









Research Article

Nutritional Quality and Assessment of Contaminants in Farmed Atlantic Salmon (*Salmo salar* L.) of Different Origins

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Atlantic salmon represents an important source of valuable proteins and lipids rich in n-3 fatty acids and micronutrients. However, there are reports that these marine fish still contain contaminants at levels that raise health concerns. Although the Stockholm Convention already bans some compounds, they can still be detected because of their persistence. The present study reports nutritional parameters and the occurrence of persistent and bioaccumulative chemicals in the tissues of fifty-five salmon from several major farming areas. The protein content of all samples was almost identical, averaging to 19.2% w/w, while lipids averaged 14.9% w/w. Fish from Chilean farms contained 6.0% less fat and a lower level of vitamin E than from other sources, that is, 2.2 mg per 100 g (w/w). Fish from Scottish farms contained higher levels of eicosapentaenoic and docosahexaenoic acid. Halogenated contaminants from polychlorinated biphenyls, organochlorinated pesticides, brominated flame retardants, and perfluoroalkylated and polyfluoroalkylated substances were measured, and generally, they were found to be at very low concentrations that did not exceed the legislation limits applicable in the European Union. These results showed that the compositional differences between Atlantic salmon from several important farming areas were only minor, but some significant differences were demonstrated in total fat content and fatty acid profiles.

1. Introduction

Aquaculture is now the fastest growing food sector in the world, providing more than half of the world's fish protein [1]. One of the most economically important aquaculture species is the Atlantic salmon (*Salmo salar* L.), with current production exceeding 2.6 million tonnes [2]. Currently, salmon is intensively farmed in many parts of the world, especially in Norway, Scotland, Canada, and Australia [3].

Atlantic salmon is an important component of a healthy diet. In the literature, the protein content is reported to be between 17.4 and 21.1% w/w [4]. Lipids are also nutritionally valuable, usually exceeding 12% w/w, and are rich in highly unsaturated fatty acids (HUFAs) [4]. Tocopherols, the most

important naturally occurring lipophilic antioxidants, are also significant. However, the continuous development of fish farming over the last two decades has led to major changes in the composition of fish feed. Previously, fishmeal and fish oils were mainly used as feed. Now, fish feed mostly contains vegetable oils, which are cheaper and more sustainable, but unlike fish sources, do not contain HUFAs. In this context, seaweed and microbial or transgenic crop oils are being introduced as alternative sources of HUFAs. Levels of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) in the feed are also important because they affect not only the total lipid content of fish but also the fish growth, body composition, bone development, and eicosanoid production [5–8].

Contrary to the nutritional benefits of fish consumption, salmon also accumulate organic pollutants, such as polychlorinated biphenyls (PCBs), organochlorinated pesticides (OCPs), brominated and other halogenated flame retardants (HFRs), and perfluoroalkylated and polyfluoroalkylated substances (PFAS) [9]. Despite the fact that some of these compounds are prohibited from long-term use and are listed under the annexes of the Stockholm Convention on Persistent Organic Pollutants (POPs), they are still often detected in fish, in relatively high concentrations [9, 10]. These chemicals are endocrine disruptors for fish, and moreover, their intake contributes to the total body load of POPs in humans [11]. To protect consumers from the consumption of contaminated fish, the European Commission has set the maximum limits for indicator PCBs (congeners 28, 52, 101, 138, 153, and 180), dioxin-like PCBs, polychlorinated dibenzo-*p*-dioxins, and dibenzofurans (PCDDs/PCDFs) by the regulation no. 1881/2006 [12]. Nevertheless, a wide range of other potentially dangerous contaminants is still detected in fish, at varying levels depending on the origin of the fish and the tissue type [13–16].

In this report, we describe the comprehensive and quantitative analyses of the important nutrients and significant persistent and bioaccumulative contaminants in farmed salmon. We have analysed 55 samples of farmed salmon from various breeding areas and provided a comparison with European regulatory or guideline levels to determine whether contaminant concentrations in salmon tissue remain at previously reported levels [17], thus posing a continuing risk to the health of people who consume commercially produced salmon.

2. Materials and Methods

2.1. Atlantic Salmon. Atlantic salmon (*Salmo salar* L.) was provided by Bidfood (Czech Republic) from March to May 2017. Forty samples were obtained from aquacultures of three coastal areas in the Norwegian North Sea: south (NS) around Bergen, central (NC) around Trondheim, and north around Tromsø (NN); eight samples were from Achnacroish–Argyll and Orkney Islands located in Scotland (S), two samples from Iceland (I), and five samples from Chile (L). The fillets were deboned and stripped of visible fat from the abdominal and dorsal regions. Fillets (~200 g) from the central part of fish halves with an average weight of 1.75 kg were homogenised using a flesh-suitable mixer and kept in the freezer at -55°C until they were analysed.

2.2. Dry Matter, Protein, and Total Lipid Analyses. The dry matter was determined gravimetrically after drying approximately 1.5 g of homogenised samples at $102 \pm 2^{\circ}\text{C}$ in an automatic analytical moisture analyser with infrared heating (Ohaus MB 45, Switzerland). The Kjeldahl method was used to determine nitrogen by the KT200 Kjeltec system (FOSS, Denmark). The protein content in the fillets was estimated by multiplying the determined nitrogen content by a nitrogen-to-protein conversion factor of 6.25 [18]. The total lipid content, after trituration of the sample with desiccant

(sodium sulfate p. a.), was determined gravimetrically by extraction in petroleum ether using the Soxtec system HT6 (FOSS Tecator AB, Sweden). Dry matter, protein, and total lipid analyses were carried out in triplicate.

2.3. Fatty Acid Analysis. The composition of fatty acids was determined from the aliquot part of total lipids, which were extracted from fillets with chloroform-methanol (2:1, *v/v*) according to the method of Folch et al. [19]. Derivatization of fatty acids was based on the base-catalysed reaction according to the IUPAC method 2.301 [20]. The fatty acid methyl esters (FAMES) were then extracted into hexane. FAMES were analysed by gas-liquid chromatography using an SP-2560 fused silica capillary column (100 m \times 0.25 mm, i.d., 20 μm film thickness) (Supelco, USA) in an Agilent 6890 gas chromatograph (Agilent Technologies, USA) equipped with a flame ionization detector (FID). The oven temperature was 175°C for 30 min, and then, it was increased by $1^{\circ}\text{C}/\text{min}$ to 210°C where it was maintained for 40 min. One μl of the sample was injected in the split mode (ratio 50:1) into the injector. The detector and injection port temperatures were 220°C , and the nitrogen carrier gas flow was $1 \text{ ml}\cdot\text{min}^{-1}$. FAMES were identified by comparing the FAME retention time with 37 component FAME mixtures and individual standards (Supelco, USA). The quantification was carried out by the internal normalization method, and the results were expressed as relative percentages of all identified fatty acids. FAME's analyses were carried out in duplicate.

2.4. Tocopherol Analysis. The tocopherol content was determined from the aliquot part of total lipids using reverse-phase HPLC with amperometric detection under the conditions described by Fišnar et al. [21]. The system consisted of a nonsteel high-pressure pump (LCP 4020.31; ECOM, Prague, Czech Republic), a manual sample injector (7725i; Rheodyne, Oak Harbor, WA, SA), a column heater (LCO 101; ECOM) set to 28°C , and an HP 1049A series amperometric detector equipped with a glassy carbon working electrode and a solid-state Ag/AgCl reference electrode (Agilent Technologies, Santa Clara, CA, USA). Chromatographic separation was performed using a Hypersil ODS column (4.6 mm \times 200 mm \times 5 mm; Agilent Technologies). A mixture of acetonitrile and methanol (1:1, *v/v*) containing LiClO_4 p.a. ($0.02 \text{ mol}\cdot\text{l}^{-1}$) and NaCl p.a. ($0.005 \text{ mol}\cdot\text{l}^{-1}$) was used as the mobile phase at a flow rate of $1.0 \text{ ml}\cdot\text{min}^{-1}$. Samples were dissolved in acetone ($0.1 \text{ g}\cdot\text{ml}^{-1}$), and 1 ml of the solution was injected into the column. Quantification was achieved by external calibration using the respective tocopherol standards. All samples were determined in duplicates.

2.5. Analysis of Persistent Organic Pollutants. The method for the determination of GC-MS amenable compounds (PCBs, OCPs, and brominated flame retardants (BFRs) with exception of hexabromocyclododecane (HBCD) and tetrabromobisphenol A (TBBPA)) is described in detail in the

study by Kalachova et al. [22]. The list of targeted substances is summarised in the Supplementary Material. Briefly, analytes were extracted from a homogenate of fish muscle tissue with ethyl acetate (Honeywell, USA) after the addition of water and with the support of inorganic salts; subsequently, the extract was purified by solid phase extraction (SPE) on a silica minicolumn. Before instrumental analysis, the residue was redissolved in isoctane with internal standards of PBDE 37 and 77 ($5 \text{ ng}\cdot\text{ml}^{-1}$) and ^{13}C -PBDE 209 ($50 \text{ ng}\cdot\text{ml}^{-1}$). For the PCBs and OCPs analyses, gas chromatography coupled with tandem mass spectrometry in electron ionization (Agilent Technologies, USA; GC-EI-MS/MS) on the DB-5MS capillary column (Agilent Technologies, USA; $30 \text{ m} \times 0.25 \text{ mm} \times 0.25 \mu\text{m}$) was employed. Analysis of GC amenable BFRs was performed using GC-MS operated in negative ion chemical ionization (NICI), and a DB-XLB (Agilent Technologies, USA; $15 \text{ m} \times 0.18 \text{ mm} \times 0.07 \mu\text{m}$) capillary column was used for their separation.

The procedure applied for the analysis of PFAS, HBCD, and TBBPA was published by Lacina et al. [23] and Lankova et al. [24] with a slight modification of the purification step. Fish muscle tissue, after the addition of water, was extracted by acetonitrile (Honeywell, USA), supported by the addition of inorganic salts, and a crude extract was purified by dispersive solid phase extraction (DSPE) using a SupelQuE z-SEP + sorbent (Supelco, USA). After evaporation, the residues were redissolved in methanol and analysed using ultra-performance liquid chromatography interfaced with tandem mass spectrometry with electrospray ionization operated in negative mode (Agilent Technologies, USA; UHPLC-ESI-MS/MS). The mobile phases consisted of (A) 5 mM ammonium acetate in deionized water and (B) methanol, and an Acquity UPLC BEH C_{18} (Waters, USA; $100 \text{ mm} \times 2.1 \text{ mm} \times 1.7 \mu\text{m}$) column was used for the separation of the target substances.

To ensure the quality assurance/quality control (QA/QC) process, the procedural blank was analysed with each batch of samples. Concentrations of all target contaminants were below the respective method quantification limits (MQLs). Both methods were previously validated and were only verified by analysing 6 replicates of the artificially contaminated blank fish sample within this study. The recoveries were in the range of 80–110% with the values of repeatability below 15%.

2.6. Statistical Analysis. The results are expressed as the mean \pm standard deviation (SD). Except for dry matter, protein, and total lipids, which were performed in three replicates, all remaining determinations were performed in two repetitions. Statistical analyses of the obtained data were performed with Excel (Microsoft Corp., Redmond, WA, USA) and Statistica, version 13.1 (StatSoft, Inc., Tulsa, OK, USA) using one-way analysis of variance with Scheffe's post hoc test. For the statistical analyses of POPs results, ANOVA followed by Tukey's post hoc tests were used. Differences were considered significant for a confidence interval at the 95% level ($p < 0.05$) in all cases.

3. Results and Discussion

3.1. Nutrients. The average results obtained for proteins, total lipids, sum of tocopherols, and dry matter content are presented in Table 1, and they are arranged according to the breeding area. The cluster dendrogram based on proteins, lipids, and dry matter shown in Figure 1 describes the differences between the groups. It is shown that the Chilean samples differ the most according to the main nutrients. In contrast, samples from all studied areas in Norway and Scotland were most similar.

The dry matter, on average around 37% (w/w), was slightly above the values reported in nutritional databases [4, 25, 26], where it ranged from 31.5% to 36.6% (w/w). Table 1 shows that the samples from the individual areas did not differ from each other.

The protein content averaged 19.2% (w/w), while moderately higher contents were observed in Chilean samples, specifically 20.6% (w/w). Both values were consistent with the range 17.4%–22.1% (w/w) published in the literature [4, 25, 26]. In Jensen's study [27], 15.4% was measured for farmed salmon.

The fatness of the fish is the most variable parameter of main nutrients. The total lipid content of salmon in the literature [4] ranges from 12.5% to 16.5% (w/w). From the monitored set of samples with an average total fat content of 14.9% (w/w), Chilean salmon was statistically different with only 8.9% (w/w) of the measured fat.

Fish oils are rich in polyunsaturated fatty acids (PUFAs), which not only increase their nutritional value but also reduce their oxidative stability. The role of antioxidants, which protect the oil from rancidity, is fulfilled by naturally occurring tocopherols [28]. Their content, expressed as the sum of α , β , γ , and δ -tocopherol, was on an average $302 \text{ mg}\cdot\text{kg}^{-1}$ oil, that is, 4.5 mg per 100 g (w/w). In Chilean salmon, corresponding to their lower total fat, only 2.2 mg per 100 g (w/w) of tocopherols was measured. These results correspond to the sources in the literature, which state the range of 1.9–3.6 mg per 100 g (w/w) [4, 29, 30]. If tocopherols were related only to fat amount, there was no statistically significant difference between the samples from individual areas. If the amount of tocopherol was expressed per wet muscle tissue, the Norway-South and Chile differed statistically.

The fatty acid profiles of the examined fish are presented in Table 2. The fatty acids with a content of more than 1% are listed. Dominant fatty acids with content above 10% included oleic acid (C 18 : 1 $\Delta 9\text{c}$), linoleic acid (C 18 : 2 $\Delta 9\text{c}$, 12c (n-6)), and palmitic acid (C 16 : 0). The oleic acid content averaged 38.03%, with a statistically significant difference observed only in the Scottish salmon group. Similarly, Table 2 shows that the Scottish samples also statistically differed the most in the content of linoleic acid, palmitic acid, EPA, DHA, and other acids.

The saturated fatty acid (SFA) averaged 17.56%, which is slightly higher than that of in Jensen's study (15.05%) [27]. The most similar samples were from Norway-South, Norway-North, and Iceland, compared to the Scottish samples, where statistically significant differences were observed. For

TABLE 1: Dry matter, proteins, total lipids, and sum of tocopherols determined in Atlantic salmon from different origins.

Constituents	Norway-Central (<i>n</i> = 17)	Norway-North (<i>n</i> = 10)	Norway-South (<i>n</i> = 13)	Scotland (<i>n</i> = 8)	Iceland ¹ (<i>n</i> = 2)	Chile (<i>n</i> = 5)
Dry matter (g/100 g)	37.6 ± 2.7 ^a	38.7 ± 3.3 ^a	36.9 ± 2.3 ^a	38.4 ± 2.5 ^a	39.6 ^a	33.5 ± 1.1 ^a
Proteins (g/100 g)	18.9 ± 0.7 ^{ab}	19.3 ± 0.9 ^{ab}	18.8 ± 0.5 ^b	19.6 ± 0.9 ^{ab}	18.9 ^{ab}	20.6 ± 0.7 ^a
Total lipids (g/100 g)	15.8 ± 2.8 ^a	15.4 ± 2.4 ^a	15.1 ± 1.4 ^a	15.1 ± 2.4 ^a	18.3 ^a	8.9 ± 0.9 ^b
The sum of tocopherols (mg/kg oil)	307.7 ± 73.0 ^a	288.8 ± 48.7 ^a	342.8 ± 40.3 ^a	284.0 ± 94.4 ^a	262.1 ^a	249.4 ± 60.2 ^a
The sum of tocopherols (g/100 g)	4.8 ± 0.9 ^{ab}	4.5 ± 1.0 ^{ab}	5.1 ± 0.5 ^a	4.4 ± 0.5 ^{ab}	4.9 ^{ab}	2.2 ± 0.4 ^b

Values are expressed as mean ± standard deviation (SD). ¹SD was not calculated due to the low number of samples from Iceland (*n* = 2). Values marked with different letters within the same row indicate a statistically significant difference by one-way analysis of variance with Scheffe's post hoc test (*p* < 0.05).

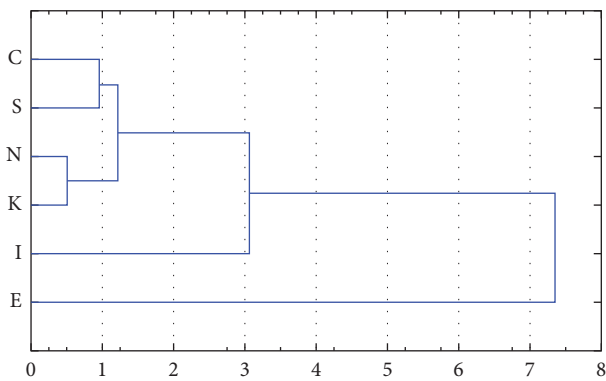


FIGURE 1: Single-linkage hierarchical cluster dendrogram for tested salmon samples: C, Norway-Central; S, Norway-South; N, Norway-North; K, Scotland; I, Iceland; E, Chile.

monounsaturated fatty acids (MUFAs), differences were only observed in the Scottish group, where a lower value of 41.46% was measured, compared to the overall average of 47.91%. The PUFAs content of the analysed fish differed between areas. The most different was the Scottish (36.95%) and Chilean samples (30.23%). All measured values were lower than those described in Jensen's [27] and Blanchet's [31] studies.

Wild salmon were reported with 6.0–7.0% (w/w) of lipids with 6.6% EPA and 13.1–14.5% DHA (expressed as % of total fatty acid) [27, 31]. Our results showed that the lipid content of farmed Atlantic salmon was markedly higher but was not qualitatively similar to that of wild Atlantic salmon. Although 90% of traditional Norwegian salmon diets were composed of marine ingredients in 1990, in 2013, it was only approximately 30% [32]. This shift from marine ingredients to mostly plant-based ingredients has allowed the aquaculture industry to increase production to meet the increasing global demand for food without compromising wild fisheries. However, it has also led to significant changes in the composition of lipids in fish tissues.

3.2. Contaminants. Within the second part of this study, the fish samples were examined on the presence of several groups of halogenated contaminants represented by PFASs, BFRs, PCBs, and OCPs. Of the 64 targeted chemicals, only 17 were detected at least in one sample. The results of these detected compounds are summarised in Table 3 (mean ± SD

concentrations in $\mu\text{g}\cdot\text{kg}^{-1}$ wet weight (WW)). The SD was calculated from concentrations from samples of the respective locality. The samples from Norway were sorted by the location of the farm where the salmon were bred, that is, farms in the central, southern, and northern parts of Norway.

3.2.1. Polychlorinated Biphenyls. From the group of indicator PCBs, all congeners were detected in concentrations above the MQLs, $0.05\ \mu\text{g}\cdot\text{kg}^{-1}$ WW, in salmon samples from Norway. None of the measured concentrations exceeds the legislation limit for the sum of six non-dioxin-like (NDL) PCBs ($75\ \mu\text{g}\cdot\text{kg}^{-1}$ WW) in the Commission Regulation (EC) No. 1881/2006 (No. 28, 52, 101, 138, 153, and 180) in the samples from Norway was in the range of 1.30–6.65 $\mu\text{g}\cdot\text{kg}^{-1}$ WW (median: 3.65 $\mu\text{g}\cdot\text{kg}^{-1}$ WW); in addition, hexa-CBs (PCB 138 and PCB 153) were the most abundant congeners found at concentrations in the range of <0.05 – $2.02\ \mu\text{g}\cdot\text{kg}^{-1}$ WW (median 1.12 $\mu\text{g}\cdot\text{kg}^{-1}$ WW) and 0.317 – $2.30\ \mu\text{g}\cdot\text{kg}^{-1}$ WW (median 1.28 $\mu\text{g}\cdot\text{kg}^{-1}$ WW), respectively. As can be seen in Table 3, it should be noted that the concentrations of detected congeners and their sum in Norway samples were similar to each other, that is, no statistical differences (ANOVA followed by Tukey's post hoc tests; *p* > 0.05) were observed within the localities. The sum of 6 NDL-PCBs in samples from farms located in central, southern, and northern parts of Norway was 2.03–6.65, 2.15–5.25, and 1.30–6.13 $\mu\text{g}\cdot\text{kg}^{-1}$ WW, respectively. In the samples from Scotland, CB 28 and CB 52 were not detected in any of the analysed samples, and detection frequencies (DFs) of other PCBs were 100% (CB 101), 100% (CB 138), 100% (CB 153), and 75% (CB 180). The sum of 6 NDL-PCBs was in the range 0.456–2.56 $\mu\text{g}\cdot\text{kg}^{-1}$ WW (median: 1.53 $\mu\text{g}\cdot\text{kg}^{-1}$ WW). PCBs in Icelandic salmon were not quantified, and only CB 101 and CB 153 were detected in samples from Chile with DF = 40% for both congeners and with amounts in the range of <0.05 – 0.421 and <0.05 – $1.89\ \mu\text{g}\cdot\text{kg}^{-1}$ WW.

The results obtained within our study were compared with the Norwegian survey published by Nøstbakken et al. [33], which was dedicated to trends in contamination of farmed salmon with PCBs and other pollutants during the 13-year period (1999–2011). Although they found some statistical variations between years of the sampling, no trends were observed and the concentrations of NDL-PCBs

TABLE 2: Fatty acid composition (as % of total fatty acids) of total lipids extracted from fillets of salmon samples.

Fatty acid	Norway-Central (<i>n</i> = 17)	Norway-North (<i>n</i> = 10)	Norway-South (<i>n</i> = 13)	Scotland (<i>n</i> = 8)	Iceland ¹ (<i>n</i> = 2)	Chile (<i>n</i> = 5)
Myristic acid (C14:0)	3.47 ± 0.46 ^a	3.02 ± 0.25 ^a	3.39 ± 0.35 ^a	4.80 ± 0.90 ^b	3.37 ^a	3.08 ± 0.49 ^a
Palmitic acid (C16:0)	10.87 ± 0.86 ^b	10.04 ± 1.41 ^b	10.26 ± 0.45 ^b	13.32 ± 1.79 ^a	9.32 ^b	11.97 ± 1.27 ^{ab}
Palmitoleic acid (C16:1 Δ9c)	3.05 ± 0.36 ^a	2.99 ± 0.23 ^a	2.94 ± 0.15 ^a	3.86 ± 0.95 ^b	2.51 ^a	2.79 ± 0.17 ^a
Stearic acid (C18:0)	2.22 ± 0.19 ^{bc}	2.17 ± 0.44 ^{bc}	2.09 ± 0.10 ^c	2.55 ± 0.22 ^b	1.85 ^c	3.30 ± 0.26 ^a
Oleic acid (C18:1 Δ9c)	38.38 ± 1.35 ^a	40.34 ± 1.56 ^a	39.22 ± 0.66 ^a	30.75 ± 4.67 ^b	37.66 ^a	40.91 ± 1.99 ^a
Vaccenic acid (C18:1 Δ11c)	3.63 ± 0.88 ^{ab}	3.56 ± 0.30 ^{ab}	3.30 ± 0.24 ^b	3.70 ± 0.56 ^{ab}	4.98 ^a	3.83 ± 0.47 ^{ab}
Linoleic acid (C18:2 Δ9c, 12c)	14.53 ± 0.66 ^a	14.95 ± 0.38 ^a	15.05 ± 0.28 ^a	12.54 ± 1.82 ^b	15.53 ^a	15.74 ± 0.61 ^a
α-Linolenic acid (C18:3 Δ9c, 12c, 15c)	6.50 ± 0.98 ^a	6.20 ± 0.91 ^{ab}	6.77 ± 0.76 ^a	5.52 ± 1.39 ^{ab}	6.4 ^{ab}	4.20 ± 0.34 ^b
Eicosenoic acid (C20:1 Δ11c)	2.38 ± 0.62 ^a	2.39 ± 0.39 ^a	2.24 ± 0.38 ^a	1.86 ± 0.83 ^a	3.36 ^a	1.84 ± 0.23 ^a
Eicosadienoic acid (C20:2 Δ11c, 14c)	1.13 ± 0.09 ^a	1.31 ± 0.22 ^a	1.13 ± 0.07 ^a	0.65 ± 0.15 ^b	0.71 ^b	0.80 ± 0.09 ^b
Eicosapentaenoic acid (C20:5 Δ5c, 8c, 11c, 14c, 17c)	3.00 ± 0.29 ^a	2.56 ± 0.21 ^a	3.09 ± 0.18 ^a	5.49 ± 1.67 ^b	2.98 ^a	2.08 ± 0.28 ^a
Docosapentaenoic acid (C22:5 Δ7c, 10c, 13c, 16c, 19c)	1.20 ± 0.13 ^b	1.26 ± 0.2 ^{ab}	1.16 ± 0.12 ^b	1.65 ± 0.50 ^a	0.82 ^b	0.93 ± 0.08 ^b
Docosahexaenoic acid (C22:6 Δ4c, 7c, 10c, 13c, 16c, 19c)	4.39 ± 0.63 ^b	3.86 ± 0.50 ^b	4.27 ± 0.42 ^b	6.52 ± 2.15 ^a	4.15 ^b	3.00 ± 2.00 ^b
Total <i>n</i> -6	17.00 ± 0.54 ^a	17.48 ± 0.74 ^a	17.14 ± 0.43 ^a	15.65 ± 1.68 ^b	19.06 ^a	17.89 ± 0.35 ^a
Total <i>n</i> -3	17.09 ± 1.41 ^b	16.03 ± 1.53 ^b	17.64 ± 0.97 ^b	20.48 ± 2.60 ^a	15.45 ^{bc}	11.24 ± 0.40 ^c
Saturated fatty acids (SFA)	17.20 ± 1.21 ^{bc}	15.90 ± 1.98 ^c	16.62 ± 0.67 ^c	21.59 ± 3.00 ^a	15.41 ^c	19.66 ± 1.78 ^{ab}
Monounsaturated fatty acids (MUFA)	48.31 ± 1.04 ^a	50.12 ± 1.02 ^a	48.51 ± 0.80 ^a	41.46 ± 4.01 ^b	49.68 ^a	50.11 ± 1.93 ^a
Polyunsaturated fatty acids (PUFA)	34.48 ± 1.35 ^b	33.97 ± 1.41 ^b	35.15 ± 1.00 ^{ab}	36.95 ± 1.41 ^a	34.90 ^{ab}	30.23 ± 0.61 ^c

Values are expressed as mean ± standard deviation (SD). ¹SD was not calculated due to the low number of samples from Iceland (*n* = 2). Values marked with different letters within the same row indicate a statistically significant difference by one-way analysis of variance with Scheffe's post hoc test (*p* < 0.05).

during these years were similar (median: 5.94 μg·kg⁻¹ WW) and were comparable with our results (median: 3.65 μg·kg⁻¹ WW). Another Norwegian study published by Lundebye et al. [34] focused on PCBs and other contaminants in farmed and wild Atlantic salmon. They concluded that wild Atlantic salmon were slightly more contaminated with PCBs (sum of 6 NDL PCBs: 2.0–11.9 μg·kg⁻¹ WW, mean: 6.6 μg·kg⁻¹ WW) compared to farmed salmon (2.0–9.4 μg·kg⁻¹ WW, mean: 4.0 μg·kg⁻¹ WW) and also these results agree well with our findings (1.30–6.65 μg·kg⁻¹ WW, mean: 3.74 μg·kg⁻¹ WW).

3.2.2. Organochlorinated Pesticides. Among the targeted OCPs, HCB, *p,p'*-DDE, *o,p'*-DDD, and *p,p'*-DDD were identified in all samples from Norway, while PCBs were detected in 95% of the samples. Similar to PCBs, concentrations of detected OCPs were generally very low and the range of concentrations was in the following order: <0.05–0.141 μg·kg⁻¹ WW for PCBs; 0.076–1.13 μg·kg⁻¹ WW for *o,p'*-DDD; 0.834–3.49 μg·kg⁻¹ WW for HCB; 0.315–4.89 μg·kg⁻¹ WW for *p,p'*-DDD, and 1.57–22.8 μg·kg⁻¹ WW for *p,p'*-DDE. DDT isomers were not found in any of the analysed samples, which indicate that there is no ongoing exposure to DDT. Isomers of hexachlorocyclohexane (α-HCH, β-HCH, and γ-HCH), hexachlorobutadiene (HCBd), and *o,p'*-DDE were not detected in any samples. Similar to PCBs, no statistically

significant differences (ANOVA followed by Tukey's post hoc tests; *p* > 0.05) in OCP concentrations were observed between farm locations. In the case of samples from Scotland, *p,p'*-DDD (0.333–2.83 μg·kg⁻¹ WW), HCB (0.407–1.99 μg·kg⁻¹ WW), and *p,p'*-DDE (1.26–18.0 μg·kg⁻¹ WW) were found in all samples, while the concentrations of the other OCPs were below the MQLs (0.05 μg·kg⁻¹ WW). *p,p'*-DDE was the most abundant compound in the DDT group and represents 63–86% of the total DDTs content. In Chilean samples, only *p,p'*-DDE (0.326–25.9 μg·kg⁻¹ WW) was found in all samples, and the DFs of *o,p'*-DDD, *p,p'*-DDD, and HCB were 20%, 20%, and 80%, respectively. The remaining OCPs were not detected in any sample. With the exception of *p,p'*-DDE (<0.05–0.252 μg·kg⁻¹ WW), no OCP residues were found in Icelandic fish.

The OCPs were also analysed by Nøstbakken et al. [33] in the period from 1999 to 2011 and found that the levels of the sums of DDTs declined over the years. The median of total DDTs was 9.40 μg·kg⁻¹ WW, which was approximately three times higher as compared to our results (median: 2.93 μg·kg⁻¹ WW). There was no information about the percentage of DDE in total DDT and which DDT isomer or metabolite was detected. In a study by Lundebye et al. [34], the same trend was observed as in the case of PCBs: the wild Atlantic salmon contained higher levels of total DDT (mean: 8 μg·kg⁻¹ WW) and HCB (mean: 1.6 μg/kg WW) compared to the farmed salmon: 5 μg·kg⁻¹ WW and 1 μg·kg⁻¹ WW,

TABLE 3: Concentrations in $\mu\text{g}\cdot\text{kg}^{-1}$ wet weight for organohalogenated pollutants determined in Atlantic salmon from different origins.

Pollutant	Norway-Central ($n = 17$)	Norway-North ($n = 10$)	Norway-South ($n = 13$)	Scotland ($n = 8$)	Iceland ^b ($n = 2$)	Chile ($n = 5$)
PCB 28	0.162 ± 0.048	0.177 ± 0.089	0.176 ± 0.040	<0.05*	<0.05*	<0.05*
PCB 52	0.258 ± 0.089	0.250 ± 0.150	0.280 ± 0.078	<0.05*	<0.05*	<0.05*
PCB 101	0.448 ± 0.239	0.568 ± 0.422	0.442 ± 0.142	0.288 ± 0.237	0.136 [#]	<0.05*
PCB 138	1.11 ± 0.37	1.10 ± 0.63	1.24 ± 0.32	0.303 ± 0.123	<0.05*	<0.05*
PCB 153	1.23 ± 0.43	1.38 ± 0.59	1.38 ± 0.35	0.653 ± 0.429	0.435 [#]	<0.05*
PCB 180	0.337 ± 0.102	0.342 ± 0.190	0.372 ± 0.094	0.175 ± 0.131	<0.05*	<0.05*
∑NDL-PCB	3.54 ± 1.23	3.82 ± 1.40	3.88 ± 0.94	1.47 ± 0.685	0.671 [#]	<0.30*
o,p'-DDD	0.112 ± 0.027	0.301 ± 0.372	0.120 ± 0.023	<0.05*	0.377 [#]	<0.05*
p,p'-DDD	0.519 ± 0.142	1.41 ± 1.66	0.561 ± 0.131	1.02 ± 0.79	1.01 [#]	<0.05*
p,p'-DDE	2.23 ± 0.56	5.83 ± 6.98	2.38 ± 0.39	4.89 ± 5.49	6.43 [#]	0.139 [#]
HCB	1.81 ± 0.67	1.58 ± 0.74	1.57 ± 0.69	1.12 ± 0.48	1.67 [#]	<0.05*
PCBs	0.079 ± 0.021	0.080 ± 0.036	0.078 ± 0.014	<0.05*	<0.05*	<0.05*
PBDE 47	0.201 ± 0.069	0.188 ± 0.095	0.223 ± 0.047	0.044 ± 0.034	<0.05*	<0.05*
PBDE 49	0.036 ± 0.018	0.038 ± 0.018	0.042 ± 0.015	<0.05*	<0.05*	<0.05*
PBDE 100	0.047 ± 0.026	0.054 ± 0.021	0.055 ± 0.021	0.058 ± 0.032	<0.05*	<0.05*
PFHpA	0.016 ± 0.012	0.011 ± 0.010	0.020 ± 0.012	<0.01*	<0.01*	<0.01*
PFOA	0.123 ± 0.064	0.085 ± 0.088	0.079 ± 0.066	<0.01*	<0.01*	<0.01*
FOSA	0.075 ± 0.023	0.070 ± 0.030	0.058 ± 0.025	0.022 ± 0.033	<0.01*	<0.01*

Values are expressed as mean ± standard deviation (SD). *Concentration below the respective method quantification limit (MQL). [#]SD was not calculated due to the low number of samples from the respective locality (Iceland, Chile).

respectively. The mean amounts of HCB and total DDTs in this study were $1.61 \mu\text{g}\cdot\text{kg}^{-1}$ WW and $3.07 \mu\text{g}\cdot\text{kg}^{-1}$ WW, respectively. These results showed that concentrations of the sums of DDTs were lower in this study, while the levels of HCB were slightly higher compared to the previous Norwegian study. No difference was observed in PCBs contamination, and levels were similar in wild ($0.16 \mu\text{g}\cdot\text{kg}^{-1}$ WW) and farmed ($0.15 \mu\text{g}\cdot\text{kg}^{-1}$ WW) salmon and were higher than PCBs amounts in our study ($0.08 \mu\text{g}\cdot\text{kg}^{-1}$ WW).

3.2.3. Brominated Flame Retardants. BFRs concentrations were the lowest among all targeted contaminants, and only BDE 47 (DF = 95%), BDE 100 (DF = 68%), BDE 49 (DF = 43%), and α -HBCD (DF = 11%) were found in the Norwegian salmon samples in amounts above the MQLs, which ranged between $0.05 \mu\text{g}\cdot\text{kg}^{-1}$ WW for PBDEs and other BFRs and $5 \mu\text{g}\cdot\text{kg}^{-1}$ WW for DBDPE. BDE 47 was the predominant PBDE congener found in concentrations <0.05 – $0.335 \mu\text{g}\cdot\text{kg}^{-1}$ WW, followed by α -HBCD (<0.05 – $0.141 \mu\text{g}\cdot\text{kg}^{-1}$ WW), BDE 100 (<0.05 – $0.120 \mu\text{g}\cdot\text{kg}^{-1}$ WW), and BDE 49 (<0.05 – $0.076 \mu\text{g}\cdot\text{kg}^{-1}$ WW). In salmon samples from Scotland, only BDE 47 (DF = 38%), BDE 100 (DF = 63%), and α -HBCD (DF = 13%) were detected, with concentrations fairly lower as compared to samples from Norway. BFRs residues were not found in samples from Iceland and Chile. Information on BFR contamination of salmon in the literature is scarce. Only the study published by Lundebye et al. [34] was dedicated to the sum of seven PBDEs including congeners Nos. 28, 47, 99, 100, 153, 154, and 183. BDE 47 levels were in the range of 0.1 – $1.0 \mu\text{g}\cdot\text{kg}^{-1}$ WW (mean: $0.6 \mu\text{g}\cdot\text{kg}^{-1}$ WW) in wild salmon and 0.16 – $4.10 \mu\text{g}\cdot\text{kg}^{-1}$ WW (mean: $0.5 \mu\text{g}\cdot\text{kg}^{-1}$ WW) in farmed salmon. These concentrations were higher compared to our data, where only BDE 47, BDE 49, and BDE 100 were detected, and the sum of their concentrations was <0.05 – $0.517 \mu\text{g}\cdot\text{kg}^{-1}$ WW (mean:

$0.295 \mu\text{g}\cdot\text{kg}^{-1}$ WW). Although no legislation limit is established for PBDEs, fish and seafood are considered the major sources of these pollutants [35].

3.2.4. Perfluoroalkylated and Polyfluoroalkylated Substances. Among the targeted PFAS, PFOA (DF = 100%), PFOA (DF = 80%), and PFHpA (DF = 55%) were detected in salmon samples from Norway. PFOA was the most abundant compound found at concentrations of <0.01 – $0.218 \mu\text{g}\cdot\text{kg}^{-1}$ WW, followed by PFOA 0.020 – $0.127 \mu\text{g}\cdot\text{kg}^{-1}$ WW and PFHpA <0.01 – $0.038 \mu\text{g}\cdot\text{kg}^{-1}$ WW. The concentrations of other PFAS were below the MQLs ($0.01 \mu\text{g}\cdot\text{kg}^{-1}$ WW) as well as their alternatives (ADONA, GenX, and isomers of F-53B). Surprisingly, PFOS was not detected in any of the Norwegian sampling samples. To the best of our knowledge, this is the first study to monitor the occurrence of PFAS alternatives in fish. In samples from Scotland, PFOA levels were below the MQLs ($0.01 \mu\text{g}\cdot\text{kg}^{-1}$ WW), PFOA was found in 65% of samples with amounts of <0.01 – $0.101 \mu\text{g}\cdot\text{kg}^{-1}$ WW, and PFOS was quantified in 30% of the samples at concentrations around the MQLs. None of the other target PFAS as well as their alternatives were detected in the samples from Scotland. In the case of samples from Chile, only PFOS was found in 20% of samples around the MQLs and samples from Iceland were free of all PFAS residues. Our data were in good agreement with the data from a Dutch study [36], where the amounts of \sum PFAS in farmed salmon from Norway and Scotland were generally low and did not exceed $0.5 \mu\text{g}\cdot\text{kg}^{-1}$ WW. Thus, PFOA was the major contributor to total PFAS concentrations in farmed salmon from Norway. In Scottish salmon, the profile of detected PFAS was richer, that is, PFOA, PFNA, PFTrDA, and PFOS were detected. Analogous results were achieved in a Finnish study [37]. The amounts of all studied PFAS were below MQLs which ranged between 0.35

and $0.62 \mu\text{g}\cdot\text{kg}^{-1}$ WW. Generally, the concentrations of PFAS in farmed fish are lower compared to wild marine fish, freshwater fish, or crustacean/bivalves [35, 36].

Although no legislation is applied for PFAS in foodstuffs, the European Commission is planning the limit for four major PFAS and their sum, that is, 2.0, 0.10, 0.10, 0.10, and $2.0 \mu\text{g}\cdot\text{kg}^{-1}$ WW for PFOS, PFOA, PFNA, PFHxS, and $\sum 4\text{PFAS}$, respectively. Based on the current TWI and data from the scientific online publication “Our World in Data” [38], the percentage fulfilment of TWI can be calculated. The average consumption of fish in the Czech Republic in 2017 was 9.31 kg per capita per year, which is about 180 g of fish per week. Considering the average weight of a human adult (70 kg) and a sample with the highest amount of four PFAS (PFOA, PFNA, PFHxS, and PFOS), $\sum 4\text{PFAS} = 0.248 \mu\text{g}\cdot\text{kg}^{-1}$ WW (in case that concentration of relevant PFAS representative was below MQL, the upper-bound approach was considered, that is, the value of MQL was counted), which corresponds with 44.6 ng of $\sum 4\text{PFAS}$ in 180 g of fish and a weekly intake of 0.63 ng/kg BW; the TWI was filled by 14.5%. If a lower-bound approach was assumed, that is, 0 was counted; when the relevant PFAS representative was below MQL, the TWI was filled by 12.7%. It should be noted that drinking water, eggs, milk, meat, and cereals are more significant sources of PFAS for the Czech population compared to fish. To increase TWI by the consumption of fish, the average consumption would have to be 7 times higher compared to the current consumption (1260 g per week/65.5 kg per year), which is very unlikely in the Czech Republic. However, PFOSA was found in almost all samples, and it was suggested that it could easily breakdown within in vivo metabolism into PFOS [39], and therefore, the estimates of TWI fulfilment are needed to be interpreted with caution as it is not known as what amount of PFOSA is changed to PFOS within the metabolism and how this could affect the total PFOS intake.

4. Conclusions

Farmed Atlantic salmon have an important role in human nutrition, and increased production is necessary in order to meet future demands for dietary protein and lipid. Our results demonstrate that farmed salmon, with an average protein content of 19.2% (w/w), is a suitable source of this macronutrient. As a fatty fish, Atlantic salmon also contained an average of 14.9% (w/w) lipids, including significant amounts of vitamin E which serves as a protective factor against PUFA-induced free radical damage. Although wild-caught salmon has been reported to contain a higher HUFA proportion per lipid than farmed salmon, its total lipid content is lower. Farmed salmon, despite lower ratios of EPA and DHA to fat, does not lose EPA and DHA due to their higher levels of total lipids, averaging 430 mg EPA + DHA/100 g fillets for fish from Chile, 940–1110 mg EPA + DHA/100 g fillets for fish from Norway, 1240 mg EPA + DHA/100 g fillets for fish from Iceland, and 1720 mg EPA + DHA/100 g fillets for fish from Scotland. As a result, consuming one 150 g serving of salmon per week is sufficient to provide the recommended weekly intake of EPA and DHA.

Of 64 possible halogenated contaminants, comprising PFAS, BFRs, PCBs, and OCPs, 20 representatives were detected in at least one sample. PFAS concentrations were highest in samples from Norway. No BFR residues were found in samples from Iceland and Chile. From the PCB group, the highest levels were measured in the Norwegian group, but the concentrations did not exceed the legislative limit for the sum of six NDL-PCBs. In samples from Iceland and Chile, the findings were below MQL. Concentrations of contaminants from the OCP group were very low, overall.

These results have demonstrated that human consumption of farmed Atlantic salmon is safe. However, further studies could focus on improving the balance of macronutrients and micronutrients in various feeds that affect the nutritional value of salmon. Regular monitoring of contaminants from the environmental burden should also be continued.

Abbreviations

BDE:	Brominated diphenyl ether
BFR:	Brominated flame retardant
DDD:	Dichlorodiphenyldichloroethane
DDE:	Dichlorodiphenyldichloroethylene
DDT:	Pesticide dichlorodiphenyltrichloroethane
DHA:	Docosahexaenoic acid
EFSA:	European Food Safety Authority
EPA:	Eicosapentaenoic acid
FAME:	Fatty acid methyl ester
FID:	Flame ionization detector
FOSA:	Perfluorooctanesulfonamide
HBCD:	Hexabromocyclododecane
HCB:	Hexachlorobenzene
HCH:	Hexachlorocyclohexane
HFR:	Halogenated flame retardant
HUFA:	Highly unsaturated fatty acid
MQL:	Method quantification limit
MUFA:	Monounsaturated fatty acid
NDL-PCB:	Nondioxin-like polychlorinated biphenyl
OCP:	Organochlorinated pesticide
PBDE:	Polybrominated diphenyl ether
PCB:	Polychlorinated biphenyl
PCBs:	Pentachlorobenzene
PCDD:	Polychlorinated dibenzo- <i>p</i> -dioxin
PCDF:	Polychlorinated dibenzofuran
PFAS:	Perfluoroalkylated and polyfluoroalkylated substances
PFHxS:	Perfluoro-1-hexanesulfonate
PFNA:	Perfluoro- <i>n</i> -nonanoic acid
PFOA:	Perfluoro- <i>n</i> -octanoic acid
PFOS:	Perfluoro-1-octanesulfonate
POP:	Persistent organic pollutant
PUFA:	Polyunsaturated fatty acid
SFA:	Saturated fatty acid
TBBPA:	Tetrabromobisphenol A
TDI:	Tolerably daily intake
TWI:	Tolerably weekly intake.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

A detailed description of used certified standards is provided. . (Supplementary Materials)

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