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Seasonal Variation of Off-Flavours in a Full-Scale Recirculating Aquaculture System Rearing Rainbow Trout *Oncorhynchus mykiss*—A Case Study

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ABSTRACT

Recirculating aquaculture system (RAS) is a promising strategy for economically and environmentally sustainable fish farming. Unfortunately, microorganisms in an RAS may produce off-flavours that accumulate in fish flesh and reduce consumer attraction for aquaculture-produced fish. Traditionally, geosmin (GSM) and 2-methylisoborneol (MIB), the compounds causing musty and earthy flavour, have been the most studied off-flavour compounds, but lately other compounds have also been considered important subjects of study. So far, only a little is known about the formation of different compounds at an RAS farm and their concentrations' fluctuations during the seasons. This case study aimed at monitoring the changes in off-flavour concentrations in different locations of a full-scale (1 M kg a^{-1}) RAS farm rearing rainbow trout (*Oncorhynchus mykiss*). Off-flavours were measured in fish, in recirculating water and in the inlet water throughout a year. Some of the compounds were introduced to the RAS via inlet water, whereas others were formed at the farm, mostly ranging from 0 to 30 ng L^{-1}. The concentrations of GSM and MIB were below 20 ng L^{-1} and in most cases below 10 ng L^{-1}, whereas methional peaked up to 70 ng L^{-1} in the fall and winter. In fish, the concentrations mainly remained below 600 ng kg^{-1} but occasionally MIB peaked up to 1900 ng kg^{-1}. The results highlight the need for sufficient treatment of inlet water even in the winter to maintain suitable conditions to produce fish of high quality.

1 | Introduction

Over 57% of the aquatic foods consumed by humans worldwide come from aquaculture fisheries (FAO 2024). Recirculating aquaculture systems (RAS) combine intensive fish production with minimal ecological impact (Martins et al. 2010). RAS is a complex technology that requires large initial investments and thorough training for effective farm management. Although microorganisms constitute an essential component of all RAS facilities, they are not exclusively beneficial to RAS functions. As the water exchange is reduced, undesirable substances and off-flavours accumulate in the system (Ben-Asher et al. 2024) that taint the flavour of the fish product (Lindholm-Lehto and Vielma 2019). This issue is considered one of the main challenges of aquaculture production worldwide, as it significantly reduces fish marketability and negatively impacts economy of most RAS farms (Azaria and van Rijn 2018; Wongprawmas et al. 2022).

Profitability of land-based RAS is unfortunately still restricted by high investment costs, complex solids disposal and off-flavour accumulation (Davidson et al. 2022). Especially, off-flavours easily accumulate into fish flesh and induce unwanted odour and flavour to the fish product which can lead to rejected products, negative consumer perception and lost revenue (Davidson et al. 2022). Typically, musty, muddy and earthy odours and flavours are caused by geosmin (GSM, *trans*-1,10-dimethyl-

trans-9-decalol) and 2-methylisoborneol (MIB, (1-R-exo)-1,2,7,7-tetramethyl-bicyclo[2.2.1]heptan-2-ol; Gerber 1968, 1969), but many other unwanted off-flavour-inducing compounds have also been identified in water and in fish (Mahmoud and Buettner 2017; Lindholm-Lehto 2022; Noguera 2025). So far, off-flavours are removed from the fish before sale by depurating the fish in clean water and withholding feed (Davidson et al. 2020).

Depuration not only consumes a lot of clean water and delays sale, but it can also have detrimental health effects to fish, loss of weight and cause distress (Davidson et al. 2024). For example, cold water species, such as Atlantic salmon (*Salmo salar*) and Murray cod (*Maccullochella peelii*), often lose 5%–10% of their body mass during the depuration period (Burr et al. 2012; Palmeri et al. 2008), reducing potential income by 5%–10% (Ben-Asher et al. 2024).

An efficient depuration period may last from a few days to weeks (Howgate 2004; Lindholm-Lehto 2022; Davidson et al. 2020). Depuration requires water 2–5-fold compared to a grow-out system's volume per day, depuration process being the primary source of water use and discharge in RAS fish production (Ben-Asher et al. 2024). Water consumption of a depuration unit can range from 500 to 1200 L kg^{-1} fish, whereas a typical grow-out period (in an RAS, without a denitrification unit) consumes 250–500 L kg^{-1} fish (Ben-Asher et al. 2024).

The quality of inlet water is in major role for a successful depuration period and for the entire RAS. In some cases, off-flavours can occur already in the inlet water (Wang et al. 2015), especially when lake or river water is used as a water source. The occurrence of off-flavours may vary seasonally and peak, for example, in the spring or summer when microbial actions are increased (Wang et al. 2015; Lindholm-Lehto 2022). This may increase off-flavour accumulation, the need for inlet water treatment and the required depuration time.

Diverse organisms have been identified as off-flavour producers, including fungi (Breheret et al. 1999), amoebae (Jüttner and Watson 2007), photoautotrophic cyanobacteria and filamentous heterotrophic bacteria, particularly actinomycetes and myxobacteria (Olsen et al. 2016; Södergren et al. 2025). For example, several environmental factors have been identified to promote cyanobacterial dominance: elevated nitrogen (Elser et al. 2009) and/or phosphorus (Downing et al. 2001), low nitrogen to phosphorus ratios (TN:TP) (Smith 1983), reduced mixing (Visser et al. 1996) and elevated temperatures (Paerl and Huisman 2008). Therefore, these factors may play a role in the off-flavour formation in a water body used as an inlet water source.

A biofilter is often the main reservoir of microbes in an RAS (Rurangwa and Verdegem 2015; Lindholm-Lehto et al. 2019; Podduturi et al. 2020), but GSM- and MIB-producing bacteria have been found to colonize other RAS sections too (Auffret et al. 2013; Noguera 2025). For example, Noguera (2025) reported that the highest concentrations of GSM and MIB were found in the drum filter sludge instead of a biofilter (Noguera 2025). Typically, aerobic components, such as nitrification reactors, aerobic sumps and settlers, are the major sources for generation of off-flavour compounds in RAS (Lukassen et al. 2019; Podduturi et al. 2020). Although off-flavour compounds are (semi)volatile, CO_2 stripping units are insufficient in volatilizing the off-flavour compounds (Lalezary et al. 1984; Ben-Asher et al. 2024).

Ozone (O_3) and hydrogen peroxide (H_2O_2), among other oxidizing chemicals, are often used for disinfection and water purification purposes, because they react effectively with organic matter and, in the case of freshwater, leave no toxic by-products (Spiliotopoulou et al. 2018). Oxidants can disinfect, reduce turbidity and colour, and control nitrogen species (Park et al. 2013) in water. For example, O_3 can reduce fish disease outbreaks (Summerfelt et al. 2009; Dahle et al. 2020), improve solids removal and reduce turbidity (Summerfelt et al. 1997). Improved solids removal often leads to cleaner pipes and tanks, decreasing the required maintenance work (Summerfelt et al. 1997; Pettersson et al. 2022). Additionally, ozone and H_2O_2 can be used to treat incoming water, effluent water, or to control the quality of recirculating water (Powell and Scolding 2016). However, the use of ozone increases production costs and requires control mechanisms to avoid hazardous events for the farm personnel and overdosing to protect the reared species and bacterial communities at the biofilters. H_2O_2 addition, on the other hand, enriches water with oxygen which may offer potential savings in oxygen expenses (Ben-Asher et al. 2024).

Different combination treatments, such as O_3/H_2O_2, O_3/UV, UV/TiO_2 and UV/H_2O_2, referred to as advanced oxidation processes (AOPs) (Rurangwa and Verdegem 2015; Rodriguez-Gonzalez et al. 2019), have been employed to oxidize off-flavour compounds. The effect of AOPs is based mainly on the generation of highly reactive hydroxyl radical species. AOPs have also attracted attention for their rapid ability to mitigate off-flavours in water (Rodriguez-Gonzalez et al. 2019; Lindholm-Lehto and Vielma 2019; Ben-Asher et al. 2023) and in fish flesh in RAS (Pettersson et al. 2022, 2024).

In this study, water quality and off-flavours were monitored throughout a year in water and in fish flesh of a full-scale RAS which produces 3 million kg of rainbow trout. The farm was operated according to normal procedures, and no changes were made due to the monitoring period. We aimed at monitoring and understanding the seasonal variations and the changes in off-flavours in different locations at the farm. The effects on off-flavour occurrence after oxidant additions were also one of the targets. As far as we are aware, full-scale farms have rarely been the subjects of monitoring the water quality and off-flavours in different seasons.

This study was performed in a full-scale commercial facility, and the setup was therefore of a monitoring-type instead of featuring accurately planned setups. A large production scale with big financial investments and high expectations rarely allows process-related trials. Therefore, the goal was to monitor and learn from off-flavour-related challenges (if any) faced at the farm. The results may offer further understanding for the optimization of full-scale processes and the required measures to achieve fish products of high quality with moderate depuration time.

2 | Materials and Methods

2.1 | Facility and Rearing Conditions

The commercial RAS farm annually produces 3 million kg of rainbow trout *Oncorhynchus mykiss*. The facility consists of a unit 1 (production of 1 million kg) and of a bigger unit 2 which is built later with somewhat different RAS architecture. This study was performed at the unit 1. The process design concept was according to Danish Billund Akvakultur A.S.

The RAS concept was explained in detail in Lindholm-Lehto et al. (2020). In short, a total area of 4400 m^2 included 17 circular bottom-drained coated tanks of concrete: ten 540 m^3 rearing tanks with a height of 5.5 and 12 m in diameter and seven 240 m^3 depuration tanks (Figure S1). All the rearing tanks were part of one RAS with shared water treatment processes, replacing only 1% of the recirculating water. From the circular tanks, water, solid particles and sludge were removed via bottom drains. Water was led from the rearing tanks into three drum filters (Hydrotech, HDF2009-1AS 304), equipped with a 90 μm mesh size to remove particulate matter.

Fully stabilized up-flow fixed-bed biofilters were employed to transform ammonium into nitrite and then into less harmful nitrate. Dissolved carbon dioxide was removed from the water using a countercurrent trickling filter at a flow rate of 2500 L s^{-1} and air at about 10 m^3 s^{-1}. The hydraulic retention time of the RAS was 77.5 h. The circulating water was treated with UV light (6 Ultraqua MR8-440-SS) at 120 mJ cm^{-1}). In the rearing tanks, water temperature was kept at 15.5°C ± 0.4°C, and in depuration at 10.6°C ± 1.6°C.

In the recirculating water, pH was adjusted with an addition of Na_2CO_3 (200 kg day^{-1}) and NaOH (25%, 1600 g day^{-1}) and kept at 7.01 ± 0.2. Additionally, salt was added to the rearing tanks 175 kg day^{-1}. Oxygen levels were maintained at 8.0–10.0 mg L^{-1} in the fish tanks (consumption of O_2 91 t a^{-1}).

Inlet water was pumped 30 ± 3 L s^{-1}. In RAS, water renewal rate was 600 L kg^{-1} feed (average water removal 15–30 L s^{-1}). To the inlet and recirculating water, ozone was added 320 g h^{-1} (10.7 g O_3 L^{-1}) and H_2O_2 (Bang & Bonsomer, Helsinki, Finland) 240 g h^{-1} (49.5% H_2O_2, 4 L H_2O_2 L^{-1}) and applied UV light (Atlantium RZ-163) to disinfect and to ensure good water quality. Additionally, O_3 was added 3–5 g t^{-1} to the skimmers (protein skimmers produce sludge of ozone bubbles, attract protein-amino acid molecules and other organic and inorganic compounds) to treat the depuration water. The treated inlet water was pumped to the depuration tanks before entering the circulation.

Inlet water was pumped via a coarse mechanical filter from Lake Unnukka (62°25′ N 27°55′ E) from the depth of 2–5 m (varies seasonally due to changes in water depth). It belongs to Vuoksi catchment area with a surface area of 80.45 km^2, an average depth of 6.27 m and a water volume of 0.5 km^3. It is part of Lake Saimaa, the largest lake in Finland, based on its surface area of 4400 km^2. Lake Unnukka is considered a mesotrophic lake with a brownish colour due to the high content of humic matter. In more detail, the water quality in Lake Unnukka is described by the following parameters: visibility 1–5 m; colour 30–160 mg L^{-1} Pt, humic content (COD_{Mn}) 7.3–18 mg L^{-1}, dissolved oxygen at 0–1 m 8–10 mg L^{-1}, α-chlorophyl 5.5–19.8 μg L^{-1}, total nitrogen 480–1400 μg L^{-1} and total phosphorous 9–60 μg L^{-1} (Savo-Karjalan Vesiensuojeluyhdistys 2025).

Water quality parameters of total ammonia, ammonium, nitrite and nitrate nitrogen were regularly monitored by quick spectrophotometric laboratory tests (Procedure 8038 Nessler, LCK340, LCK341, Table S1). Turbidity was measured with a Hach 2100Q Turbidimeter, USA, and UV transmittance (UV-T, %) was measured at 254 nm for water clarity.

2.2 | Fish Handling

The rainbow trout fry originated from the Hollola flow-through hatchery. They were allowed to grow to a weight of 50–100 g at the Huutokoski RAS farm before they were brought to the facility. The fish were typically reared until they reached 700 g. On average, there were 45,000–47,000 fish in each rearing tank, each growing on average from 130 to 700 g, with a biomass from 9600 to 38,800 kg in each tank. Moreover, there were 20,000–25,000 individuals in each depuration tank. The fish were visually inspected on a daily basis. Mortalities (if any) were removed, and changes in fish behaviour were monitored and recorded. For this study, monitoring and sampling occurred from February 2022 to February 2023, 12 times in total. The fish farm was run and operated normally, and no changes were made due to the monitoring period.

During the monitoring period, feeding ranged from 1.95% to 1.4% of biomass. The fish were fed with BioMar Orbit 921 4.5 and 6 mm pellets containing 4.5 mm: 42%–45% protein, 25%–28% lipid, 7% total N and 0.9% total P and 6 mm: 40%–43% protein, 25%–28% lipid, 6.6% total N and 0.9% total P as given by the manufacturer. Additionally, Alltech Fennoaqua Oy´s Crystal Omega Astax 4.5 and 6 mm pellets were used. They contained 4.5 mm: 41%–43% protein, 30%–33% lipid, 1%–2% crude fibre, 4%–8% ash and 0.94% total P and 6 mm: 40%–43% protein, 31%–34% lipid, 1%–2% crude fibre, 4%–8% ash and 0.94% total P as given by the manufacturer.

Feeding was evenly executed with a commercial centralized pipe feeding system (Arvo-Tec, Joroinen, Finland) 10–14 times per day in constant light. Feed was withheld during depuration.

2.3 | Sampling and Analysis

2.3.1 | Sampling

Circulating water was sampled directly from the selected growout and depuration tanks, and inlet water directly from the pipeline after the treatment steps. Water was collected in clean and capped 250 mL and 1 L (high-density polyethylene [HDPE]) bottles. The 250 mL bottles were stored frozen at −22°C until off-flavour analysis. The 1 L bottles were stored at +5°C and sent for analysis at Eurofins Environment Testing Finland Oy (see Section 2.3.3) within 1 day after sampling.

Additionally, inlet water from Lake Unnukka (62°24′30″ N, 27°55′00″ E) was sampled from the inlet pipeline after the UV treatment and the O_3 and H_2O_2 additions. Water samples were taken directly from the depuration and from the rearing tanks. Water samples were collected in 250 mL HDPE plastic bottles with HDPE plastic caps and stored frozen at −22°C before the analysis.

Fish were randomly sampled from the selected rearing and depuration tanks. In most cases, samples were taken from tanks 13 (rearing tank) and tank 4 (depuration) but occasionally from other tanks due to farm management (tank was under cleaning, etc.). From each tank, three fish were taken, euthanized by a sharp blow on the head, gutted, filleted and stored frozen at −22°C until analysed. The fish were then thawed and sampled from the lateral part of the fillet for the analysis.

In the case of depuration, the fish had been varying numbers of days in depuration (1–16 days) at the time of sampling. The samples were divided into three groups for the statistical analysis (beginning: 1–5 days, middle: 6–11 days and end: 12–16 days in depuration), four samplings in each group.

2.3.2 | Off-Flavour Analysis

The selected off-flavours (Table S2) were analysed by using a method based on automated head space solid-phase microextraction (HS-SPME) with a PAL3 autosampler assembly (CTC Analytics, Switzerland). This was coupled with gas chromatography and tandem mass spectrometry (GC-QQQ, 7000 Series Triple Quadrupole mass spectrometer, Agilent, Santa Clara, CA, USA) with an EI/CI interface, the EI (70 eV) source connected. A Phenomenex Zebron ZB-5MSi (Torrance, CA, USA) capillary column (30 m × 0.25 mm × 0.25 µm) was used to separate the analytes. The detection was performed in multiple reaction monitoring (MRM) mode. More detailed description of the validated method, levels of detection (LOD) and quantification (LOQ) has been presented in Lindholm-Lehto (2022).

The method allowed the detection and quantification of 14 selected off-flavour compounds in water and in fish flesh. The compounds were selected on the basis of the feedback and descriptions received by the commercial RAS farm rearing rainbow trout and descriptions of a professional cook who tasted the fish before depuration (Lindholm-Lehto 2022). These included compounds with following aromas (Table S2): buttery (acetoin), goat-like (hexanoic acid), grass (hexanal), fruity-acid, irritating (octanoic acid), fruit-like (octanal), musty (GSM), undesirable, musty (3-Isobutyl-2-methoxypyrazine, 2-Isopropyl-3-methoxypyrazine), earthy (MIB), onion-/potato-/meat-like (methional), sweet, rose, flowery (phenyl acetaldehyde), terpenic (α-Terpineol), medicinal, phenolic, iodine-like (2,4,6-Trichloroanisole) and vanilla, sweet (vanillin).

2.3.3 | Water Quality Measurements

Chemical oxygen demand (COD), total organic carbon (TOC) and dissolved organic carbon (DOC) were determined from the inlet water, recirculating water and depuration water. The measurements were performed by Eurofins Environment Testing Finland Oy according to SFS 5504:1988 (COD_{Cr} ± 12%, LOQ 30 mg O_2 L^{-1}) and SFS-EN 1484:1997 (TOC ± 15% (>2.7 mg L^{-1}), LOQ 1 mg L^{-1}; DOC ± 15% (at 2 mg L^{-1}), LOQ 1 mg L^{-1}).

Analysis of chlorine (Cl^-), nitrite-N (NO_2-N), sulphate (SO_4^{2-}), nitrate-N (NO_3-N) and phosphate (PO_4^{3-}) was determined by ion chromatography as shown in Lindholm-Lehto et al. (2020), including the method validation data. In short, the samples were first purified by a solid-phase extraction (SPE) cartridge (Phenomenex Strata C18-E, 500 mg/3 mL, 55 µm and 70 Å) and filtered through a 0.2 µm syringe filter (13 mm Ø, regenerated cellulose, Teknokroma). The chromatographic separation was conducted on a Dionex Integrion HPIC System (Dionex, Sunnyvale, CA, USA) with an AG28-Fast-4 µm guard column (IonPac, Dionex), an anion pre-column (Ion PacTM AG11-HC-4 µm, 4 mm × 25 mm) and an anion separation column (Ion PacTM AS11-HC-4 µm, 4 mm × 250 mm), operated with a Chromeleon 7.2 software.

2.4 | Statistical Analyses

Statistical analyses were performed with IBM SPSS Statistics for Windows, Version 27.0.1.0 (IBM Corporation, released 2020, Armonk, USA). A linear mixed model analysis was performed to study the statistical differences in off-flavour concentrations in fish muscle between the beginning (1–5 days), middle (6–11 days) and at the end (12–16 days) of the depuration. The confidence interval was set at 95%.

3 | Results

3.1 | Off-Flavours in Water

In the inlet water, off-flavour compounds were observed mostly at individual concentrations of 20 ng L^{-1} or lower (Figure 1). From the 14 selected compounds (Table S2), seven (GSM, hexanal, methional, MIB, octanoic acid, phenyl acetic acid and vanillin) were found above their levels of quantification. Most of the compounds were at the same level throughout the year. However, increased concentrations of methional (up to 70 ng L^{-1}) were observed in the early spring 2022 and again in the fall and winter 2022–2023.

In the circulating water, eight off-flavour compounds were detected (GSM, hexanal, methional, MIB, octanal, octanoic acid, phenylacetic acid and vanillin, Figure 2) up to 30 ng L^{-1}. For example, GSM remained at 5-15 ng L^{-1} throughout the year, whereas concentrations of MIB ranged from 10 to 30 ng L^{-1}. Increased concentrations of methional (up to 65 ng L^{-1}) were observed in the circulating water in the early spring 2022 and again in the fall–winter 2022–2023, similar to observations in the inlet water (Figure 1).

In the depuration water, GSM, hexanal, methional, MIB, octanal, octanoic acid, phenylacetic acid and vanillin were detected (Figure 3). The concentrations were mostly at 20 ng L^{-1} or lower, excluding methional which peaked up to 65 ng L^{-1} in the early spring 2022 and again in the fall–winter 2022–2023.

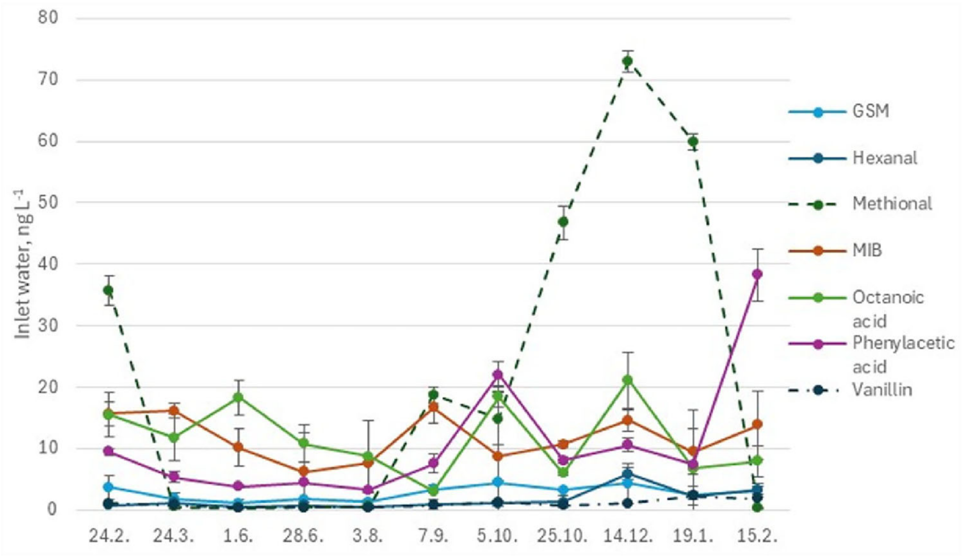

FIGURE 1 | Concentrations of GSM, hexanal, methional, MIB, octanoic acid, phenyl acetic acid and vanillin in the inlet water (ng L^{-1}, n = 2 (technical replicates), n = 3 (number of fish) ± standard deviation, SD). GSM, geosmin; MIB, 2-methylisoborneol.

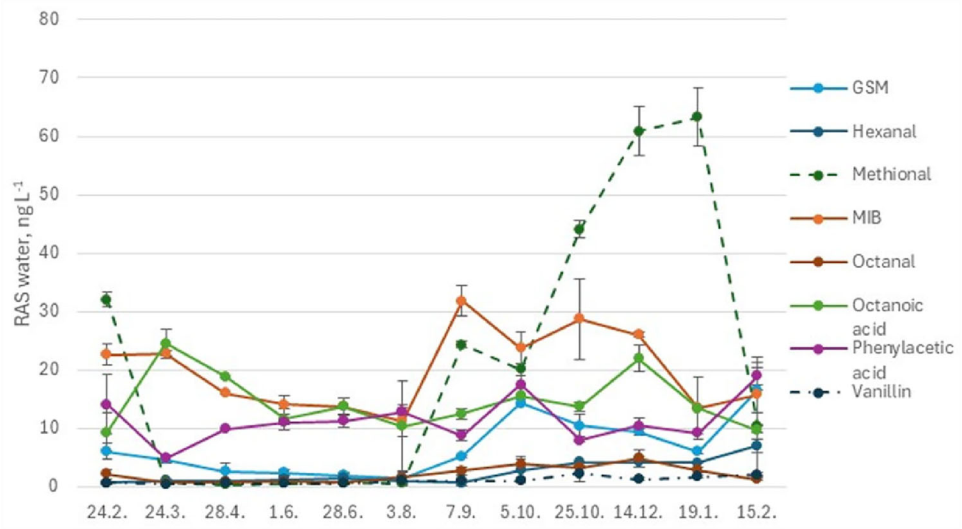

FIGURE 2 | Concentrations of GSM, hexanal, methional, MIB, octanoic acid and vanillin in the recirculating RAS water (ng L^{-1}, n = 2 (technical replicates), ±standard deviation, SD). GSM, geosmin; MIB, 2-methylisoborneol.

3.2 | Off-Flavours in Fish

In total, 13 selected off-flavour compounds were detected (Figure 4) in fish muscle tissue sampled from the rearing tanks. Many of the compounds were detected at 200 ng kg^{-1} concentrations or lower, including methional, but higher concentrations were found for GSM, hexanal, MIB, octanal and vanillin (up to 1900 ng kg^{-1} for MIB). The highest concentrations of MIB were found in the spring and summer, whereas the other compounds did not show clear seasonal trends.

In the depuration, concentrations of selected off-flavour compounds were at 200 ng kg^{-1} or lower for most compounds in fish flesh (Figure 5). Higher concentrations (up to 1250 ng kg^{-1}) were found for GSM, hexanal, MIB and octanal. Only IBMP remained below its LOQ. Slight increase in MIB was observed in the spring and summer, but besides that, clear seasonal trends were not observed for any of the compounds.

In depuration, only GSM concentrations were significantly different (p = 0.020) in the beginning (Days 1–5) than at the end (Days 12–16) of the depuration (Table S3). For all the other studied off-flavour compounds, the differences were not significantly different (p > 0.05), although their concentration decreased during depuration.

3.3 | Water Quality Parameters

The concentrations of DOC and TOC mostly remained below 20 mg L^{-1} and COD below 50 mg L^{-1}. All of the parameters peaked in November 2022 (Figure 6). The highest values were observed in

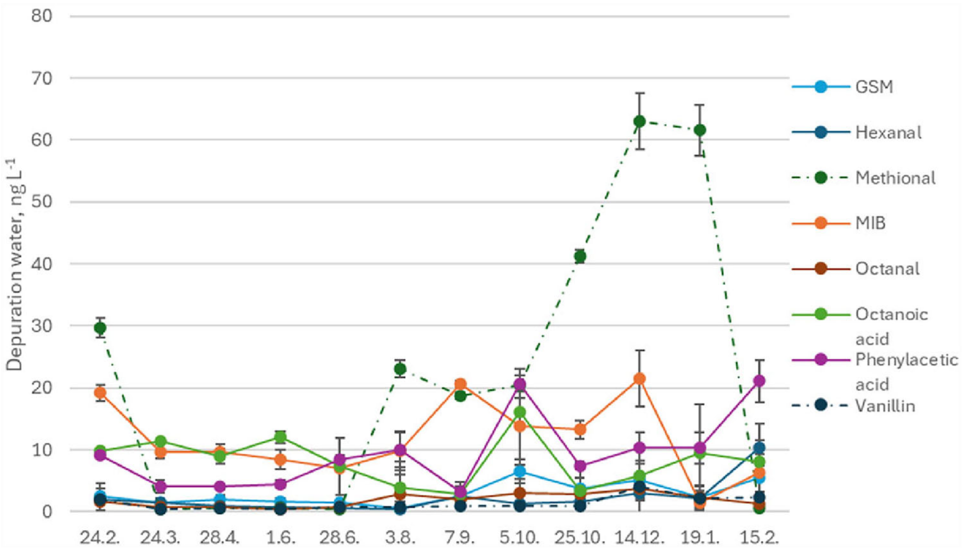

FIGURE 3 | Concentrations of GSM, hexanal, methional, MIB, octanoic acid and vanillin in the depuration water (ng L^{-1}, $n = 2$ (technical replicates), ±standard deviation, SD). GSM, geosmin; MIB, 2-methylisoborneol.

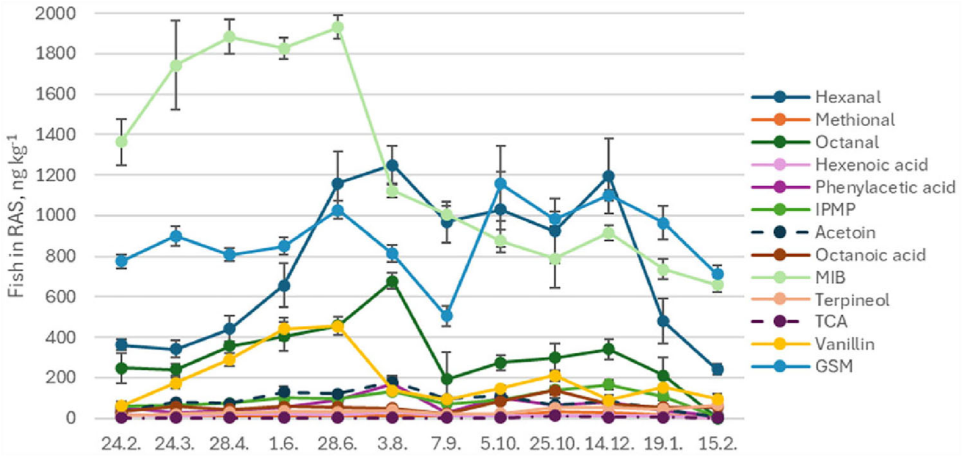

FIGURE 4 | Concentrations in fish sampled from rearing tanks (ng kg^{-1}, $n = 3$ (number of fish) ± standard deviation, SD). GSM, geosmin; IPMP, 2-isopropyl-3-methoxypyrazine; MIB, 2-methylisoborneol; TCA 2,4,6-trichloroanisole.

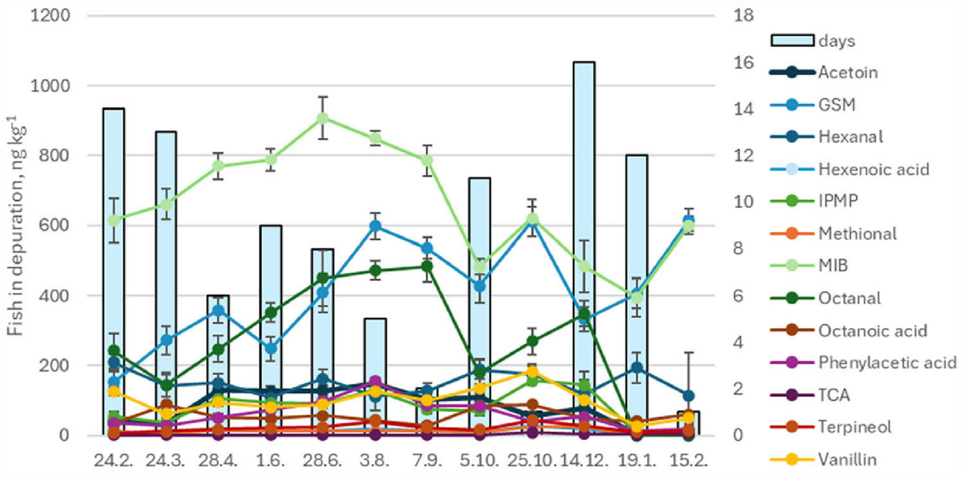

FIGURE 5 | Concentrations in fish sampled from depuration tanks (ng kg^{-1}, $n = 3$ (number of fish) ± standard deviation, SD). Blue columns show the number of days in depuration. GSM, geosmin; IPMP, 2-isopropyl-3-methoxypyrazine; MIB, 2-methylisoborneol; TCA, 2,4,6-trichloroanisole.

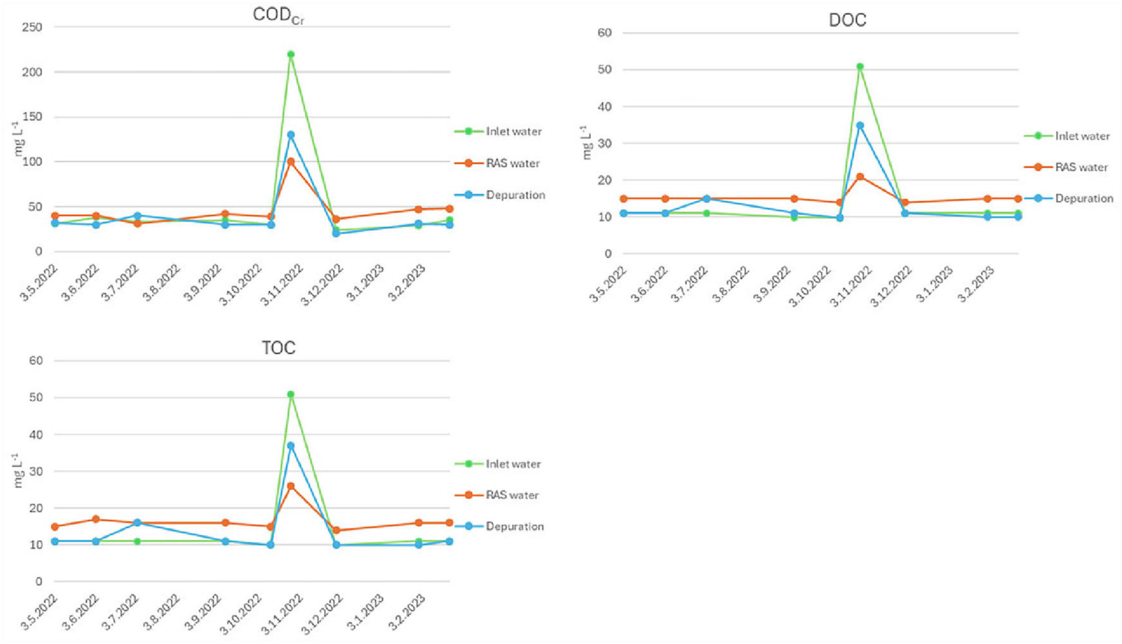

FIGURE 6 | Concentrations of chemical oxygen demand (COD$_{Cr}$, mg L^{-1}), dissolved organic carbon (DOC, mg L^{-1}) and total organic carbon (TOC, mg L^{-1}) in inlet water, recirculating RAS water, and in the depuration water from May 2022 to February 2023.

the inlet water but also in recirculating and depuration water.

Selected anions were also monitored in the inlet water (Figure 7A), in a selected rearing tank (Figure 7B) and in a depuration tank (Figure 7C). All in all, very low concentrations were observed, although increased levels of chlorine and phosphate were occasionally observed. The changes were very small throughout seasons without any clear trends.

Nitrogen species of NH_4-N were at 0.43 ± 0.07 mg L^{-1}, NO_2-N 0.21 ± 0.05 mg L^{-1} and NO_3-N 25.9 ± 4.5 mg L^{-1} (Table S1). Alkalinity was adjusted and kept at 85 ± 21 mg L^{-1}. Furthermore, UV-T (43.4% ± 3.2%) shows the ability of light passing through the water column, and turbidity (0.58 ± 0.1 NTU) which describes suspended particles via cloudiness. None of these factors showed large fluctuations throughout the year or similar peaks to those observed for TOC, DOC and COD (Figure 6).

4 | Discussion

4.1 | Water Quality

Organic matter contents (turbidity, UV-T, TOC and DOC) were low most of the year in the inlet water and at the farm. Organic matter is removed by drum filters, and the lowest concentrations were observed in RAS water, but the effect may also be due to the O_3 addition (Malone 2013; Gupta et al. 2024). The O_3 addition and decreased organic matter contents also prevented the increase of off-flavour-producing bacteria and the biofilm formation at the facility (Summerfelt et al. 1997), which further enhances the successful off-flavour removal. The hydroxyl radicals formed by the AOP treatment were able to react with the target molecules, despite of organic load in the system (Pettersson et al. 2022).

Increased concentrations of COD, DOC and TOC were measured in the fall. At the time of increased COD, DOC and TOC concentrations, no heavy rains were recorded which would have led to runoff of organic matter from the soil that would explain the elevated organic matter contents (Figure S2A; FMI 2025). However, the flow rates in Voimakanava, the point of intake of inlet water decreased in the fall (Figure S3). This may have affected the quality of the inlet water and led to increased organic matter content. At the time of this study, there was a lot of industrial activity in the area (e.g., construction work for capacity increase at the Stora Enso Oy´s containerboard mill and construction of the Finnforel Oy´s unit 2) which may have also affected the release of organic matter locally and near the inlet water source.

Throughout the study, the parameters describing nitrogen species and overall water quality remained relatively stable (Table S1). This suggests that production conditions were stable throughout the monitoring period, and the added oxidants did not show adverse effects, for example, towards the function of biofilters. Some increase in turbidity can be seen in the summer 2022 (Table S1). This can be due to the increased temperatures and increased microbial production, typical for warmer times of year (Figure S2B,C, Watson 2004; Wang et al. 2015).

In the Nordic countries, alkalinity is typically low in lake waters, and concentrations of 0.22–0.25 mmol L^{-1} (22–25 mg $CaCO_3$ L^{-1}) were recorded for Lake Unnukka (Hertta 2025). Therefore, alkalinity was regularly adjusted and measured to moderate level (on average 85 mg L^{-1}), being in the recommended range for aquaculture (50–300 mg $CaCO_3$ L^{-1}, Timmons et al. 2018).

As a mesotrophic lake, Lake Unnukka has moderate productivity, as shown by the low concentrations of nitrate and phosphate. Increased levels of nitrate and phosphate are known to pro-

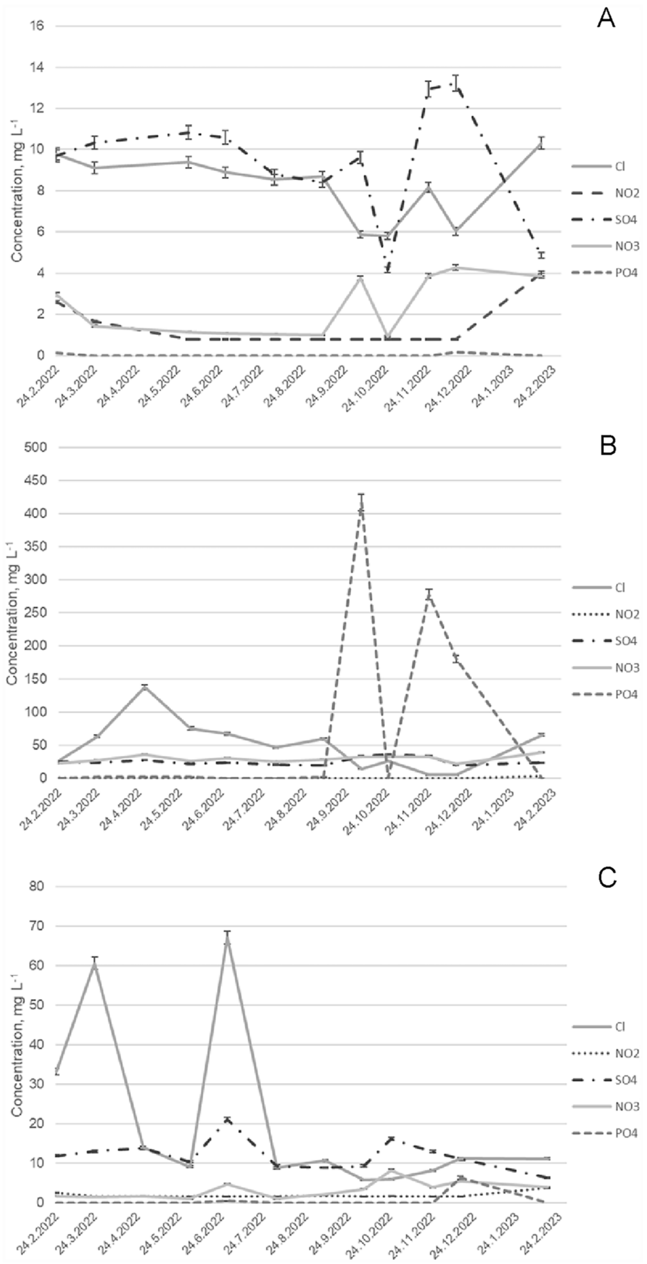

FIGURE 7 | Concentrations of Cl^-, NO_2^--N, SO_4^{2-}, NO_3^--N and PO_4^{3-} in the (A) inlet water, (B) recirculating water and in (C) depuration from February 2022 to February 2023 (mg L^{-1}, $n = 2$, ± SD).

mote the increase of cyanobacteria (Elser et al. 2009; Downing et al. 2001) and off-flavours produced by them, but increased concentrations were not observed here in the inlet water. Concentrations of phosphate were very low in the inlet water and in depuration. However, increased levels of phosphate were occasionally observed in RAS water. The peaked values were up to 100 times compared to those reported by others (e.g., 1.5–4 mg L^{-1}, Pulkkinen et al. 2021; 9.9 mg L^{-1} Tejido-Nuñez et al. 2020). This may have been due to uneaten feed in water at the time of sampling because phosphorus is a common component in ingredients and finished fish feeds (Hua and Bureau 2006).

Chlorine concentrations ranged from 6 to 10 mg L^{-1} which can be considered typical for a freshwater lake. In most freshwater lakes, the chlorine content remains below 53 mg L^{-1} (Bermarija et al. 2023). Higher peaks observed in the rearing water and in depuration are most likely due to salt additions (175 kg day^{-1}). Furthermore, the concentrations of sulphate ranged from 6 to 10 in the inlet water but were at about 20 mg L^{-1} in RAS water and in depuration, still remaining below the recommended limit value of <50 mg L^{-1} for RAS water (Timmons et al. 2018). No seasonal trends were observed during the period of study.

4.2 | Off-Flavours in Water

The concentrations of MIB ranged from 6 to 16 ng L^{-1} in the inlet water, whereas 11–32 ng L^{-1} were detected in RAS and 1–21 ng L^{-1} in depuration. For GSM, the concentrations were lower ranging from 1 to 4.5 ng L^{-1} (inlet water), from 2 to 17 ng L^{-1} (RAS) and from 0.5 to 6 ng L^{-1} (depuration). They were in a typical range for an RAS, although every RAS, its microbiome and tendency to produce off-flavours are unique. For example, Davidson et al. (2022) reported 1–3 ng L^{-1} GSM and 0.5–10 ng L^{-1} MIB, whereas Petersson et al. (2022) reported 1–50 ng L^{-1} GSM and 10–90 ng L^{-1} MIB. Furthermore, the concentrations were in the same range compared to the results of our earlier study from the same system: 0–35 ng L^{-1} GSM and 5–65 ng L^{-1} MIB (Lindholm-Lehto et al. 2020).

Among the studied off-flavours, methional was increased in the fall and winter, but only very low concentrations were detected in the summer. Methional has an intensive onion-like or potato-like flavour with a sensory threshold of 50 µg L^{-1} (in milk, Cardoso et al. 2012) and odour threshold of 0.5 µg L^{-1} (in wine, Escudero et al. 2000).

High temperatures and eutrophication affect the occurrence of off-flavours in lake and river water, and in some cases high concentrations (over 100 ng L^{-1} MIB) have been reported even in winter (Wang et al. 2015). In this study, any seasonal fluctuation or increased concentrations were only observed for MIB and methional. However, the seasonal effects (increased concentrations in the spring and summer) were seen to some extent in recirculating and in depuration water. This leads to consider if the water treatment was sufficient at the warmer time of year. On the other hand, the traditional parameters of water quality were at recommended levels (Timmons et al. 2018). The concentrations of all the other off-flavours, including GSM, were very low, suggesting that the overall quality of inlet water was good at the time of monitoring.

Methional and acrolein have been identified as reaction products of the photooxidation of methionine in the presence of riboflavin (Tzeng et al. 1990; Krax et al. 2024). Methionine is an essential amino acid that is widely included in fish feed (Wang et al. 2023) and acts as substructure for protein synthesis, energy metabolism and reproduction in animals (Wang et al. 2021) but is also formed via microbial actions in the environment (Li et al. 2024). Riboflavin, also known as vitamin B2, is present in fish feed (Deng and Wilson 2003), but it is also synthesized by bacteria, plants and fungi (Hoffpauir and Lamb 2025) and therefore present in nature.

Methionine is one of the most sensitive amino acids to photooxidation (Remucall and McNeil 2011), and it can be easily oxidized by several oxidants, including O_3, H_2O_2 and UV light (Hellwig

2019). Methional easily degrades into methanethiol, which then oxidizes into dimethyl disulphide (Luo et al. 2024). This suggests that methional may be formed in nature and possibly also in the RAS process. Furthermore, methional may be further degraded or transformed, possibly by photooxidation, in the summer with intensified UV radiation.

Photooxidation reactions (e.g., degradation, transformation) are common for many organic compounds in the aquatic environment (Lindholm-Lehto et al. 2016). Furthermore, the inlet water was treated with oxidizing chemicals (O_3, H_2O_2) and UV throughout the year with, and the concentrations of methional were reduced in the recirculating and in depuration water compared to inlet water. All this suggests that the main source of methional was of environmental origin. Furthermore, the highest concentrations of methional were measured in the fall 2022, at the time of lowest waterfall at the point of inlet water intake and the increased organic matter contents. It remains as a subject of future studies to resolve the formation pathways of methional in the area.

4.3 | Off-Flavours in Fish

In RAS, the highest concentrations of MIB were observed in fish in the spring and summer, ranging up to 1900 ng kg^{-1}. On the other hand, in the fall and winter, the concentrations were much lower, from 700 to 1100 ng kg^{-1}. They are all above sensory thresholds reported for MIB (700 ng kg^{-1} in rainbow trout, Robertson et al. 2005, 100–200 ng kg^{-1} in catfish *Ictalurus punctatus*, Grimm et al. 2004). This suggests that increased microbial activity in the warmer time of year (Wang et al. 2015; Watson 2004) enhanced MIB formation, affecting recirculating water and increasing the accumulation in fish flesh. In water, the highest peaks were observed in the late summer and the lowest in the winter, but fluctuations did not show a clear trend between seasons.

For GSM, similar changes were not observed, and its concentrations remained low in fish flesh (200–600 ng kg^{-1} in depuration). The sensory threshold for GSM ranges from 250 to 900 ng kg^{-1} (Grimm et al. 2004; Robertson et al. 2005), suggesting that the GSM concentrations should still be lower to avoid any consumers' unwanted sensations. This is in agreement with GSM's lower concentrations in water compared to higher concentrations of MIB. We did not observe notable differences in biomasses, lipid contents or size of individuals between samplings which would explain any differences.

Most of the selected off-flavour compounds were detected in fish flesh, both in the rearing tanks and in depuration. Interestingly, some of compounds that were below detection or quantification in water (acetoin, hexenoic acid, IPMP, TCA and α-terpineol) but still were observed in fish flesh. This highlights the importance of analysing fish flesh when assessing products' consumer acceptance. Determining sensory thresholds for other compounds besides GSM and MIB in fish is highly important (Lindholm-Lehto 2022).

As the accumulation of off-flavours strongly relies on octanol-water partition coefficient values (Howgate 2004), 2,4,6-trichloroanisole has the highest K_{ow} value of 3.6 among the studied compounds (Table S1). However, TCA was not detected in water, and only very low concentrations were found in fish. GSM with the K_{ow} value of 3.1 led to accumulation of moderate concentrations in fish (800–1100 ng kg^{-1} in RAS), although its concentrations were quite low in water. On the other hand, octanoic acid was clearly observed in water, but with K_{ow} of 2.4 only 50–100 ng kg^{-1} were found in fish. Octanoic acid was found in the inlet, recirculating and depuration waters roughly the same concentrations suggesting that the oxidants did not seem to degrade or remove it.

On the basis of the presence of GSM, hexanal, methional, MIB, octanoic acid, phenyl acetic acid and vanillin in the inlet water, it suggests that they are (at least partly) of environmental origin. Even Pettersson et al. (2024) reported that some of the off-flavour compounds seem to originate from the environment, whereas others are formed in RAS (Pettersson et al. 2024). They reported that GSM, MIB and α-terpineol were formed in RAS, whereas other compounds were mostly of environmental origin. These may of course change between RASs and inlet water sources.

Although methional was increased in the inlet water, in recirculating water, and in depuration, it showed very low concentrations in fish muscle tissue, even in the fall and winter, at the time of increased concentrations in water. This suggests that it did not readily accumulate into the fish flesh that is supported by its low octanol-water coefficient value (log P_{ow} of methional 0.938; Table S2).

On the basis of the statistical analysis, the concentrations in fish muscle were not significantly different in the beginning, middle and the end of the depuration period of 16 days (Table S3). Only GSM concentrations were significantly different in the beginning and in the end of the depuration. This leads us to consider if the inlet water was clean enough and if all the observed off-flavours can be reduced by depuration. The sizes and the lipid contents of the sampled fish were not determined and therefore not taken into account. Off-flavour compounds typically accumulate into the lipid fraction of the fish flesh (Burr et al. 2012; Lindholm-Lehto and Vielma 2019), and by adding this piece of information, it might allow us to find significant differences. However, the sampled fish were about similar in size, which lets us assume roughly the same lipid content.

Previous studies have shown potential in removing off-flavours by different AOP treatments (e.g., Rodriguez-Gonzalez et al. 2019; Pettersson et al. 2022, 2024; Santiago-Espiñeira et al. 2025). For example, they used 70–110 mg O_3 L^{-1} (Spiliotopoulou et al. 2018), AOP (O_3 0.4 mg L^{-1} and H_2O_2 0.10 μL L^{-1}, Pettersson et al. 2022) and 1.2 mg L^{-1} of O_3, 37.9 g O_3 kg^{-1} feed and 0.6 μL L^{-1} of H_2O_2 (26.5 g H_2O_2 kg^{-1} feed, Pettersson et al. 2024). In this study, O_3 was added 10.7 g O_3 L^{-1} and 4.0 L H_2O_2 L^{-1} to inlet water. The doses were much higher compared to the published results from pilot-scale experiments, but here the treatments were applied in water used for depuration where the biomass ranged from 6000 to 22,000 kg of fish. For most off-flavours, the oxidants kept the concentrations low, although the depuration period was still justified. The studied off-flavour compounds remained low during the monitoring period, suggesting highly intensive process conditions with high-requirement of water exchange with very clean (off-flavour-free) water.

5 | Conclusions

This case study showed the effects of water quality throughout the entire RAS. Overall, the water quality remained good during the year of monitoring. However, some seasonal variations were observed: Some off-flavour compounds peaked during the warmer time of year, whereas others peaked in the winter when the degrading UV light was limited. Fortunately, high concentrations were not accumulated in fish.

Changes in temperature, rainfall, water flow at the point of inlet water intake and other environmental conditions at different seasons affected the water quality at the fish farm despite the use of aggressive water treatment procedures. A combination of oxidative chemicals reduced the concentrations of off-flavour compounds in the inlet water and throughout the facility. Although the use of oxidants degraded and removed off-flavour compounds, the oxidants also reacted unselectively with all organic matter. To conclude, the use of oxidants at suitable concentrations is definitely justified to control off-flavour accumulation in fish.

Author Contributions

Petra Camilla Lindholm-Lehto: chemical analyses and method development, conceptualizing, methodology, planning, writing – original draft.

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Ethics Statement

Ethical approval of this study was obtained from the Finnish Food Authority, and the experiment was performed in accordance with the guidelines of Directive 2010/63/EU (Directive 2010/63/EU on the protection of animals used for scientific purposes).

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials: aff270191-sup-0001-SuppMat.docx