quality in fish. *Archives of Animal Breeding 49* (Special Issue), 137–146.

Kijowski, J. (2001). Muscle proteins. In Z. E. Sikorski (Ed.), *Chemical and functional properties of food proteins*. (233–264). CRC Press.

Klonowski, I., Heinz, V., Toepfl, S., Gunnarsson, G., & Þorkelsson, G. (2006). Applications of pulsed electric field technology for the food industry. In J. Raso, & V. Heinz (Eds.), *Icelandic fisheries laboratories* (pp. 197–221). Springer.

Kong, F., Tang, J., Rasco, B., & Crapo, C. (2007). Kinetics of salmon quality changes during thermal processing. *Journal of Food Engineering*, *83*(4), 510–520. https://doi.org/10.1016/j.jfoodeng.2007.04.002

Kong, F., Tang, J., Rasco, B., Crapo, C., & Smiley, S. (2007). Quality changes of salmon (*Oncorhynchus gorbuscha*) muscle during thermal processing. *Journal of Food Science*, *72*(2), 103–111. https://doi.org/10.1111/j.1750-3841.2006.00246.x

Lakshmanan, R., Miskin, D., & Piggott, J. R. (2005). Quality of vacuum packed cold-smoked salmon during refrigerated storage as affected by high-pressure processing. *Journal of the Science of Food and Agriculture*, *85*(4), 655–661. https://doi.org/10.1002/jsfa.1972

Lakshmanan, R., Parkinson, J. A., & Piggott, J. R. (2007). High-pressure processing and water-holding capacity of fresh and cold-smoked salmon (*Salmo salar*). *LWT - Food Science and Technology*, *40*(3), 544–551. https://doi.org/10.1016/j.lwt.2005.12.003

Leistner, L. (2000). Basic aspects of food preservation by hurdle technology. *International Journal of Food Microbiology*, *55*(1), 181–186. https://doi.org/10.1016/S0168-1605(00)00161-6

Lerfall, J. (2011). *The effect of pancreas disease and salting conditions on the quality of raw and cold-smoked Atlantic salmon (Salmo salar L.)* [PhD Thesis, Norwegian University of Life Sciences]. Ås, Norway.

Lerfall, J., Hasli, P. R., Skare, E. F., Olsen, R. E., Rotabakk, B. T., Roth, B., Slinde, E., & Egelandsdal, B. (2017). A comparative study of diploid versus triploid Atlantic salmon (*Salmo salar* L.). The effects of rearing temperatures (5, 10 and 15°C) on raw material characteristics and storage quality. *Food Chemistry*, *225*, 37–44. https://doi.org/10.1016/j.foodchem.2017.01.012

Lerfall, J., Jakobsen, A. N., Skipnes, D., Waldenstrøm, L., Hoel, S., & Rotabakk, B. T. (2018). Comparative evaluation on the quality and shelf life of Atlantic salmon (*Salmo salar* L.) fillets using microwave and conventional pasteurization in combination with novel packaging methods. *Journal of Food Science*, *83*(12), 3099–3109. https://doi.org/10.1111/1750-3841.14384

Lerfall, J., & Rotabakk, B. T. (2016). Muscle temperature at the point of filleting—Subsequent effect on storage quality of prerigor filleted raw- and cold-smoked Atlantic salmon. *Food Science and Technology International*, *22*(2), 153–163. https://doi.org/10.1177/1082013215577737

Lerfall, J., Roth, B., Skare, E. F., Henriksen, A., Betten, T., Dziatkowiak-Stefaniak, M. A., & Rotabakk, B. T. (2015). Pre-mortem stress and the subsequent effect on flesh quality of pre-rigor filleted Atlantic salmon (*Salmo salar L.*) during ice storage. *Food Chemistry*, *175*, 157–165. https://doi.org/10.1016/j.foodchem.2014.11.111

Li-Chan, E. C. Y. (1996). The applications of Raman spectroscopy in food science. *Trends in Food Science & Technology*, *7*(11), 361–370. https://doi.org/10.1016/S0924-2244(96)10037-6

Li, J., Shi, J., Huang, X., Zou, X., Li, Z., Zhang, D., Zhang, W., & Xu, Y. (2020). Effects of pulsed electric field on freeze-thaw quality of Atlantic salmon. *Innovative Food Science & Emerging Technologies*, *65*, 102454. https://doi.org/10.1016/j.ifset.2020.102454

Li, W., Wang, P., Xu, X., Xing, T., & Zhou, G. (2014). Use of low-field nuclear magnetic resonance to characterize water properties in frozen chicken breasts thawed under high pressure. *European Food Research and Technology*, *239*(2), 183–188. https://doi.org/10.1007/s00217-014-2189-9

Listrat, A., Lebret, B., Louveau, I., Astruc, T., Bonnet, M., Lefaucheur, L., Picard, B., & Bugeon, J. (2016). How muscle structure and composition influence meat and flesh quality. *The Scientific World Journal*, *2016*, 3182746. https://doi.org/10.1155/2016/3182746

Llave, Y., Udo, T., Fukuoka, M., & Sakai, N. (2018). Ohmic heating of beef at 20 kHz and analysis of electrical conductivity at low and high frequencies. *Journal of Food Engineering*, *228*, 91–101. https://doi.org/10.1016/j.jfoodeng.2018.02.019

Løje, H. (2007). *The quality of cold smoked salmon—Influence of raw material and technological parameters* [PhD Thesis, Technical University of Denmark]. Denmark.

Løje, H., Nielsen, H. H., Hyldig, G., & Jørgensen, B. M. (2017). Liquid holding capacity and liquid leakage of raw salmon and trout fillets. *Food Science and Quality Management*, *68*, 11–15.

Magnussen, O. M., Haugland, A., Torstveit Hemmingsen, A. K., Johansen, S., & Nordtvedt, T. S. (2008). Advances in superchilling of food—Process characteristics and product quality. *Trends in Food Science & Technology*, *19*(8), 418–424. https://doi.org/10.1016/j.tifs.2008.04.005

Mallikarjunan, P. K. (2016). Physical measurements. In D.-W. Sun (Ed.), *Handbook of frozen food processing and packaging* (2nd ed., pp. 549–562). CRC Press.

Maltin, C., Balcerzak, D., Tilley, R., & Delday, M. (2003). Determinants of meat quality: Tenderness. *Proceedings of the Nutrition Society*, *62*(2), 337–347. https://doi.org/10.1079/PNS2003248

Martínez-López, B., Bertelsen, N. W., & Jessen, F. (2019). Determination of transport properties and mechanistic modeling of the coupled salt and water transport during osmotic dehydration of salmon induced by dry salting. *Journal of Food Process Engineering*, *42*(4), e13019. https://doi.org/10.1111/jfpe.13019

Ministry of Health and Care Services. (2015). *Regulations on voluntary labeling of foodstuffs with the Keyhole [in Norwegian]*. https://lovdata.no/dokument/SF/forskrift/2015-02-18-139

Mørkøre, T., Hansen, A. Å., Unander, E., & Einen, O. (2002). Composition, liquid leakage, and mechanical properties of farmed rainbow trout: Variation between fillet sections and the impact of ice and frozen storage. *Journal of Food Science*, *67*(5), 1933–1938. https://doi.org/10.1111/j.1365-2621.2002.tb08749.x

Mørkøre, T., Mazo T, P I., Tahirovic, V., & Einen, O. (2008). Impact of starvation and handling stress on rigor development and quality of Atlantic salmon (*Salmon salar* L.). *Aquaculture*, *277*(3), 231–238. https://doi.org/10.1016/j.aquaculture.2008.02.036

Mørkøre, T., Vallet, J. L., & Cardinal, M. (2001). Fat content and fillet shape of Atlantic salmon: Relevance for processing yield and quality of raw and smoked products. *Journal of Food Science*, *66*, 1348–1354. https://doi.org/10.1111/j.1365-2621.2001.tb15213.x

Murray, J., & Burt, J. R. (2001). *The composition of fish. Torry Advisory No. 38, FAO*.

Nott, K. P., Evans, S. D., & Hall, L. D. (1999). Quantitative magnetic resonance imaging of fresh and frozen-thawed trout. *Magnetic Resonance Imaging*, *17*(3), 445–455. https://doi.org/10.1016/S0730-725X(98)00189-1

Offer, G., & Trinick, J. (1983). On the mechanism of water holding in meat: The swelling and shrinking of myofibrils. *Meat Science*, *8*(4), 245–281. https://doi.org/10.1016/0309-1740(83)90013-X

Ofstad, R., Egelandsdal, B., Kidman, S., Myklebust, R., Olsen, R. L., & Hermansson, A.-M. (1996). Liquid loss as effected by post mortem ultrastructural changes in fish muscle: Cod (*Gadus morhua* L) and salmon (*Salmo salar*). *Journal of the Science of Food and Agriculture*, *71*(3), 301–312. https://doi.org/10.1002/(SICI)1097-0010(199607)71:3⟨301::AID-JSFA583⟩3.0.CO;2-0

Ofstad, R., Kidman, S., Myklebust, R., & Hermansson, A. M. (1993). Liquid holding capacity and structural changes during heating of fish muscle: Cod (*Gadus morhua* L.) and salmon (*Salmo salar*). *Food Structure*, *12*(2), 163–174.

Ofstad, R., Kidman, S., Myklebust, R., Olsen, R. L., & Hermansson, A.-M. (1995). Liquid-holding capacity and structural changes in comminuted salmon (*Salmon salar*) muscle as influenced by pH, salt and temperature. *Lebensmittel-Wissenshaft und Technologie*, *28*, 329–339. https://doi.org/10.1016/S0023-6438(95)94599-7

Ojagh, S. M., Núñez-Flores, R., López-Caballero, M. E., Montero, M. P., & Gómez-Guillén, M. C. (2011). Lessening of high-pressure-induced changes in Atlantic salmon muscle by the combined use of a fish gelatin–lignin film. *Food Chemistry*, *125*(2), 595–606. https://doi.org/10.1016/j.foodchem.2010.08.072

Oswell, N. J., Gilstrap, O. P., & Pegg, R. B. (2021). Variation in the terminology and methodologies applied to the analysis of water holding capacity in meat research. *Meat Science*, *178*, 108510. https://doi.org/10.1016/j.meatsci.2021.108510

Ovissipour, M., Rasco, B., Tang, J., & Sablani, S. (2017). Kinetics of protein degradation and physical changes in thermally processed Atlantic salmon (*Salmo salar*). *Food and Bioprocess Technology*, *10*(10), 1865–1882. https://doi.org/10.1007/s11947-017-1958-4

Pedersen, D. K., Morel, S., Andersen, H. J., & Balling Engelsen, S. (2003). Early prediction of water-holding capacity in meat by multivariate vibrational spectroscopy. *Meat Science*, *65*(1), 581–592. https://doi.org/10.1016/s0309-1740(02)00251-6

Rizo, A., Fuentes, A., Barat, J. M., & Fernández-Segovia, I. (2018). Development of a novel smoke-flavoured salmon product by sodium replacement using water vapour permeable bags. *Journal of the Science of Food and Agriculture*, *98*(7), 2721–2728. https://doi.org/10.1002/jsfa.8767

Rizo, A., Máñes, V., Fuentes, A., Fernández-Segovia, I., & Barat, J. M. (2015). A novel process for obtaining smoke-flavoured salmon using water vapour permeable bags. *Journal of Food Engineering*, *149*, 44–50. https://doi.org/10.1016/j.jfoodeng.2014.10.009

Rørå, A. M. B., & Regost, C. (2003). Liquid holding capacity of farmed Atlantic salmon muscle at low temperature heating-effect of frozen and ice storage. *Journal of Aquatic Food Product Technology*, *12*(3), 17–31. https://doi.org/10.1300/J030v12n03_03

Rørå, A. M. B., Regost, C., & Lampe, J. (2003). Liquid holding capacity, texture and fatty acid profile of smoked fillets of Atlantic salmon fed diets containing fish oil or soybean oil. *Food Research International*, *36*(3), 231–239. https://doi.org/10.1016/S0963-9969(02)00141-2

Rotabakk, B. T., Melberg, G. L., & Lerfall, J. (2017). Effect of season, location, filleting regime and storage on water-holding properties of farmed Atlantic salmon (*Salmo salar* L.). *Food Technology & Biotechnology*, *56*(2), 238–246. https://doi.org/10.17113/ftb.56.02.18.5346

Rotabakk, B. T., & Skuland, A. V. (2017). *Effect of freezing and thawing of salted and smoked Atlantic salmon (Salmo salar)*. 47th WEFTA Conference, Dublin, Ireland.

Roth, B., Nortvedt, R., Slinde, E., Foss, A., Grimsbø, E., & Stien, L. H. (2010). Electrical stimulation of Atlantic salmon muscle and the effect on flesh quality. *Aquaculture*, *301*(1), 85–90. https://doi.org/10.1016/j.aquaculture.2010.01.008

Roth, B., Øines, S., Rotabakk, B. T., & Birkeland, S. (2008). Using electricity as a tool in quality studies of Atlantic salmon. *European Food Research and Technology*, *227*(2), 571–577. https://doi.org/10.1007/s00217-007-0758-x

Roth, B., Slinde, E., & Arildsen, J. (2006). Pre or post mortem muscle activity in Atlantic salmon (*Salmo salar*). The effect on rigor mortis and the physical properties of flesh. *Aquaculture*, *257*(1), 504–510. https://doi.org/10.1016/j.aquaculture.2005.10.021

Schubring, R. (2006). Thermal stability, texture, liquid holding capacity and colour of smoked salmon on retail level. *Thermochimica Acta*, *445*(2006), 168–178. https://doi.org/10.1016/j.tca.2005.05.021

Sigurgisladottir, S., Sigurdardottir, M. S., Torrissen, O., Vallet, J. L., & Hafsteinsson, H. (2000). Effects of different salting and smoking processes on the microstructure, the texture and yield of Atlantic salmon (*Salmo salar*) fillets. *Food Research International*, *33*(10), 847–855. https://doi.org/10.1016/S0963-9969(00)00104-6

Sivertsvik, M., Rosnes, J. T., & Kleiberg, G. H. (2003). Effect of modified atmospheric packaging and superchilled storage on the microbial and sensory quality of Atlantic salmon (*Salmo salar*) fillets. *Journal of Food Science*, *68*(4), 1467–1472. https://doi.org/10.1111/j.1365-2621.2003.tb09668.x

Skipnes, D. (2014). Heat Processing of Fish. In I. S. Boziaris (Ed.), *Seafood processing: Technology, quality and safety* (pp. 61–81). John Wiley & Sons. https://doi.org/10.1002/9781118346174.ch4

Skipnes, D., Østby, M. L., & Hendrickx, M. E. (2007). A method for characterising cook loss and water holding capacity in heat treated cod (*Gadus morhua*) muscle. *Journal of Food Engineering*, *80*(4), 1078–1085. https://doi.org/10.1016/j.jfoodeng.2006.08.015

SSB. (2020). *Aquaculture (terminated in Statistics Norway)* https://www.ssb.no/en/fiskeoppdrett/

Stevik, A. M., Duun, A. S., Rustad, T., O'Farrell, M., Schulerud, H., & Ottestad, S. (2010). Ice fraction assessment by near-infrared spectroscopy enhancing automated superchilling process lines. *Journal of Food Engineering*, *100*(1), 169–177. https://doi.org/10.1016/j.jfoodeng.2010.03.042

Stien, L. H., Kiessling, A., & Manne, F. (2007). Rapid estimation of fat content in salmon fillets by colour image analysis. *Journal of Food Composition and Analysis*, *20*(2), 73–79. https://doi.org/10.1016/j.jfca.2006.07.007

Strasburg, G., Xiong, Y. L., & Chiang, W. (2007). Physiology and chemistry of edible muscle tissues. In S. Damodaran, K. L. Parkin, & O. R. Fennema (Eds.), *Fennema's food chemistry fourth edition* (pp. 923–973). CRC Press.

Sun, Y., Ma, L., Ma, M., Zheng, H., Zhang, X., Cai, L., Li, J., & Zhang, Y. (2018). Texture characteristics of chilled prepared Mandarin fish (*Siniperca chuatsi*) during storage. *International Journal of*

Food Properties, *21*(1), 242–254. https://doi.org/10.1080/10942912.2018.1451343

Szmańko, T., Lesiów, T., & Górecka, J. (2021). The water-holding capacity of meat: A reference analytical method. *Food Chemistry*, *357*, 129727. https://doi.org/10.1016/j.foodchem.2021.129727

Thorarinsdottir, K. A., Arason, S., Bogason, S. G., & Kristbergsson, K. (2004). The effects of various salt concentrations during brine curing of cod (*Gadus morhua*). *International Journal of Food Science & Technology*, *39*(1), 79–89. https://doi.org/10.1046/j.0950-5423.2003.00757.x

Toepfl, S., Siemer, C., & Heinz, V. (2014). Effect of high-intensity electric field pulses on solid foods. In D. W. Sun (Ed.), *Emerging technologies for food processing* (pp. 147–154). Academic Press.

Valø, T., Jakobsen, A. N., & Lerfall, J. (2020). The use of atomized purified condensed smoke (PCS) in cold-smoke processing of Atlantic salmon—Effects on quality and microbiological stability of a lightly salted product. *Food Control*, *112*, 107155. https://doi.org/10.1016/j.foodcont.2020.107155

van der Sman, R. G. M. (2007). Soft condensed matter perspective on moisture transport in cooking meat. *AIChE Journal*, *53*(11), 2986–2995. https://doi.org/10.1002/aic.11323

Varmbo, G., Skåra, T., Olsen, S. O., & Sivertsvik, M. (2000). *Modelling of water holding capacity (WHC) in ground Atlantic salmon (Salmo Salar), as affected by heat, pH and salt content*. 30th WEFTA Plenary Meeting, Torshavn, Faroe Islands.

Veliyulin, E., & Aursand, I. G. (2007). 1H and 23Na MRI studies of Atlantic salmon (*Salmo salar*) and Atlantic cod (*Gadus morhua*) fillet pieces salted in different brine concentrations. *Journal of the Science of Food and Agriculture*, *87*(14), 2676–2683. https://doi.org/10.1002/jsfa.3030

Veliyulin, E., Borge, A., Singstad, T., Gribbestad, I., & Erikson, U. (2006). Post-mortem studies of fish using magnetic resonance imaging. In G. A. Webb (Ed.), *Modern magnetic resonance* (pp. 959–966). Springer. https://doi.org/10.1007/1-4020-3910-7_111

Wang, D., Correia, L. R., & Tang, J. (1998). Modeling of salt diffusion in Atlantic salmon muscle. *Canadian Agricultural Engineering*, *40*(1), 29–34.

Wang, D., Tang, J., & Correia, L. R. (2000). Salt diffusivities and salt diffusion in farmed Atlantic salmon muscle as influenced by rigor mortis. *Journal of Food Engineering*, *43*(2), 115–123. https://doi.org/10.1016/S0260-8774(99)00140-5

Wang, S., Xiang, W., Fan, H., Xie, J., & Qian, Y. F. (2018). Study on the mobility of water and its correlation with the spoilage process of salmon (*Salmo solar*) Stored at 0 and 4°C by low-field nuclear magnetic resonance (LF NMR 1H). *Journal of Food Science and Technology*, *55*(1), 173–182. https://doi.org/10.1007/s13197-017-2880-5

Warner, R. D. (2014). Measurement of water holding capacity and colour: Objective and subjective. In *Encyclopedia of meat sciences* (2nd ed., Vol. 2, pp. 164–171). Elsevier.

Wong, D. W. S. (2018). Proteins. In *Mechanism and theory in food chemistry*. (2nd ed., pp. 55–122). Springer International Publishing. https://doi.org/10.1007/978-3-319-50766-8

Wu, D., & Sun, D. W. (2013). Application of visible and near infrared hyperspectral imaging for non-invasively measuring distribution of water-holding capacity in salmon flesh. *Talanta*, *116*, 266–276. https://doi.org/10.1016/j.talanta.2013.05.030

Wu, X.-F., Zhang, M., Adhikari, B., & Sun, J. (2017). Recent developments in novel freezing and thawing technologies applied to foods. *Critical Reviews in Food Science and Nutrition*, *57*(17), 3620–3631. https://doi.org/10.1080/10408398.2015.1132670

Yagiz, Y., Kristinsson, H. G., Balaban, M. O., Welt, B. A., Ralat, M., & Marshall, M. R. (2009). Effect of high pressure processing and cooking treatment on the quality of Atlantic salmon. *Food Chemistry*, *116*(4), 828–835. https://doi.org/10.1016/j.foodchem.2009.03.029

Zhang, M., Mittal, G. S., & Barbut, S. (1995). Effects of test conditions on the water holding capacity of meat by a centrifugal method. *LWT - Food Science and Technology*, *28*(1), 50–55. https://doi.org/10.1016/S0023-6438(95)80012-3

Zhu, F., Peng, J., Gao, J., Zhao, Y., Yu, K., & He, Y. (2014). Determination and visualization of fat contents in salmon fillets based on visible and near-infrared hyperspectral imagery. *Transactions of the Chinese Society of the Agricultural Engineering*, *30*(23), 314–323. https://doi.org/10.3969/j.issn.1002-6819.2014.23.040

Zhu, S., Ramaswamy, H. S., & Simpson, B. K. (2004). Effect of high-pressure versus conventional thawing on color, drip loss and texture of Atlantic salmon frozen by different methods. *LWT - Food Science and Technology*, *37*(3), 291–299. https://doi.org/10.1016/j.lwt.2003.09.004

How to cite this article: Chan, S. S., Roth, B., Jessen, F., Jakobsen, A. N., & Lerfall, J. (2022). Water holding properties of Atlantic salmon. *Compr Rev Food Sci Food Saf*. *21*,477–498. https://doi.org/10.1111/1541-4337.12871