

Water temperature and velocity alter mineral composition and iodine concentration in Atlantic salmon (*Salmo salar*)

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Abstract

Atlantic salmon (*Salmo salar*) is an important farmed marine species globally, providing important nutritional benefits; however, how environmental conditions during production influence its nutritional quality in terms of mineral composition remains poorly understood. The present study addressed this gap by analysing the chemical and mineral composition of salmon reared under optimum (15°C) and suboptimum elevated (20°C) water temperatures, combined with low (0.22 m s⁻¹) and moderate (0.45 m s⁻¹) water velocities. Salmon whole body, skin, skin-off muscle and skin-on muscle were analysed. Mineral concentrations were consistently higher in skin than in muscle tissues, indicating the nutritional value of retaining skin for consumption. Moisture, lipid, protein, ash, and gross energy concentrations showed no differences among treatments. Suboptimum elevated temperature (20°C) increased magnesium, sodium, iron, and zinc concentrations in the whole body, but markedly reduced iodine concentrations in skin (162–180 vs 84–88 mg kg⁻¹) and skin-off muscle (25–41 vs 4–9 mg kg⁻¹). Moderate water velocity reduced magnesium, sodium, selenium, and iodine concentrations in selected tissues. Temperature × velocity interactions affected magnesium and sodium concentrations in muscle. These results demonstrate that elevated temperature can substantially alter the mineral composition of Atlantic salmon, with pronounced reductions in iodine concentrations. Such changes may have important implications for the nutritional value of salmon as a food source and highlight the need to consider environmental conditions in aquaculture to maintain seafood nutrient quality under a warming climate.

Highlights

- Atlantic salmon skin contained higher mineral concentrations than muscle tissues.
- Suboptimum elevated temperature reduced iodine concentration in salmon skin and muscle.
- Suboptimum elevated temperature increased magnesium, sodium, iron, and zinc concentrations in salmon whole body.
- Moderate water velocity reduced magnesium, sodium, selenium, and iodine concentrations in selected tissues.
- Suboptimum environmental conditions affect salmon mineral nutritional quality.

1. Introduction

Anthropogenic climate change has led to a global surface temperature increase of ~ 1.1°C since pre-industrial times, with projections of warming of 1.4–4.4°C by 2100 depending on emission scenarios (IPCC 2023). Oceans, which absorb over 90% of excess heat, have experienced record breaking warmth since 19th century, especially in the upper 700 m ocean layer (IPCC 2023; Cheng et al. 2024; EPA 2024; NOAA 2024). The Southern Hemisphere's extratropical oceans (30°S–50°S) have absorbed the majority of the excess heat since 2005, and southeastern Australia, including the Tasman Sea (a global marine hotspot), is warming nearly four times faster than the global average of near-surface water temperatures (Roemmich et al. 2015; Wijffels et al. 2016; CSIRO and The Bureau of Meteorology 2022; Cai et al. 2023). Tasmania experienced unprecedented marine heatwaves (MHWs) in 2015–16 and 2017–18, with sea surface anomalies exceeding 3.2°C and durations of up to 251 days (Oliver et al. 2017; Perkins-Kirkpatrick et al. 2019). MHWs are projected to intensify and persist into the future, posing major risks to marine ecosystems, fisheries and aquaculture, including key farming species such as oysters, abalone, and Atlantic salmon (Hobday et al. 2018; Ugalde et al. 2018; Oliver et al. 2019; CSIRO and The Bureau of Meteorology 2022; IPCC 2023; Brown et al. 2024; CSIRO 2024).

Atlantic salmon (*Salmo salar*), a cold-water species native to the North Atlantic Ocean (temperate and subarctic regions), is farmed globally, with major industries in Norway (1.6 M t/year), Chile (0.7 M t/year), the UK (0.2 M t/year), and is locally important in Tasmania, Australia (0.08 M t/year) (Thorstad et al. 2010; FAO 2024). The global economic value of Atlantic salmon production exceeded 2.7 M t (USD 21 billion) in 2023 ((FAO 2025). Atlantic salmon is highly regarded for its nutritional benefits, being rich in high-quality proteins and fatty acids (Foran et al. 2005; Nøstbakken et al. 2021; FAO 2024). Although Atlantic salmon can grow across a relatively broad temperature range (approximately 1.0–26.7°C, with optimal growth efficiency typically reported around 12–18°C), performance and physiological condition are strongly influenced by temperature (Elliott and Elliott 2010; Jobling et al. 2010). Recent work has highlighted that defining a single optimum temperature for farmed salmonids is complex due to variation across production stages, environments, geographical regions and interacting stressors (Carter et al. 2026). In this context, ocean warming poses significant challenges for the Atlantic salmon farming industry, particularly in Tasmania and other global marine hotspots, as highlighted in recent reviews (Carter et al. 2026; Zhan et al. 2026). Water temperature is an important environmental factor affecting salmonid physiology, growth, health and nutrient composition (Brett 1979; Islam et al. 2022; Agarwal et al. 2024). Therefore, understanding how elevated water temperatures will affect salmon aquaculture is crucial for optimising farming practices and ensuring the sustainable production of high-quality Atlantic salmon (Carter et al. 2010; Stehfest et al. 2017; D'Abramo and Slater 2019; Reid et al. 2019; Korus et al. 2024).

As salmon aquaculture is predicted to shift towards open ocean aquaculture (OOA) farming to address space limitations, Atlantic salmon farms will face more challenging conditions compared to near-shore sites, such as stronger water currents and waves (Holmer 2010; Bjelland et al. 2015; Gentry et al. 2017; Hvas et al. 2021). Increased water velocity, such as likely to be experienced in these OOA conditions, has been shown to enhance swimming performance, feed efficiency, disease resistance and bone mineral concentration in salmonids, while also influencing body shape, muscle fibre density, fillet colour and lipid concentration (Totland et al. 1987; Jobling et al. 1993; Castro et al. 2011; Totland et al. 2011; Timmerhaus et al. 2021; Prescott et al. 2023; Prescott et al. 2024; Prescott et al. 2025). Water velocity is also reported to activate innate immunity and mucus production gene expression in the skin, and excessive swimming, beyond the optimum velocity, is reported to negatively impact Atlantic salmon skin structure and welfare (Timmerhaus et al. 2021). Therefore, due to global climate change and future aquaculture strategy (Zhan et al. 2026), Atlantic salmon farmed in the future are likely to be grown under increased water velocity and/or warmer water temperatures. The effect of these changes in water conditions on Atlantic salmon performance and nutritional

composition of the resulting salmon products is not well understood. It is important to explore how OOA scenarios and associated warming temperatures can alter Atlantic salmon growth and product quality, in order to ensure sustainable production and maintain quality in the future (Carter et al. 2026).

Minerals play vital roles in numerous physiological and biological processes, including osmoregulation, muscle function, and bone development (Soetan et al. 2010; Lall 2022). A recent systematic review demonstrated that salmon mineral composition (e.g. iron, zinc, iodine and selenium) is highly variable and influenced by production conditions, including geographical origin, rearing environment, and feed composition (Zhan et al. 2025). The review also identified a lack of data on salmon edible tissues, particularly muscle and skin, at harvest size (Zhan et al. 2025). This knowledge gap limits our understanding of how production conditions influence the nutritional quality of salmon as a food source. Therefore, the present study seeks to investigate how elevated water temperatures and velocity, both individually and in combination, affect the growth, proximate composition and mineral composition of Atlantic salmon, with particular emphasis on differences in mineral composition among key tissues (whole body, skin, skin-on muscle and skin-off muscle). By exploring the interactions between these environmental stressors, this research aims to improve the understanding of how climate-related changes may influence the nutritional quality of farmed salmon. Overall, this research will provide valuable insights for optimising farming conditions and maintaining the nutritional quality of Atlantic salmon under climate change, ensuring sustainable aquaculture practices and nutrient-rich Atlantic salmon production for human consumption.

2. Methodology

2.1 Atlantic salmon husbandry and sampling

Atlantic salmon (*Salmo salar*) post-smolts were maintained in recirculating aquaculture systems (RAS) supplied with seawater at the Experimental Aquaculture Facility (EAF), Institute for Marine and Antarctic Studies, University of Tasmania, Australia (Nuez-Ortín et al. 2018; Witkowski et al. 2019). The experimental design and workflow are outlined in Figure 1, with detailed husbandry methodology provided in Appendix 1.

The current study (April to July 2021) sampled experimental salmon from the same experiment as previously described by Foddai et al. (2025), which was approved by the Animal Ethics Committee of the University of Tasmania (A0073503). Four treatments were applied to the Atlantic salmon in triplicate for 90 d throughout the experiment.

Salmon were sampled at 0 and 90 d following anaesthesia/euthanasia with Aquí-S; detailed biometric methods and data are reported in Foddai et al. (2025) and Appendix 1. Key biometric measurements were recorded to characterise salmon across treatments and triplicate tanks (Table 1). Whole body fish ($n = 5$ salmon tank⁻¹) and muscle ($n = 10$ salmon tank⁻¹) samples were pooled by tank and then stored at -20°C until used for chemical analysis (see below).

2.2 Whole body fish sampling

Frozen whole fish samples were thawed in a refrigerator overnight in preparation for mincing the next day. Five experimental salmon from each tank were randomly selected and pooled to form a single composite sample for analysis.

The thawed whole body samples were minced in a commercial bowl cutter (Mado, MTK 661, Dornhan, Germany) following a standard procedure on a per tank basis (<https://www.mado.de/en/project/mtk-661/>). Duplicate 200 g whole body sub-samples from each tank were collected and further homogenised using a blender (Braun JB9042BK) with dry ice. Homogenised experimental salmon mince from each sub-sample (50 g) was freeze-dried to a constant weight and stored at -20°C until further analysis.

2.3 Muscle and skin sampling

Frozen muscle samples were thawed in a refrigerator overnight. A 4 cm Norwegian Quality Cut (NQC) muscle sample was further taken (Figure 2) within 6 h of starting the thawing process. Any remaining vertebrae and fine bones were removed from the muscle to replicate commercial removal of pin bones prior to sale.

The NQC muscle sample was further divided into two 2 cm cuts. For the “skin off” sample, the skin was peeled off the muscle using a fillet knife following commercial operation procedure. The removed skin then made up the “skin only” sample, and any residues of subcutaneous fat were left on the skin to maintain consistency with the commercial product form. The other 2 cm cut was used for the “skin-on” sample, which included the muscle with the skin still attached.

Skin-off and skin-on muscle samples were homogenised using a food processor (The Kitchen Wizz® 11 Plus) for 60 s on a per tank basis. A sub-sample from each tank (skin-on muscle, 30 - 50 g tank⁻¹; skin-off muscle, 30 - 50 g tank⁻¹) was freeze-dried to a constant weight. Skin samples (5-12 g tank⁻¹) were pooled on a per tank basis, frozen and then freeze-dried. The freeze-dried samples were then milled using a ball mill (Mixer Mill MM 200 - RETSCH). All skin and muscle samples were stored at -20°C until further analysis.

2.4 Chemical composition analysis

Freeze-dried whole salmon and feed samples were analysed for chemical composition (moisture, total lipid, crude protein, ash and gross energy) including mineral composition. Due to the limited amount of muscle and skin sample, moisture, total lipid, crude protein and mineral composition were analysed. All analyses are presented on a wet weight (WW) basis. Moisture concentration of samples was determined using gravimetric analysis by oven drying at 105°C

for 24 h (AOAC 1995). Total lipid was determined gravimetrically using modified Bligh and Dyer (1959) method. Total lipid was extracted using a mixture of dichloromethane, methanol and MilliQ water (1:1:0.9 v/v/v) (Cequier-Sánchez et al. 2008; Yagiz et al. 2009; Wirtz et al. 2022). Crude protein concentration was determined using nitrogen (N) concentration by Kjeldahl method and a conversion factor of $6.25 \times N$ was used to calculate crude protein concentration (Carter et al. 2025). Ash concentration was determined by the combustion of Atlantic salmon samples in a furnace at 600°C for 2 h (AOAC 1995). Bomb calorimetry was used to determine the gross energy (MJ kg^{-1}) according to the manufacturer's specifications (Parr 6400 Automatic Isoperibol Calorimeter, IL, USA) as described by (Wirtz et al. 2022).

The mineral composition (aluminium, arsenic, boron, calcium, cadmium, cobalt, chromium, copper, iron, iodine, phosphorus, potassium, lead, magnesium, manganese, molybdenum, nickel, sodium, selenium, sulphur and zinc) in whole Atlantic salmon samples was determined after nitric acid (HNO_3) digestion (or alkaline extraction for iodine) using Inductively Coupled Plasma Mass Spectrometry (ICP-MS, iCAP-Q or iCAP-TQ, Thermo Fisher Scientific, Bremen, Germany) at the University of Nottingham, United Kingdom. Mineral composition in Atlantic salmon muscle samples, skin samples and feed samples were analysed at CSIRO (Commonwealth Scientific and Industrial Research Organisation), Adelaide, Australia using ICP - Atomic Emission Spectroscopy (ICP-AES, Agilent 5100, Agilent Technologies, USA), except for iodine and selenium concentration in Atlantic salmon muscle samples and skin samples, that were determined using ICP-MS (Agilent 8900 Triple Quadrupole, Agilent Technologies, USA). In both cases, HNO_3 was used to digest experimental salmon samples ($500 \text{ mg sample}^{-1}$) using a microwave digestion system prior to multi element analysis. Iodine extraction was conducted following the method of Julshamn et al. (2001). Briefly, experimental salmon samples ($500 \text{ mg sample}^{-1}$) were digested by adding 5 mL Milli-Q water, thoroughly mixing, then adding 1 mL 25% Tetramethylammonium hydroxide (TMAH). Samples were oven heated at 90°C for 3 h, left to cool, then diluted using Milli-Q water to 10 mL. The solution was then filtered through a $0.45 \mu\text{m}$ membrane filter. To verify how well the samples were digested or extracted from, four blanks and certified reference materials (CRMs) fish muscle (ERM®-BB422), prawn tissue (NMIA MX009), dogfish liver (DOLT-5), fish protein (DORM-4), hay powder (BCR-129) and tomato leaves (Tom-1573a) were used. The recovery rates of CRMs for the certified minerals exceeded 80% across whole-body, muscle, and skin mineral analysis.

2.5 Statistical analysis

Chemical and mineral composition data (Supplementary Table 1) were tested to determine whether they were normally distributed and had equal variance using Shapiro-Wilk normality test and Levene's test, respectively. The statistical differences between treatments were determined using two-way ANOVA test for temperature, velocity and temperature $\times$ velocity interaction effects followed by Tukey HSD post-hoc test. Statistical significance was defined as $p < 0.5$. All statistical analysis and graphing were conducted in R version 4.4.2 (R Core Team 2024) and RStudio version 2024.09.1+394 (RStudio Team 2024) using the dplyr (Wickham et al. 2023), agricolae (Mendiburu 2023), car (Fox et al. 2024) and ggplot2 (Wickham et al. 2025) packages.

3. Results

3.1 Chemical composition of Atlantic salmon tissues

The whole body had a statistically lower mean moisture concentration (623 g kg^{-1}) compared to muscle samples, while the skin had the lowest mean moisture concentration (532 g kg^{-1}) among all tissues (Figure 3). The skin had the highest crude protein concentration compared to other tissues and the whole body had the lowest crude protein concentration (Figure 3). The mean total lipid concentration in the skin ($248 \text{ g kg}^{-1} \text{ WW}$) was statistically higher than in other tissues, whereas all the other tissues had similar total lipid concentrations to each other (Figure 3).

Moisture, total lipid and gross energy were not statistically different between water temperature and velocity treatments for the whole body, skin, skin-on muscle, and skin-off muscle. Temperature $\times$ velocity interaction effects also showed no statistical differences (Table 2). Temperature and the temperature $\times$ velocity interaction effects presented statistical differences in the skin crude protein, with the lowest crude protein concentration in the skin of Atlantic salmon from UNT/20 treatment (Table 2). Ash concentration was statistically lower in Atlantic salmon at elevated temperature groups (Table 2).

3.2 Mineral composition in Atlantic salmon tissues

Mineral composition differed statistically between the whole body, skin and muscle tissues, but no statistical differences were observed between skin-on and skin-off muscle (Figure 4; Figure 5). Among the macro minerals, phosphorus and calcium had the highest concentrations in the skin, followed by the whole body (Figure 4). However, magnesium and potassium were higher in the whole body than in the skin (Figure 4). Sodium concentrations were similar between the whole body and skin (Figure 4). Muscle tissues (both skin-on and skin-off) generally exhibited the lowest concentrations of phosphorus, calcium, magnesium, and sodium, whereas potassium showed the highest concentrations in muscle tissues (Figure 4).

For trace minerals, the whole body presented higher concentrations of zinc and iodine compared to the skin, with the lowest concentrations of these minerals found in both skin-on and skin-off muscle tissues (Figure 5). Conversely, iron and selenium had the highest concentrations in the skin, with similar concentrations observed in the whole body and muscle tissues (Figure 5).

3.3 Effects of water temperature and velocity on mineral concentrations of Atlantic salmon

Water temperature increased the phosphorus, calcium, magnesium and sodium concentrations in Atlantic salmon whole body (Table 3). Magnesium (skin, skin-on and skin-off muscle) and sodium (skin-on and skin-off muscle) also had increased concentrations in Atlantic salmon at elevated temperatures (Table 3). Increasing water velocity from 0.22 m s^{-1} (UNT) to 0.45 m s^{-1} (TRN) decreased magnesium concentration in the skin-on muscle and sodium

concentration in the skin-off muscle (Table 3). The temperature × velocity interaction affected magnesium in the skin-on muscle and sodium in the skin-off muscle (Table 3). Magnesium concentration in the skin-on muscle was lower in the TRN/15 treatment than in the other treatments, while sodium concentration in the skin-off muscle was highest in the UNT/20 treatment and lowest in the 15 °C treatments (Table 3). The concentration of potassium in Atlantic salmon tissues was not affected by water temperatures and velocities (Table 3).

For trace minerals, water temperature increased the concentrations of iron and zinc in the Atlantic salmon whole body, except for iodine which presented significantly decreased concentration at suboptimum elevated temperature (Table 4). Skin-off muscle had increased zinc concentration in Atlantic salmon at elevated temperatures (Table 4). However, concentrations of iodine were decreased in the skin, skin-on and skin-off muscle of Atlantic salmon at suboptimum elevated temperatures. Selenium in Atlantic salmon skin also had decreased concentration with increasing temperature (Table 4). Water velocity influenced selenium in the skin-on muscle, and iodine in the skin-off muscle, with decreasing concentrations at TRN compared to UNT treatments (Table 4). The concentrations of trace minerals were not impacted by the temperature × velocity interaction effect (Table 4).

4. Discussion

4.1 Many important minerals were in higher concentrations in skin compared to muscle

Minerals are essential for human health and need to be obtained from food, including calcium, phosphorus, magnesium, potassium, iron, iodine selenium and zinc, that contribute to bone and muscle development, energy production, haemoglobin formation, oxygen transport, blood glucose control, blood pressure regulation, antioxidant, immune function and thyroid hormone production (Soetan et al. 2010; Stein 2010). Fish are an important dietary source of essential trace minerals (Özden and Erkan 2011; Tilami and Sampels 2018; Jayasekara et al. 2020; Farmery and Bogard 2022). In the present study, Atlantic salmon skin (including scales) contains higher mineral concentrations compared to skin-off muscle, notably calcium (136.8-fold), iron (15-fold), iodine (5.9-fold), and zinc (8.5-fold). These findings align with previous studies on salmonids and other fish species showing higher mineral concentration in skin (Schmid et al. 2003; Storelli et al. 2006; Uysal et al. 2008; Yılmaz et al. 2010; Schenone et al. 2014; Aydın and Tokaloğlu 2015), highlighting the nutritional benefits of consuming salmon skin.

Collagen peptide chelates minerals such as calcium, copper, iron, and zinc, enhancing their bioavailability and stability (Charoenphun et al. 2013; Guo et al. 2013; de la Hoz et al. 2014; Pal and Suresh 2016; Wu et al. 2017; Luo et al. 2020; Yang X-H et al. 2023). This mineral-binding capacity might be a major factor contributing to the high mineral concentration in collagen-rich tissues, such as fish skin and scales, which contain approximately 51% and 24% collagen by dry weight, respectively (Dave et al. 2019). Wang et al. (2025) then reported that Atlantic salmon skin is rich in collagen and contains high concentrations of minerals, particularly calcium and iron. Although skin-on and skin-off muscles generally showed similar overall mineral concentrations due to the small proportion of skin relative to the muscle, encouraging consumers to eat the skin as well as the muscle could enhance their dietary intake of these essential nutrients in particular, including calcium, iron, iodine and zinc.

From an industry perspective, reusing Atlantic salmon skin in value-added products has the potential to reduce processing waste and improve resource efficiency (Ling et al. 2024; Nelluri et al. 2024; Seifzadeh 2025). By emphasising the health advantages and culinary versatility of Atlantic salmon skin, producers and retailers have created opportunities for new product innovations, such as crispy salmon skin snacks, collagen supplements and high-quality pet food products (Holmyard 2019; Shoup 2021; Scalia-Bruce 2023; Nelluri et al. 2024). Retaining skin on salmon products aligns with sustainable seafood practices by maximising utilisation of each salmon, reducing processing waste, and improving product yield and value recovery for salmon producers.

4.2 Water temperature impact on mineral composition

Iodine

In the present study, Atlantic salmon exposed to elevated temperatures showed a reduction in iodine concentrations in the skin, skin-on and skin-off muscle. Iodine is a crucial component of deiodinases which are essential for thyroid hormones (TH) synthesis that regulates basal metabolic rate (BMR) and oxygen consumption in fish tissues (Eales and Brown 1993; Leatherland 1994; Power et al. 2001; Eales 2019). The requirement of iodine in fish may increase with higher TH turnover to maintain homeostasis in fish exposed to elevated temperatures (Eales 2019). Elevated temperatures increase energy and metabolic demands supported by TH production (Eales and Brown 1993; Leatherland 1994; Power et al. 2001; Eales 2019), which likely relies on iodine availability. Temperature is positively correlated with TH levels and clearance rates, processes also dependent on iodine availability (Eales 1985; Gupta and Thapliyal 1991; Peter and Oommen 1993; Little et al. 2013). As skin and muscle are less involved in deiodination, iodine may be redistributed to organs more directly involved in TH production, such as the thyroid tissue, head kidney, liver, brain, intestine, and pituitary (Mol et al. 1998; Deal and Volkoff 2020). In the present study, the iodine had lower concentrations in the whole body, skin and muscle tissues in Atlantic salmon from elevated temperature, suggesting that iodine might be redistributed to these TH-related tissues with higher clearance rate. Additionally, iodine had a lower concentration in the skin-off muscle of Atlantic salmon in the present study from the higher water velocity treatment. Increased water velocity is known to enhance thyroid activity, increase plasma iodine concentration, boost iodine excretion, and stimulate TH secretion in salmonids (Higgs and Eales 1971; Kiessling et al. 1994; Deschamps et al. 2009). Since the present study did not analyse specific TH-related tissues, more research is needed to determine how iodine concentrations in these tissues may have changed. These findings underscore the critical need to address iodine redistribution mechanisms in Atlantic salmon under sub-optimum conditions.

Selenium

The present study observed contrasting trends in selenium concentrations in Atlantic salmon at elevated temperatures, with levels decreasing in the skin but remaining stable in the whole body. Selenium is critical for synthesising selenoenzymes and selenoproteins, such as iodothyronine deiodinases, which regulate TH metabolism, and glutathione peroxidase, an antioxidant enzyme that protects against oxidative damage (Berry et al. 1991; Arthur et al. 1992; Behne et al. 1992; Köhrlé 2000; Mariotti et al. 2012; Lall 2022). Elevated temperatures increase TH turnover and reactive oxygen species (ROS) production

(Kaur et al. 2005; Heise et al. 2006; Lushchak and Bagnyukova 2006; Leggatt et al. 2007; Little et al. 2013; Nakano et al. 2014; Banh et al. 2016; Wang et al. 2016), likely heightening selenium demand for metabolic and antioxidant functions in salmon. Liver, kidney and gill are primary sites for oxidative stress response, muscle tissues also exhibit increased oxidative stress biomarkers under thermal stress (Lushchak and Bagnyukova 2006; Leggatt et al. 2007; Hegazi et al. 2010; Nakano et al. 2014; Banh et al. 2016). As skin plays a less important role during oxidative stress response, this may explain selenium preferential redistribution from skin to metabolically active tissues while maintaining similar concentration in muscle, safeguarding function and mitigating damage at suboptimum elevated temperature in the present study. The role of selenium in immunity is equally critical, particularly in the skin, the first barrier against environmental stressors (Ángeles Esteban 2012; Pacitti et al. 2016; Pohl et al. 2018; Lall 2022; Kokkali et al. 2023; Sumana et al. 2023). However, increased susceptibility to infections under heat stress, as shown in Atlantic cod and sticklebacks (Magnadóttir et al. 1999; Wegner et al. 2008; Karvonen et al. 2013; Scharsack et al. 2021), raises questions about whether selenium redistribution compromises skin immunity. The lack of data on selenium concentration in other tissues, such as plasma, liver, kidney, and gill, limits our understanding of its relocation mechanisms and broader impacts on Atlantic salmon health and product quality. Further research is essential to explore these dynamics under warming conditions.

Iron

Elevated temperatures increased whole-body iron concentrations in the present study. Iron homeostasis, regulated by the temperature-sensitive hormone hepcidin, is disrupted under thermal stress, with suppressed hepatic expression associated with upregulated cytochrome b reductase (*cybrd*) enhancing Fe³⁺ to Fe²⁺ conversion (Hilton and Lambert 2008; Neves et al. 2016; Wang et al. 2023). Elevated temperature also raises iron digestibility and iron concentrations in plasma, liver, and whole-body (Bowen et al. 2006; Wang et al. 2023). Iron is vital for electron transfer, energy metabolism, and antioxidant defence through heme-based enzymes like catalase (CAT), which convert H₂O₂ into water and oxygen (Zámocký and Koller 1999; Nicholls et al. 2000; O'Brien 2000; Bury and Grosell 2003; Ghosh et al. 2008; Guo et al. 2018; Lall 2022; Ahmad et al. 2023). Thermal stress increases H₂O₂ production and boosts mitochondrial activity, ATP synthesis, and CAT levels in fish (Kaur et al. 2005; Banh et al. 2016; Sambrasus et al. 2017), highlighting the heightened demand for iron in antioxidant mechanisms.

Iron is also crucial for oxygen transport via haemoglobin and myoglobin, but elevated temperatures reduce haemoglobin-oxygen binding affinity (Weber and Campbell 2011; Lall 2022; Morrison et al. 2023). Wang et al. (2023) reported increased haematopoiesis at elevated temperature with higher red blood cell and haemoglobin levels in spotted seabass (*Lateolabrax maculatus*). In contrast, Atlantic salmon showed reduced haemoglobin and haematocrit at 20°C in UNT groups (Foddai et al. 2025). This might suggest species-specific physiological responses to elevated temperatures. Overall, elevated temperatures might increase iron concentrations primarily in antioxidant-active tissues to mitigate oxidative stress rather than for storage in Atlantic salmon in the present study. Future research should explore the mechanisms of iron metabolism in Atlantic salmon at suboptimum elevated temperatures.

Zinc

Higher zinc concentrations were observed in the whole body and skin-off muscle of Atlantic salmon at elevated temperatures in the present study. This aligns with findings of increased zinc in the liver of coho salmon (*Oncorhynchus kisutch*) under thermal stress (Bowen et al. 2006). Zinc, primarily absorbed through the diet via the intestine, shows increased digestibility at elevated temperatures, as noted in spotted seabass (Hardy et al. 1987; Bury et al. 2003; Yuan et al. 2023). The gills also mediate zinc exchange between water and plasma (Hardy et al. 1987; Bury et al. 2003; Feeney et al. 2005; Zheng et al. 2008).

Zinc metabolism relies on transporters such as ZnT (SLC30A), ZIP (SLC39A), metal-responsive transcription factors (MTFs) and metallothioneins (MTs), which are temperature-sensitive and expressed in various tissues across fish body (Feeney et al. 2005; Zheng et al. 2008; Zhao et al. 2014; Kambe et al. 2015; Sappal et al. 2016; He et al. 2023). Elevated temperatures impact the expression of ZnT, ZIP and MTFs, particularly in the liver (He et al. 2023), and thermal stress-induced cortisol elevation may also enhance MTs and ZnT1 expression in gills, influencing zinc influx and metabolism (Bury et al. 2008; Chadwick and McCormick 2017; Vargas-Chacoff et al. 2018; Yang et al. 2021). Zinc is also important for bone development and immune function (Prabhu et al. 2016; Baevefjord et al. 2019), suggesting the absorbed extra zinc might also store in the high-demand tissues like bones under elevated temperatures in the present study. However, contrasting findings, such as increased zinc in plasma and bile but not in whole body or vertebrae in Atlantic salmon at 16°C compared to 12°C (Philip et al. 2023), emphasise the need for advanced analytical techniques, such as isotope analysis, to clarify its physiological roles and mechanisms under warming conditions.

Sodium

Elevated temperatures led to increased sodium concentrations in the whole body and muscle tissues of Atlantic salmon in the present study, likely due to disruptions in osmoregulation in gill. Thermal stress affects gill morphology, reduces Na-K-ATPase (NKA) activity, and impairs the expression of key osmoregulatory proteins, such as NKAα1b and Na-K-Cl cotransporter (NKCC), leading to inefficient sodium excretion and accumulation in the plasma of seawater fish including Atlantic salmon (24°C) and gilthead sea bream (26°C) (Duston et al. 1991; Liu et al. 2015; Chadwick and McCormick 2017; Vargas-Chacoff et al. 2018; Bernard et al. 2020; Vargas-Chacoff et al. 2020; Yang et al. 2021; Yang S et al. 2023). In marine fish, gills actively excrete Na⁺ absorbed from seawater, but thermal stress impairs this function, causing potential sodium retention in the Atlantic salmon body observed in the present study.

Increased oxygen demand during thermal stress exacerbates this issue by raising gill ventilation and ion permeability, further challenging osmoregulation with accelerating Na⁺ efflux and presenting lower plasma sodium in freshwater fish species (Randall et al. 1972; Gonzalez and McDonald 1992; Steiner et al. 2022). Passive ion transport from the environment to the fish body shows opposite mechanisms between freshwater and seawater fish species (Na⁺ passive diffusion in freshwater fish: from fish to environment; in seawater fish: from environment to fish). This imbalance in sodium regulation might further contribute to sodium retention and challenge osmoregulation in Atlantic salmon at elevated temperature in the present study.

Increased water velocities are reported to upregulate osmoregulatory genes (Esbaugh et al. 2014), which is supported our finding with lower sodium concentration in the skin-off muscle of Atlantic salmon at moderate velocity conditions in the present study. However, velocity effects on sodium in skin-off muscle only take place at elevated temperatures in the present study. Understanding the temperature and velocity interaction mechanism is critical to understand Atlantic salmon growth and overall health due to impaired osmoregulation at suboptimum elevated conditions.

Magnesium

The present study recorded increased magnesium concentrations in the Atlantic salmon whole body, skin and muscle tissues at elevated temperatures. Mild stress increases magnesium in fish erythrocytes, while severe stress typically depletes it (Zaprudnova 2018). Our observation aligns with reports of elevated plasma magnesium in chinook salmon (*Oncorhynchus tshawytscha*) held at stressed conditions and elevated temperatures (Young et al. 2019; Casanovas et al. 2021; Steiner et al. 2022).

Marine teleosts actively excrete Mg^{2+} to maintain plasma concentrations lower than seawater (Takvam et al. 2021). Thermal stress, however, damages kidney function and disrupts gene expression (Liu et al. 2015; Huang et al. 2018; Yang et al. 2020; Pandey et al. 2021; Jing et al. 2023), which might reduce the ability of magnesium excretion. Magnesium is mainly stored in bones and scales and it is also important for muscle strength, so it likely explains the increased presence in Atlantic salmon whole body and soft tissues in the present study. This disrupted magnesium homeostasis is likely due to chronic systemic stress responses and impaired magnesium excretion, highlighting potential challenges in managing Atlantic salmon health and quality under elevated temperatures.

4.3 Water temperature is important for seafood product quality

Atlantic salmon whole body data show increased concentrations of minerals (except for iodine) at elevated temperatures, which could improve the value of Atlantic salmon by-products (e.g., bones, scales, and organs) for applications in health supplements, animal feed, and fertilisers. These by-products are often rich in minerals and could serve as a sustainable resource for secondary industries. Given that Atlantic salmon muscle is the primary edible portion consumed by humans, the observed temperature-related changes in muscle mineral composition may influence the nutritional value of salmon products. Importantly, iodine concentration is much lower in Atlantic salmon raised at elevated temperature and moderate water velocity than from optimum water conditions; iodine concentrations were 53% less in the skin and 90% less in the skin-off muscle, leading to 9.6 µg (skin) and 3.7 µg (skin-off muscle) reduction in iodine availability per serving for human consumers. This reduction poses new challenges in climate change and OOA practices in the future with the diminished nutritional value of Atlantic salmon as a dietary iodine source. It is worth noting that feed supplementation enhances Atlantic salmon mineral concentrations at optimum conditions (Zhan et al. 2025), and also improves antioxidant capacity, immunity, food consumption and growth performance in fish under thermal stress (Kumar et al. 2017; Ibrahim et al. 2019; Kamunde et al. 2019; Dawood et al. 2020; Kumar et al. 2022), and therefore supplementation of feed with iodine may be necessary under elevated temperatures. However, the prevalence of vertebral deformities and cataracts in Atlantic salmon exposed to elevated temperatures cannot be mitigated by trace mineral supplementation in feed (Bjerkås and Sveier 2004; Fraser et al. 2019; Philip et al. 2023). For the Atlantic salmon farming industry, this highlights the dual challenge of maintaining salmon health and welfare under elevated temperatures while safeguarding the nutritional quality of farmed products for consumers, as demonstrated in the recent modelling study of future ocean warming scenarios in major salmon farming regions and their projected impacts on salmon mineral nutritional quality (Zhan et al. 2026). Therefore, it is suggested that future research could prioritise strategies to improve salmon health, welfare and resilience at future warming temperatures, whilst also optimising the product quality and nutritional concentration for human health.

5. Conclusion

The present study comprehensively examines the mineral composition of Atlantic salmon tissues, with particular emphasis on the trace mineral concentration in the skin. These findings support the promotion of Atlantic salmon skin consumption for human health benefits and open avenues for innovative product development in the salmon industry. Importantly, this study highlights that changes in mineral composition in whole-body and edible portions, possible future farming under suboptimum elevated water temperature and moderate velocity. Reduced iodine concentrations in the Atlantic salmon whole body, skin and muscle tissues could raise concerns about the final product nutrient for human health. The present study suggests that further research should explore the mechanisms underlying changes in Atlantic salmon mineral composition under suboptimum conditions. The findings provide valuable insights into the trace mineral nutrition of Atlantic salmon for both human consumption and salmon by-product industries, particularly under global climate change and future OOA expansion. It suggests the strategies for Atlantic salmon aquaculture management might need to be improved, including changing the mineral concentration of feeds, to assist salmon aquaculture adapt to future challenges while maintaining salmon health and product quality.

Declarations

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Author contributions

X. Z., L. R. A., B. P., E. H. B. and C. G. C. conceptualised the work and developed the methodology. X. Z. contributed data curation, investigation, validation and formal analysis, and L. R. A., B. P. and C. G. C contributed supervision, funding acquisition, project administration and resources. All authors contributed to data visualisation, writing and editing for the manuscript.

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Conflict of interest

The authors declare no competing conflicts of interest to the current manuscript.

Data availability statement

The authors confirm that the data supporting the findings of the present study are available within the article and its supplementary materials.

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Tables

Table 1 Biometric parameters (mean ± SE) of body weight, fork length, and condition factor (K) of Atlantic salmon reared under four treatments (UNT/15, UNT/20, TRN/15, and TRN/20) at the end of a 90-day trial, presented at the individual tank level.

Biometrics	Treatments and duplicate tanks							
	UNT/15			UNT/20			TRN/15	
	Tank 1	Tank 2	Tank 3	Tank 1	Tank 2	Tank 3	Tank 1	Tank 2
Wet weight (g)	956.00 ± 70.33	739.40 ± 77.77	769.00 ± 37.78	818.00 ± 59.12	836.20 ± 58.57	939.60 ± 56.08	661.30 ± 75.12	719.00
Fork length (cm)	382.50 ± 12.03	361.90 ± 8.09	363.30 ± 10.95	368.00 ± 6.76	359.20 ± 9.01	384.50 ± 9.03	350.50 ± 10.54	355.80
K	1.68 ± 0.03	1.48 ± 0.08	1.59 ± 0.03	1.62 ± 0.04	1.83 ± 0.18	1.64 ± 0.03	1.46 ± 0.10	1.57 ± 0.02

Table 2 The concentration (Mean ± SE) of moisture, crude protein, total lipid, ash and gross energy in the whole body, skin, skin-on muscle and skin-off muscle of Atlantic salmon (*Salmo salar*) reared under four treatments (UNT/15, UNT/20, TRN/15 and TRN/20) for a 90-day trial. Different superscripts denote statistical difference ($p < 0.05$) when there was a statistically significant difference due to an interaction between Temperature × Velocity

Chemicals	Treatments				<i>p</i> value		
	UNT/15	UNT/20	TRN/15	TRN/20	Temperature	Velocity	Temperature × Velocity
<i>Moisture (g kg⁻¹)</i>							
Whole body	624.17 ± 1.66	622.82 ± 4.51	619.70 ± 3.61	624.36 ± 4.83	0.6980	0.6440	0.4500
Skin	528.95 ± 25.82	540.88 ± 5.07	513.99 ± 23.03	546.63 ± 18.97	0.3370	0.8910	0.7010
Skin-on muscle	651.08 ± 3.89	648.40 ± 11.38	638.35 ± 9.89	654.60 ± 3.85	0.3460	0.5760	0.2420
Skin-off muscle	658.98 ± 5.57	656.87 ± 2.41	646.81 ± 6.55	659.42 ± 4.37	0.3470	0.3390	0.2240
<i>Crude protein (g kg⁻¹WW)</i>							
Whole body	178.61 ± 0.76	180.58 ± 2.59	178.82 ± 3.01	181.66 ± 3.35	0.3910	0.8210	0.8690
Skin	290.51 ± 4.74 ^a	253.07 ± 1.80 ^b	284.89 ± 6.89 ^a	286.68 ± 0.75 ^a	0.0259 (15 > 20)	0.0786	0.0168
Skin-on muscle	210.50 ± 1.74	216.12 ± 0.75	205.32 ± 9.66	207.21 ± 2.93	0.6330	0.2750	0.7580
Skin-off muscle	209.30 ± 3.96	216.79 ± 6.11	209.01 ± 3.21	211.27 ± 3.49	0.3150	0.5350	0.5380
<i>Total lipid (g kg⁻¹WW)</i>							
Whole body	172.76 ± 4.49	167.59 ± 1.40	180.58 ± 6.35	175.62 ± 1.50	0.2290	0.1210	0.9820
Skin	245.17 ± 53.72	235.91 ± 33.20	295.37 ± 31.91	211.67 ± 41.44	0.3390	0.7080	0.9900
Skin-on muscle	182.99 ± 7.09	185.30 ± 12.79	207.97 ± 20.84	178.26 ± 6.79	0.3240	0.4560	0.2810
Skin-off muscle	198.46 ± 14.35	191.61 ± 1.53	208.32 ± 22.96	186.18 ± 2.62	0.3570	0.8470	0.6350
<i>Ash (g kg⁻¹WW)</i>							
Whole body	30.89 ± 0.79	28.74 ± 0.99	30.30 ± 0.43	28.81 ± 0.37	0.0467 (15 > 20)	0.7076	0.6815
<i>Gross energy (MJ kg⁻¹WW)</i>							
Whole body	11.27 ± 0.08	11.10 ± 0.17	11.42 ± 0.16	11.08 ± 0.16	0.1250	0.6610	0.5790

Table 3 The concentration (Mean ± SE) of macro minerals (phosphorus, calcium, magnesium, sodium and potassium) in the whole body, skin, skin-on muscle and skin-off muscle of Atlantic salmon (*Salmo salar*) reared under four treatments (UNT/15, UNT/20, TRN/15 and TRN/20) for a 90-day trial. Different superscripts denote statistical difference ($p < 0.05$) when there was a statistically significant difference due to an interaction between Temperature × Velocity.

Macro minerals	Treatments				<i>p</i> value		
	UNT/15	UNT/20	TRN/15	TRN/20	Temperature	Velocity	Temperature × Velocity
<i>Phosphorus (g kg⁻¹ WW)</i>							
Whole body	3.65 ± 0.03	4.17 ± 0.22	3.53 ± 0.11	4.18 ± 0.32	0.0120 (15 < 20)	0.7430	0.7340
Skin	6.31 ± 0.34	5.96 ± 0.45	5.65 ± 0.04	6.43 ± 0.20	0.3630	0.5748	0.0737
Skin-on muscle	2.37 ± 0.06	2.40 ± 0.07	2.29 ± 0.03	2.39 ± 0.03	0.1970	0.3340	0.4610
Skin-off muscle	2.12 ± 0.05	2.24 ± 0.09	2.09 ± 0.03	2.19 ± 0.04	0.0736	0.4574	0.8332
<i>Calcium (g kg⁻¹ WW)</i>							
Whole body	3.30 ± 0.09	4.32 ± 0.33	3.23 ± 0.21	4.34 ± 0.54	0.0075 (15 < 20)	0.9168	0.8728
Skin	8.32 ± 0.54	8.06 ± 0.63	7.38 ± 0.12	9.04 ± 0.52	0.1357	0.8596	0.0827
Skin-on muscle	0.64 ± 0.06	0.64 ± 0.04	0.58 ± 0.01	0.66 ± 0.03	0.3690	0.5320	0.3780
Skin-off muscle	0.06 ± 0.00	0.07 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.5280	0.7980	0.4210
<i>Magnesium (g kg⁻¹ WW)</i>							
Whole body	0.34 ± 0.00	0.39 ± 0.01	0.32 ± 0.01	0.39 ± 0.01	0.0007 (15 < 20)	0.3081	0.6636
Skin	0.28 ± 0.02	0.29 ± 0.02	0.24 ± 0.00	0.31 ± 0.02	0.0395 (15 < 20)	0.5320	0.0688
Skin-on muscle	0.20 ± 0.00 ^a	0.20 ± 0.00 ^a	0.18 ± 0.00 ^b	0.20 ± 0.00 ^a	0.0020 (15 < 20)	0.0226 (LV > MV)	0.0292
Skin-off muscle	0.20 ± 0.00	0.21 ± 0.01	0.19 ± 0.00	0.20 ± 0.00	0.0234 (15 < 20)	0.2403	0.8650
<i>Sodium (g kg⁻¹ WW)</i>							
Whole body	0.85 ± 0.05	1.06 ± 0.06	0.81 ± 0.01	1.04 ± 0.01	0.0015 (15 < 20)	0.4810	0.8432
Skin	0.90 ± 0.08	0.89 ± 0.09	0.93 ± 0.03	1.09 ± 0.06	0.1900	0.1440	0.2480
Skin-on muscle	0.41 ± 0.03	0.53 ± 0.01	0.40 ± 0.01	0.47 ± 0.01	0.0014 (15 < 20)	0.0879	0.2176
Skin-off muscle	0.37 ± 0.01 ^c	0.51 ± 0.00 ^a	0.36 ± 0.02 ^c	0.44 ± 0.01 ^b	< 0.0001 (15 < 20)	0.0048 (LV > MV)	0.0252
<i>Potassium (g kg⁻¹ WW)</i>							
Whole body	3.21 ± 0.03	3.24 ± 0.04	3.11 ± 0.06	3.20 ± 0.03	0.2220	0.1470	0.5620
Skin	2.14 ± 0.12	2.06 ± 0.01	1.93 ± 0.07	1.96 ± 0.06	0.6593	0.0954	0.5094

Skin-on muscle	3.63 ± 0.08	3.68 ± 0.05	3.47 ± 0.05	3.61 ± 0.06	0.2350	0.1300	0.5250
Skin-off muscle	3.64 ± 0.08	3.80 ± 0.14	3.55 ± 0.09	3.72 ± 0.06	0.1220	0.3770	0.9580

Table 4 The concentration (Mean ± SE) of trace minerals (zinc, iron, iodine and selenium) in the whole body, skin, skin-on muscle and skin-off muscle on Atlantic salmon (*Salmo salar*) reared under four treatments (UNT/15, UNT/20, TRN/15 and TRN/20) for a 90-day trial.

Trace minerals	Treatments				<i>p</i> value		
	UNT/15	UNT/20	TRN/15	TRN/20	Temperature	Velocity	Temperature × Velocity
<i>Zinc (mg kg⁻¹ WW)</i>							
Whole body	28.80 ± 0.59	36.88 ± 0.65	31.05 ± 1.12	36.73 ± 1.60	0.0002 (15 < 20)	0.2537	0.2521
Skin	24.56 ± 1.91	23.94 ± 1.48	21.85 ± 1.21	26.48 ± 1.02	0.1680	0.8070	0.1220
Skin-on muscle	3.95 ± 0.25	4.23 ± 0.12	4.23 ± 0.27	4.15 ± 0.04	0.6670	0.5970	0.4290
Skin-off muscle	2.82 ± 0.05	2.74 ± 0.02	2.97 ± 0.06	2.95 ± 0.10	0.0315 (15 < 20)	0.4688	0.6382
<i>Iron (mg kg⁻¹ WW)</i>							
Whole body	8.80 ± 0.13	10.33 ± 0.43	9.02 ± 0.32	10.00 ± 0.14	0.0043 (15 < 20)	0.9264	0.4127
Skin	79.32 ± 29.95	62.91 ± 33.12	53.09 ± 4.19	93.54 ± 15.68	0.5130	0.9670	0.2400
Skin-on muscle	8.47 ± 2.13	14.48 ± 3.42	10.04 ± 2.71	5.65 ± 0.80	0.9743	0.2228	0.0583
Skin-off muscle	5.85 ± 1.46	5.83 ± 0.84	3.81 ± 0.24	4.30 ± 0.63	0.9321	0.0973	0.7959
<i>Iodine (μg kg⁻¹ WW)</i>							
Whole body	330.84 ± 22.80	258.43 ± 29.77	351.82 ± 19.60	308.69 ± 23.80	0.0399 (15 > 20)	0.2172	0.5798
Skin	180.13 ± 21.11	87.55 ± 23.11	161.86 ± 6.71	84.43 ± 14.99	0.0014 (15 > 20)	0.5152	0.6682
Skin-on muscle	49.55 ± 11.60	14.34 ± 5.72	60.20 ± 7.68	9.73 ± 3.71	0.0012 (15 > 20)	0.6564	0.3924
Skin-off muscle	41.18 ± 6.14	8.74 ± 4.52	24.93 ± 3.24	3.99 ± 1.00	0.0015 (15 > 20)	0.0483 (LV > MV)	0.2766
<i>Selenium (μg kg⁻¹ WW)</i>							
Whole body	305.64 ± 0.68	307.12 ± 1.75	298.10 ± 4.69	306.10 ± 9.64	0.2890	0.3090	0.4700
Skin	390.29 ± 18.84	334.09 ± 3.02	386.63 ± 19.73	346.35 ± 5.30	0.0196 (15 > 20)	0.8339	0.6293
Skin-on muscle	306.70 ± 2.45	303.19 ± 7.98	294.20 ± 4.42	287.28 ± 5.84	0.2188	0.0279 (LV > MV)	0.7477
Skin-off muscle	286.53 ± 4.80	308.47 ± 1.77	290.73 ± 6.10	299.58 ± 8.86	0.0653	0.8188	0.3594

Figures

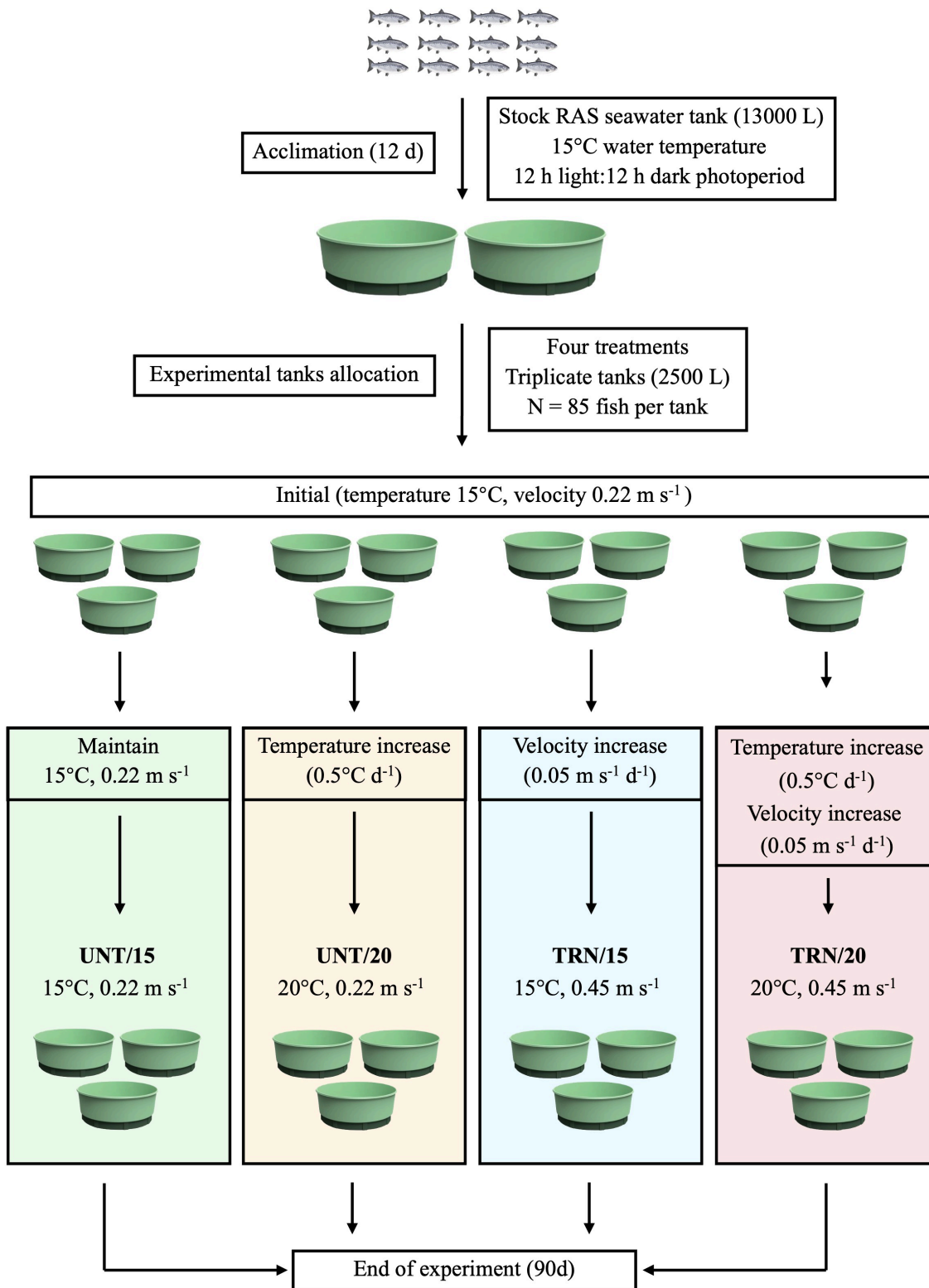


Figure 1

Experimental design and workflow illustrating the combination of temperature and water velocity treatments followed by a 90-day growth trial. UNT/15 and UNT/20 indicate untrained swimming (low velocity; $0.22 \pm 0.01 \text{ m s}^{-1}$) at 15°C and 20°C; TRN/15 and TRN/20 indicate trained swimming (moderate velocity; 0.45 m s^{-1}) at 15°C and 20°C. Detailed husbandry methodology is provided in Appendix 1.

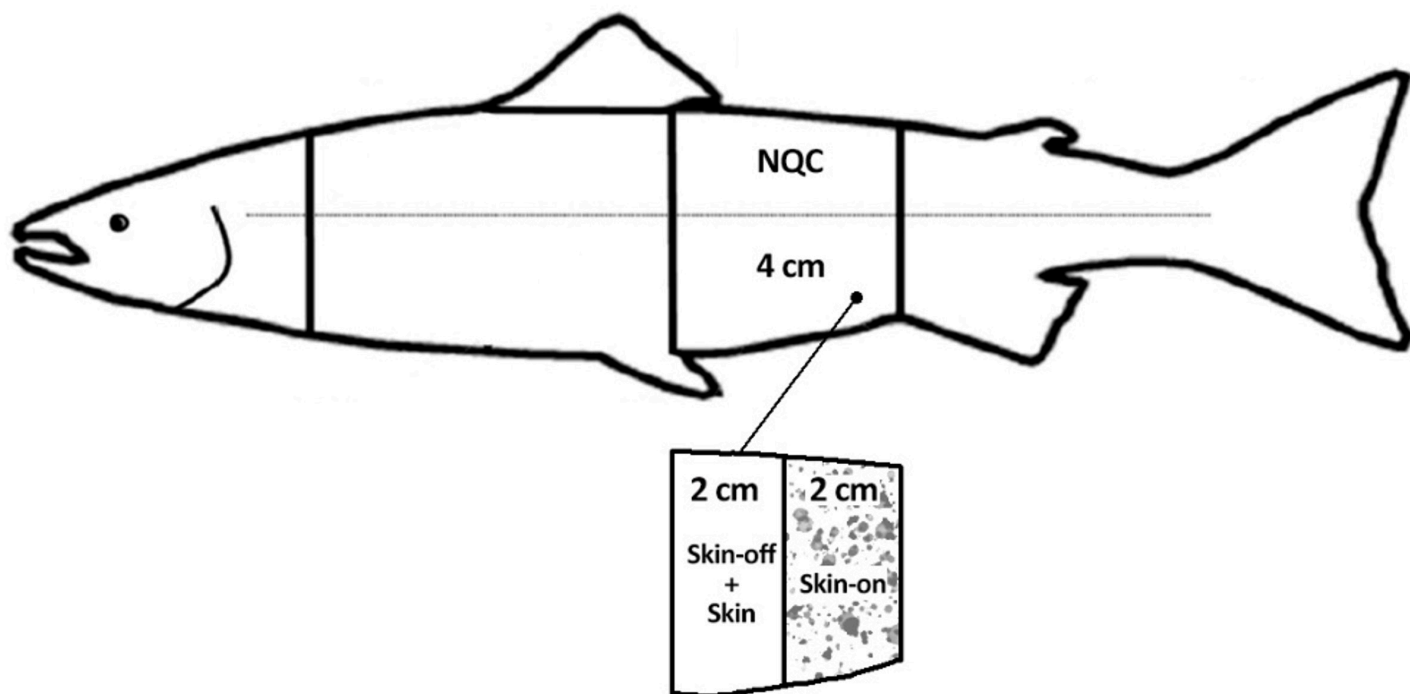


Figure 2

Sampling position for determining the mineral composition using the Norwegian Quality Cut (NQC). The left 2 cm NQC provided skin samples and skin-off muscle samples, and the right 2 cm NQC is used to collect skin-on muscle samples.

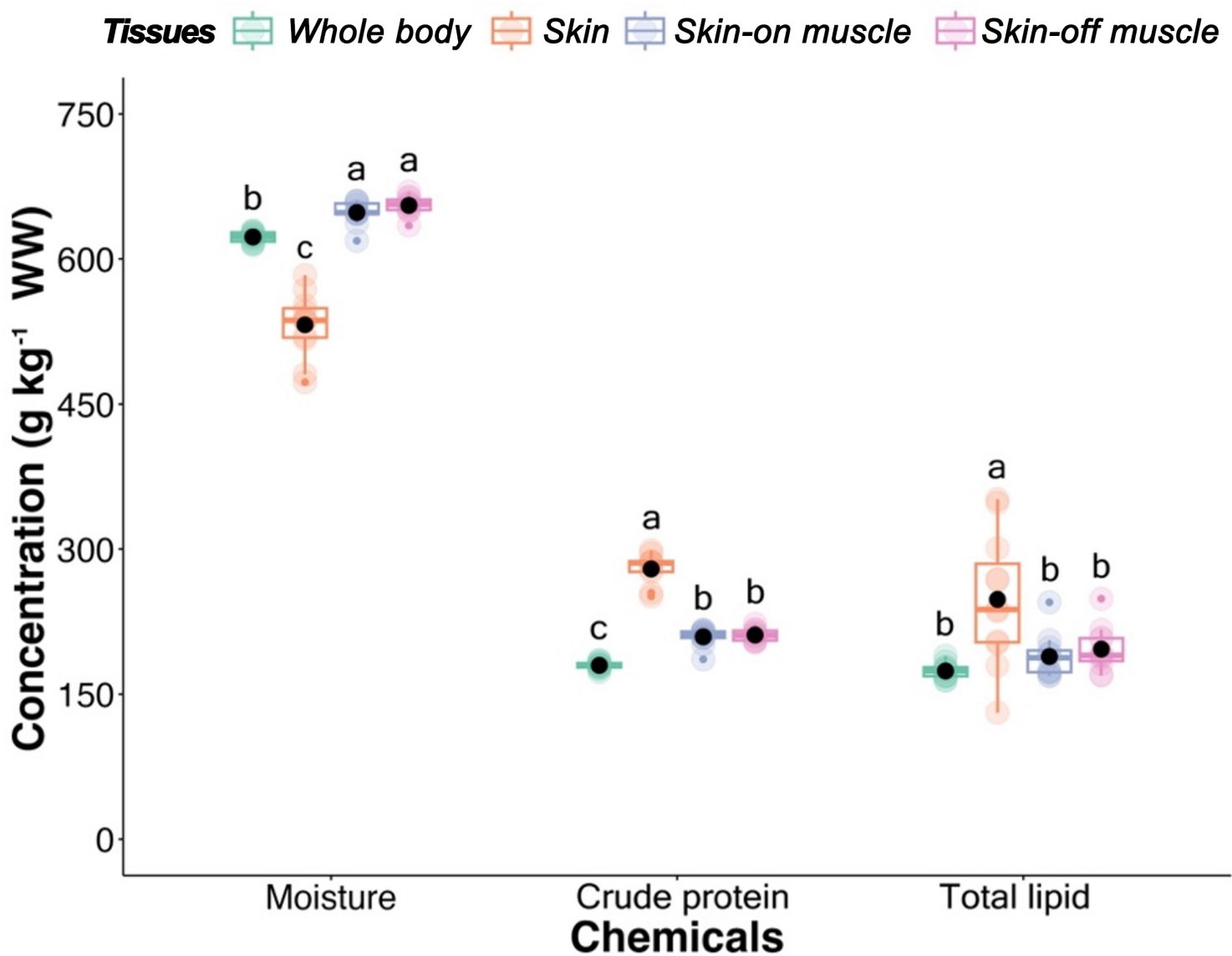


Figure 3

The concentration of chemicals (moisture, crude protein and total lipid) in different tissues (whole body, skin, skin-on muscle and skin-off muscle) of Atlantic salmon. The lower and upper quartiles in the boxplot represent 25% and 75% of the data. The middle line in the boxplot represents the median data (50%). The lower and upper edges of the plot indicate the largest/smallest value within the 1.5 times interquartile range above 75%/below 25%. The black dots in the boxplot represent the mean value of the data. Different superscripts denote statistical difference ($p < 0.05$) between tissues. Each coloured dot represents raw data.

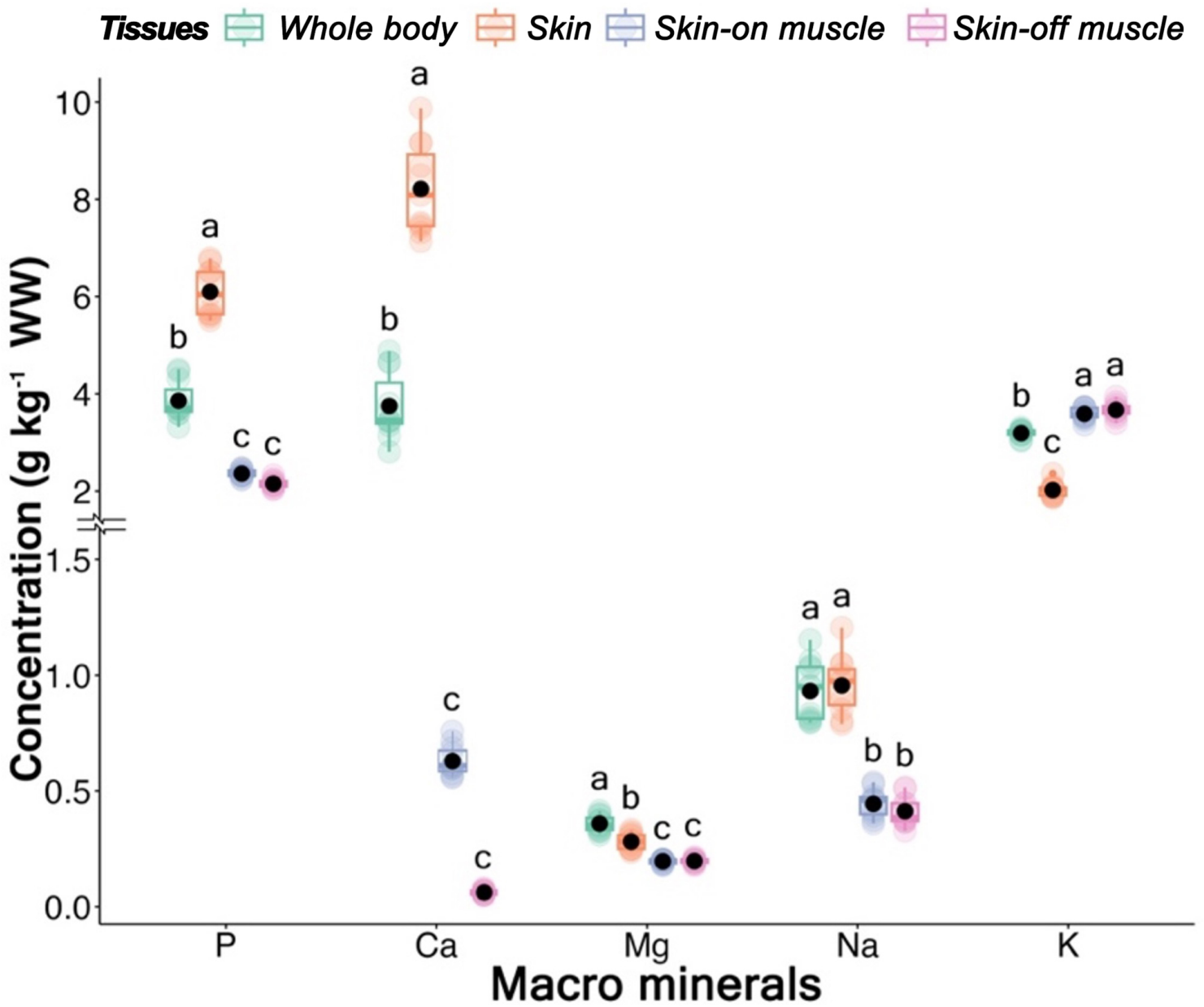


Figure 4

The concentration of macro minerals (P, phosphorus; Ca, calcium; Mg, magnesium; Na, sodium and K, potassium) in different tissues (whole body, skin, skin-on muscle and skin-off muscle) of Atlantic salmon. The lower and upper quartiles in the boxplot represent 25% and 75% of the data. The middle line in the boxplot represents the median data (50%). The lower and upper edges of the plot indicate the largest/smallest value within the 1.5 times interquartile range above 75%/below 25%. The black dots in the boxplot represent the mean value of the data. Different superscripts denote statistical difference ($p < 0.05$) between tissues. Each coloured dot represents raw data.

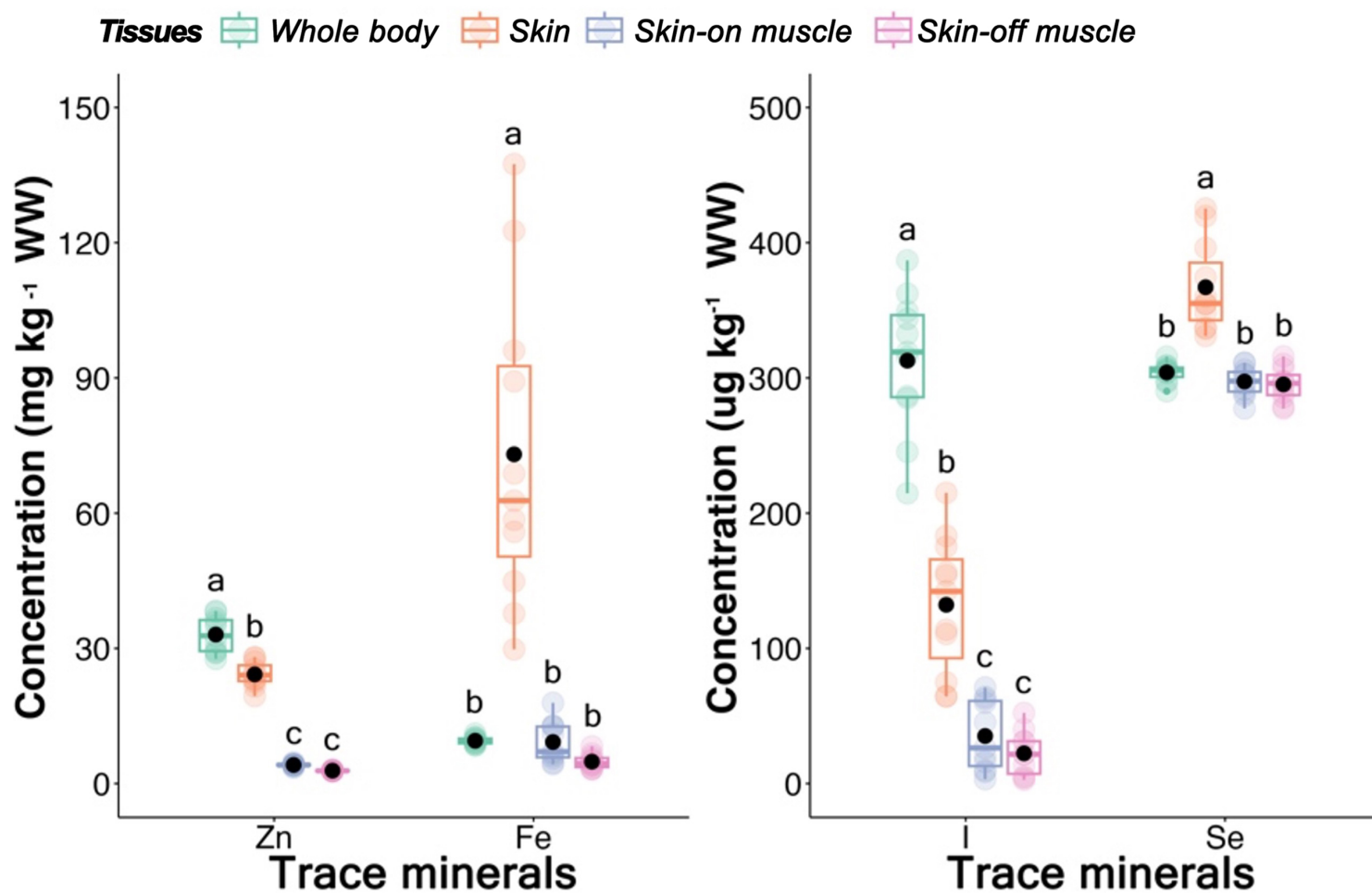


Figure 5

The concentration of trace minerals (Zn, zinc; Fe, iron; I, iodine and Se, selenium) in different tissues (whole body, skin, skin-on muscle and skin-off muscle) of Atlantic salmon. The lower and upper quartiles in the boxplot represent 25% and 75% of the data. The middle line in the boxplot represents the median data (50%). The lower and upper edges of the plot indicate the largest/smallest value within the 1.5 times interquartile range above 75%/below 25%. The black dots in the boxplot represent the mean value of the data. Different superscripts denote statistical difference ($p < 0.05$) between tissues. Each coloured dot represents raw data.

Supplementary Files

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