Hindawi
Aquaculture Research
Volume 2023, Article ID 5542117, 12 pages
https://doi.org/10.1155/2023/5542117

Research Article

A Comparative Analysis of the Nutritional Quality of Salmon Species in Canada among Different Production Methods and Regions

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Received 31 July 2023; Revised 30 October 2023; Accepted 11 November 2023; Published 15 December 2023

Academic Editor: Houguo Xu

Nutritional information of fresh seafood, including salmon, is not commonly available to the public, which can lead to misconceptions. The aim of this study was to determine the nutritional content of salmon fillets, comparing: (1) Canadian salmon, both wild (pink, chinook, and sockeye) and farmed (Atlantic salmon); (2) Canadian farmed Atlantic salmon grown in ocean net pens or land-based recirculating aquaculture systems (RAS); and (3) farmed Atlantic salmon raised in Canada compared with Scotland, Chile, and Ireland. Samples were purchased from retail stores in Canada and analyzed for moisture, crude protein, total lipid, fatty acids, amino acids, cholesterol, mercury, and color. The greatest differences in nutritional content were between species, rather than if it was wild or farmed. Compared to salmon raised in net pens, salmon raised in RAS had three times more eicosapentaenoic acid (EPA) + docosahexaenoic acid (DHA) per serving (0.7/100 g vs. 2.3/100 g, respectively), twice as much omega-3s (14% vs. 30%) and redder in color (24.7 vs. 30.1) but higher in saturated fats (18% vs. 24%). Scottish salmon had over double the amount of EPA + DHA per 100 g (1.6 g) than salmon from Canada (0.70 g), Chile (0.66 g), and Ireland (0.61 g). While nutritional content differed among salmon types, each type can provide dietary essential nutrients that can benefit consumers.

1. Introduction

Salmon is known as an excellent source of nutrients and contains essential omega-3 fatty acids, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) [1]. There are various species of salmon available to consumers. In Canada, the most popular are Atlantic (*Salmo salar*), pink (*Oncorhynchus gorbuscha*), chinook (*Oncorhynchus tshawytscha*), sockeye (*Oncorhynchus nerka*), coho (*Oncorhynchus kisutch*), and Chum (*Oncorhynchus keta*) salmon. Atlantic salmon is considered an endangered species in Canada due to overfishing [2]. In 2000, all commercial salmon fisheries in Eastern Canada were required to close, and mandatory catch and release was implemented [2]. While Indigenous communities retain the right to fish Atlantic salmon for food, social, and ceremonial purposes, as per the Constitution Act from 1982 [2], any Atlantic salmon that is purchased or consumed by the public in Canada is always farmed.

Atlantic salmon is one of the most successfully farmed fish globally, which means there is a high potential for growth, as the demand for sustainably produced food increases [3]. Norway, Chile, United Kingdom, and Canada are the four largest producers of Atlantic, which combined, produce 95.6% of Atlantic salmon globally [3]. The largest producer of Atlantic salmon is Norway, accounting for over half the global annual production [3, 4]. Canada is the fourth largest producer of farmed Atlantic salmon, making up 7% of the total salmon produced globally [3, 5]. The annual value of the salmon produced in Canada is $735.2 million, making it Canada's largest aquaculture export [6].

Traditionally, farmed salmon are reared in freshwater hatcheries until they reach smoltification and are transferred to cages or net pens in coastal ocean waters for postsmolt grow-out. However, in the past decade, there has been an increase in the development of land-based closed containment recirculating aquaculture systems (RAS). Because the salmon are grown in tanks on land in closed systems, this method allows for more environmental control, reduced interaction with the marine environment, allows flexibility in production location, and is not limited to coastal regions [7]. The development of RAS facilities can be promoted by using economic incentives, such as eco-labeling, because it appeals to many consumers that are more willing to pay more for a product with eco-labeling [7, 8]. However, the impact on the final nutritional value of salmon raised in net pens compared to salmon raised in RAS has not been reported to our knowledge.

Canadian consumers have shown some concerns related to aquaculture, such as environmental risks, the impact of farmed fish on wild populations, fish welfare, and the use of antibiotics [9]. It is a common misconception that eating wild salmon is healthier and safer than eating farmed salmon. Osmond et al. [10] found that 49% of Canadians prefer wild salmon over farmed salmon, for several reasons, including that they prefer to consume a product that was raised in its natural habitat and that wild salmon have less contaminants and are more nutritious and sustainable. The media often focuses on contaminants and the negative impact of farming fish and has resulted in decreased consumer confidence in salmon products [5, 8]. Although nutritional labeling is not required on unpackaged, fresh seafood products in Canada, eco-labeling and environmental certifications can improve consumer confidence [8]. Overall, the health benefits of consuming farmed salmon have been found to outweigh any potential risks from consuming contaminants [5, 11]. However, because this information is often not available to the consumer, coupled with the fact that there is a plethora of negative articles about salmon in the media, it can result in consumers avoiding salmon altogether, despite the health benefits.

The nutritional value, particularly the omega-3 content, can depend on the season, diet, and/or food availability, species, age, sex, and reproductive status of the fish and therefore can be highly variable [1, 12]. The amount of EPA + DHA in farmed salmon depends mostly on their diet [12, 13] and this may be different depending on the country. For example, Scottish salmon farming focuses on creating a premium product, whereas Norwegian salmon farming focuses more on the sustainability of the farming practices [12]. Therefore, Norwegian salmon farms may include higher amounts of terrestrial oils in their diets than Scottish farms, resulting in lower EPA and DHA [12]. The color of salmon is an important indicator of the freshness, quality, species, flavor, and price of the product [14, 15]. Redder salmon is associated with being fresher, having a higher quality, better flavor and texture, and higher price [14]. In Norway, astaxanthin makes up 15% of the feed cost, and the cost of feed makes up 50% of the total farming cost [15]. Therefore, ensuring that farmed salmon have the characteristic red color to meet consumer expectations is an important, yet costly part of salmon farming [15]. These production differences may result in different nutritional and sensory profiles of farmed salmon depending on the region; however, this has not been investigated and is important from a consumer perspective.

A previous study by Colombo and Mazal [1] compared the nutritional content of six salmon types raised or caught in Canada. Wild pink salmon was the lowest in fat and highest in moisture, making it the least nutritious option. Wild sockeye, wild chinook, and farmed Atlantic salmon were found to be excellent options for consumers because they were the most nutrient dense. The present study will expand on the previous study by analyzing the nutritional content of different salmon types.

This study will evaluate the nutritional value of different types of salmon available to Canadian consumers and compared among rearing conditions and geographical locations. Since the nutritional content is not normally available, this could improve consumer knowledge and confidence in their choice of salmon product. Three categories of salmon will be compared to determine differences in nutritional content: (1) Canadian salmon species and wild and farmed salmon originating from the Atlantic and Pacific coasts of Canada, (2) Canadian farm-raised salmon grown in net pens compared to land-based RAS, and (3) farm-raised Atlantic salmon from Canada, Ireland, Scotland, and Chile. This research can provide baseline data on nutritional content for different salmon types to help consumers understand the nutritional value of different types of salmon.

2. Materials and Methods

2.1. Experimental Design. Different types of salmon fillets were purchased from stores in Canada (Truro, Nova Scotia, and Toronto, Ontario) in June 2021. These types were selected because they were readily available for purchase by any consumer through retail. This study was limited by the salmon types available for purchase in our location; however, it represents the selection that average Canadian consumers can conveniently access. The salmon types included: wild pink ($n = 4$), wild chinook ($n = 4$), wild sockeye ($n = 2$), farmed Atlantic salmon (net pen raised in Canada, $n = 8$), farmed Atlantic salmon (RAS raised in Canada, $n = 8$), and farmed Atlantic salmon from Scotland ($n = 4$), Ireland ($n = 4$), and Chile ($n = 4$). Chinook salmon is commonly known as King salmon or Spring salmon, and Sockeye salmon is commonly known as red salmon. Sample selection was representative of salmon types available to Canadian consumers. Samples were prepared within 1 week of purchase and analysis was conducted within 3 weeks of purchase. While it is recognized that nutritional composition and sensory properties may change over time and may also depend on slaughter method, our goal was to collect data from fillets that were available at the store and consumed by the public.

The salmon samples were prepared for analysis at Dalhousie University Agricultural Campus (Truro, Nova Scotia, Canada). The frozen salmon samples (all but farmed Atlantic net pen raised in Canada) were thawed in a refrigerator overnight at 4°C, then kept cold in a cooler bag with ice packs while in the lab. Color analyses were conducted first, then the fillets were prepared for biochemical analyses.

2.2. Color Analysis. Fillet color was analyzed using a Miniscan XE™ colorimeter (Hunter Associates Laboratory, Reston, Virginia, USA). The colorimeter was placed on the same area of each fillet. It was placed away from the lateral line, as this area is lighter than the other parts of the fillet. The colorimeter was wiped with a Kimwipe between each filet. The Hunter color scale was used to produce quantitative values for color, which was measured within the L* (lightness), a* (redness), and b* (yellowness), color space in accordance with the Commission Internationale de l-Eclairage [16].

2.3. Sample Preparation for Biochemical Analysis. The skin from the salmon samples was removed using a filleting knife, as the skin was not included in the analysis since most consumers do not eat the skin. The thickness of each fillet was measured in centimeters with a ruler before homogenization. Each fillet was homogenized using an electric meat grinder (Paderno, Pardinox Inc., Toronto, Ontario, Canada), and the meat grinder was washed between each sample. A sample of 25 g was removed and reserved in separate bags for the mercury analysis (see below) and stored at −80°C prior to analysis. The remaining sample was freeze-dried and then ground in a blender into a fine powder (Nutri Ninja blender, imported by Shark Ninja operating LLC, Quebec, Canada). The homogenous, dry powder samples were stored in a −80°C freezer until further biochemical analysis was completed.

2.4. Biochemical Analysis. The crude lipid of the samples was analyzed using an ANKOM TX15 fat extractor (Ankom Technology, New York, USA) and followed the manufacturer's operating procedure, which is based on the AOCS Standard Procedure Am 5-04 [17] for rapid determination of oil/fat utilizing high-temperature solvent extraction. Protein was analyzed using the LECO FP-528 nitrogen analyzer (LECO, St. Joseph, Michigan, USA) using the Dumas conversion factor (crude protein = nitrogen × 6.25).

Lipids were extracted and derivatized to obtain fatty acid methyl esters (FAMEs) with the Folch et al. [18] method for extraction and Christie and Han [19] for methylation. Approximately 20 mg of each homogenized sample (see sample preparation above) were weighed into test tubes, then 3 mL of 2 : 1 chloroform:methanol was added. The resulting extract was derivatized into FAMEs using H_2SO_4 in methanol as a catalyst. The resulting FAMEs were analyzed by gas chromatography (SCION 436; SCION Instruments, Livingston, UK) at the Marine Lipid Lab at Dalhousie University (Halifax, Nova Scotia, Canada). For full methodological details on extraction and derivatization, see Colombo and Mazal's [1] study.

Amino acid and cholesterol were analyzed by the University of Missouri, Experiment Station Chemical Laboratories (Columbia, Missouri, USA). Ten grams per fillet of the homogenous freeze-dried sample was packaged with dry ice. For amino acids, cation-exchange chromatography (cIEC-HPLC) and postcolumn ninhydrin derivatization and quantitation were used. For cholesterol, high-performance liquid chromatography (HPLC) was used. For all biochemical analyses, dry weight values were converted to a wet weight basis to reflect more accurate nutritional values for consumption.

2.5. Mercury Analysis. Mercury was analyzed by Bureau Veritas Laboratories (Mississauga, Ontario, Canada). Twenty-five grams of the wet sample for each filet was placed in labeled sample bags and packaged with dry ice. Mercury was analyzed using the Standards Council of Canada accredited method for determination of total mercury in fish, shellfish, and food products by cold vapor atomic fluorescence spectroscopy (SOM-DAR-CHE-012).

2.6. Literature Review of Salmon Species. Literature was reviewed to create a new data set of key fatty acids from different species of salmon. The research papers were collected from Dalhousie University Libraries Novanet Research Engine and Google Scholar. The search terms "salmon" and "fatty acid" were used. Once the appropriate research paper was selected, the paper was thoroughly read to determine if the key fatty acids of interest were reported: linoleic acid (LNA; 18 : 2*n*-6), alpha-linoleic acid (ALA; 18 : 3*n*-3), EPA, DHA, total saturated fatty acids (SFA), total monounsaturated fatty acids (MUFA), and total polyunsaturated fatty acids (PUFA). The collected data were entered into a database in Microsoft Excel. Most research papers contained all the target fatty acids, but there were some instances where a fatty acid was not reported, however was not considered zero unless reported as such. The species, and whether it was wild or farmed, was recorded. The location was also recorded but too variable to use as a factor of interest. Most studies were reported in % total fatty acid, which was used in the analysis. If fatty acids were reported as a quantity (e.g., mg/g) and the total FA was provided, then % total fatty acid was calculated. If it was not possible to convert to %, the data were not used.

2.7. Statistical Analysis. Four comparative analyses were conducted to determine the difference in biochemical composition and sensory properties depending on the following factors: species, wild or farmed, farmed production method (net pen or RAS raised), and farming location (Canada, Scotland, Ireland, Chile). For the species comparison analysis, farmed Atlantic salmon included those from net pen and RAS raised in Canada only (in order to negate any potential variability due to the location factor). Each variable was tested for normality by an Anderson–Darling test before continuing with the statistical analysis. A general linear regression was performed to analyze these residuals. For each model tested, the normality, homogeneity, and independence of residuals were considered. Two-sample *t*-tests were used to compare the Canadian wild and farmed salmon samples and to compare the Canadian net pen and land-based salmon samples.

3. Results

3.1. Comparison of Species in Canada. Nutritional content was different among species of salmon (Table 1). Pacific pink salmon had a significantly higher moisture content, with Atlantic salmon having the lowest moisture. Atlantic and chinook salmon had the highest fat content compared to pink and sockeye salmon, and chinook was higher in fat

Table 1: Nutritional, biochemical, mercury, and sensory quality parameters of different salmon species, with comparison among species and whether the salmon were farmed or wild-caught[1].

Parameter	Atlantic (farmed) ($n = 16$)	Pink (wild) ($n = 4$)	Chinook (wild) ($n = 4$)	Sockeye (wild) ($n = 2$)	Species p-value	Wild vs. farmed p-value
Moisture (% ww)	62.7 ± 5.5^{b}	78.4 ± 0.5^{a}	64.4 ± 0.9^{b}	68.0 ± 3.3^{ab}	<0.001	0.006
Protein (% ww)	20.6 ± 2.1	17.4 ± 0.8	20.4 ± 0.8	22.6 ± 0.5	0.560	0.461
Fat (% ww)	11.6 ± 2.9^{a}	1.0 ± 0.6^{c}	9.8 ± 1.4^{ab}	4.2 ± 0.8^{bc}	<0.001	<0.001
Cholesterol (% ww)	77.6 ± 22.5^{b}	176.6 ± 37.8^{a}	48.9 ± 6.3^{b}	66.7 ± 8.2^{b}	<0.001	0.163
Mercury (μg/g ww)	0.02 ± 0.02	0.01 ± 0.01	0.04 ± 0.004	0.05 ± 0.01	0.056	0.235
Amino acids (g/100 g WW)						
Threonine	0.91 ± 0.01^{a}	0.78 ± 0.03^{b}	0.91 ± 0.03^{a}	0.98 ± 0.02^{a}	0.040	0.379
Valine	1.22 ± 0.19^{a}	0.73 ± 0.018^{b}	1.20 ± 0.03^{a}	1.08 ± 0.11^{ab}	<0.001	0.016
Methionine	0.60 ± 0.06^{ab}	0.53 ± 0.02^{b}	0.60 ± 0.02^{ab}	0.67 ± 0.01^{a}	0.041	0.667
Isoleucine	0.10 ± 0.12^{a}	0.84 ± 0.04^{b}	1.04 ± 0.04^{a}	1.09 ± 0.03^{a}	0.010	0.532
Leucine	1.55 ± 0.17^{ab}	1.37 ± 0.05^{b}	1.58 ± 0.05^{ab}	1.73 ± 0.04^{a}	0.036	0.718
Phenylalanine	0.86 ± 0.10^{a}	0.72 ± 0.02^{b}	0.90 ± 0.02^{a}	0.95 ± 0.03^{a}	0.007	0.526
Lysine	1.76 ± 0.20^{ab}	1.53 ± 0.06^{b}	1.80 ± 0.06^{ab}	1.94 ± 0.05^{a}	0.033	0.554
Histidine	0.56 ± 0.06^{a}	0.45 ± 0.02^{b}	0.61 ± 0.02^{a}	0.61 ± 0.04^{a}	0.001	0.783
Tryptophan	0.23 ± 0.03^{ab}	0.20 ± 0.03^{b}	0.25 ± 0.01^{a}	0.25 ± 0.01^{ab}	0.028	0.851
Arginine	1.1 ± 0.12	1.1 ± 0.04	0.91 ± 0.61	1.3 ± 0.03	0.176	0.212
Fatty acids (% of total fatty acids)						
18 : 1n-9	27.1 ± 10.1^{a}	8.15 ± 2.4^{b}	18.1 ± 0.6^{ab}	13.5 ± 0.02^{ab}	0.002	<0.001
18 : 2n-6	10.1 ± 7.9^{a}	1.7 ± 1.0^{b}	1.5 ± 0.1^{b}	1.8 ± 0.7^{b}	0.036	0.003
18 : 3n-3	2.3 ± 1.5	0.8 ± 0.2	1.3 ± 0.1	0.8 ± 0.1	0.114	0.016
20 : 5n-3	6.6 ± 3.7	7.3 ± 0.5	7.8 ± 0.3	4.8 ± 0.3	0.703	0.718
20 : 4n-6	0.6 ± 0.3	0.4 ± 0.02	0.5 ± 0.02	0.4 ± 0.04	0.553	0.166
22 : 6n-3	7.7 ± 4.1^{b}	14.8 ± 1.8^{a}	12.2 ± 0.5^{ab}	11.4 ± 1.5^{ab}	0.006	0.001
ΣSFA[2]	21.1 ± 3.6^{b}	23.8 ± 3.1^{ab}	27.4 ± 0.3^{a}	21.2 ± 0.8^{ab}	0.012	0.014
ΣMUFA[3]	41.4 ± 5.7^{b}	43.6 ± 2.4^{ab}	39.3 ± 0.5^{b}	54.0 ± 2.9^{a}	0.013	0.286
ΣPUFA[4]	37.1 ± 3.0^{a}	32.0 ± 1.8^{b}	32.6 ± 0.7^{b}	24.1 ± 2.1^{c}	<0.001	<0.001
Σn-3	22.2 ± 8.9	28.0 ± 2.2	28.1 ± 1.5	20.2 ± 1.5	0.296	0.158
Σn-6	11.9 ± 8.0^{a}	2.8 ± 1.0^{b}	2.7 ± 0.1^{b}	3.0 ± 0.8^{b}	0.023	0.002
n-3/n-6	5.3 ± 7.6	10.9 ± 3.6	10.5 ± 0.4	6.9 ± 1.3	0.305	0.075
EPA + DHA (g/100 g WW)	1.5 ± 0.9^{a}	0.2 ± 0.1^{b}	1.8 ± 0.2^{a}	0.6 ± 0.04^{ab}	0.016	0.102
Color						
L (lightness)	54.3 ± 3.1^{a}	56.1 ± 2.6^{a}	50.1 ± 0.3^{b}	52.9 ± 0.6^{ab}	0.027	0.340
A (redness)	27.4 ± 4.9^{ab}	22.4 ± 1.5^{b}	31.4 ± 0.36^{a}	26.7 ± 3.2^{ab}	0.044	0.766
B (yellowness)	29.2 ± 5.1	24.8 ± 1.8	26.4 ± 0.6	24.5 ± 1.5	0.179	0.011

[1]Values are mean ± standard deviation; different superscripts letters indicate differences among species. [2]Saturated fatty acid. [3]Monounsaturated fatty acid. [4]Polyunsaturated fatty acid.

than pink salmon. Pink salmon had the highest cholesterol content compared to all other species. There was no difference in protein content among species or between wild and farmed. Mercury ranged from 0.01 to 0.05 μg/g but was not different among species or between wild and farmed. There were significant differences in the essential amino acid profile among species: overall, pink salmon had the lowest amount of each amino acid compared to all other species.

In terms of fatty acids, Atlantic salmon contained a higher proportion of 18 : 1*n*-9 compared to pink salmon, but chinook and sockeye did not vary among species. Atlantic salmon also contained a higher level of LNA compared to all other species. There was no significant difference in the proportion of EPA or arachidonic acid among species. The DHA level was lower in Atlantic salmon compared to pink salmon. There was no difference among species in total *n*-3 fatty acids, but Atlantic had a higher level of *n*-6 fatty acids compared to all other species. The amount of EPA + DHA per serving (g/100 g wet weight) was higher in Atlantic and chinook salmon compared to pink salmon.

In terms of color, chinook salmon were lighter in color compared to Atlantic salmon and pink salmon, while pink salmon was less red than chinook salmon, with no difference in redness among Atlantic salmon, chinook salmon, and sockeye salmon.

3.2. Comparison of Wild and Farmed Salmon. There were fewer significant differences comparing farmed and wild salmon, compared to differences among species (Table 1). Moisture content (%) was higher in wild salmon (70.7 ± 6.9) compared to farmed (62.7 ± 5.5), while fat content (% wet weight) was higher in farmed (11.6 ± 2.9) compared to wild (5.2 ± 1.4). Valine (% wet weight) was higher in farmed salmon (1.3 ± 0.2) than wild salmon (0.9 ± 0.2). The 18-carbon fatty acids (18 : 1*n*-9, LNA, and ALA) were higher in farmed compared to wild salmon, while wild salmon was higher in DHA ($13.1\% \pm 1.9$ vs. $7.8\% \pm 4.1$) and total SFA (24.7 ± 3.1 vs. 21.1 ± 3.6) compared to farmed. Farmed salmon were higher in total PUFA and *n*-6 fatty acids. There was no difference in EPA + DHA per serving between wild and farmed salmon. In terms of color, farmed salmon were more yellow in color compared to wild salmon.

3.3. Comparison of Net Pen and RAS-Raised Atlantic Salmon in Canada. There were few significant differences between net pen compared to RAS raised salmon (Table 2). Net pen salmon contained higher levels of 18-carbon fatty acids (18 : 1*n*-9, ALA, and LNA) but contained lower EPA and DHA compared to RAS salmon. Total SFA and PUFA were lower in net pen salmon, but MUFA was lower in RAS salmon. Total *n*-3 fatty acids were twice as high in RAS salmon compared to net pen salmon, and total *n*-6 fatty acids were more than four times higher in net pen-raised salmon. Total EPA + DHA per serving (g/100 g wet weight) was three times higher in land-based raised salmon. Salmon raised in RAS were more red and yellow in color than those raised in net pens.

3.4. Comparison of Atlantic Salmon from Canada, Chile, Ireland, and Scotland. There were no significant differences in moisture, protein, fat, cholesterol, or any of the essential amino acids among Atlantic salmon farmed in Canada, Chile, Ireland, and Scotland (Table 3). Mercury content was not different among farmed salmon raised in these countries and was below detection limits for Canadian and Irish salmon. The fatty acid profile showed significant differences in salmon among different countries. Oleic acid (18 : 1*n*-9) was highest in salmon from Ireland and lower in salmon from Canada and Chile, while salmon from Scotland had the lowest level. Salmon from Canada had higher LNA than salmon from Ireland. ALA was higher in salmon from Chile compared to Scotland. EPA was higher in salmon from Scotland compared to Ireland but did not differ among the other groups. Salmon from Scotland had the highest DHA level compared to Canada and Chile and was significantly lowest in salmon from Ireland. Salmon from Scotland had the highest SFA but lowest MUFA, while Irish salmon had the highest MUFA and lowest SFA. Total PUFA was highest in Scottish salmon compared to all groups, and lowest in Irish salmon. Scottish salmon also had the highest *n*-3 content compared to all groups and was lowest in Irish salmon. The *n*-3/*n*-6 ratio was highest in Scottish salmon but did not differ among the other groups. The amount of EPA + DHA per 100 g serving was highest in Scottish salmon. Canadian salmon were less yellow in color compared to Scottish salmon.

3.5. Literature Review of Salmon Species. A total of 185 fatty acid profiles from 57 studies were included in the data set and is summarized in Table 4. The full data set and references can be viewed in the Supplementary Information (Table S1). Salmon species found in the literature included those analyzed in this study (Atlantic, pink, chinook, and sockeye), as well as coho, chum, and Masu (*Oncorhynchus masou*). Within this data set, farmed salmon had significantly higher LNA ($p < 0.001$) and ALA ($p = 0.014$), but lower EPA ($p = 0.007$; Table 4). Total SFA was higher in wild salmon ($p < 0.001$), while MUFA was higher in farmed salmon ($p < 0.001$). DHA ($p = 0.463$) and total PUFA were not different between wild and farmed salmon ($p = 0.559$). Among species, LNA was highest in Atlantic salmon compared to any other species, while chinook, chum, pink, and sockeye were among the lowest (Table 4). ALA was also higher in Atlantic salmon compared to chinook, chum, masu, and pink salmon. EPA was lower in masu compared with Atlantic, chinook, chum, and pink salmon. DHA and total PUFA were not different among species. Total SFA were higher in masu compared to any other species. Atlantic salmon had higher total MUFA compared to chinook and coho, and chum was higher in PUFA than coho.

4. Discussion

4.1. Canadian Salmon Species, Wild and Farmed. Nutritional and quality measurements varied among species of salmon

Table 2: Nutritional, biochemical, mercury, and quality parameters of farmed Atlantic salmon in Canada raised in net pens compared to salmon raised in land-based closed contained-recirculating aquaculture systems ($n = 8$ for each type, mean ± standard deviation, presented on a wet weight basis)[1].

Nutrient	Net pen	Land-based	p-Value
Moisture (%)	63.4 ± 7.9	61.9 ± 1.5	0.632
Protein (%)	20.3 ± 3.1	20.4 ± 0.9	0.944
Fat (%)	11.3 ± 4.1	11.9 ± 1.2	0.651
Cholesterol (%)	76.3 ± 35.0	78.9 ± 21.2	0.829
Mercury (μg/g)	Not detected	Not detected	–
Amino acids (g/100 g WW)			
Threonine	0.89 ± 0.14	0.92 ± 0.04	0.490
Valine	1.23 ± 0.26	1.22 ± 0.10	0.953
Methionine	0.59 ± 0.0857	0.61 ± 0.02	0.501
Isoleucine	0.97 ± 0.15	1.02 ± 0.45	0.458
Leucine	1.51 ± 0.23	1.58 ± 0.06	0.431
Phenylalanine	0.84 ± 0.13	0.89 ± 0.05	0.300
Lysine	1.73 ± 0.27	1.80 ± 0.09	0.497
Histidine	0.55 ± 0.09	0.57 ± 0.02	0.592
Tryptophan	0.25 ± 0.04	0.22 ± 0.01	0.141
Arginine	1.16 ± 0.12	1.20 ± 0.05	0.567
Fatty acids (% of total fatty acids)			
18 : 1n-9	36.5 ± 2.5	17.6 ± 3.1	<0.001
18 : 2n-6	17.7 ± 2.5	2.7 ± 1.8	<0.001
18 : 3n-3	3.6 ± 1.1	0.9 ± 0.2	<0.001
20 : 5n-3	3.2 ± 1.2	9.9 ± 1.8	<0.001
20 : 4n-6	0.5 ± 0.2	0.7 ± 0.4	0.164
22 : 6n-3	3.9 ± 0.6	11.4 ± 1.9	<0.001
ΣSFA[2]	17.8 ± 0.2	24.4 ± 1.0	<0.001
ΣMUFA[3]	46.5 ± 0.7	36.3 ± 3.4	<0.001
ΣPUFA[4]	35.4 ± 0.7	38.9 ± 3.5	0.015
Σn-3	14.1 ± 1.3	30.2 ± 4.3	<0.001
Σn-6	19.4 ± 2.5	4.4 ± 1.9	<0.001
n-3/n-6	0.7 ± 0.2	9.8 ± 8.6	0.010
EPA + DHA (g/100 g WW)[5]	0.70 ± 0.2	2.3 ± 0.5	<0.001
Color			
L (lightness)	53.2 ± 2.5	55.5 ± 3.4	0.154
A (redness)	24.7 ± 4.8	30.1 ± 3.5	0.023
B (yellowness)	26.6 ± 3.6	31.8 ± 5.2	0.036

[1]Values are mean ± standard deviation. [2]Saturated fatty acid. [3]Monounsaturated fatty acid. [4]Polyunsaturated fatty acid. [5]Eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA)

in this study, which was expected based on previous studies [1, 20]. Species was a stronger factor than whether the salmon was wild or farmed-raised. Pink salmon contained the highest level of moisture (78%), and as such, is less nutrient-dense compared to other species. Therefore, consuming pink salmon requires a greater serving size to obtain the same amount of nutrients compared to the other salmon types. Total fat was higher in Atlantic and chinook salmon, and subsequently lower water content. Pink salmon is known to contain a lower fat content with high water content [1]; however, this also translates to lower EPA and DHA amounts that are stored in the fillet. Farmed salmon were also higher in fat compared to wild salmon. Higher or lower fat content in various types of salmon provides options for people with different dietary needs. Notably, there was no difference in protein or mercury content among species. The mercury content for all species was well below the consumption guidelines by Health Canada. Salmon is not included in Health Canada's dietary recommendations for heavy metals because the level of mercury does not pose a risk to human health [21]. Cholesterol in pink salmon was two to three times higher compared to other species. Indeed, cholesterol serves essential functions in the body and is necessary for maintaining cell membrane structure and for synthesis of vitamin D, bile acids, and some hormones; although consuming too much can lead to cardiovascular disease [22]. Compared to other nutritious

Table 3: Nutritional, biochemical, mercury, and quality parameters of farmed Atlantic salmon raised in net pens in Canada ($n = 8$), Chile, Ireland, and Scotland ($n = 4$ per group, mean ± standard deviation, presented on a wet weight basis)[1].

Nutrient	Canada	Chile	Ireland	Scotland	p-Value
Moisture (%)	63.4 ± 7.9	66.2 ± 1.5	61.3 ± 2.4	63.6 ± 3.1	0.660
Protein (%)	22.0 ± 2.5	20.7 ± 0.8	22.0 ± 8.0	19.4 ± 0.5	0.686
Fat (%)	11.3 ± 4.1	9.5 ± 1.8	12.9 ± 2.6	13.0 ± 2.9	0.415
Cholesterol (%)	76.3 ± 25.0	67.4 ± 4.1	75.2 ± 6.9	64.0 ± 5.1	0.621
Mercury (μg/g)	Not detected	0.02 ± 0.01	Not detected	0.06 ± 0.01	0.621
Amino acids (g/100 g WW)					
Threonine	0.89 ± 0.13	0.89 ± 0.04	0.89 ± 0.02	0.82 ± 0.02	0.618
Valine	1.22 ± 0.19	1.13 ± 0.05	1.31 ± 0.08	1.01 ± 0.04	0.141
Methionine	0.59 ± 0.07	0.59 ± 0.03	0.59 ± 0.02	0.54 ± 0.01	0.556
Isoleucine	0.97 ± 0.12	0.96 ± 0.05	0.97 ± 0.04	0.89 ± 0.03	0.159
Leucine	1.51 ± 0.23	1.52 ± 0.07	1.53 ± 0.06	1.38 ± 0.04	0.522
Phenylalanine	0.84 ± 0.12	0.84 ± 0.03	0.87 ± 0.02	0.77 ± 0.02	0.448
Lysine	1.73 ± 0.19	1.73 ± 0.07	1.74 ± 0.06	1.59 ± 0.05	0.619
Histidine	0.56 ± 0.06	0.54 ± 0.03	0.55 ± 0.02	0.49 ± 0.02	0.267
Tryptophan	0.25 ± 0.04	0.24 ± 0.02	0.25 ± 0.01	0.21 ± 0.01	0.104
Arginine	1.16 ± 0.12	1.16 ± 0.05	1.16 ± 0.04	1.07 ± 0.02	0.627
Fatty acids (% of total fatty acids)					
18 : 1n-9	36.5 ± 2.5^{b}	35.6 ± 0.7^{b}	45.5 ± 0.2^{a}	16.9 ± 0.5^{c}	<0.001
18 : 2n-6	17.4 ± 2.5^{a}	17.4 ± 0.1^{ab}	14.2 ± 0.3^{b}	15.0 ± 0.2^{ab}	0.016
18 : 3n-3	3.6 ± 1.1^{ab}	4.5 ± 0.1^{a}	4.4 ± 0.1^{a}	2.4 ± 0.01^{b}	0.004
20 : 4n-6	0.5 ± 0.1	0.4 ± 0.02	0. ± 0.01	0.05 ± 0.02	0.219
20 : 5n-3	3.2 ± 1.2^{ab}	3.2 ± 0.2^{ab}	2.5 ± 0.07^{b}	4.4 ± 0.1^{a}	0.029
22 : 6n-3	3.9 ± 0.6^{b}	4.5 ± 0.4^{b}	2.8 ± 0.2^{c}	8.8 ± 0.3^{a}	<0.001
ΣSFA[2]	17.8 ± 1.2^{b}	17.9 ± 0.4^{b}	16.0 ± 0.6^{c}	22.0 ± 0.2^{a}	<0.001
ΣMUFA[3]	46.5 ± 0.7^{b}	45.2 ± 0.7^{c}	54.9 ± 0.2^{a}	38.1 ± 0.1^{d}	<0.001
ΣPUFA[4]	35.4 ± 0.8^{c}	36.7 ± 0.3^{b}	28.9 ± 0.5^{d}	39.5 ± 0.3^{a}	<0.001
Σn-3	14.1 ± 1.3^{c}	15.7 ± 0.5^{b}	12.1 ± 0.3^{d}	20.9 ± 0.3^{a}	<0.001
Σn-6	19.4 ± 2.5^{a}	19.3 ± 0.2^{a}	15.8 ± 0.3^{b}	17.1 ± 0.3^{ab}	0.008
n-3/n-6	0.7 ± 0.2^{b}	0.8 ± 0.03^{b}	0.8 ± 0.001^{b}	1.2 ± 0.03^{a}	<0.001
EPA + DHA (g/100 g WW)	0.70 ± 0.2^{b}	0.66 ± 0.06^{b}	0.61 ± 0.1^{b}	1.6 ± 0.3^{a}	<0.001
Color					
L (lightness)	53.2 ± 2.5	56.0 ± 1.0	53.3 ± 0.3	52.6 ± 2.2	0.329
A (redness)	24.7 ± 4.8	31.2 ± 4.0	29.3 ± 1.3	30.3 ± 1.2	0.051
B (yellowness)	26.5 ± 3.6^{b}	34.0 ± 4.1^{a}	30.4 ± 1.5^{ab}	31.8 ± 0.9^{a}	0.012

[1]Values are mean ± standard deviation; different superscripts letters indicate differences among countries. [2]Saturated fatty acid. [3]Monounsaturated fatty acid. [4]Polyunsaturated fatty acid.

animal-based protein sources, salmon (regardless of species) contains less cholesterol [23].

The amino acid profile did not vary due to salmon being farmed or wild. Among species, however, there were some minor, yet significant differences. The fatty acid profile was more highly variable, however. It is well-known that salmon fillet fatty acid composition is reflective of the diet. Differences observed in fatty acid content of salmon in this study not only demonstrate species differences but also likely indicate dietary differences. Certain fatty acids are considered biomarkers and used as indicators for diet composition and different food or prey items [24]. For example, farmed salmon contained higher levels of 18-carbon fatty acids (18 : 1n-9, 18 : 2n-6, 18 : 3n-3) than wild salmon. Modern salmon feeds contain vegetable oils as a primary fat source in the diet, which contain majority 18-carbon fatty acids, and are reflected in the tissue fatty acid profile. There was no difference in EPA content; however, DHA was highest in pink salmon (as a % of fatty acids, not total amount) compared to Atlantic salmon and was higher in wild salmon compared to farmed salmon. Species differences were also observed in the larger data set from the literature (see Table 4), which supports the above findings.

For the amount of EPA + DHA per serving, there was no difference between wild and farmed salmon, despite previous studies have found that farmed salmon contain lower amounts of EPA and DHA [12, 25, 26]. Rather, there were differences due to species. Atlantic and chinook salmon had the highest EPA and DHA per serving. The present study did not find differences in the total sum n-3 PUFA content,

Table 4: Select fatty acids and fatty acid groups of different salmon species obtained from a data set extracted from a literature review including 57 studies (full data set and references available in Table S1)[1].

Salmon fatty acids	Atlantic ($n = 84$)	Chinook ($n = 14$)	Chum ($n = 17$)	Coho ($n = 10$)	Masu ($n = 29$)	Pink ($n = 15$)	Sockeye ($n = 13$)	p-Value
18 : 2n-6	6.5 ± 4.2^{a}	3.3 ± 2.9^{bc}	0.9 ± 0.4^{c}	4.2 ± 3.1^{abc}	4.1 ± 3.1^{b}	2.4 ± 1.6^{bc}	2.3 ± 1.7^{bc}	<0.001
18 : 3n-3	2.8 ± 2.5^{a}	1.2 ± 0.4^{b}	0.7 ± 0.2^{b}	1.3 ± 0.9^{ab}	0.5 ± 0.3^{b}	1.1 ± 0.5^{b}	1.3 ± 0.9^{ab}	<0.001
20 : 5n-3	5.5 ± 2.9^{a}	8.4 ± 2.9^{a}	9.1 ± 4.5^{a}	8.3 ± 3.2^{ab}	5.5 ± 2.3^{b}	8.5 ± 2.2^{a}	6.4 ± 2.1^{ab}	<0.001
22 : 6n-3	13.1 ± 19.1	20.4 ± 10.2	18.0 ± 13.6	17.0 ± 6.8	15.2 ± 7.4	23.5 ± 12.0	17.2 ± 11.7	0.222
ΣSFA[2]	22.9 ± 7.6^{b}	29.7 ± 5.2^{b}	27.1 ± 8.8^{b}	27.5 ± 5.1^{b}	39.1 ± 9.2^{a}	26.4 ± 6.0^{b}	27.4 ± 6.3^{b}	<0.001
ΣMUFA[3]	38.8 ± 14.1^{a}	27.5 ± 15.1^{bc}	35.8 ± 18.6^{ab}	28.2 ± 13.9^{c}	32.4 ± 10.3^{abc}	31.5 ± 10.6^{abc}	39.4 ± 14.4^{abc}	<0.001
ΣPUFA[4]	30.7 ± 10.2	39.8 ± 11.8	36.3 ± 16.1	–	28.4 ± 6.7	38.5 ± 16.9	36.7 ± 13.3	0.327

[1]Values are mean ± standard deviation; different superscripts letters indicate differences among countries. [2]Saturated fatty acid. [3]Monounsaturated fatty acid. [4]Polyunsaturated fatty acid.

although farmed salmon contained higher n-6 PUFA, which is likely due to inclusion of some vegetable oils, for example, canola. Atlantic salmon still contained a high amount of n-3 fatty acids, likely because only 50%–80% of the lipid in the diet can be replaced with terrestrial plant oils to maintain health and quality of the fish. Sprague et al. [12] found that on average, wild salmon contained 0.76 g of EPA and DHA per 100 g of wet weight, whereas farmed salmon contained 1.36 g of EPA and DHA per 100 g of wet weight. The present study found similar values, with farmed Atlantic salmon containing 1.50 g of EPA and DHA per 100 g of wet weight, and wild salmon containing an average 0.817 g of EPA and DHA per 100 g of wet weight. The World Health Organization (WHO) recommendation is 250 mg of EPA + DHA per day and a single serving of fish is approximately 100 g according to various health authorities, such as the American Heart Health Association and the Mayo Clinic. This recommended amount of EPA and DHA is exceeded in all salmon species in this study, except for pink salmon, which 150 g (1.5 servings) would need to be consumed to meet the WHO recommendation.

Flesh coloration is an economically and evolutionarily significant trait that varies inter- and intra-specifically [27]. Carotenoids, particularly astaxanthin, are primarily responsible for the characteristic red flesh coloration of salmon. Chinook salmon were darkest in color compared to Atlantic and pink salmon but did not differ from sockeye salmon. Chinook, also known as red salmon, were also redder in color compared to pink salmon. Farmed salmon were more yellow in color compared to wild salmon. This demonstrates the variety in color and nutrient composition among species of salmon. Ambati et al. [28] found that sockeye salmon contained significantly higher astaxanthin than any other salmon type and that Atlantic salmon contained more astaxanthin than Chinook salmon. Chinook salmon is known to exhibit extreme differences in carotenoid utilization due to genetic polymorphisms [27]. It was determined that in salmon, the beta-carotene oxygenase 2-like (BCO2-l) gene was significantly associated with flesh color, with the most significant single nucleotide polymorphism explaining 66% of the variation in color. The red coloration is likely explained by a hypomorphic mutation in the proto-salmonid at the time of divergence of red-fleshed salmonid genera [27].

One of the main differences among species and between wild and farmed salmon is likely attributed to diet. Commercial salmon feeds have been refined over the past 50 years, which has ultimately reduced waste and improved digestibility and feed efficiency [29, 30]. On the contrary, the diet of wild salmon can be highly variable, even within individuals of the species, depending on food availability, their location/environment, and selective pressures [31]. Farmed salmon have genotypic and phenotypic differences compared to their wild counterparts of the same species due to both adaptation to a captive environment and breeding [31]. That study concluded that diet is not the primary cause of differences in the nutritional composition of wild and farmed salmon, and there is a genetic component to this difference. Indeed, farmed salmon have been selectively bred for several generations, which has improved harvest weight and growth [32], disease resistance [33, 34], late maturation [35], and fillet quality [36]. There are likely genetic differences which determine nutritional and color characteristics.

4.2. Net Pen and Land-Based RAS Atlantic Salmon in Canada. While protein, fat, cholesterol, and amino acid content were similar in salmon raised in both rearing systems, there were differences in fatty acid composition. Net pen salmon were significantly higher in 18-carbon fatty acids (18 : 1n-9, LNA, and ALA) than RAS salmon. This indicates differences in diet, most likely than anything else. RAS salmon were higher in SFA. Salmon typically have <27% SFA (of the total fatty acid profile) to help maintain membrane fluidity at colder temperatures [37]. The differences in SFA may relate to adaptations to temperature; where RAS salmon would be raised at a relatively constant temperature, and net pen salmon are exposed to seasonal differences. RAS salmon were twice as high in total omega-3s, while net pen-raised salmon were more than four times as high in omega-6s. One of the most important differences in fatty acid profile between these salmon types is the amount of EPA + DHA per 100 g serving. The RAS-raised salmon had about three times the amount of EPA + DHA per 100 g serving, therefore a smaller serving size would meet the recommended requirements. Approximately a 110 g serving of the RAS salmon would meet the WHO daily requirement for EPA + DHA, whereas about 350 g serving of net pen salmon is required (Figure 1). The difference in fatty acid profile could simply be due to differences in diet composition, rather than differences in production method.

There are other factors that may have contributed to differences in fatty acid profile of RAS compared to net pen-raised salmon. There are numerous biotic and abiotic factors that influence physiological functions to ultimately impact fish growth [38]. In general, aquaculture facilities are located or designed to ensure that abiotic and biotic conditions are within optimal ranges that result in the best fish growth and health, which ultimately can affect body composition and the finished fillet product. However, these conditions vary both spatially and temporally, and thus, changes in these conditions have the potential to affect growth, physiology, and product quality of fish [38]. Also, there may be genetic differences among different operations; this may have nothing to do with production method, but rather the source of salmon. Even among the same species, strain differences have been shown to impact nutritional metabolism, particularly regarding fatty acid metabolism [39, 40]. Even within the same strain, differences in nutrient metabolism and fillet fatty acid profile could be due to differences in selective breeding programs at each operation.

Redness and yellowness were higher in RAS salmon. This suggests dietary differences but might also be explained by environmental factors, such as temperature, which can impact pigmentation efficiency. The red color is due to astaxanthin, which is typically supplied in synthetic form in salmon feeds [28, 41]. Because the pigment is supplied in the diet, it could indicate differences in astaxanthin

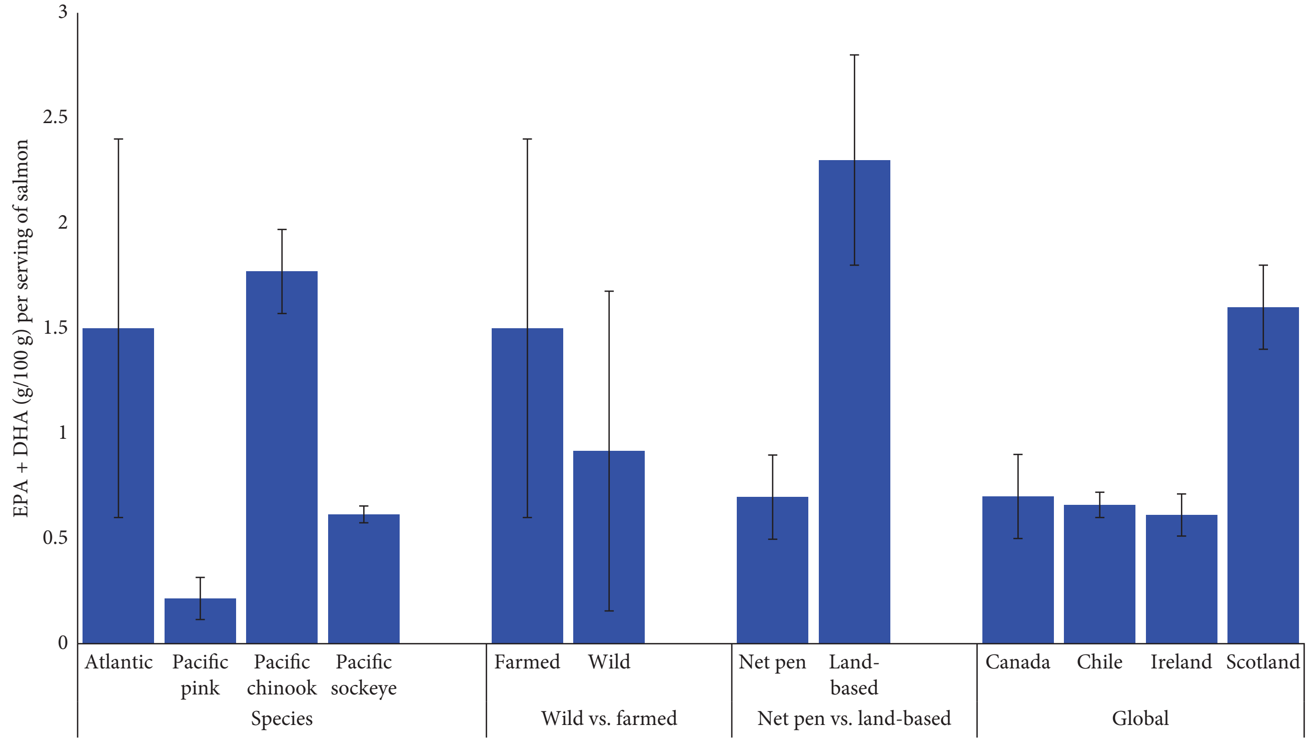

Figure 1: Amount of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) in grams per 100 g serving by salmon species, wild vs. farmed, method of production of farmed Atlantic (net pen vs. land-based closed containment-recirculating aquaculture system), and net pen raised farmed Atlantic by country. Error bars represent standard deviation.

concentration in the feed. However, exposure of net pen salmon to warmer temperatures can also result in the loss of fillet color at high temperatures, typically during summer months. Several studies have reported a decrease in fillet astaxanthin concentration/pigmentation in adult Atlantic salmon at high water temperatures [42–44]. This is likely due to increased oxidative stress and use of astaxanthin to maintain oxidative homeostasis. Therefore, environmental differences, particularly on account of temperature variability and high-temperature exposure, could have caused differences in fillet color between RAS-raised and net pen-raised salmon. On the other hand, the differences we observed in our study could also be due to genetic differences in digestibility of astaxanthin and pigmentation efficacy of different strains. Ultimately these factors influence the visual quality of the fillets which can impact consumer preference.

4.3. Comparison of Atlantic Salmon from Canada, Chile, Ireland, and Scotland. Among Atlantic salmon that were farmed in different countries, there was no difference in moisture content, protein, fat, cholesterol, mercury, or essential amino acid profile. This may indicate consistency among net pen farmed Atlantic salmon regardless of location. However, there were differences in the fillet fatty acid profile. Scottish farmed salmon contained more than twice the amount of EPA + DHA per serving compared to any other farmed Atlantic salmon in this study and also had a higher n-3/n-6 ratio. Sprague et al. [12] noted that Scottish salmon farming has a focus on creating a premium product that is high in essential nutrients, such as EPA and DHA. Scottish farmed salmon also contained the most SFA and the lowest MUFA. Irish farmed salmon had the highest oleic acid (18 : 1n-9) and the lowest LNA (18 : 2n-6). These differences in fillet fatty acid content suggest that different lipid sources were used in diets in different countries. Comparably, another study reported Norwegian farmed Atlantic salmon fillet composition [45], and the values for crude lipid were higher (21%) than farmed Atlantic salmon in the present study but were lower in crude protein (19%) compared with Canadian, Chilean, Irish, and Scottish salmon. The reported n-6/n-3 ratio in that study (1.0) [45] was in between Scottish salmon (0.8) and Canadian/Chilean/Irish salmon (~1.3) in the present study. While some of the largest companies that produce aquafeeds (e.g., Skretting, Cargill) supply salmon operations around the world, there are different feed types and potential regional differences in lipid supply. The types of feed ingredients that are used can change over time, as availability and price of ingredients can change, as well as other factors like climate change and political conflict, which are drivers for change in ingredient supply [46]. Likely the fillet fatty acid content differs among salmon from different countries due to diet; however, other possibilities such as environment, strain, and selective breeding, all may have impacted the fillet fatty acid profile, which have been discussed in the previous section.

5. Conclusion

There were nutritional differences among the types of salmon investigated in this study. Species, rearing method (RAS or net pen raised), and country of origin were all significant factors that determined the nutritional content of salmon fillets. Diet is likely an underlying factor that contributed to these differences, particularly regarding rearing method and country of origin. This knowledge expands on the known nutritional benefits of salmon to help consumers make informed decisions and to increase awareness of differences in salmon species, as well as sustainable harvest and production methods. This information may serve as a benchmark data set on the nutritional information of salmon for stakeholders and policymakers. This study was limited by the salmon types available for purchase in our location; however, it represents the selection that average Canadian consumers can conveniently access. Future research could expand on this study by investigating the nutritional and contaminant composition of various salmon types raised or caught in other geographic locations and understanding the impact of diet, strain, and method of production on final fillet composition and quality.

Data Availability

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

Conflicts of Interest

The authors have no relevant financial or nonfinancial interests to disclose.

Acknowledgments

This work was supported by a Discovery Grant by the Natural Science and Engineering Research Council (NSERC) awarded to S. Colombo (RGPIN/05400-2018). The authors would like to thank Tanya Muggeridge, Zeyu Zhang, and Janice MacIsaac for assistance in using lab equipment and John Gillies for acquiring and shipping salmon samples.

Supplementary Materials

Table S1: the full data set of 185 fatty acid profiles from 57 studies that were included in the literature review and references. (*Supplementary Materials*)

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