

Farmed Atlantic salmon (*Salmo salar* L.) and the consumer: Variation in the nutritional composition of raw fillet cuts

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ARTICLE INFO

Keywords:

Aquaculture

Consumers

Nutritional labelling

Omega-3 fatty acids

Pigmentation

ABSTRACT

The chemical composition of farmed Atlantic salmon can vary according to both body-size and diet composition. Since consumers typically purchase portions, understanding nutrient distribution is important. Twenty-one similar-sized salmon, fed the same feed, were filleted and divided into five equal-length cuts for analysis. Lipid content, class and fatty acid composition varied throughout the fillet with tails supplying the least amount ($\text{g} \cdot 100 \text{ g}^{-1}$) of EPA and DHA omega-3 fatty acids. Additionally, considerable variation was observed between the two industry-standard cuts, which combined represented the fillet average well. Protein and microminerals were relatively stable across the fillet with subtle differences unlikely to impact consumers. Carotenoid pigment decreased from head to tail, reflecting lipid and protein, contrary to previous studies. Results are of interest and relevance to producers and retailers in terms of understanding variances in fillet composition, refining nutritional labelling and accurately informing consumers about the nutrient profile of salmon portions.

1. Introduction

Atlantic salmon (*Salmo salar* L.) is one of the world's most recognised fish species, largely owing to the success of its cultivation where annual global production currently stands at around 3 million metric tonnes (FAO, 2024). Accordingly, salmon frequently appears towards the top of the most consumed fish species, particularly among UK, North American, Japanese and European consumers (EUMOFA, 2024; NFI, 2024). As with other seafood, salmon is renowned for being a rich source of nutrients including the omega-3 ($n-3$) long-chain polyunsaturated fatty acids (LC-PUFA), eicosapentaenoic (EPA; 20:5 $n-3$) and docosahexaenoic (DHA; 22:6 $n-3$) acids, which are considered beneficial to human health and development (Calder, 2018). However, while the ordinary consumer might expect the nutritional content of farmed salmon to be similar and consistent, in reality, there can be marked differences in the levels of many nutrients such as mineral and EPA and DHA contents of retail salmon (Henriques et al., 2014; Sprague et al., 2020).

The nutritional composition of farmed animals is, therefore, important from the producer, retailer and consumer perspectives. The producer and retailer have an interest in ensuring that the nutritional content of the final product meets specifications targeted (e.g. fat and

protein content etc.), while also complying with nutritional labelling requirements so that consumers remain accurately informed. However, the growing aquaculture sector has faced increasing pressure in sourcing suitable ingredients for aquafeeds. Although there has been an overall trend for a reduction in the use of the finite marine ingredients, fishmeal and fish oil, and an increase in plant-based alternatives leading to a decline in levels of some specific nutrients such as EPA and DHA in both feed and fish (Aas et al., 2022; Hannisdal et al., 2025; Reksten et al., 2022; Sprague et al., 2016), individual producers may tailor feed formulations to contain either high or low levels of marine ingredients to produce a product based on health, cost and/or sustainability aspects accordingly (Sprague et al., 2020).

Within the salmon industry, as with most farming sectors, it is common practice to monitor feed performance and its impact on flesh quality through the routine sampling of farmed fish by means of a standardised cut (Sigurgisladdottir et al., 1997). Typically, this consists of either the original 'Mowi' or Scottish Quality Cut (SQC), encompassing the region under the dorsal fin, or the more favoured Norwegian Quality Cut (NQC) covering the region from the rear of the dorsal fin to anterior of the anal fin. Nevertheless, like most other large-sized fish (e.g. tuna, cod), farmed salmon is seldom purchased whole, instead being filleted

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<https://doi.org/10.1016/j.foodchem.2026.149048>

Received 25 July 2025; Received in revised form 19 February 2026; Accepted 25 March 2026

Available online 27 March 2026

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and sold as portions either direct from the fresh fish counter or pre-packaged from the chiller cabinets in retailers (Sprague et al., 2020). Consequently, the portion, and therefore nutritional value, selected by consumers may not necessarily be that of the standard cut, which itself may not be representative of the whole fillet (Nøstbakken et al., 2023; Sigurgisladdottir et al., 1997). Although fish size, diet composition and environment are the main factors affecting the nutrient content of farmed fish flesh (Bell et al., 1998; Olsen & Mortensen, 1997; Shearer, 1994), parameters such as lipid (fat) content and pigmentation are known to vary throughout the fillet from head to tail (Aursland et al., 1994; Bell et al., 1998; Christiansen & Wallace, 1988; Katikou et al., 2001; Nickell & Bromage, 1998; Nøstbakken et al., 2023; Olsen & Mortensen, 1997; Refsgaard et al., 1998). However, these studies generally centred on specific parts of the fillet rather than the entire range of portions available for purchase. Furthermore, little is known on how fatty acids vary throughout the fillet, particularly with respect to EPA and DHA contents and how portion choice may impact nutritional outcomes. Thus, the present study examined the nutrient (lipid, protein, moisture, energy, fatty acid and minerals) and pigment compositions of fillets from harvest size Atlantic salmon separated into five distinct equal-length cuts representative of the range of portions typically available for purchase by consumers.

2. Materials and methods

2.1. Sample collection and preparation

Twenty-one head-on, gutted salmon of similar harvest-size (4549 ± 317 g, 76.9 ± 3.1 cm, mean $\pm$ SD weight and length, respectively) reared in the same cage and fed the same standard commercial diet (e.g. 9 mm pellet size, 38% protein, 36% lipid) were supplied, on ice, by a commercial Scottish salmon producer. On arrival to the laboratory, the left-hand side was filleted and further divided into five equal-length cuts labelled A–E, head to tail, as illustrated in Fig. 1, to replicate the fillet portions typically available to consumers. Cuts were skinned, boned and trimmed, where required, ensuring that all muscle (red and white) was included with the composite, before homogenising to a smooth pâté using a Robot-Coupe Blixer® 4 V.V. blender mixer (Robot-Coupe, Vincennes, Cedex, France) and storing at -20°C until analysed. Ethical approval for the study was granted by the Animal Welfare and Ethical Review Body (AWERB) at the University of Stirling (AWERB/167/208New Non ASPA).

2.2. Proximate composition and energy content

Samples were analysed using standard analytical methods with moisture content determined by oven-drying at 105°C for 20 h (AOAC, 2000). Protein contents were determined by weighing out ~ 0.25 g of homogenised sample and adding 2 copper catalyst tablets (Fisher Scientific, Loughborough, UK) before digesting at 400°C for 1 h (Foss Digestor 2040, Foss Analytical AB, Högnäs, Sweden). Total nitrogen levels were measured by Kjeldahl (Foss Kjeltect™; Foss Analytical AB, Högnäs, Sweden) and protein values calculated as $\text{N} \times 6.25$ (Persson et al., 2008). Energy content was determined by bomb calorimetry

(Parr® 6200 isoperibol calorimeter; Parr Instrument Company, Moline, Illinois, USA) standardised with a 1 g calorific benzoic acid pellet (No. 3415; Parr Instrument Company, Moline, Illinois, USA). Approximately 0.6 g of oven-dried flesh was weighed in a crucible and inserted into an electrode assembly, where a length of firing wire was looped above the sample. The unit was then screwed into the bomb, filled to a set pressure with oxygen (industrial grade 99.5% purity; BOC Ltd., Glasgow, UK) before placed in a bucket filled with a known weight of distilled water. The electrodes were attached and the instrument fired, resulting in a change in temperature that was used to determine the calorific value of each sample. Moisture contents were used to convert results to a wet weight basis. Total lipid was extracted from ~ 1 g homogenised sample in 20 volumes of ice-cold chloroform/methanol (2:1, v/v) with an Ultra-Turrax tissue disruptor (Fisher Scientific, Loughborough, UK) before determining gravimetrically according to Folch et al. (1957). Non-lipid impurities were isolated by washing with 0.88% (w/v) KCl before the upper aqueous layer was removed by aspiration and the lipid-containing lower solvent layer dried under oxygen-free nitrogen (OFN industrial grade; BOC Ltd., Glasgow, UK) and kept in vacuo in a desiccator for 16 h. The lipid extract was made up to a 10 mg.mL^{-1} solution using chloroform/methanol (2:1, v/v) containing 0.01% (w/v) butylated hydroxytoluene (Sigma-Aldrich Chemie GmbH, Steinheim, Germany), flushed with OFN, and stored at -20°C .

2.3. Lipid class and fatty acid compositions

Separation of lipid classes of total lipid extracts was performed by double-development high-performance thin layer chromatography (HPTLC) with methyl acetate/isopropanol/chloroform/methanol/0.25% aqueous KCl (25:25:25:10:9, by vol.) and isohexane/diethyl ether/acetic acid (85:15:1, by vol.) as first and second development systems, respectively (Henderson & Tocher, 1992; Olsen & Henderson, 1989). Classes were visualised by charring at 160°C for 15 min after spraying with 3% (w/v) aqueous cupric acetate in 8% phosphoric acid solution (v/v) and quantified by scanning densitometry at 370 nm using a CAMAG-3 TLC scanner (Version Firmware 1.14.16; CAMAG, Muttenz, Switzerland) linked to a PC equipped with winCats Planar Chromatography Manager. Identities of individual classes were confirmed by comparison to Rf values of authentic standards run alongside samples.

Fatty acid methyl esters (FAME) from total lipid extracts were prepared by acid-catalysed transmethylation at 50°C for 16 h using 2 mL of 1% (v/v) sulphuric acid (95%, Aristar®, BDH Chemicals, Poole, UK) in methanol and 1 mL of toluene (Christie, 1993). FAME were extracted and purified by adsorption chromatography using 500 mg / 6 mL sorbent acid washed silica solid-phase extraction cartridges (Clean-up® silica extraction columns; UCT, Bristol, Pennsylvania, USA). Cartridges were preconditioned with 5 mL isohexane before the sample was added and FAME eluted using 10 mL isohexane/diethyl ether (95:5, v/v). FAME were separated and quantified by gas-liquid chromatography (GC) using a Thermo Finnigan Trace GC (Thermo Scientific, Milan, Italy) equipped with a $30 \text{ m} \times 0.32 \text{ mm i.d.} \times 0.25 \mu\text{m}$ ZB-wax column (Phenomenex, Cheshire, UK), ‘on column’ injection and flame ionisation detection. Hydrogen was used as the carrier gas at constant pressure (175 kPa) with the initial oven thermal gradient from 50°C to 150°C at $40^\circ\text{C.min}^{-1}$, then 195°C at 2°C.min^{-1} , 205°C at $0.5^\circ\text{C.min}^{-1}$ to a final temperature of 230°C at $40^\circ\text{C.min}^{-1}$. Individual FAME were identified by comparison to known in-house (Marinol) and commercial standards (Restek 20-FAME Marine Oil Standard; Thames Restek UK Ltd., Buckinghamshire, UK) as well as published data (Tocher & Harvie, 1988). The data were collected and processed using Chromcard data system for Windows (Version 2.11; Thermo Fisher Scientific Inc., Milan, Italy). Heptadecanoic acid (17:0) was used as internal standard to calculate fatty acid content per g of tissue.

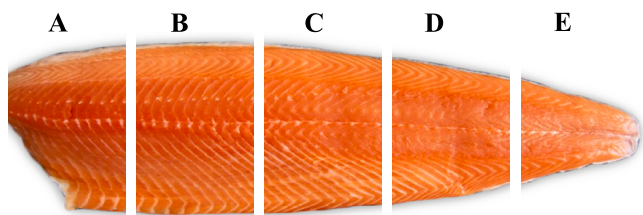


Fig. 1. Example of the five equal-length cuts derived from a farmed Atlantic salmon (*Salmo salar* L.) fillet used in the current study.

2.4. Carotenoid pigment analysis

Since different pigment sources are available for use by the salmon industry (Sprague et al., 2017), and with the source of pigment used in the current study unknown, a sample of flesh was subjected to carotenoid analysis to confirm the suitability of the extraction and detection conditions. Once established, the Panaferd-AX® carotenoid method was applied to all samples. Briefly, approximately 3 g of homogenised sample was weighed directly in a glass centrifuge tube before the addition of 1 mL deionised water and 5 mL tetrahydrofuran/methanol (20:1, by vol.), vortex mixed for 1 min and placed on a wrist-action flask shaker (Stuart® Scientific SF1; Cole-Parmer Ltd., Staffordshire, UK) for 5 min. Then, 10 mL isohexane was added and vortex mixed before centrifuging at 340g for 5 min. The upper layer was transferred to a 50 mL volumetric flask and the original sample extracted a further two times by repeating the process. The combined extracts were then made up to volume using isohexane/tetrahydrofuran/methanol (40:20:1, by vol.) before a 10 mL aliquot was removed, dried under OFN and redissolved in 2 mL isohexane prior to analysis by high performance liquid chromatography (HPLC). Samples were analysed on a Thermo Scientific UltiMate™ 3000 UHPLC system (Thermo Scientific, Hemel Hempstead, UK) equipped with a 100 mm × 4.6 mm i.d. Roc 3 µ silica column (Thames Restek UK Ltd., Buckinghamshire, UK) and detection at 474 nm. An isocratic solvent system consisting of isohexane/acetone/isopropanol (82:16:2, v/v/v) was used at a flow rate of 1.0 mL.min⁻¹. Astaxanthin and lutein were quantified using external standards obtained from DSM (Heerlen, Netherlands).

2.5. Mineral and trace element analysis

Total minerals (calcium, cobalt, copper, iron, magnesium, manganese, phosphorous, selenium, sodium, vanadium and zinc) were analysed by inductively coupled plasma-mass spectrometry (ICP-MS) following microwave digestion (Betancor et al., 2015). Approximately 30 mg of sample was weighed into Teflon (PTFE) microwave digestion vessels before the addition of 5 mL of 69% nitric acid (Aristar® analytical grade; VWR Chemicals, Poole, UK) followed by microwave digestion (MARS Xpress; CEM Microwave Technology Ltd., Buckingham, UK) in three stages consisting of 21–190 °C for 10 min at 800 W, 190 °C for 20 min at 900 W and a final 30 min cooling period. Sample digests were transferred to 10 mL volumetric flasks and made up to volume with Milli-Q® ultrapure water (Milli-Q® Direct 8 Water purification system, 18.2 MΩ.cm; Millipore UK Ltd., Watford, UK), after which a 0.4 mL aliquot was transferred to a 10 mL centrifuge tube where 0.2 mL methanol was added, in order to enhance selenium sensitivity (Larsen & Stürup, 1994), and made up to volume with Milli-Q® water.

Samples were analysed by ICP-MS (Thermo Scientific™ iCAP™ RQ ICP-MS; Thermo Scientific, Hemel Hempstead, UK), using collision cell technology, coupled to an ASX-560 autosampler (Teledyne Cetac Technologies, Omaha, Nebraska, USA). The instrument operated in He KED (kinetic energy discrimination) mode for interference removal and was tuned before analysis using a tuning solution (1 ppb in 2% HNO₃ and 0.5% HCl; Thermo Scientific, Bremen, Germany). Plasma power was set to 1550 W, nebuliser gas flow at 1.09 L.min⁻¹, auxiliary gas flow at 0.80 L.min⁻¹, and helium gas flow at 4.5 mL.min⁻¹. Dwell time was 0.05 s for all elements except selenium which was 0.5 s. A multi-element calibration curve was prepared fresh using 2% (v/v) HNO₃ and diluted to appropriate concentrations (5000–15,000 ppb for phosphorous, 5005–15,020 ppb for major elements and 5–20 ppb for minor elements). Internal standards, rhodium and scandium (5 ppb) were added on-line for correction of instrumental drift during analysis. A certified reference material (Fish muscle ERM-BB42; Institute for Reference materials and Measurements (IRMM), Geel, Belgium) was included with sample batches to monitor the integrity of the sample procedure.

2.6. Statistical analysis

Data were analysed using Minitab® statistical software package (version 21.4.1; Minitab Inc., Pennsylvania, USA) with differences in mean values of measured parameters between cuts compared by one-way analysis of variance (ANOVA). Data were transformed, where necessary, using the arcsine or natural logarithm transformations and normality assessed using the Kolmogorov Smirnov test and homogeneity of variances by Bartlett's test and examination of residual plots. Post hoc comparisons were made using Tukey's test. Relationships were assessed using Pearson's correlation coefficient (r) and Runs test used to check for linearity, with failed data indicating a non-linear relationship (Graphpad Instat® v 3.01; GraphPad Software Inc., San Diego, USA). Results are presented as means and standard deviation with a significance of $P < 0.05$ applied to all statistical tests performed.

3. Results and discussion

3.1. Lipid, protein, moisture and energy contents

The mean lipid content of the raw farmed salmon fillets analysed in the present study was $10.9 \pm 0.9\%$ wet weight (ww), within the range typically reported for commercially produced market-sized Scottish salmon (Bell et al., 1998; Henriques et al., 2014; Sprague et al., 2016, 2020). Several factors are known to affect the lipid content of farmed salmon flesh with the main determinant being the lipid content of the feeds, based on tailored oil inclusion levels (Bell et al., 1998), together with fish size (Shearer, 1994), and genetic strain (Bell et al., 2010). In the current study, all fish sampled were intentionally selected to be of a similar size (4–5 kg) and originating from the same strain and cage, where they were fed the same diet, to minimise any external effects which is not necessarily the case for retail-bought salmon (Henriques et al., 2014; Sprague et al., 2020). Nevertheless, when fillets were separated into the five distinct cuts (A–E, head to tail) lipid contents were found to vary such that cuts sited closer to the head (A, B and C, 12.0 ± 1.3 , 13.1 ± 1.3 and $12.0 \pm 1.2\%$, respectively) contained a significantly higher lipid content than cut D ($9.9 \pm 1.0\%$), with the caudal (tail) region (E, $7.7 \pm 1.2\%$) containing the least amount of lipid overall (Table 1). Although previous studies have demonstrated lipid content to vary throughout the fillet, both rostral to caudal in addition to dorsal to ventral/belly (Aursland et al., 1994; Bell et al., 1998; Katikou et al., 2001; Nickell & Bromage, 1998; Refsgaard et al., 1998), these have been more region-specific, focussing on the different types of muscle (e.g. red versus white) or specific sections within the fillet (e.g. belly flap, dorsal fat depot). Both red and white muscle were included in analysed samples since both are present in retail portions and normally consumed, although skin was separated as consumers do not always eat this section and most portions sold in UK retailers already have the skin removed (Sprague et al., 2020). In addition, the dorsal and belly regions of fillets were trimmed to reflect that typically sold to UK consumers. In many parts of the world such as Japan the belly region is considered a delicacy due its flavour and texture, whereas in the UK consumers tend to be more averse to this offcut. While trimming may result in a lower lipid content compared to untrimmed portions, Bell et al. (1998) note that this was dependent upon the body section whence the portion was taken.

In contrast to lipid, the protein content of the different cuts remained relatively consistent at around 20.9% ww, corresponding to levels reported previously for UK retail salmon (Sprague et al., 2020). Protein levels are comparatively constant in any given species, being largely reliant upon fish size and life-cycle stage (Shearer, 1994; Shearer et al., 1994). Nonetheless, as with lipid content, the tail cut (E) was found to contain slightly but significantly less protein ($20.3 \pm 0.8\%$), than the mid-fillet cuts C and D, 21.3 ± 1.1 and $21.4 \pm 1.2\%$, respectively (Table 1). This minor difference would be of little importance to the consumer and is mostly a consequence of biological factors. Salmon

Table 1

Lipid, moisture, protein (%) and energy contents (kJ.100g⁻¹ and kcal.100 g⁻¹ ww) and fatty acid compositions (wt% of total lipid and absolute content, g.100 g⁻¹ ww flesh) of farmed Atlantic salmon (*Salmo salar*) fillet cuts (A–E) analysed in the current study. Cuts (mean ± sd) bearing different superscript lettering within same row are significantly different (*P* < 0.05), *n* = 21. ‘Fillet’ represents data for the entire fillet, based on average content of the five cuts, presented for comparative purposes.

	CUT					Fillet
	A	B	C	D	E	
Lipid (%)	12.0 ± 1.3 ^b	13.1 ± 1.3 ^a	12.0 ± 1.2 ^b	9.9 ± 1.0 ^c	7.7 ± 1.2 ^d	10.9 ± 0.9
Moisture (%)	65.0 ± 1.6 ^c	63.2 ± 2.0 ^d	63.5 ± 1.8 ^{cd}	67.0 ± 2.0 ^b	71.1 ± 1.7 ^a	66.0 ± 1.6
Protein (%)	20.6 ± 1.1 ^{ab}	20.9 ± 0.9 ^{ab}	21.3 ± 1.1 ^a	21.4 ± 1.2 ^a	20.3 ± 0.8 ^b	20.9 ± 1.1
Energy (kJ.100 g ⁻¹ ww)	1000.4 ± 61.0 ^b	1071.8 ± 66.3 ^a	1045.0 ± 52.9 ^{ab}	915.6 ± 69.5 ^c	774.3 ± 62.6 ^d	961.4 ± 124.3
Energy (kcal.100 g ⁻¹ ww)	239.0 ± 14.6 ^b	256.1 ± 15.8 ^a	249.7 ± 12.6 ^{ab}	218.7 ± 16.6 ^c	185.0 ± 15.0 ^d	229.7 ± 29.7
14:0	3.1 ± 0.5	3.2 ± 0.5	3.1 ± 0.5	3.2 ± 0.5	3.1 ± 0.4	3.1 ± 0.5
16:0	10.5 ± 0.3 ^b	10.4 ± 0.4 ^b	10.6 ± 0.4 ^b	10.6 ± 0.4 ^b	10.9 ± 0.3 ^a	10.6 ± 0.3
18:0	2.3 ± 0.1	2.3 ± 0.1	2.3 ± 0.1	2.3 ± 0.1	2.4 ± 0.1	2.3 ± 0.1
20:0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0
Total saturated ¹	16.5 ± 0.7	16.4 ± 0.8	16.5 ± 0.8	16.7 ± 0.8	17.0 ± 0.6	16.6 ± 0.7
16:1n-7	3.7 ± 0.2	3.8 ± 0.2	3.8 ± 0.2	3.7 ± 0.2	3.7 ± 0.2	3.7 ± 0.2
18:1n-9	26.1 ± 0.8 ^a	26.4 ± 0.8 ^a	26.1 ± 0.9 ^a	25.8 ± 0.7 ^a	25.1 ± 0.7 ^b	25.9 ± 0.7
18:1n-7	2.6 ± 0.1	2.6 ± 0.1	2.6 ± 0.1	2.6 ± 0.1	2.6 ± 0.1	2.6 ± 0.1
20:1n-11	0.9 ± 0.1	0.9 ± 0.1	0.9 ± 0.1	0.9 ± 0.1	0.9 ± 0.1	0.9 ± 0.1
20:1n-9	7.2 ± 0.3 ^a	7.2 ± 0.3 ^a	7.3 ± 0.3 ^a	7.2 ± 0.3 ^a	6.9 ± 0.3 ^b	7.1 ± 0.3
22:1n-11	8.6 ± 0.6	8.6 ± 0.5	8.7 ± 0.5	8.6 ± 0.6	8.3 ± 0.5	8.5 ± 0.5
22:1n-9	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1
24:1n-9	0.6 ± 0.0	0.6 ± 0.0	0.6 ± 0.0	0.6 ± 0.0	0.6 ± 0.1	0.6 ± 0.0
Total monoenes ²	51.0 ± 0.6 ^{bc}	51.5 ± 0.5 ^a	51.3 ± 0.6 ^{ab}	50.7 ± 0.6 ^c	49.3 ± 0.7 ^d	50.8 ± 0.5
18:2n-6	9.2 ± 0.3 ^a	9.3 ± 0.3 ^a	9.3 ± 0.3 ^a	9.2 ± 0.2 ^a	8.9 ± 0.3 ^b	9.2 ± 0.3
20:2n-6	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.0	0.7 ± 0.0
20:4n-6	0.3 ± 0.0 ^{bc}	0.3 ± 0.0 ^c	0.3 ± 0.0 ^{bc}	0.3 ± 0.0 ^b	0.4 ± 0.0 ^a	0.3 ± 0.0
22:5n-6	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
Total n-6 PUFA ³	10.5 ± 0.3 ^a	10.6 ± 0.3 ^a	10.6 ± 0.3 ^a	10.5 ± 0.3 ^a	10.3 ± 0.3 ^b	10.5 ± 0.3
18:3n-3	3.2 ± 0.1	3.3 ± 0.1	3.2 ± 0.1	3.2 ± 0.1	3.2 ± 0.1	3.2 ± 0.1
18:4n-3	1.3 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.3 ± 0.1	1.3 ± 0.1	1.3 ± 0.1
20:4n-3	1.4 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.3 ± 0.1	1.4 ± 0.1
20:5n-3 (EPA)	4.4 ± 0.2 ^b	4.3 ± 0.2 ^b	4.3 ± 0.2 ^b	4.4 ± 0.2 ^b	4.6 ± 0.2 ^a	4.4 ± 0.2
22:5n-3 (DPA)	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.1

Table 1 (continued)

	CUT					Fillet
	A	B	C	D	E	
22:6n-3 (DHA)	8.7 ± 0.5 ^{bc}	8.2 ± 0.4 ^d	8.5 ± 0.7 ^{cd}	9.0 ± 0.4 ^b	10.1 ± 0.6 ^a	8.9 ± 0.4
Total n-3 PUFA ⁴	21.4 ± 0.7 ^{bc}	20.8 ± 0.7 ^c	21.1 ± 1.0 ^{bc}	21.5 ± 0.6 ^b	22.9 ± 0.7 ^a	21.5 ± 0.6
Total PUFA ⁵	32.5 ± 0.6 ^b	32.0 ± 0.7 ^b	32.2 ± 0.9 ^b	32.6 ± 0.5 ^b	33.7 ± 0.5 ^a	32.6 ± 0.5
n-3/ n-6	2.0 ± 0.1 ^b	2.0 ± 0.1 ^b	2.0 ± 0.1 ^b	2.1 ± 0.1 ^b	2.2 ± 0.1 ^a	2.1 ± 0.1
Total saturates (g.100 g ⁻¹ ww)	1.77 ± 0.23 ^a	1.93 ± 0.22 ^a	1.77 ± 0.23 ^a	1.47 ± 0.18 ^b	1.16 ± 0.18 ^c	1.62 ± 0.17
Total monoenes (g.100 g ⁻¹ ww)	5.45 ± 0.60 ^b	6.04 ± 0.59 ^a	5.51 ± 0.59 ^b	4.48 ± 0.52 ^c	3.39 ± 0.57 ^d	4.97 ± 0.42
Total n-6 PUFA (g.100 g ⁻¹ ww)	1.13 ± 0.14 ^b	1.25 ± 0.13 ^a	1.14 ± 0.12 ^b	0.93 ± 0.10 ^c	0.71 ± 0.12 ^d	1.03 ± 0.09
Total n-3 PUFA (g.100 g ⁻¹ ww)	2.28 ± 0.19 ^a	2.44 ± 0.25 ^a	2.26 ± 0.22 ^a	1.90 ± 0.20 ^b	1.57 ± 0.23 ^c	2.09 ± 0.17
Total PUFA (g.100 g ⁻¹ ww)	3.47 ± 0.33 ^{ab}	3.75 ± 0.38 ^a	3.46 ± 0.33 ^b	2.87 ± 0.30 ^c	2.31 ± 0.35 ^d	3.17 ± 0.25
EPA (g.100 g ⁻¹ ww)	0.47 ± 0.04 ^a	0.50 ± 0.05 ^a	0.47 ± 0.05 ^a	0.38 ± 0.05 ^b	0.32 ± 0.05 ^c	0.43 ± 0.04
DPA (g.100 g ⁻¹ ww)	0.19 ± 0.02 ^{ab}	0.21 ± 0.02 ^a	0.19 ± 0.02 ^b	0.16 ± 0.02 ^c	0.12 ± 0.02 ^d	0.17 ± 0.02
DHA (g.100 g ⁻¹ ww)	0.93 ± 0.06 ^a	0.97 ± 0.10 ^a	0.91 ± 0.09 ^a	0.79 ± 0.07 ^b	0.69 ± 0.08 ^c	0.86 ± 0.06
EPA + DHA (g.100 g ⁻¹ ww)	1.40 ± 0.10 ^a	1.47 ± 0.15 ^a	1.37 ± 0.14 ^a	1.17 ± 0.11 ^b	1.01 ± 0.13 ^c	1.28 ± 0.10
EPA + DPA + DHA (g.100 g ⁻¹ ww)	1.59 ± 0.12 ^a	1.68 ± 0.17 ^a	1.56 ± 0.15 ^a	1.33 ± 0.13 ^b	1.13 ± 0.15 ^c	1.46 ± 0.11

¹ Includes 15:0, 22:0 and 24:0.
² Includes 16:1n-9, 17:1 and 20:1n-7.
³ Includes 18:3n-6, 20:3n-6 and 22:4n-6.
⁴ Includes 20:3n-3 and 21:5n-3.
⁵ Includes 16:2, 16:3, 16:4.

growth is both allometric and indeterminate resulting in a characteristic thickening of the loin, corresponding to sample cuts A-C in the present study, before tapering off towards the tail. As such, the musculature will vary according to the anatomical location, whereby fibre number and diameter size will differ, affecting the collagen content and textural properties of the flesh (Jonsson et al., 2001), which may well account for differences seen in protein levels. This is, perhaps, a reflection of the difference in musculature activity along the fillet, whereby the proportion of white anaerobic muscle fibres used in high-speed swimming decline towards the caudal region, whereas the aerobic red muscle fibres involved in sustained swimming increases (Johnston, 1999; Kiessling, Ruohonen, & Bjørnevik, 2006). As such, the greater metabolic activity in

the caudal region exerted by red muscle fibres, which utilise lipids for energy, may account for this region accumulating less lipid. The lower protein concentration observed in the caudal region may also be related to swimming activity reflecting reduced muscle thickness and a higher proportion of connective tissue. Nevertheless, it is perhaps the quality of protein, i.e. type and amount of amino acids present, rather than the quantity of protein per se which is important when assessing the nutritional value, although the amount of available amino acids would be restricted by the overall protein content. However, amino acids were not measured in the present study since it is the proximate compositions (i.e. fat, moisture protein) alongside energy, carbohydrate, fibre and *n*-3 fatty acids that are normally included on the nutritional labels of retail salmon (Sprague et al., 2020). Carbohydrate and fibre content, also not analysed, would be trace if at all present given that the bulk of the flesh muscle (>96.8% in this study) was comprised of protein, lipid and moisture.

Changes to the proportions of protein, water or lipid will invariably affect the other such that the sum remains constant. Although protein and ash (mineral) content are also linked to energy demands it is the inverse relationship between lipid and moisture that shows the most dynamic response in maintaining the compositional balance of the tissue (Hardy & Keay, 1972; Shearer, 1994). Accordingly, moisture levels were highest within tails (71.1 ± 1.7 compared to 67.0 ± 2.0 to $63.2 \pm 2.0\%$ ww cuts D and B, respectively), exhibiting a non-linear negative relationship with lipid content. Similarly, as lipid contains around twice the amount of energy as either protein or carbohydrate, the energy content of the sampled regions also showed a strong positive linear correlation with lipid level ($r^2 = 0.7960$, $P < 0.001$), ranging from 185.0 ± 14.9 kcal.100 g⁻¹ ww (774.3 kJ.100 g⁻¹ ww) in the tail (E) to 256.1 ± 15.8 kcal.100 g⁻¹ ww (774.3 kJ.100 g⁻¹ ww) in cut B (Table 1). It is, however, the makeup of the lipid, particularly with respect to the level of *n*-3 fatty acids, that appeal to consumers conscientious about their health.

3.2. Fatty acid and lipid class composition

It is well known that the fatty acid profile of the flesh of fish generally reflects the profile of the dietary lipid source (Sargent et al., 2002; Sprague et al., 2016). Thus, as expected the fatty acid profile, as a proportion of total lipid, for all cuts sampled in the present study were similar being largely characterised by oleic (18:1*n*-9, 25.9%), palmitic (16:0, 10.6%), linoleic (18:2*n*-6, 9.2%), gondoic (20:1*n*-9, 7.1%), cetoleic (22:1*n*-11, 8.5%) and α -linolenic (18:3*n*-3, 3.2%) acids, with the *n*-3 LC-PUFA, EPA and DHA, accounting for around 4.4 and 8.9% of the total lipid, respectively (Table 1). This profile is reflective of modern commercial aquaculture feeds whereby a blend of fish and alternative oils, primarily vegetable such as rapeseed, are used as a consequence of an increased demand for farmed seafood together with the supply constraints of traditional wild-capture marine ingredients, fishmeal and fish oil, while continuing to meet the nutritional requirements of the farmed species. However, a differentiated supply of salmon products with varying fatty acid profiles are available to consumers based on differing feed formulations and feeding strategies (Henriques et al., 2014; Shepherd et al., 2017; Sprague et al., 2020), whereby 18:1*n*-9, 18:2*n*-6 and 18:3*n*-3 levels are generally characteristic of vegetable oil inclusion and EPA and DHA of marine oil inclusion (Sprague et al., 2016, 2026). The potential for differences between individual fish purchased from retailers further emphasises the importance of obtaining fish fed the same diet, ideally from the same cage, when undertaking studies such as the present one.

In terms of fillet variation, the tail (E) was found to contain a significantly ($P < 0.001$) higher proportion of total fatty acids as EPA and DHA (4.6 and 10.1%, respectively), contributing to a higher total *n*-3 PUFA level (22.9%) as well as significantly lower levels of 18:2*n*-6 (8.9%), total *n*-6 PUFA (10.3%), 18:1*n*-9 (25.1%), 20:1*n*-9 (6.9%) and total monoenes (49.3%) as compared to all other cuts (A-D, range 4.3–4.4% EPA; 8.2–9.0% DHA; 20.8–21.5% total *n*-3 PUFA; 9.2–9.3%

18:2*n*-6; 10.5–10.6% total *n*-6 PUFA; 25.8–26.4% 18:1*n*-9; 7.2–7.3% 20:1*n*-9; and 50.7–51.5% total monoenes) (Table 1). This difference can probably be attributed largely to the variation in lipid content and, more importantly, lipid class composition between the different fillet cuts. Aursland et al. (1994) and Nanton et al. (2007) for example, observed a higher proportion of the storage lipid, triacylglycerol (TAG), and monounsaturated fatty acids in addition to a lower proportion of polar lipids and *n*-3 PUFA in the lipid-rich tissues of visceral fat and belly flap as compared to muscle tissue. Lipid class composition of cuts sampled from the current study revealed a significantly reduced level of TAG and increased level of the structural phospholipids, primarily phosphatidylcholine (PC) and phosphatidylethanolamine (PE), in cut E relative to all other portions (Table 2). Although both polar, but especially neutral, lipids can reflect the fatty acid composition of dietary oil sources in the same way as total fatty acids (Ruiz-Lopez et al., 2015), EPA and DHA are known to have an important role in the structural lipids of fish membranes by providing increased flexibility (Sargent et al., 2002). In particular, PE and phosphatidylserine, as well as PC to some extent, have been shown to contain higher levels of DHA depending on tissue type (Tocher & Harvie, 1988). As discussed above, the caudal region of muscle contains a greater proportion of aerobic red muscle fibres that allow for sustained swimming (Johnston, 1999; Kiessling, Ruohonen, & Bjørnevik, 2006). Red muscle typically contains higher concentrations of *n*-3 LC-PUFA-rich phospholipids than found within white muscle (Porter et al., 1992), likely reflecting the high density of membrane-rich mitochondria that provide the energy (Frøyland et al., 2000). Therefore, it can be hypothesised that the higher phospholipid content, principally PE and PC, in the caudal region of fillets would most likely have contributed to the higher proportion of EPA and DHA observed. Nevertheless, this is probably of little relevance to the human consumer since it is the combination of lipid content together with lipid class and total fatty acid compositions that ultimately determine the absolute amounts of fatty acids supplied.

3.3. EPA and DHA content

One of the unique selling points of seafood, particularly oily fish such as salmon, is their almost exclusive contribution of the *n*-3 LC-PUFA, EPA and DHA, to the human diet (Sprague et al., 2016; Sprague et al., 2026). Nevertheless, levels of these beneficial fatty acids have decreased in farmed salmon over the years as the inclusion levels of alternative ingredients, typically of terrestrial plant-based origin and therefore devoid of EPA and DHA, have risen to support increased salmon production (Aas et al., 2022; Reksten et al., 2022; Sprague et al., 2016). Despite this, EPA and DHA contents have been shown to vary markedly between retail salmon based on the different feed formulations and strategies employed (Gillies et al., 2023; Henriques et al., 2014; Sprague et al., 2020). As such, the present study ensured that all fish originated from the same strain, reared in the same cage, and fed the same diet to mitigate against any such influences, including being exposed to the same environmental factors such as temperature, oxygen and salinity that are all known to potentially affect the nutritional content of farmed fish flesh (Bell et al., 1998; Olsen & Mortensen, 1997; Shearer, 1994).

The average EPA + DHA content of fillets from fish sampled in the current study was 1.28 ± 0.10 g.100 g⁻¹ ww, which agrees with average data for farmed Scottish salmon (Sprague et al., 2016, 2020). Even so, there was a distinct difference in the amount supplied by various fillet cuts (Table 1). The highest content was found in B (1.47 ± 0.15 g.100 g⁻¹ ww), whereas the lowest was in the tail cut (E, 1.01 ± 0.13 g.100 g⁻¹ ww). Although this is, perhaps, unsurprising particularly as these cuts contained the highest and lowest lipid levels, respectively, the current study is the first, to our knowledge, to focus on the variation in fatty acid contents through the salmon fillet from the consumer perspective. Consequently, the portion selected will ultimately determine the amounts of these health beneficial fatty acids delivered to the discerning consumer.

Table 2

Lipid class composition (% of total lipid) of farmed Atlantic salmon (*Salmo salar*) fillet cuts (A–E) analysed in the current study. Cuts (mean $\pm$ sd) bearing different superscript lettering within same row are significantly different ($P < 0.05$), $n = 21$. Fillet* represents data for the entire fillet, based on average of all cuts, presented for comparative purposes.

	CUT					Fillet
	A	B	C	D	E	
<i>Lipid class (% total lipid)</i>						
Phosphatidylcholine	4.4 ± 0.8 ^b	3.5 ± 0.5 ^d	3.7 ± 0.7 ^{cd}	4.2 ± 0.7 ^{bc}	5.3 ± 0.9 ^a	4.2 ± 0.6
Phosphatidylethanolamine	2.3 ± 0.6 ^b	1.7 ± 0.5 ^c	1.8 ± 0.5 ^c	2.3 ± 0.5 ^b	3.1 ± 0.5 ^a	2.2 ± 0.4
Phosphatidylinositol	0.5 ± 0.3 ^a	0.4 ± 0.3 ^{ab}	0.3 ± 0.2 ^b	0.4 ± 0.2 ^{ab}	0.5 ± 0.2 ^{ab}	0.4 ± 0.2
Sphingomyelin	0.2 ± 0.1 ^{ab}	0.1 ± 0.0 ^b	0.2 ± 0.1 ^{ab}	0.2 ± 0.0 ^a	0.2 ± 0.0 ^a	0.2 ± 0.1
Phosphatidylserine	0.0 ± 0.1 ^b	0.0 ± 0.0 ^b	0.0 ± 0.1 ^b	0.0 ± 0.1 ^b	0.1 ± 0.0 ^a	0.0 ± 0.0
Total polar	7.4 ± 1.5^b	5.8 ± 1.3^c	5.9 ± 1.3^c	7.1 ± 1.2^b	9.2 ± 1.5^a	7.1 ± 1.1
Triacylglycerol	83.8 ± 2.1 ^{bc}	86.1 ± 1.8 ^a	85.4 ± 2.2 ^{ab}	83.5 ± 1.8 ^c	78.8 ± 3.0 ^d	83.5 ± 1.8
Sterols	4.4 ± 0.8 ^b	4.3 ± 0.4 ^b	4.3 ± 0.7 ^b	4.6 ± 0.6 ^b	5.3 ± 0.6 ^a	4.6 ± 0.6
Diacylglycerol	2.2 ± 0.5 ^b	1.9 ± 0.4 ^b	2.1 ± 0.6 ^b	2.3 ± 0.6 ^b	2.9 ± 0.7 ^a	2.3 ± 0.5
Free fatty acids	1.4 ± 0.7 ^b	1.1 ± 0.6 ^b	1.4 ± 0.8 ^b	1.5 ± 0.8 ^b	2.5 ± 1.4 ^a	1.6 ± 0.7
Pigmented material*	0.8 ± 0.3 ^b	0.8 ± 0.3 ^b	0.9 ± 0.4 ^b	1.0 ± 0.4 ^{ab}	1.3 ± 0.4 ^a	1.0 ± 0.3
Total neutral	92.6 ± 1.5^b	94.2 ± 1.3^a	94.1 ± 1.3^a	92.9 ± 1.2^b	90.8 ± 1.5^c	92.9 ± 1.1

* May also include monoacylglycerols.

Global health authorities typically advocate consuming between 0.25 and 0.5 g EPA + DHA.day⁻¹ for optimal cardiac health (EFSA, 2010; ISSFAL, 2004; Mozaffarian & Rimm, 2006; SACN/COT, 2004). A 140 g serving of salmon, as recommended by the UK's health authority (SACN/COT, 2004), from the current study would provide between 1.41 $\pm$ 0.19 and 2.06 $\pm$ 0.20 g EPA + DHA (cuts E and B, respectively), equating to around 563 to 823% of the lower level suggested by the European Food Safety Authority (EFSA) or 282 to 411% of the upper recommendation put forward by the International Society for the Study of Fatty Acids and Lipids (ISSFAL) for cuts E and B, respectively. Seafood is, however, the main dietary source of EPA + DHA and guidelines recommend consuming two portions a week including one oily species such as farmed salmon (EFSA, 2010; SACN/COT, 2004). Accordingly, single 140 g servings, originating from cuts from the present study, would supply 80 to 118% of the lower 1.75 g weekly EPA + DHA intake set by EFSA and 40 to 59% of the higher 3.5 g intake endorsed by ISSFAL. In a recent study it was suggested that three portions of seafood, of which two are oily, are needed to attain the weekly recommendations, especially for those set at higher levels (Sprague et al., 2026). It should also be noted that owing to the thickness varying across the fillet, sample cuts from the current study were not of equal weight, ranging from approximately 120 to 400 g E to B and C, respectively. Cuts used in the present study were indicative of the different areas on the fillet that are available to consumers. Within the industry, salmon fillets are typically processed into standardised portion weights using a highly automated process, which are then sold pre-packaged in retailers (Sprague et al., 2020). Consequently, the portions that consumers select visually, particularly if based on preferences for leaner (e.g. tail) or fattier (mid-fillet) regions, will affect the amount of nutrients supplied including *n*-3 LC-PUFA and, consequently, how much of the recommended dietary intake level they can satisfy. Nevertheless, farmed salmon remains one of the highest providers of EPA + DHA per portion to humans (Sprague et al., 2026).

3.4. Carotenoid pigment

The distinctive pink-red colouration of salmon flesh, due to the almost unique ability of salmonids to accumulate carotenoid pigments in muscle, is an important characteristic for consumers when purchasing fresh salmon due to the association with product quality (Alfnes et al., 2006; Anderson, 2000; Sigurgisladottir et al., 1994). Carotenoids, alongside tocopherols, provide antioxidant properties that benefit both the fish and consumer (Refsgaard et al., 1998). However, like most other animals, salmon are unable to synthesise carotenoid pigments de novo

and instead obtain them through their diet. For many years farmed salmon feeds contained synthetic carotenoid pigments (i.e. Carophyll® Pink) consisting of astaxanthin, as well as canthaxanthin, in order to achieve the desired colour for the consumer. Increased market pressures, changes in consumer preferences and developments in biotechnological processes have resulted in a shift in availability from synthetic to more natural, organic forms of carotenoid pigments including bacterial, yeast and microalgal sources (Sprague et al., 2017).

In the present study, the carotenoid profile observed was consistent with that from the aerobic gram-negative astaxanthin-producing bacterium, *Paracoccus carotinifaciens* sp., alternatively known by its commercial name Panaferd-AX® and approved for use in salmon feed since 2007 (EFSA, 2007). In addition to both astaxanthin and canthaxanthin, Panaferd-AX® also contains adonirubin and adonixanthin, biosynthetic intermediates from β -carotene conversion to astaxanthin, at levels of up to 30% of astaxanthin (Britton et al., 1998). Thus, portions from the current study were characterised in the order of astaxanthin > adonirubin > canthaxanthin > adonixanthin with lutein and asteroideone being minor components, possibly from the xanthophyll components of other plant-based ingredients in the feeds and as an intermediary metabolite, respectfully (Hayashi et al., 2021). Total carotenoid content of the entire fillet was 3.74 $\pm$ 0.66 mg.kg⁻¹, within the expected range of 3–7 mg.kg⁻¹ for farmed salmon (Bell et al., 1998; Refsgaard et al., 1998). The highest pigment contents were found in the rostral region and subsequently decreased throughout fillet cuts towards the caudal region (4.22 $\pm$ 0.90 to 2.78 $\pm$ 0.81 mg.kg⁻¹, portions A and E, respectively) (Table 3). Only the tail cut contained a significantly lower amount of total carotenoid, primarily due to significantly lower contents of astaxanthin (1.81 $\pm$ 0.57 mg.kg⁻¹) and adonirubin (0.71 $\pm$ 0.17 mg.kg⁻¹) than most other cuts (2.85–2.41 and 1.00–0.85 mg.kg⁻¹ A–D, astaxanthin and adonirubin, respectively). This contradicted previous studies where carotenoid pigmentation was suggested to increase towards the tail (Bell et al., 1998; Christiansen & Wallace, 1988; Nickell & Bromage, 1998; Olsen & Mortensen, 1997; Refsgaard et al., 1998). However, in most of the earlier studies the epaxial (dorsal) or hypaxial (belly) muscle was examined separately rather than a transect comprising both as performed in the current investigation and which is normally available for consumers to purchase. The pigment source used in the present study, *P. carotinifaciens*, varies from the synthetic source used in earlier studies, whereby astaxanthin isomers are known to differ, largely 3S,3'S in Panaferd®-AX compared to a mixture of 3S,3'S, 3R,3'S and 3R,3'R in synthetic, which affects both bioavailability and functional performance, including deposition (Snell & Carberry, 2022). Carotenoids generally start to be deposited in the flesh of salmonids at

Table 3

Carotenoid pigment levels (mg.kg⁻¹ ww, mean ± sd) in the different cuts of farmed Atlantic salmon (*Salmo salar*) flesh (n = 21). Values within the same row bearing different superscript lettering are significantly different (*P* < 0.05). Fillet* represents data for the entire fillet, based on average of all cuts, presented for comparative purposes only.

	CUT					Fillet
	A	B	C	D	E	
<i>Carotenoid pigment (mg.kg⁻¹)</i>						
Astaxanthin [*]	2.85 ± 0.63 ^a	2.80 ± 0.61 ^a	2.72 ± 0.49 ^a	2.41 ± 0.57 ^a	1.81 ± 0.57 ^b	2.52 ± 0.46
Adonirubin	1.00 ± 0.21 ^a	0.93 ± 0.20 ^a	0.91 ± 0.15 ^a	0.85 ± 0.17 ^{ab}	0.71 ± 0.17 ^b	0.88 ± 0.15
Canthaxanthin	0.18 ± 0.04 ^a	0.16 ± 0.03 ^{ab}	0.16 ± 0.03 ^{ab}	0.16 ± 0.03 ^{ab}	0.14 ± 0.03 ^b	0.16 ± 0.02
Adonixanthin	0.11 ± 0.04 ^a	0.11 ± 0.05 ^a	0.10 ± 0.05 ^a	0.09 ± 0.04 ^{ab}	0.07 ± 0.04 ^b	0.10 ± 0.04
Lutein	0.06 ± 0.02 ^{ab}	0.06 ± 0.01 ^a	0.06 ± 0.02 ^{ab}	0.06 ± 0.03 ^{ab}	0.04 ± 0.02 ^b	0.06 ± 0.02
Asteroidenone	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
<i>Total Carotenoids</i>	<i>4.22 ± 0.90^a</i>	<i>4.08 ± 0.88^a</i>	<i>3.97 ± 0.69^a</i>	<i>3.59 ± 0.80^a</i>	<i>2.78 ± 0.81^b</i>	<i>3.74 ± 0.66</i>

* Includes all E, 9Z and 13Z isomers.

approximately 100 g body weight, with around 10–18% of ingested carotenoid retained (Nickell & Bromage, 1998; Storebakken and No, 1992; Ytrestøyl et al., 2006), with dietary lipid content known to positively affect carotenoid uptake (Lin et al., 2024; Nickell & Bromage, 1998; Storebakken & No, 1992). Fish in the current study were fed the same pigment source (same feed) and the similar fish weights would have reduced any effect of body size.

Fatty acid composition has also been suggested to influence carotenoid deposition, with saturated fatty acids and PUFA thought to preferentially bind astaxanthin compared to monounsaturated fatty acids (Lerfall et al., 2016; Vo et al., 2023), and EPA and DHA levels also affecting astaxanthin concentrations (Ytrestøyl et al., 2023). As previously stated, the tail cut contained a significantly higher proportion of both saturated and PUFA, including EPA and DHA, and less monoenes than all other cuts, but the tail also contained the lowest amounts of astaxanthin, and all other carotenoids measured. Despite the higher proportion (%) of EPA + DHA, lipid content was much lower in the tail resulting in this cut containing the least absolute content (g.100 g⁻¹) of EPA + DHA overall. Flesh colour is generally lighter in high fat regions as the lipid ‘dilutes’ the carotenoids which can interfere with the perception of colour (Refsgaard et al., 1998). In this study there was a tendency for all carotenoid pigments to increase as lipid increased, although the relationship was non-linear. Lin et al. (2024) observed a strong correlation between flesh lipid and carotenoid contents in the flesh of Arctic charr (*Salvelinus alpinus*). Astaxanthin is lipid soluble and binds to the actomyosin complex in white muscle protein, specifically F-actin rather than myosin (Young et al., 2017). Both lipid and protein were lowest within the tail compared to any other sampled areas. It has been proposed that the number and size of muscle fibres could affect the pigmentation of the fillet based on the availability of binding sites (Nickell & Bromage, 1998), with white muscle fibres more enriched in the rostral region compared to the tail (Kiessling, Stien, et al., 2006), mirroring the pattern of pigmentation in the present study. While further investigation is necessary to understand the deposition of carotenoids in salmonid muscle, from the consumer standpoint the influence of colour as a visual assessment of salmon portions becomes more

difficult as carotenoid contents increase and, therefore, would perhaps have little or no influence, despite the significant differences in carotenoid contents, when selecting portions for purchase.

3.5. Minerals and trace elements

Macrominerals such as calcium (Ca) and phosphorus (P), as well as trace elements including selenium (Se), are important in both the development and health of fish and humans (Lall, 2022). For farmed salmon, many of these minerals can be absorbed from the surrounding water, particularly in the seawater phase, although dietary sources remain important for many key elements (Lall & Kaushik, 2021). Nevertheless, as with EPA + DHA levels, the micronutrient content of salmon feeds has also shown a steady decline as more of the mineral-rich fishmeal is replaced by alternative ingredients (Hannisdal et al., 2025; Reksten et al., 2022; Sissener et al., 2013). For example, increased inclusion of plant-based ingredients within salmon feeds resulted in a reduction of Se deposited within flesh (Betancor et al., 2016). While the essential levels of these micronutrients supplied in diets may still satisfy the nutritional requirements of salmon there is concern for the human consumer. Mineral levels measured within the fillet remain within the range reported for farmed salmon flesh (Nøstbakken et al., 2023; Sprague et al., 2020). Whilst there was a tendency for tails to contain lower amounts of the elements analysed, no significant differences (*P* > 0.05) were observed with the exception of magnesium (Mg) where levels were higher in cut B than those in E (Table 4). Skeletal tissue typically stores more Mg than muscle tissue although, within muscle, Mg is involved in many important physiological functions including muscle contraction (Lall, 2022; Lall & Kaushik, 2021). As the energetic process of swimming requires muscular contractions (McKenzie, 2011), originating from the head and extending along the flank to the tail, where the caudal muscle exerts a greater amount of power to propel the fish through the water body, it may be that the lower Mg levels observed in the tail reflect the

Table 4

Macro minerals g.kg⁻¹ flesh ww) and trace elements (mg.kg⁻¹ flesh ww) in the different cuts of farmed Atlantic salmon (*Salmo salar*) flesh (n = 21). Values within the same row bearing different superscript lettering are significantly different (*P* < 0.05). ‘Fillet’ represents data for the entire fillet, based on average of all cuts, presented for comparative purposes only.

	CUT					Fillet
	A	B	C	D	E	
<i>Macro minerals (g.kg⁻¹)</i>						
Potassium	6.59 ± 1.57	7.31 ± 1.95	7.16 ± 1.67	6.71 ± 1.87	5.86 ± 1.66	6.78 ± 1.58
Phosphorus	4.26 ± 1.17	4.33 ± 1.28	4.22 ± 1.10	3.97 ± 1.18	3.63 ± 1.08	4.12 ± 1.06
Sodium	0.49 ± 0.09 ^b	0.47 ± 0.09 ^b	0.47 ± 0.09 ^b	0.50 ± 0.11 ^b	0.74 ± 0.19 ^a	0.54 ± 0.10
Calcium	0.42 ± 0.18	0.43 ± 0.24	0.39 ± 0.19	0.36 ± 0.19	0.36 ± 0.17	0.40 ± 0.19
Magnesium	0.42 ± 0.08 ^{ab}	0.43 ± 0.09 ^b	0.41 ± 0.09 ^{ab}	0.39 ± 0.09 ^{ab}	0.35 ± 0.07 ^a	0.40 ± 0.07
<i>Trace elements (mg.kg⁻¹)</i>						
Zinc	6.80 ± 1.11	6.71 ± 1.59	6.60 ± 1.00	6.65 ± 1.14	6.31 ± 1.26	6.61 ± 1.22
Iron	3.88 ± 1.61	3.69 ± 1.67	3.97 ± 1.71	3.85 ± 1.45	3.44 ± 1.21	3.77 ± 1.52
Copper	0.76 ± 0.21	0.73 ± 0.23	0.77 ± 0.19	0.80 ± 0.19	0.69 ± 0.12	0.75 ± 0.19
Selenium	0.26 ± 0.02	0.26 ± 0.04	0.26 ± 0.03	0.26 ± 0.02	0.26 ± 0.04	0.26 ± 0.03
Manganese	0.24 ± 0.06	0.23 ± 0.05	0.23 ± 0.06	0.23 ± 0.05	0.21 ± 0.03	0.23 ± 0.05
Chromium	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.01	0.03 ± 0.01	0.03 ± 0.02
Vanadium	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01

muscle involvement in the swimming motion. Since the tail (caudal) portion musculature accumulates less lipid than the other cuts samples, it may be that differences in Mg contents are a reflection of the lipid and moisture composition of cuts (Knox et al., 1981). Conversely, sodium (Na) was found to be significantly higher in the tail compared to all other sections (0.74 ± 0.19 compared to around 0.50 g.kg^{-1}). Given the importance of Na as a crucial electrolyte in osmoregulation, it is perhaps unsurprising that there was a positive relationship between muscle tissue moisture and sodium content ($r^2 = 0.7879$, $P = 0.0182$). Nevertheless, these small but significant differences in mineral contents between cuts are unlikely to impact or interest the health-conscious consumer.

3.6. Consequences for producers, retailers and the consumer

For quality control and assurance purposes, salmon producers routinely sample fish at set intervals of the grow-out stage to ensure that flesh quality parameters are on target to meet the set specifications at harvest. Accordingly, a standardised cut is often taken for wet chemistry analysis, although non-invasive techniques using near-infrared spectroscopy have also been developed for rapid quality assessment (Folkestad et al., 2008; Lintvedt et al., 2023; Solberg et al., 2003). The two commonly used cuts, SQC and NQC, relate to the region either directly below the dorsal fin or to the rear of the dorsal and front of the anal fin, respectively (Sigurgisladottir et al., 1997). As observed in the present study there were significant differences between these representative cuts, C and D, in terms of lipid, moisture, energy and EPA + DHA contents. For instance, the mean difference in lipid content was 2.1% (12 and 9.9%, C and D, respectively), representing a 22% variance. From a production perspective this would probably be inconsequential as comparison is generally made on identical cuts for consistency, providing any differences in body size and diet formulation are considered as these affect lipid and pigment deposition (Bell et al., 1998; Olsen & Mortensen, 1997; Shearer, 1994). However, understanding such variances would enable the assessor to factor in adjustments when comparing data from different cuts, which could vary within the same company, by region or in the literature such as the retail sampling of salmon products (e.g. Gillies et al., 2023; Henriques et al., 2014; Nøstbakken et al., 2023; Sprague et al., 2020).

Retailers have an interest in reporting the nutritional composition of foods, especially since 2016 when it has been mandatory within Europe

and the UK to accurately display and update this information on product labels (Regulation (EU) No 1169/2011). For live animals, such as farmed salmon, this can be difficult to control given the many biotic and abiotic factors affecting the nutritional content compared to processed foods. Nevertheless, nutrition declarations are often afforded tolerances, typically around $\pm 20\%$, to account for such occurrences, with declared values being based on average values from analysis or accepted calculations. Comparing the nutrient content of the individual cuts with the fillet average resulted in the tail (E) being below the -20% threshold for both lipid and EPA + DHA, marginally within for energy (80.5%), whereas cut B was level with the upper tolerance limit for lipid (Fig. 2). No differences were observed for moisture and protein, which were relatively close to the fillet average. However, NQC is generally more favoured when measuring quality parameters, being easier to sample and prepare due to the absence of fins as found in the SQC, despite containing significantly lower levels of total fat and EPA + DHA than the whole fillet (Nøstbakken et al., 2023). When other cuts were compared to the NQC (D) those nearer the head (A, B and C) exceeded the $+20\%$ threshold for lipid while the tail (E) was below, whereas EPA + DHA contents were either close (A and C) or exceeded the upper threshold (B) and the tail lower albeit still above the minimum tolerance (Fig. 3). Instead, it is suggested that a larger cut encompassing both the SQC and NQC (cuts C + D) would represent a more accurate assessment of the overall fillet values (see Fig. 2), including total carotenoid level which is important from both production and consumer perspectives. Tail cuts, on the other hand, should probably be analysed and sold separately due to the lower amounts of nutrients, specifically lipid and EPA + DHA, found in this region. Anecdotal evidence suggests certain demographics such as older consumers prefer salmon tail portions, possibly reflecting differences in the sensory quality of the portions based on anatomical location selected (Chan et al., 2023), which itself will be reflected by the differences in nutrients (e.g. lipid content). While tail portions have occasionally been observed to be sold separately from other cuts, they are more commonly found pre-packed and sold alongside other body regions at the same price point (e.g. Sprague et al., 2020). Factoring in differences such as sensory quality, nutrient content and price may influence how consumers opt to purchase salmon although, apart from tail pieces, establishing where on the body such cuts are taken would, unless witnessed, be difficult for the ordinary consumer.

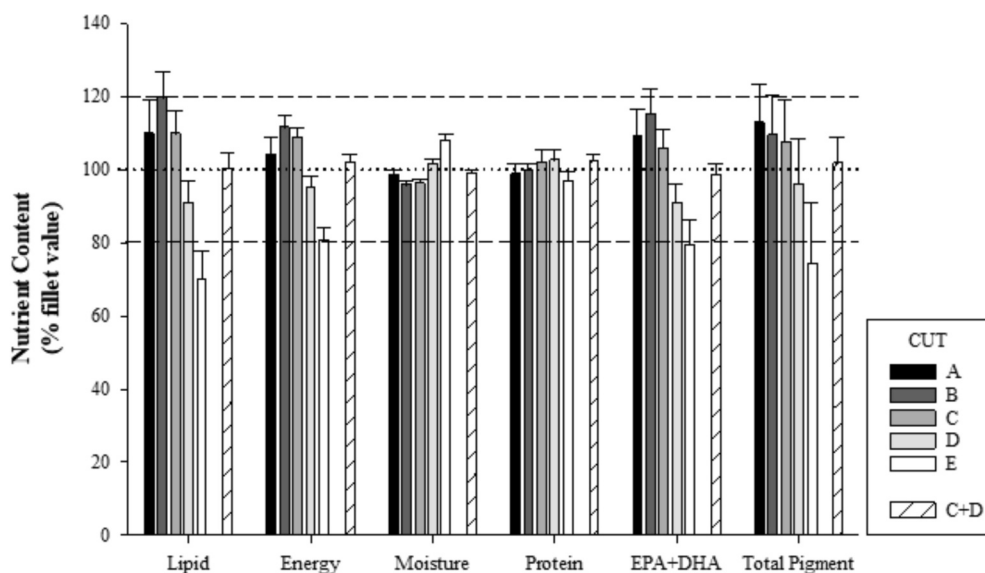


Fig. 2. Comparison of the nutrient, energy and total pigment content of individual salmon cuts (A–E), and combined SQC and NQC regions (C + D), relative to the overall fillet content (dotted line at 100%) and the $\pm 20\%$ accepted tolerance values (bold dotted lines at 80 and 120%, respectively).

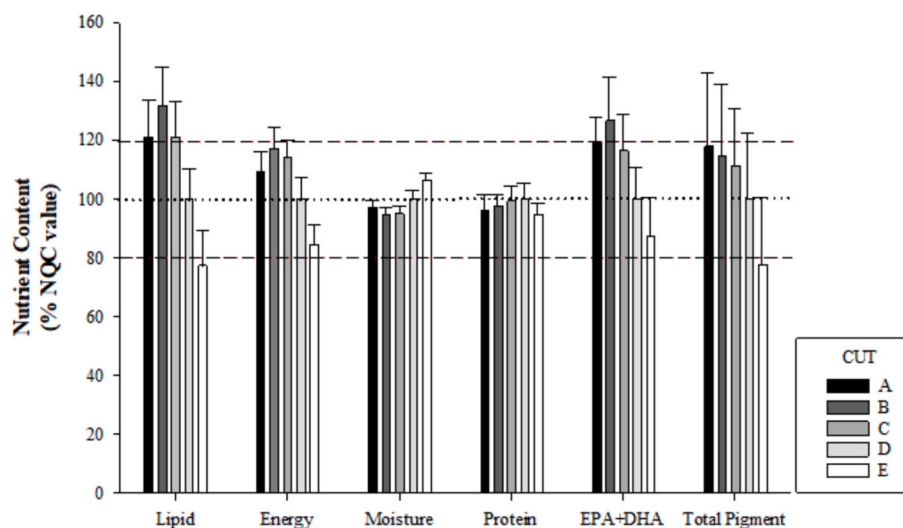


Fig. 3. Comparison of the nutrient, energy and total pigment content of individual salmon cuts (A–E), relative to the NQC (D) portion (dotted line at 100%) and the $\pm$ 20% accepted tolerance values (bold dotted lines at 80 and 120%, respectively).

4. Conclusion

Understanding the nutritional content of farmed salmon is important throughout the entire supply chain from production through to retail, including consumers. The results from the current study provide a valuable insight into the distribution of nutrients throughout the fillet as presented to the final human consumer, particularly regarding the lipids. Consequently, portion selection affects the lipid content, class composition and fatty acid profile that ultimately determines the amount of EPA and DHA omega-3 fatty acids supplied, whereby tail cuts delivered significantly less than all other cuts, but especially those closer to the head. While both protein and minerals demonstrated minor changes across fillet cuts these are considered less likely to impact consumer intake levels. Fillet pigmentation decreased towards the tail, contradicting results from previous studies, which may reflect the whole cut transect being analysed together with the role that both lipids and protein have in the uptake and binding of carotenoids in the muscle. Although results from the present study relate directly to the fish studied, similar patterns would be expected to occur in other harvest-size salmon irrespective of body size or feed formulation. Combining both industry standard cuts would improve the assessment of the fillet average rather than relying upon current estimations, specifically the NQC. Adopting such practices would assist the monitoring of farmed fish to provide a more accurate assessment of the fillet for nutritional labelling and informing the consumer.

CRediT authorship contribution statement

M. Sprague: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **S. Calloni:** Writing – review & editing, Investigation, Formal analysis. **X. Gong:** Investigation, Formal analysis. **A. Scobbie:** Investigation, Formal analysis. **J. Di Toro:** Writing – review & editing, Investigation, Formal analysis. **W.A. Struthers:** Investigation, Formal analysis. **D.R. Tocher:** Writing – review & editing, Supervision, Conceptualization. **M.B. Betancor:** Writing – review & editing, Supervision, Investigation, Formal analysis.

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.

Data availability

Data will be made available on request.

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