



Evaluation of physical and instrumentally determined sensory attributes of Atlantic salmon portions packaged in modified atmosphere and vacuum skin

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ABSTRACT

Fresh Atlantic salmon (*Salmo salar*) were slaughtered and stored on ice at 0 °C then portioned and packaged six to eight days later in modified atmosphere (CO₂:N₂ 60:40) packaging (MAP), vacuum skin packaging and open air. All fillet portions were stored in refrigerated conditions at 4 °C. Physical and instrumentally determined sensory quality parameters, including water holding properties, pH, colour, texture and microbiological shelf life, were examined for three weeks. The results showed that both MAP and vacuum skin packaging gave comparable quality in drip loss, water holding capacity, texture and microbiological shelf life. Both packaging groups displayed increased lightness and decreased redness and yellowness throughout storage after filleting. Fillets kept in MAP had consistently lower pH with a darker, more reddish, and yellowish colour than skin packaged fillets. Fillets stored in air had the shortest microbiological shelf life (<13 days) even when they were portioned later. It is concluded that the microbiological shelf life of MAP and vacuum skin packaged fillets at 4 °C was around 18–20 days with a limit of 10⁶ cfu/g and therefore effectively extends the microbiological shelf life of raw fillets by 1.5 times.

1. Introduction

Fish and fishery products are nutritious food which is increasingly popular worldwide. As such, high-quality food with an extended shelf life is essential for both producers and consumers. Quality is a broad term which can relate to sensory, biochemical, chemical, physical and microbiological aspects. Water holding capacity (WHC), defined as the ability of the muscle to hold water, is one of the most important quality parameters in fish. WHC is correlated to drip loss which is the exudate lost during thawing, storage or transport. As WHC is related to tenderness, juiciness, moisture and thereby weight retention and economic costs, producers prefer a product with high water holding capacity and low drip loss.

An effective packaging for fish should keep the fish moist, maintain WHC, hinder bacterial and enzymatic processes, provide a barrier against moisture and oxygen to decrease lipid oxidation, and prevent the sorption of external odors (Bindu & Sreejith, 2018). There are various types of modern packaging technologies used including modified

atmosphere, traditional vacuum packaging and vacuum skin packaging that can prolong the microbiological shelf life of fish and promote sensorial attributes for commercial purposes. Modified atmospheric packaging (MAP) is one of the most popular food preservation and packaging techniques that manipulate the amount of headspace of CO₂, N₂ and O₂ before package sealing to delay bacterial and chemical reactions (Tsironi & Taoukis, 2018). The most crucial gas in MAP is CO₂ due to its fungistatic and bacteriostatic properties (Sivertsvik, Jeksrud, & Rosnes, 2002). A good barrier packaging material is crucial to prevent O₂ from permeating into the package and CO₂ out. The composition of gas mixture used in MAP depends on the fish species. For fatty fish species like salmon, the CO₂ levels used are higher with a significantly lower O₂ than lean species like cod to reduce oxidative rancidity and bacterial growth (Nagarajarao, 2016).

In Northern Europe, MAP and vacuum packaging accompanied by chilled storage are popular preservation methods to store fish in markets. Contrastingly, packaging techniques in Southern Europe are still underutilized, as fishes are mainly sold on ice by fishmongers in wet

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markets (Duran-Montgé, Permanyer, & Belletti, 2015). However, when the ice melts, the fishes become contaminated, which speeds up biochemical reactions and microbial spoilage. Since fish and fishery products are highly perishable, the packaging method is an essential process in the seafood value chain to reach markets worldwide and decrease food spoilage and wastage. In combination with protective packaging, a low storage temperature is also important to improve the microbiological shelf life of fish.

Vacuum skin packaging is a relatively new technique derived from traditional vacuum packaging and has been gaining rapid commercial momentum as the preferred packaging method for fresh and premium food options. This technology encloses the product like a blanket and secures the product tightly by simultaneously heating the transparent upper barrier film, then sealing the bottom of the tray. The shrinkage of the upper film by heating in skin packaging prevents wrinkles or air pockets, which reduces the visible dispersion of oil and water exudate while maintaining the exact shape of the product (Lagerstedt, Ahnström, & Lundström, 2011; Vázquez et al., 2004). Most studies on skin packaging are related to meat products, while only a few focused on aquatic products. According to the review on raw beef by Stella, Bernardi, and Tirloni (2018), skin packaging maintains excellent quality and extends the shelf life of meat compared to traditional vacuum packaging. Skin packaged beef and pork also gave lower drip loss than those in MA and traditional vacuum (Kameníket al., 2014). Therefore, skin packaging maintains similar functionalities as traditional vacuum packaging, yet the perfectly contoured product wrapped on the tray offers an attractive appearance and added value to consumers.

Galli, Franzetti, Carelli, Piergiovanni, and Fava (1993) reported that

MA packaging on chilled cod fillets provided a more superior product than skin packaged and air stored fillets in terms of microbiological quality. Consequently, a study on the effect of vacuum skin packaging on Atlantic pomfret fillets revealed that those that were skin packaged had a significantly longer shelf life with better sensory, biochemical and microbiological quality than traditional vacuum and air stored fillets at refrigerated conditions (Pérez-Alonso, Aubourg, Rodríguez, & Barros-Velázquez, 2004). Nevertheless, there is a lack of research on the influence of skin packaging on the quality of fresh Atlantic salmon products, which is a commercially important fish species. Therefore, this study aims to evaluate physical and instrumentally determined sensory quality parameters including drip loss, water holding capacity, microbiological shelf life, colour and texture on fillet portions of Atlantic salmon packed in modified atmospheric versus skin packaging under refrigerated storage. Since MAP is mainly used as the commercial packaging method for regular fresh salmon portions (excluding sashimi-grade salmon), this was chosen as the reference product to compare with the growing popularity of skin packaging.

2. Materials and methods

2.1. Raw material, processing and packaging

On 9 June 2020, 320 tons of Atlantic salmon (*Salmo salar*) from the same cage were starved for 7 d, crowded for 1 h on Hillersvik locality in Sveio municipality. They were then pumped, bled, and gutted onboard a fish slaughter vessel by the cage (seawater temperature: ~ 12.5 °C, temperature after slaughter: ~ 6.3 °C). For this study, 34 fish (5.1 ± 0.7

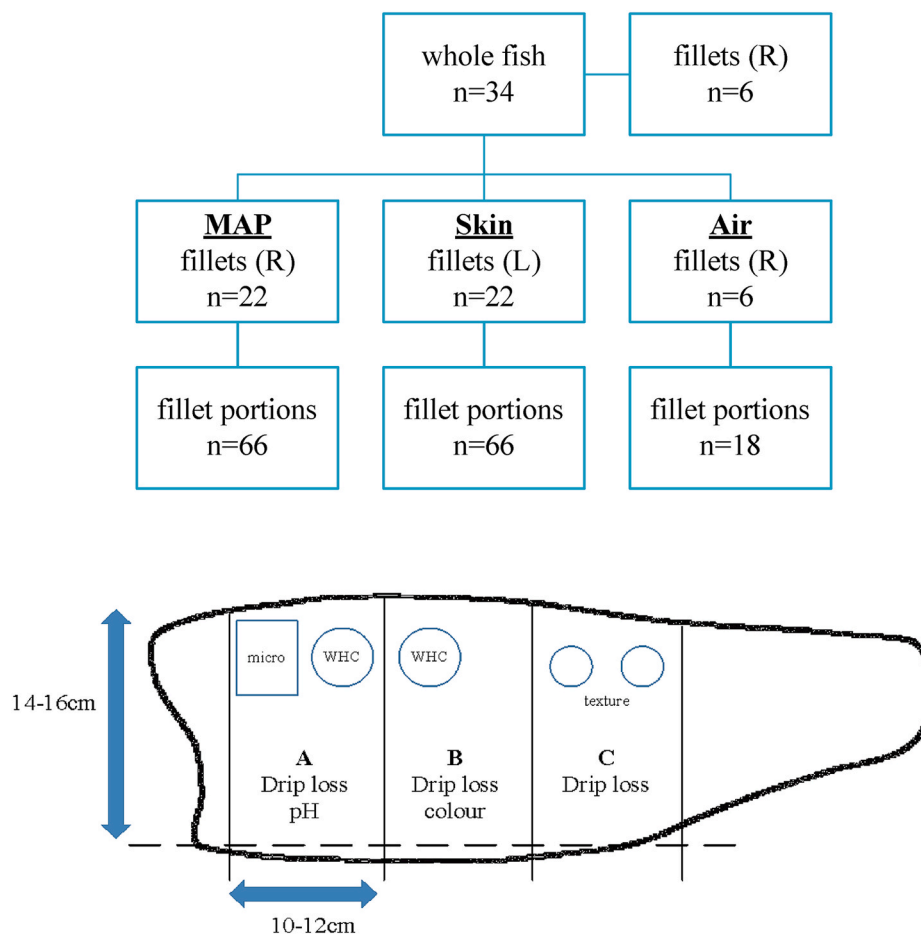


Fig. 1. (a) Experimental overview, including sample size. MAP, skin and air represent fillet portions in modified atmospheric packaging, skin packaging and unsealed packaging exposed to air. R and L represent right and left fillets, respectively. (b) Schematic illustration showing how fillets were portioned into A, B and C portions, and where the analysis on each portion was done on the left and right fillets.

kg) were collected from the vessel and packed with ice in expanded polystyrene (EPS) boxes. TrackSense Pro® temperature loggers (Ellab AS, Denmark) were inserted in the gut area towards the tail in 2 random fishes and the boxes. These boxes were transported to Nofima AS, Stavanger within 2 h and kept in a 0 °C storage room.

On day 6 post mortem, 6 fish were first filleted and used to analyze WHC, microbiology, colour and texture. Afterwards, 22 fish were filleted and portioned into 3 pieces per fillet (Fig. 1b, each portion approximately 200–300 g). The raw portions (A, B, C) from the right and left fillets were individually packed in either under modified atmosphere (n = 66) or skin packaging (n = 66), respectively. They were then stored at 4 °C to mimic the refrigeration storage of food retailers in the markets. All the packaging trays used were C2187-1F black crystallized polyethylene terephthalate trays (CPET, 187x137 × 40 mm, Faerch, Denmark) containing Absorber white Super 3000 water-absorbent pads (80 × 120 mm, NorEngros, Norway). For MAP, the air was released before introducing food grade 60% CO₂ and 40% N₂ gas mixture (Linde Gas, Oslo, Norway) into the package then heat sealing with lidding film Cryovac OSF33ZA (PET sealant, thickness 33 µm, oxygen permeability 60 cm³/m²/24 h/bar (23 °C, 0% RH), Sealed Air, Norway). For skin packaging, the lidding film used was Skintite HB 125 alu/pet (PE/EVOH combination, thickness 125 µm, oxygen permeability 2 cm³/m²/24 h/atm (23 °C, 50% RH), water vapour transmission rate 4 g/m²/24h (38 °C, 90% RH), Plus Pack, Norway). A Multivac T2000 Tray sealer (Multivac, Norway) was used to seal the packages. The remaining 6 fish were filleted on day 8, and the right fillets were also portioned into 3 pieces (n = 18) but kept in unsealed packaging bags exposed to air at 4 °C.

Sampling for quality analysis was periodically carried out on days 9, 13, 16 and 20 post mortem. Portions A, B and C originating from the same fillet (n = 5 or n = 6 fillet each group) were analyzed on both packaging methods for direct comparison (Fig. 1b). pH was measured on portion-A on each sampling day using a SevenGo pro pH meter (Mettler Toledo Inc., USA). Headspace gas was measured on MA packages on days 6, 16 and 20 using a PBI Dansensor CheckMate 9900 Headspace Gas Analyzer (Nordic Supply System, Norway). For the fillet portions exposed to air, 6 random portions were taken (n = 6) on days 13, 16 and 20 where drip loss, WHC, pH and microbiological analysis were analyzed.

2.2. Quality analysis

2.2.1. Drip loss and water holding capacity

Drip loss was measured by weighing each fillet portion immediately after opening the packaged samples and is calculated as the mass of drip (g) divided by the initial mass of the product (g), expressed in percentage (%). Water holding capacity was measured from both portions A and B above the lateral line described by Skipnes, Østby, and Hendrickx (2007). Muscle samples were punched (diameter 31 mm, height 6 mm) and transversally sliced into 2 pieces. Weighed samples of the top portions were placed in metal carriers (Part No. 4750, Hettich Lab Technology, Germany) and centrifuged at 530×g for 15 min at 4 °C. The bottom portions were weighed and dried for dry matter analysis, thereby water content, by drying the samples for 72 ± 6 h at 105 °C to ensure complete water evaporation.

2.2.2. Microbiological analysis

Microbiological analysis was carried out in accordance to the NMKL method No. 184 (NMKL, 2006) to determine total psychrotrophic viable plate count (TPC), total mesophilic bacterial count (TMC) and H₂S producing bacteria (HSPB). A piece of muscle (~10 g, without skin) was aseptically excised from portion A on the anterior part of the epaxial muscle. The samples were homogenized in stomacher bags containing 100 mL of sterile buffered peptone water (Merck, Germany) for 120 s with a Smasher® (AES Laboratorie, bioMérieux Industry, USA). Dilution series of the homogenates were prepared in Eppendorf tubes with sterile

peptone water. Aliquots (49.2 µL) of each dilution was transferred to the Long and Hammer (L&H) plates using the Eddy Jet 2W Spiral Plater (IUL micro, Spain) while 1 mL of each dilution was transferred to the iron agar (Lyngby, Oxoid, Norway) supplemented with 0.04% L-cysteine (Sigma-Aldrich, Norway). The iron agar plates were incubated at 25 °C for 72 ± 6 h before TMC and HSPB were determined by counting the total and black colonies, respectively; while L&H plates were incubated at 15 °C for 5 d to quantify TPC. Microbial populations were expressed as log cfu/g.

Analysis for *Listeria monocytogenes* was performed according to NMKL method No. 136 (NMKL, 2010) on the last sampling day (day 20). A muscle piece (~10g, without skin) was excised from the anterior part of the epaxial muscle. The samples were placed in stomacher bags, and half Fraser broth (Merck, Germany) was added to make a 1:10 dilution and homogenized for 120 s. The homogenates were incubated at 30 °C for 24 h in 15 mL Falcon tubes. 100 µL from primary enrichment (Half Fraser) was added to 9.9 mL Full Fraser in 15 mL Falcon tubes and incubated at 37 °C for 48 h. A 10 µL loop was then used to streak out the secondary enrichment (Full Fraser) on Brilliance Listeria agar (Oxoid, Norway) and incubated at 37 °C for 24–48 h. Blue/turquoise colonies that form a transparent halo on the agar are indicative of *L. monocytogenes*.

2.2.3. Colour and texture analysis

Colourimetric assessments were performed on fillet portion-B using computer vision via a digital colour imaging system (DigiEye full system, Verivide Ltd., Leicester, U.K.). The portions were placed in a standardized lightbox (daylight, 6400K) equipped with a digital SLR camera (Nikon D80, 35 mm lens, Nikon Corp., Japan). The images taken were analyzed using the Digipix software v2.8 (Verivide Ltd., U.K.) to measure the L*a*b* values (CIE, 1994). L* describes the lightness (L* = 0 = black; L* = 100 = white), a* the redness (-a: green; +a: red) and b* the yellowness (-b: blue; +b: yellow) of the sample.

Instrumental texture analysis was carried out using a texture analyzer TA-XT® plus (Stable Micro Systems Ltd., U.K.) equipped with a 5 kg load cell at a constant speed of 2 mm/s. A flat end cylinder probe (12.7 mm P/0.5) was used to create duplicate punctures above the lateral line on fillet portion-C from each packaging method on each sampling day. The force-time graph was recorded using the Texture Exponent light software. The breaking force was defined as the force needed to penetrate the fillet surface and firmness was determined as the force to press 80% of the fillet thickness.

2.3. Statistics

Data were analyzed in Minitab® v.19 (Minitab Inc., USA) statistical software using a general linear model (GLM), where packaging method was categorized as factor and storage days as the covariate. For texture analysis, fillet height was added as an extra covariate. An interaction effect between storage days and packaging method was first considered. Otherwise, no interaction analysis was carried out. An overall paired t-test was done to test the differences between MAP and skin packaging on texture and colour. Prior to all variance analysis, the correlation between dependent and independent variables, the homogeneity of the variance and the normal distribution of the residuals were checked. The confidence level of statistical analyses was set at 95%. All results are presented in mean ± standard deviation.

3. Results and discussion

3.1. Temperature, pH and gas composition

The internal temperature of fish decreased to 0 °C within 7 h after slaughter and was stable during ice storage before filleting (data not shown). On day 6 post mortem, the pH of the fish was 6.4 ± 0.3. Subsequently, there was a significant interaction effect between storage

days and packaging type on pH ($p < 0.001$). Simple main effects analysis showed that MAP fish had a significantly lower pH than air and skin packaged fish ($p < 0.001$), but there were no differences among storage days ($p = 0.396$). Skin packaged fish had a steady decrease in pH from 6.3 ± 0.1 on day 9 to 6.2 ± 0.0 at the end of storage, while MAP fish had a steeper decline in pH to 6.1 ± 0.1 on day 9 before remaining relatively stable throughout storage. In contrast, the pH of the air packaged fish decreased to 6.1 ± 0.0 on day 16 before increasing to 6.3 ± 0.1 on day 20 (Fig. 2).

The gas composition immediately after packaging contains $59.1 \pm 0.3\%$ CO_2 (the rest N_2), and its level of residual O_2 was 0.04% . On day 16 and 20 of storage, the CO_2 level in the headspace of the chilled MA packages reduced to $37.9 \pm 0.6\%$ and $39.7 \pm 1.1\%$, respectively, both with no residual O_2 ($p < 0.001$). The observed decrease in O_2 accompanied by the slight increase in CO_2 level is likely due to respiration by aerobic bacteria present in the fish, which also explains the observed increase in bacterial load. Nevertheless, the O_2 level in the packages never exceeded 0.1% . The CO_2 level maintained relatively stable, showing that the packaging used for MAP had good barrier properties and effectively prevented permeation of CO_2 out of the trays. Similar to our results, Hansen, Mørkøre, Rudi, Langsruda, and Eiea (2009) also reported that pH of MAP samples was stable after packaging and lower than those kept in air throughout the entire storage period. The decrease in pH on MAP fish after packaging is likely attributed to incorporating CO_2 into the food. As CO_2 is highly soluble in water and fat, it exists as a dissolved gas and chemically converts into carbonic acid (HCO_3^-) in the muscle tissue. This changes the gas composition within the package, thereby explaining the lower CO_2 level in the headspace gas (DeWitt & Oliveira, 2016; Sivertsvik et al., 2002).

Rigor mortis is usually reached 24–30 h after slaughter in unstressed salmon (Wang, Tang, Correia, & Gill, 1998) with a typical pH of around 6.6 (Erikson & Misimi, 2008; Roth et al., 2012). In this study, processing was done post rigor on day 6, and the observed decrease in pH for skin packaged fillets was likely attributed to the increase in H^+ concentration due to the formation of lactic acid from glycogen reserves (Einen, Guerin, Fjæra, & Skjervold, 2002; Lerfall et al., 2015). As to previous studies, the increase in pH for chilled salmon exposed to air after 16 d indicates spoilage likely caused by bacterial contamination as the metabolic activity of bacteria decomposes nitrogen compounds and forms basic compounds like ammonia and trimethylamine (Castro et al.,

2017; Chan, Roth, Skare, et al., 2020b; Hansen et al., 2009; Sivertsvik, Rosnes, & Kleiberg, 2003).

3.2. Drip loss and water holding capacity

There was a significant non-linear increase in drip loss for all fish as storage days increases ($p < 0.001$). At the end of storage, skin packaged fish had the highest increase at $5.9 \pm 0.6\%$ followed by MAP at $5.0 \pm 1.5\%$ and air packaged fish at $4.1 \pm 0.8\%$ (Fig. 3a). There was no difference in drip loss when the different fillet portions (A, B and C) were compared ($p = 0.116$) so the average of these portions was used for result analysis. Furthermore, there was no effect of drip loss between MAP and skin packaged fillets ($p = 0.173$), but this difference became more pronounced when the air packaged fish was included ($p < 0.001$). The increase in drip loss through storage regardless of storage conditions is an established observation since drip loss is a time-dependent phenomenon (Huff-Lonergan, 2009; Rotabakk, Melberg, & Lerfall, 2017). Based on Sivertsvik et al. (2003), drip loss of air-chilled salmon fillets (4–5%) was slightly yet insignificantly higher than MA packed fillets (3%). This contrasted with our findings where drip loss of air-chilled fillets was lowest, possibly because these fillets were only filleted and portioned 2 d after the MAP and skin packaged fillets. This decreased the days of exposure, hence surface area of the fillet exposed to the surroundings which probably contributed to drip loss.

Drip loss and WHC are inversely related as muscle holds the remaining water more tightly. This was accurately seen in the results where drip loss was in the order Air < MAP < Skin (Fig. 3a) while WHC had the opposite order at the end of storage. The packaging type ($p = 0.048$) and storage days ($p < 0.001$) significantly affected the WHC in the muscle, and a significant interaction was detected ($p = 0.004$). The WHC of salmon fillets after filleting on day 6 was $92.5 \pm 1.8\%$. After packaging, WHC for skin packaged fish ($89.2 \pm 3.3\%$) was only slightly higher than MAP on day 9 ($87.2 \pm 1.8\%$) before decreasing further to $83.5 \pm 6.3\%$ on day 20, and the overall difference was insignificant ($p = 0.108$). Contrastingly, the air packaged fish maintained a relatively high WHC at about 91% throughout storage (Fig. 3b).

WHC is known to be influenced by pH, as WHC is lowest when the muscle pH is at its isoelectric point of myosin and actin (Hamm, 1986, pp. 135–199). However, including pH as a covariate in the GLM did not give any significant result ($p = 0.522$). This is in line with Hultmann and Rustad (2002) and Rotabakk et al. (2017) who found that WHC seemed unrelated to pH, probably due to the slight variations in muscle pH. The higher drip loss (lower WHC) observed in skin packaged fish towards the end of storage could be related to greater protein denaturation, supported by a stable pH decrease.

The solubility of CO_2 in muscle alters its pH and lowers the WHC (thereby increases drip loss), although Randell et al. (1999) argued that this effect is not prominent in salmon. While the MAP fish had a consistently lower WHC and higher drip loss than the air packaged fish in this study, it was challenging to compare both groups due to the different filleting days. Nevertheless, a refrigerated temperature of 4°C can contribute to the increasing drip loss of all the samples observed during storage. Duran-Montgé et al. (2015) found that superchilled storage at -1°C corresponds to lowest drip loss compared to refrigerated temperatures and temperature below -1°C . On this basis, it is therefore possible to store fillets at lower temperatures to lessen drip loss.

3.3. Appearance and texture

The colour and texture of salmon are generally perceived as important traits for consumer preference and satisfaction. A significant effect of storage duration was observed on lightness (L^* , $p < 0.001$), redness (a^* , $p = 0.019$) and yellowness (b^* , $p < 0.001$) in this study. There was also an interaction effect between storage duration and packaging method on yellowness ($p = 0.022$).

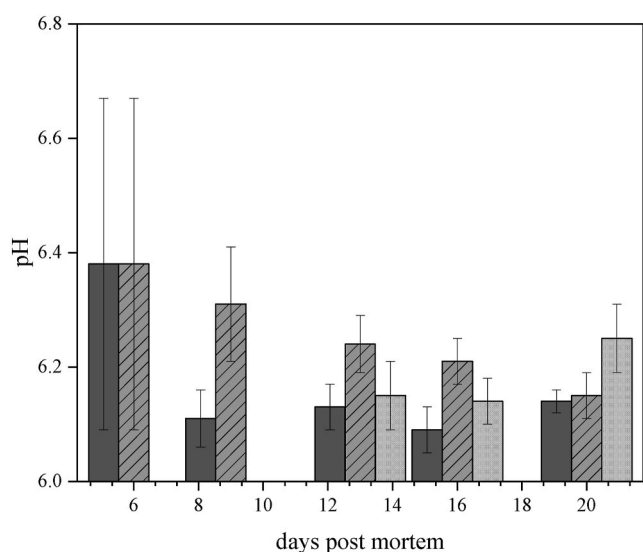


Fig. 2. pH change of raw salmon fillets packed in MAP (■), skin packaging (▨) and air (▩) during 20 days of chilled storage at 4°C ($n = 5$ or 6 ; GLM; storage days: $p = 0.396$; packaging method: $p < 0.001$; days*method: $p < 0.001$).

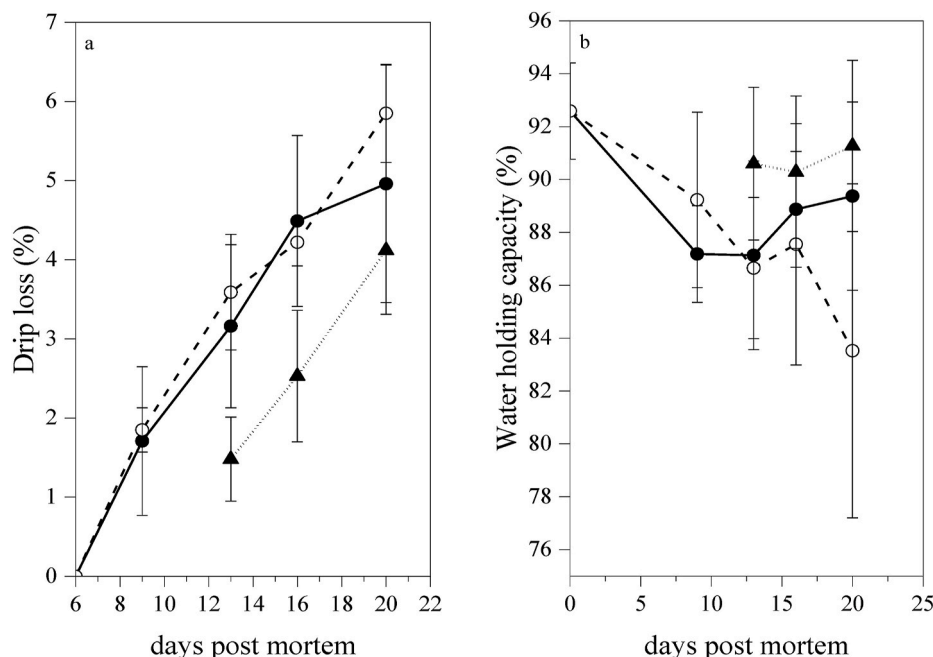


Fig. 3. (a) Drip loss (%) of raw salmon fillets packed in MAP (●), skin packaging (○) and air (▲) during 20 days of chilled storage at 4 °C (n = 15 or 18; GLM; storage days: p < 0.001; packaging method: p < 0.001). (b) Water holding capacity (%) (n = 10 or 12; GLM; storage days: p < 0.001; packaging method: p = 0.048; days*method: p = 0.004).

Between the 2 packaging methods, both groups presented comparable colour parameters on day 9, and the differences became significantly different after day 13. The skin packaged fish gave a lighter, less reddish and less yellowish colour than MAP groups at the end of storage (Table 1, L*: p = 0.024; a*: p = 0.009; b*: p = 0.005). This could be explained by protein denaturation and loss of fluids that increase the light reflection from the sample (Daskalova, 2019). Both packaging groups increased in lightness and decreased in redness and yellowness throughout storage after filleting. In line with the observations of Chan, Roth, Jessen, et al. (2020a) and Erikson and Misimi (2008), the higher translucency may be associated with rigor duration since muscle contraction affects the reflection properties of the flesh. Regardless of packaging method, losing redness and yellowness in the fillets could also be correlated to the increase in protein denaturation and drip loss during storage (Ozbay, Spencer, & Gill, 2006; Stien et al., 2005).

Table 1

Colour properties (L*a*b*) of raw salmon fillets packed in MAP and skin packaging during 20 days of chilled storage at 4 °C.

Day	Lightness (L*)		Redness (a*)		Yellowness (b*)		n
	MAP	Skin	MAP	Skin	MAP	Skin	
6	56.5 ± 2.4		36.1 ± 2.2		30.3 ± 1.5		6
9	61.8 ± 0.6	61.2 ± 1.4	35.0 ± 1.3	35.0 ± 1.6	32.0 ± 1.0	32.3 ± 1.3	6
	61.8 ± 1.7	62.3 ± 1.9	33.9 ± 0.7	33.2 ± 1.5	31.4 ± 1.2	30.4 ± 1.4	
16	63.9 ± 2.2	65.2 ± 1.4	34.7 ± 1.0	33.9 ± 1.0	32.1 ± 0.9	30.5 ± 0.5	6
	64.4 ± 2.0	67.2 ± 1.8	35.1 ± 2.6	33.4 ± 4.0	30.1 ± 2.0	27.2 ± 2.2	
Effect ^a	0.024*		0.009**		0.005**		
P _D	<0.001***		0.019*		<0.001***		
P _D *P _G	N.A.		N.A.		0.022*		

P_D: Significant levels on storage days using a general linear model (GLM) with packaging type as factors and storage days as covariance. P_D*P_G represents the interaction effect. N.A. means that there was no interaction effect, and a non-interaction analysis was done instead.

* p < 0.05, ** p < 0.01 and *** p < 0.001.

^a Overall paired t-test comparing MAP and skin packaged fish.

In this study, the breaking force observed for both packaging groups throughout the entire storage period were within the acceptable range of 8–11N (Mørkøre, Mazo, Tahirovic, & Einen, 2008). Both breaking force and firmness were significantly affected by storage days (Table 2; p < 0.001, p < 0.001, respectively) as they generally decreased with increasing storage time. The fillet height (p = 0.015) significantly affected firmness like the observed results of Chan, Roth, Jessen, et al. (2020a). A paired t-test analysis showed that MAP and skin packaging had comparable textural properties (breaking force: p = 0.317; firmness: p = 0.640). It was noticed that there was a significant decrease in firmness from days 6–9, but not on breaking force, suggesting that surface texture was not affected after packaging, but softening within the flesh occurred. Texture softening during chilled storage is a well-established effect of muscle tenderization due to protein breakdown (Erikson, Misimi, & Gallart-Jornet, 2011; Espe et al., 2004; Hansen et al., 2009; Hultmann & Rustad, 2002; Taylor, Fjaera, & Skjervold, 2002). Previous studies reported that storing fillets in MAP decreases the

Table 2

Textural properties of raw salmon fillets packed in MAP and skin packaging during 20 days of chilled storage at 4 °C.

Day	BF ^a (N)		F80 ^a (N)		n
	MAP	Skin	MAP	Skin	
6	9.6 ± 1.4		25.9 ± 5.2		6
9	9.6 ± 0.9	9.7 ± 1.2	12.1 ± 3.4	11.3 ± 3.7	6
	9.1 ± 1.3	9.8 ± 1.0	13.4 ± 3.5	10.1 ± 1.3	
16	8.6 ± 0.8	8.9 ± 1.4	10.4 ± 2.3	11.7 ± 2.4	6
20	7.7 ± 1.1	7.9 ± 1.7	10.0 ± 2.2	10.4 ± 1.8	5
Effect ^b	0.317		0.640		
P _D	<0.001***		<0.001***		
P _H	0.546		0.015*		

P_D, P_H: Significant levels on storage days and fillet height, respectively with a general linear model (GLM) using packaging type as factors and storage days and fillet height as covariance.

* p < 0.05, ** p < 0.01 and *** p < 0.001.

^a Note: BF, breaking force; F80, force at 80% compression of fillet height (firmness).

^b Overall paired t-test comparing MAP and skin packaged fish.

release of lysosomal enzymes cathepsin B+L, eventually reducing the rate of muscle proteolysis (Bahuaudet et al., 2008; Hansen et al., 2009).

Most studies were examining the colour of fillets in various packaging techniques involved a trained sensory panel as part of a guideline evaluating the freshness of fillets, rather than using computer vision with a digital colour measurement system (Duran-Montgé et al., 2015; Fernández, Aspe, & Roeckel, 2009; Giménez, Roncalés, & Beltrán, 2002; Pérez-Alonso et al., 2004; Randell et al., 1999). Therefore, the colour measurements from this study would be incomparable with previous studies. Our results suggest that storage duration was the critical determinant affecting both colour and textural quality of salmon fillets, and there is a difference in colour on MAP and skin packaged fillets towards the end of storage.

3.4. Microbiology

Microbiological analysis of fresh salmon after filleting and portioning on day 6 showed that the fillets were reared and produced at good hygienic conditions, where the average values of psychrotrophs, mesophiles and HSPB were 3.1 ± 0.3 (Fig. 4a), 1.9 ± 0.4 log cfu/g (Figs. 4b) and 1.0 ± 0.0 log cfu/g (Fig. 4c), respectively. *L. monocytogenes* was not detected in any treatment on the last sampling day. TPC ($p < 0.001$), TMC ($p < 0.001$) and HSPB ($p < 0.001$)

significantly increased throughout storage with an interaction effect for TPC ($p < 0.001$) and TMC ($p < 0.001$). When only MAP and skin packaged fish were compared, there was no effect of packaging method on microbial counts (TPC: $p = 0.262$, TMC: $p = 0.510$, HSPB: $p = 0.570$) so only storage duration was the primary determinant. However, microbial counts were significantly higher in the air packaged group (TPC: $p = 0.014$, TMC: $p = 0.028$, HSPB: $p < 0.001$), with a 10^2 - 10^3 cfu/g increase in microbial counts during storage as compared to MAP and skin packaged fish.

Fish is highly susceptible to spoilage and contamination from microbial growth and post mortem autolysis. Storing fish in air accelerates microbiological activity, especially at increasing storage temperatures. In this study, TPC was chosen to quantify some *Vibrio* spp. and *Photobacterium* spp., which is CO₂ resistant and often a specific spoilage organism in MA packaged fish. TMC was also chosen as it measures HSPB which quantifies for *Shewanella* spp., one of the most spoilage prevailing organisms in the processing environment for vacuum and air stored fish (Fogarty et al., 2019; Møretro, Moen, Heir, Hansen, & Langsrud, 2016). An aerobic plate count of $>10^6$ - 10^7 cfu/g indicates spoilage and the end of the microbial acceptance value (Hansen, Røntved, & Huss, 1998; Stannard, 1997). The air packaged group was already deemed microbiologically spoiled on day 13 (TPC: 6.6 ± 0.5 log cfu/g, TMC: 6.6 ± 0.3 log cfu/g, HSPB: 5.1 ± 0.4 log cfu/g) and day 16 (TPC: 7.9 ± 0.2 log

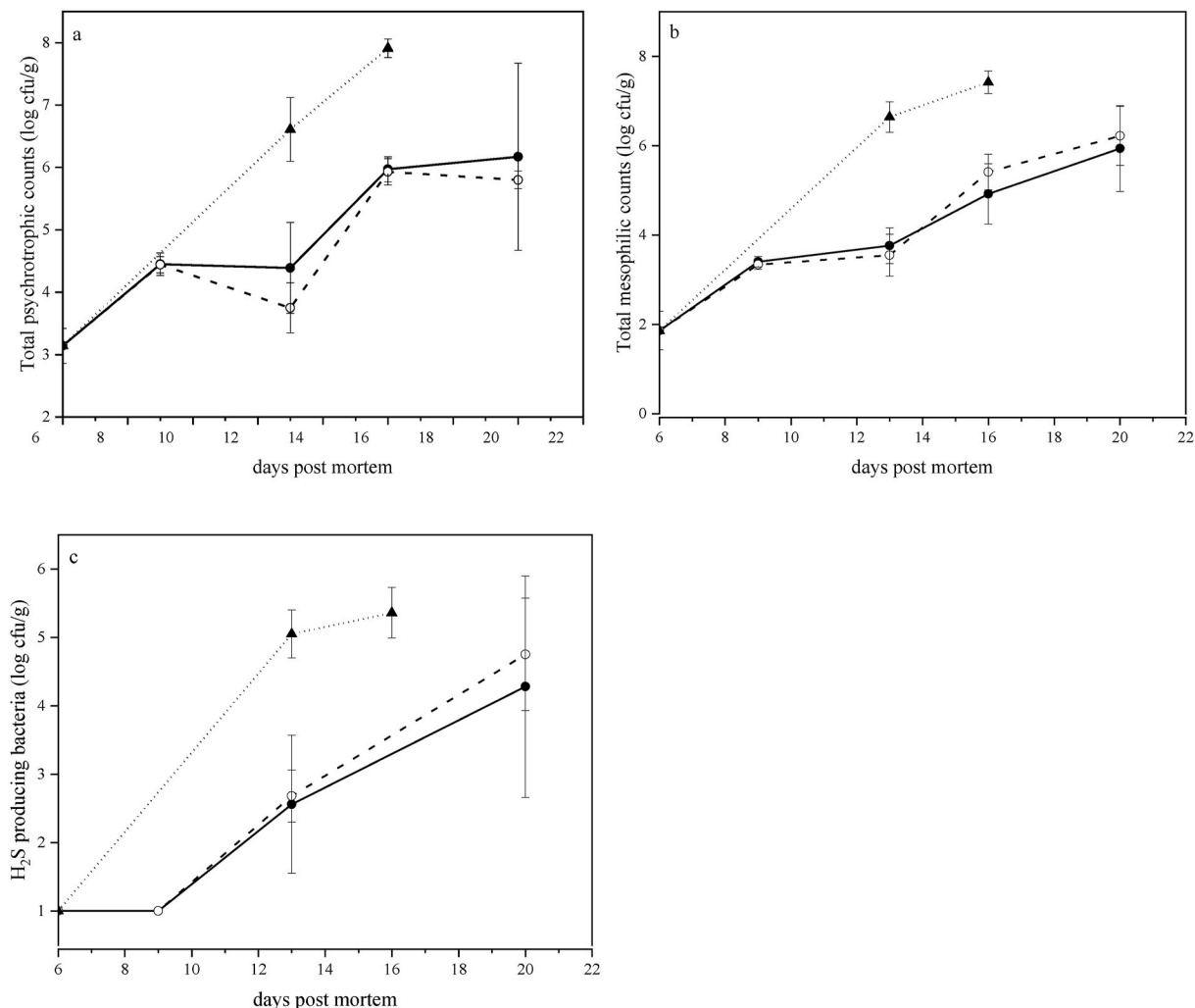


Fig. 4. (a) Total psychrotrophic counts of raw fillet portions in MAP (●), skin packaging (○) and air (▲) through storage ($n = 5$ or 6 ; GLM; storage days: $p < 0.001$; packaging method: $p = 0.014$; days*method: $p < 0.001$). (b) Total mesophilic counts ($n = 5$ or 6 ; GLM; storage days: $p < 0.001$; packaging method: $p = 0.028$; days*method: $p < 0.001$). (c) H₂S producing bacterial counts ($n = 5$ or 6 ; GLM; storage days: $p < 0.001$; packaging method: $p < 0.001$). The HSPB counts were under the detection limit of 1 log cfu/g before day 13, hence the count was assigned at this value.

cfu/g, TMC: 7.4 ± 0.3 log cfu/g, HSPB: 6.7 ± 0.4 log cfu/g) with the presence of off-odors. Therefore, the microbiological analysis was discontinued on day 20. In contrast, MAP and skin packaged fish had almost one-week longer microbiological shelf life. The relative rate of spoilage model shown in Eq. (1) can determine the spoilage rate for salmon stored in air (Dalgaard, 2002). Using the reference of 14 d of shelf life for fish stored at 0 °C (Sivertsviket et al., 2003), the estimated microbiological shelf life for salmon stored at 4 °C would be 7 d. However, regression analysis from this study (data not shown) indicates that the air packaged fish reached a bacterial growth of 10^6 cfu/g at day 12. This was probably due to the samples being filleted and exposed to air from day 8 onwards. MAP (TPC: 6.2 ± 1.5 log cfu/g, TMC: 5.9 ± 1.0 log cfu/g, HSPB: 4.3 ± 1.6 log cfu/g) and skin packaged (TPC: 5.8 ± 0.1 log cfu/g, TMC: 6.2 ± 0.7 log cfu/g, HSPB: 4.8 ± 0.8 log cfu/g) approximately had 18–20 d shelf life. It can be concluded that both MAP and skin packaging effectively extend the microbiological shelf life of raw fillets by almost 1.5 times.

$$\text{Relative rate of spoilage} = (0.1^{\text{storage temperature } [^{\circ}\text{C}] + 1})^2 \quad (1)$$

While extensive studies have been done proving that MAP and traditional vacuum packaging improves the shelf life of fish and fishery products compared to air storage (Fagan, Gormley, & Uimhuirch-earthaigh, 2004; Giménez et al., 2002; Ordóñez, López-Gálvez, Fernández, Hierro, & de la Hoz, 2000; Randell et al., 1999; Sivertsviket et al., 2003), few studies focused on the increasingly popular vacuum skin packaging (Duran-Montgé et al., 2015; Galli et al., 1993; Pérez-Alonso et al., 2004). The CO₂ in MA packages delays microbiological growth by lengthening its lag phase and reducing the accumulation of spoilage compounds like hypoxanthine and total volatile bases (TVB). This minimizes unpleasant odors (Giménez et al., 2002). The synergistic effect of superchilling and MAP extends the shelf life by up to four-fold compared to air storage at refrigerated temperature (Fernández et al., 2009; Hansen et al., 2009; Sivertsviket et al., 2003). It has also been reported that superchilling combined with skin packaging significantly extended shelf life of sea bream fillets (Duran-Montgé et al., 2015). Hence, it would be interesting to see whether superchilling combined with skin packaging would give salmon the corresponding benefits. With the extended shelf life, MAP and skin packaging techniques offer products to be delivered in bulk packages over further distances, reducing the distribution cost. However, the requirement for different formulations of headspace gas for MAP demands extra volume and display spaces. The presence of oxygen accelerates lipid oxidation which is also responsible for off-flavours and quality loss, particularly for fatty fish. The vacuum application in skin packaging eliminates the need for headspace and could be an easier and more practical packaging method offering comparable quality. With oxygen deficiency, oxidation and physiological reaction rates are partially inhibited (Floros & Matsos, 2005). The tight moulding of the top web to the product also promotes sensorial elements perceived by the consumers (Stella et al., 2018). Hence, skin packaging can add market value to reduce the need for gas and gas volume, saving storage space and enhancing sensory for retail fish sale.

4. Conclusion

The observations from this study showed that both MAP and skin packaging give similar fillet quality in terms of drip loss, WHC, texture and microbiological shelf life. However, fillets in MAP gave an overall lower pH and a darker, more reddish and yellowish colour than skin packaged fillets. Nevertheless, both MAP and skin packaging have benefits that outweigh its disadvantages which significantly extends shelf life when proper temperature control is implemented. Our findings could be beneficial for industries that seek to understand the differences of qualities of the two packaging techniques.

CRedit authorship contribution statement

Sherry Stephanie Chan: Conceptualization, Methodology, Validation, Writing – original draft. **Maren Skare:** Methodology, Data curation, Validation. **Bjørn Tore Rotabakk:** Conceptualization, Methodology, Writing – review & editing. **Morten Sivertsvik:** Supervision, Validation, Writing – review & editing. **Jørgen Lerfall:** Supervision, Validation, Writing – review & editing. **Trond Løvdal:** Supervision, Validation, Writing – review & editing. **Bjørn Roth:** Project administration, Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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