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Monitoring of Water Quality for Reduced Water Use in a Partial Recirculating Aquaculture System

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ABSTRACT

Partial recirculating aquaculture systems (PRASs) aim for combining the benefits of flow-through systems (water use of approximately 50,000 L kg^{-1} feed) and recirculating aquaculture systems (RASs, 500–1000 L kg^{-1} feed). While water quality is usually excellent in flow-through systems, large volumes of water of good quality are required. In RAS, investment and production costs can be high, and due to the microbial actions typically occurring in RAS, off-flavours can occur and accumulate in fish flesh. Here, an evaluation between three water renewal rates (4000, 2000 and 1000 L kg^{-1} feed) of a PRAS was performed. In the experiment, rainbow trout *Oncorhynchus mykiss* was reared in similar PRASs. Fish growth and a variety of water quality parameters were monitored, including 14 off-flavour compounds in the recirculating water, in the inlet water and in fish flesh. The results did not show statistical differences in feed conversion ratio (FCR), specific growth rate (SGR), and mortality between water renewal of 2000 and 4000 L kg^{-1} feed, while reduced growth was observed at 1000 L kg^{-1} feed. Additionally, total ammonia nitrogen (TAN) and nitrite–nitrogen (NO_2—N) increased at reduced water renewal rates of 1000 and 2000 L kg^{-1} feed ($p < 0.005$). Concentrations of off-flavours remained low in the circulating water, but in the circulating water and in fish flesh, they were above the known sensory thresholds at 1000 L kg^{-1}. Overall, the results suggest that 2000 L kg^{-1} feed offers good fish growth, feed use and low mortality without the unwanted off-flavour accumulation.

1 | Introduction

Land-based aquaculture systems can be roughly divided into two main groups: flow-through systems and recirculating aquaculture systems (RASs). Traditional freshwater fish farms operate using flow-through systems, which have high water renewal rates (50,000 L kg^{-1} feed; Vasquez-Mejia et al. 2023; Vielma et al. 2022) but do not apply water treatment with the exception of occasional use of water oxygenation (Tahar et al. 2018). In full RAS, on the other hand, aquaculture water is cleaned in many process steps (e.g., particle removal with drum filters and swirl separators, nitrogen compounds transformed in biofilters and CO_2 removal via trickling filters) and circulated back to the system. Typically, about 5% of water volume is replaced in RAS (water renewal 500–1000 L kg^{-1} feed; Timmons et al. 2018), although even near 0 water exchange rates have been reported (< 1%, Yogev et al. 2017; 2.1%, Gullian-Klanian and Arámburu-Adame 2013).

In flow-through systems, water quality depends on the water source, typically taken from a river or lake. Large volumes of water are required which raises concerns regarding the availability of suitable water of high quality. Additionally, environmental permits with limits of allowed nutrients release may limit the use of flow-through. In RAS, on the other hand, investment and

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management costs are high, the rearing process is complex, and the production is energy-intensive (Twibell and Barron 2024). Additionally, RASs are more prone to off-flavour formation due to microbial metabolism and accumulation in fish flesh, and even reduced growth has been observed in RAS which reduces the production´s profitability (Summerfelt et al. 2015; Mota et al. 2015).

A partial recirculating aquaculture system (PRAS) combines the rearing methods of RAS and flow-through (water use in the range of 1000–5000 L kg^{-1} feed), and in the best scenario, it can combine the benefits of these. Commonly, PRAS does not utilize biological filtration, and the water renewal rate should be adequate to keep oxygen, carbon dioxide and ammonia nitrogen levels suitable for selected fish species. In recent years, hybrid flow-through systems have appeared on the market which are equivalent to PRAS but with a low water recycling rate of around 40%–70%.

Partial recirculation aquaculture systems were developed in parallel with recirculation systems in the early 2000s. In recent years, the development of PRAS has been given a new boost by the successes of salmon production. Rainbow trout are reared in commercial PRAS farms mainly in Denmark (Danmarks Statistik 2025), but also in Germany (Sindilariu et al. 2009) and the United States (West 2010).

Higher water use of PRAS allows production without biofilters which means reduced investment costs and even reduced off-flavour compounds since biofilters have been reported as one of the hotspots for off-flavour formation in RAS (Podduturi et al. 2017, 2020). However, higher water use makes it more difficult to treat the effluent water but also brings additional costs for inlet water treatment and temperature control.

Without biofilters, nitrification is limited to surfaces harbouring autotrophic bacteria (Summerfelt et al. 2004), and a sufficient volume of replacement water is required to maintain free ammonia nitrogen at a low and non-toxic level for the reared species (12.5–30 μg L^{-1}; Timmons et al. 2018). Without biofilters, the start-up of the system is faster than in a RAS which usually employs one or several biofilters (4–10 weeks for establishing biofilter nitrification; Summerfelt et al. 2009). This may also allow the use of chlorine-based disinfectants when required for biosecurity (Summerfelt et al. 2009; Waldrop et al. 2009). Furthermore, a PRAS with dual-drain tanks has been found to increase fish production (Summerfelt et al. 2009). The tank design allows removal of waste feed and other particulate matter, acting as a swirl separator (Summerfelt et al. 2004), supporting maintenance of good water quality (Vinci et al. 2004).

A simplified PRAS allows reduced costs, for example, in pH adjustment, oxygen addition and electricity consumption. For example, energy consumption was 4.23 kW kg^{-1} feed in a PRAS, while it was 5.70 kW kg^{-1} feed in a RAS (*Oncorhynchus mykiss* in freshwater; Kiuru et al. 2022). Additionally, full capacity can be employed from the start of the system, and even quick changes in feed administration are possible. Based on these, PRAS has a great potential in salmonid culture (Summerfelt et al. 2015).

In our previous studies in 2020–2021 (unpublished data), excellent growth was observed for rainbow trout *O. mykiss*—specific growth rate (SGR) 0.95%–1.50% (end weight 1270–3410 g) and excellent feed conversion ratio (FCR 0.83–0.98 for 1270–3410 g)—in PRAS with low mortality (1.8%–6.3% in 2020, 0.1%–1.7% in 2021). Furthermore, off-flavour concentrations were below the known sensory limits in water and in fish flesh (Lindholm-Lehto and Kiuru 2024). To compare, Summerfelt et al. (2004) reported FCR 1.0–1.3 and SGR 1.32%–2.45% for juvenile rainbow trout and Arctic char *Salvelinus alpinus* (from 15 to 294 g) in PRAS, while Twibell and Barron (2024) reported SGR of 1.72% and 100% survival for 5.2–55 g spring Chinook salmon (*Oncorhynchus tshawytscha*).

In aquaculture systems with a low water renewal rate, off-flavours can be formed due to microbial activity in aquaculture water and accumulate in fish muscle tissue (Auffret et al. 2011). Off-flavours are typically produced as metabolic by-products of a variety of microbial species, such as *Cyanobacteria*, *Actinobacteria*, *Myxobacteria* and *Sorangium* (Lukassen et al. 2017; Mahmoud and Magdy 2021). Off-flavours perceived in fish are often described as musty and earthy flavours and odours that fish consumers find objectionable (Lindholm-Lehto et al. 2023). These flavours are typically induced by the terpenoid compounds geosmin (GSM) and 2-methylisoborneol (MIB) (Gerber 1968, 1969), although a variety of other compounds is also known to cause unwanted flavours in fish, including alcohols, aldehydes, carboxylic acids, pyrazines and terpenes (Podduturi et al. 2017, 2021; Mahmoud and Buettner 2017; Lindholm-Lehto 2022).

In our previous study (Lindholm-Lehto and Kiuru 2024), depuration of off-flavours was extensively studied in fish muscle and in recirculating water of PRAS and RAS. Here, our goal was to concentrate on fish growth, feed use and water quality in PRAS, including the formation of off-flavours at different water exchange rates. This study had two main goals: (1) First, study the lower limit value for the water exchange rate suitable for rainbow trout reared in PRAS, and (2) inspect if slightly elevated total ammonia nitrogen (TAN) concentration enhances fish growth and FCR. We hypothesized that the fish growth and overall water quality would remain good at all studied water exchange rates, and slightly elevated TAN concentration would enhance fish growth and feed utilisation.

2 | Materials and Methods

2.1 | Experimental Design

The experimental design was performed in six individual systems located on the Laukaa fish farm of Natural Resources Institute Finland (Luke) as described in Lindholm-Lehto and Kiuru (2024). In short, each system consisted of a 600-L bottom-drained Cornell-type tank with water removal via the bottom drain, while side-drain flow was pumped at 2.5 L s^{-1} with an air-lift pump as an aeration unit. The air was supplied to all six airlifts from one side channel blower (FPZ, Concorezzo, Italy, K04 MS, 0.75–0.90 kW). Solid particles were removed with a closed radial-flow settler in the outflow drain.

Biofilter was not used. The accumulation of toxic nitrogen species was avoided by increased water exchange rate and the addition of hydrogen peroxide (H_2O_2), which rapidly oxidizes nitrite to nitrate (J. Wang et al. 2017). Oxygen addition was not required due to the tank-specific aeration unit and relatively high water exchange rates. Dissolved oxygen was monitored daily with a hand-held meter and maintained at 9.2 ± 0.6 mg L^{-1} and CO_2 at 7.5 ± 2.4 mg L^{-1}, monitored with online measurements. Temperatures were measured daily (13.7 ± 1.2°C) with a hand-held thermometer (Traceable, VWR International, Helsinki, Finland). The pH in the system was maintained below 6.8 by adjusting the CO_2 removal. Lights were kept on 24 h per day in the rearing tanks.

The inlet water was led untreated from the oligotrophic Lake Peurunka (62.44886, 25.85201, area 694 ha, 59,600 m^3, average pH 6.7). The mean annual temperature in the area is 4°C, and the annual precipitation is 600 mm (Finnish Meteorological Institute 2023). Inlet water was taken as a 1:1 mixture of surface water (depth of 3 m) and from the aphotic layer (depth of 8 m). The temperature of the inlet water was adjusted by using a plate heat exchanger and an electric heater (Alfa Laval 3×3 kW, Alfa Laval Nordic, Aalborg, Denmark) and led to each PRAS at a rate of 0.2–1.3 L min^{-1}.

Water quality was monitored regularly with weekly water quality tests of the TAN, nitrite–nitrogen (NO_2—N) and chemical oxygen demand (COD) using quick spectrophotometric tests (Procedure 8038 Nessler, LCK341/342, LCK340 and LCK349 respectively, DS 3900, Hach Lange, USA) and free H_2O_2 with colorimetric peroxide test strips (1–25 mg L^{-1}, MQuant, Merck, Darmstadt, Germany). Additionally, dissolved O_2 (Handheld YSI Pro20, Yellow Springs, USA), CO_2 concentration and temperature were measured with hand-held sensors (S/N 1638, Franatech, Germany), and the flow rate of inlet water was adjusted manually once a week (DDI-222, Grundfos, Denmark). Alkalinity was measured using a standard titration method (ISO 9963–1:1994, TitraLab AT1000, Hach, Loveland, USA).

The selected off-flavour compounds (Tables S1–S3) were quantified with an analytical method of an automated solid phase microextraction and gas spectrometry with a triple quadrupole tandem mass spectrometry (SPME-GC-QQQ) as previously reported in Lindholm-Lehto (2022).

2.2 | Fish and Feeding

The study followed the protocols approved by the Luke Animal Care Committee, Helsinki, Finland, and EU Directive 2010/63/EU for animal experiments.

In total, 515 individuals of rainbow trout on average 252 ± 6.1 g in weight (86 individuals per tank) from the Finnish National (Jalo) breeding program (year class 2022) were studied in the experiment. Before the experiment, the fish were treated with Limoxin WS (1000 mg g^{-1}) against *Flavobacterium* (*Flavobacterium psychrophilum*) and found healthy by a veterinarian before the start of the experiment.

The fish were fed by an automated feeding system (T Drum 2000, Arvo-Tec, Huutokoski, Finland) with a commercial fish feed (4.5 mm Crystal Astax, Alltech Fennoaqua Oy, Raisio, Finland) containing 43% protein, 28% crude fat, 2.1% crude fibre, 5.9% ash, 1.05% calcium, 0.95% phosphorus and 0.6% sodium as reported by the manufacturer. The feed was administered continuously 48 times per day. The fish were visually inspected on a daily basis, and mortalities (if any) were removed and recorded.

The fish were weighed before and after the experiment (Day 0 and Day 62), and once during the experiment (after 33 days). Weighing of fish was performed in batches per rearing tank, and the number of individuals was counted. However, the weights of each individuals and weight distributions of batches were not determined. The weight of dead fish was calculated as the average of the initial and final weighing per phase and added to the tank growth.

2.3 | Experimental Setup

The fish were transferred from a recirculating system (described in Pulkkinen et al. 2021) to six similar PRASs (as described in Section 2.1) to achieve a fish density of 36 kg m^{-3} (dimensioning according to Summerfelt et al. 2004) and a biomass of 22 kg in each system before the start of the experiment. The aim was to triple the fish weight during the experiment. Before the experiment started, the fish were acclimated to the new experimental unit for 5 weeks. During the acclimation period, the fish were on a restricted diet of 1%. The water exchange rate was kept at 4000 L kg^{-1} feed in all systems.

The experiment took place from the end of February until the beginning of May (February 28 to May 2). For the experiment, the water exchange rates were adjusted to 4000, 2000 and 1000 L kg^{-1} feed, two systems each. The water exchange rates were monitored and adjusted based on the average feeding of the week.

Hydrogen peroxide (H_2O_2, Bang & Bonsomer Group Oy, Helsinki, Finland, 10 mg H_2O_2 L^{-1}) was pumped (Model PO 743–822S2, Milton Roy, Warminster, PA, USA) to the inlet water of the PRASs based on the inlet water volume and the selected water renewal rate. First, H_2O_2 (25% solution) was added to the inlet water of all six PRASs (4000 L kg^{-1} feed, 71–97 mL H_2O_2 day^{-1}; 2000 L kg^{-1} feed, 35–48 mL H_2O_2 day^{-1}; 1000 L kg^{-1} feed, 18–22 mL H_2O_2 day^{-1}; Table S4).

Additionally, 5% solution of H_2O_2 was added (4000 L kg^{-1} feed, 12 mL h^{-1}; 2000 L kg^{-1} feed, 41 mL h^{-1}; 1000 L kg^{-1} feed, 56 mL h^{-1}). The residual H_2O_2 in each tank was monitored and recorded (colorimetric peroxide test strips, MQuant, Merck, Darmstadt, Germany). The volumes of the replacement water, addition of H_2O_2 solution with the inlet water, and the additional H_2O_2 were adjusted and changed during the experiment as the feed amount varied with the biomass and the fish growth (Table S4). The H_2O_2 was kept at 3.7 ± 0.8 mg L^{-1}.

2.4 | Sampling

The fish were sampled once during the experiment and at the end of the experiment from the rearing tanks for further analyses. Three fish were randomly selected and humanely euthanized with a sharp blow on the head. The fish were weighed, gutted, filleted and sampled from the lateral part of the fillet as shown

TABLE 1 | Biomass (kg), average fish weight (g), number of individuals (sampled fish removed) and mortalities (no. and %) with the replacement water volumes of 4000, 2000 and 1000 L kg^{-1} feed in the PRAS 1–6. Phase 1, 33 days; Phase 2, 29 days.

	Water (L kg^{-1} feed)	Biomass (kg)	Average weight (g)	Individuals (no.)	Mortality (%)
Phase 1					
PRAS 1	4000	21.8→32.6	250→403	87→85	2.3
PRAS 2	2000	21.6→31.9	254→399	84→83	1.2
PRAS 3	1000	21.8→29.0	248→372	88→81	8.0
PRAS 4	4000	21.9→33.2	258→409	84→83	1.2
PRAS 5	2000	21.9→33.2	243→382	88→88	0.0
PRAS 6	1000	21.9→31.1	258→388	84→82	2.4
Phase 2					
PRAS 1	4000	32.6→49.4	403→617	81→81	0.0
PRAS 2	2000	31.9→46.7	399→607	79→77	2.5
PRAS 3	1000	29.0→40.5	372→533	77→76	1.3
PRAS 4	4000	33.2→49.3	409→624	80→79	1.3
PRAS 5	2000	33.2→49.3	382→580	85→85	0.0
PRAS 6	1000	31.1→44.7	388→573	79→78	1.3

in Hathurusingha and Davey (2016). They were stored at −22°C until the analysis. Pooled samples of three individuals were used for the off-flavour analyses.

Water samples were taken weekly for the monitoring of water quality as explained in Section 2.1. Additionally, water was sampled from the inlet water and the rearing tanks and stored in 250-mL HDPE bottles at −22°C for the off-flavour analysis.

2.5 | 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 difference in water quality parameters, off-flavours in fish muscle, feed use and growth between systems with replacement water of 4000, 2000 and 1000 L kg^{-1} feed. The confidence interval was set at 95%.

3 | Results

3.1 | Growth and Water Quality

During the experiment, the average biomass increased from the average of 21.8 ± 6.1 kg per tank (87 ± 2 individuals per tank, 252 ± 6.1 g) to 46.6 ± 3.5 kg (79 ± 3 individuals per tank, 589 ± 34 g; Table 1). The mortalities remained very low throughout the experiment, excluding PRAS 3 with 8% mortality in Phase 1 (Table 1). However, a significant difference was not found between the different water renewal rates ($p > 0.05$; Table S5).

The FCR was on average 0.92, without significant difference ($p > 0.05$) between the systems of different water renewal rates (Figure 1A; Table S5). On the other hand, the SGR was on average 1.35, with a significant difference ($p < 0.05$) between systems of 1000 and 4000 L kg^{-1} feed and between 1000 and 2000 L kg^{-1} in the second phase (Figure 1B; Table S5).

The concentrations of TAN ranged from 5.3 to 20.7 mg L^{-1}, and unionized TAN from 3 to 46 μg L^{-1}, the highest concentrations occurring at water renewal rate of 1000 L kg^{-1} feed (Figure 2A,B). Significant difference in TAN ($p = 0.001$) and ammonia was found between all three systems of water renewal rates (Table S5).

In the case of NO_2—N, the highest concentrations were found at water renewal of 2000 L kg^{-1} feed (Figure 2C). Overall, the concentrations ranged from 0.07 to 1.06 mg L^{-1} with a significant difference ($p < 0.05$) between the systems of different water renewal rates (Table S5). Similarly, for COD (Figure 2D), a significant difference was observed ($p = 0.001$) between 4000, 2000 and 1000 L kg^{-1} feed.

Alkalinity ranged from 25 to 52 mg L^{-1} (Figure 2E) with a significant difference ($p < 0.05$) between the systems with water renewal of 1000, 2000 and 4000 L kg^{-1} feed (Table S5). On average, pH was at 6.5 ± 0.2 (Figure 2F). However, a significant difference ($p < 0.05$; Table S5) was found only between 1000 and 4000 L kg^{-1} feed water renewal rates.

3.2 | Off-Flavours

For most compounds, there is a tendency for increased concentrations at 1000 L kg^{-1} feed, especially for GSM, MIB and octanal (but without a significant difference, $p < 0.05$). In the rearing tank water, the off-flavour concentrations remained low, and concentrations up to 16 ng L^{-1} (octanal) were observed (Figure S1A,B) after 1month (Phase 1). By the end of the experiment (Phase 2),

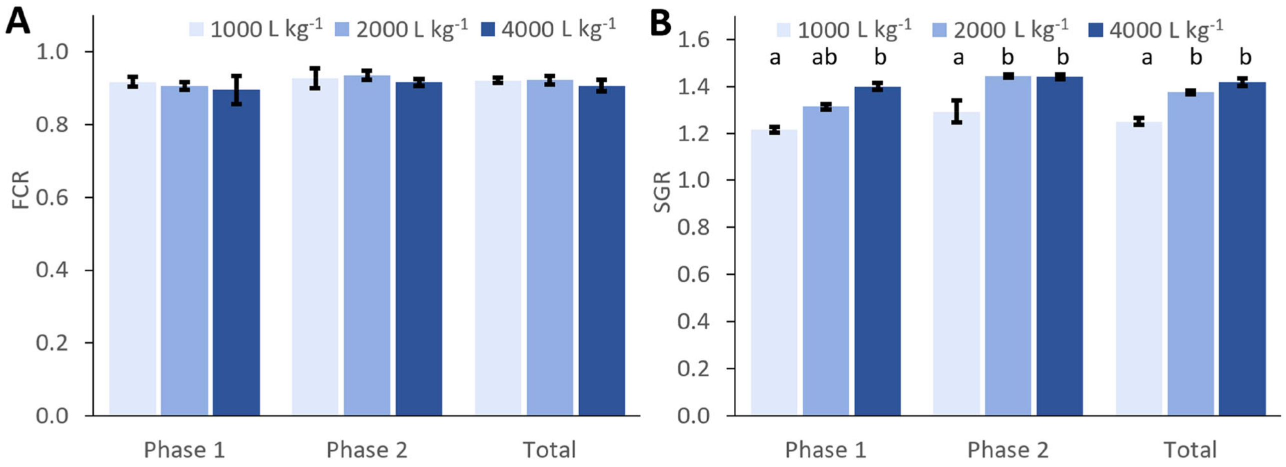

FIGURE 1 | Average (±SD) (A) FCR and (B) SGR (% biomass day^{-1}) at different water renewal rates (1000, 2000 and 4000 L kg^{-1} feed). Phase 1: the first 33 days of the experiment, Phase 2: the next 29 days of the experiment, total: the average of Phase 1 and Phase 2. The lowercase letters indicate statistically significant differences between treatments at each phase.

the concentrations ranged up to 18 ng L^{-1} in the circulating water (Figure 3). Even here, the highest concentrations were observed for GSM, MIB and octanal, all increasing as the water renewal rate decreased from 4000 to 1000 L kg^{-1} feed (Figure 3).

The concentrations in the inlet water were very low for most compounds and below or close to method LODs (Tables S2 and S6). Octanoic acid and phenylacetaldehyde ranged up to 10 ng L^{-1} in the inlet water in the beginning of the experiment but decreased by the end of the experiment. MIB was found 8.3–9.3 ng L^{-1}, while all the other compounds were found at much lower concentrations (Table S6).

Overall, the concentrations showed an increased trend at decreased water renewal rates. After 1 month of experiment, the off-flavours in fish were moderate to low, with MIB showing the highest concentrations (400–500 ng kg^{-1} for GSM and MIB; Figure S2A). At the end of the experiment, GSM showed the highest concentrations of up to 1560 ng kg^{-1} at 1000 L kg^{-1} feed (Figure 4) among the analysed compounds.

Similar to the observations in the circulating water, a tendency of increased off-flavour concentrations (but without a statistical significance of $p < 0.05$) of most compounds in fish was found at 1000 L kg^{-1} feed (Figure 4). The concentrations of MIB ranged between 400 and 300 ng kg^{-1}, while all the other compounds remained below 250 ng kg^{-1} (Figure 4). IBMP was neither detected in circulating water nor in fish flesh, while terpineol, TCA and hexenoic acid remained below the levels of quantification (LOQ).

The concentrations of GSM in fish flesh at water exchange rates of 2000 and 4000 L kg^{-1} feed were lower (600 and 500 ng kg^{-1}, respectively) than 1000 L kg^{-1} feed (1600 ng kg^{-1}), but significantly different ($p = 0.023$) only between systems with 2000 and 1000 L kg^{-1} feed (Table S7). For all the other compounds, a significant difference was not found between the different water renewal rates ($p > 0.05$), although a tendency of minor increase was observed in concentrations as the water renewal rate decreased (Figure 4).

4 | Discussion

Three different water exchange rates of PRAS (4000, 2000 and 1000 L kg^{-1} feed) without biofilters were studied. In this study, the FCRs were well below 1.0, which is somewhat lower than the FCR of 1.0–1.3 in a partial-reuse system rearing rainbow trout fingerlings reported by Summerfelt et al. (2004). This indicates overall good rearing conditions for rainbow trout. The FCR remained similar throughout the experiment in all systems without differences at different replacement water use. Poor rearing conditions (Øverli et al. 2006; Pulkkinen et al. 2018; Person-Le Ruyet et al. 2008) have been shown to increase FCR, yet here, the observed water quality did not affect the FCR. A good-quality floating feed was used in the experiment, and any uneaten feed was observed. However, the SGR was significantly lower in the lowest water exchange treatment, which reflects that fish consumed less feed in the treatment with 1000 L kg^{-1} feed. This is also in accordance with previous studies, where suboptimal water quality has been shown to decrease feed intake (Davidson et al. 2011; Pulkkinen et al. 2018).

Wood (2004) showed that low concentrations of total ammonia (70 µmol L^{-1}) could serve as a growth stimulant in rainbow trout and increase the SGR, and as a survival threshold (Papadopoulos et al. 2024). Wood (2004) suggested that especially unionized ammonia (23 μtorr, approximately 16–34 µg L^{-1}) might stimulate amino acid and protein synthesis or reduce metabolic costs, while Schram et al. (2010) reported stimulated appetite in African catfish *Clarias gariepinus*. At a theoretical level, exogenous ammonia may stimulate protein synthesis and growth if it is incorporated into amino acids (Randall and Tsui 2002). In our previous study, we reported increased growth associated with increased TAN levels (5 mg L^{-1} TAN in PRAS, meaning 0.52–1.10 µmol L^{-1} ammonia; Lindholm-Lehto and Kiuru 2024). In this study, the mean ammonia concentration was 11.5 µg L^{-1} in the mid-water exchange group and 38.2 µg L^{-1} in the lowest water exchange group. However, we did not observe increased growth. Similarly, Kolarevic et al. (2013) did not observe effects of elevated ammonia on feed utilization (0.1–32 µg L^{-1} NH_3, Atlantic salmon, *Salmo salar* parr).

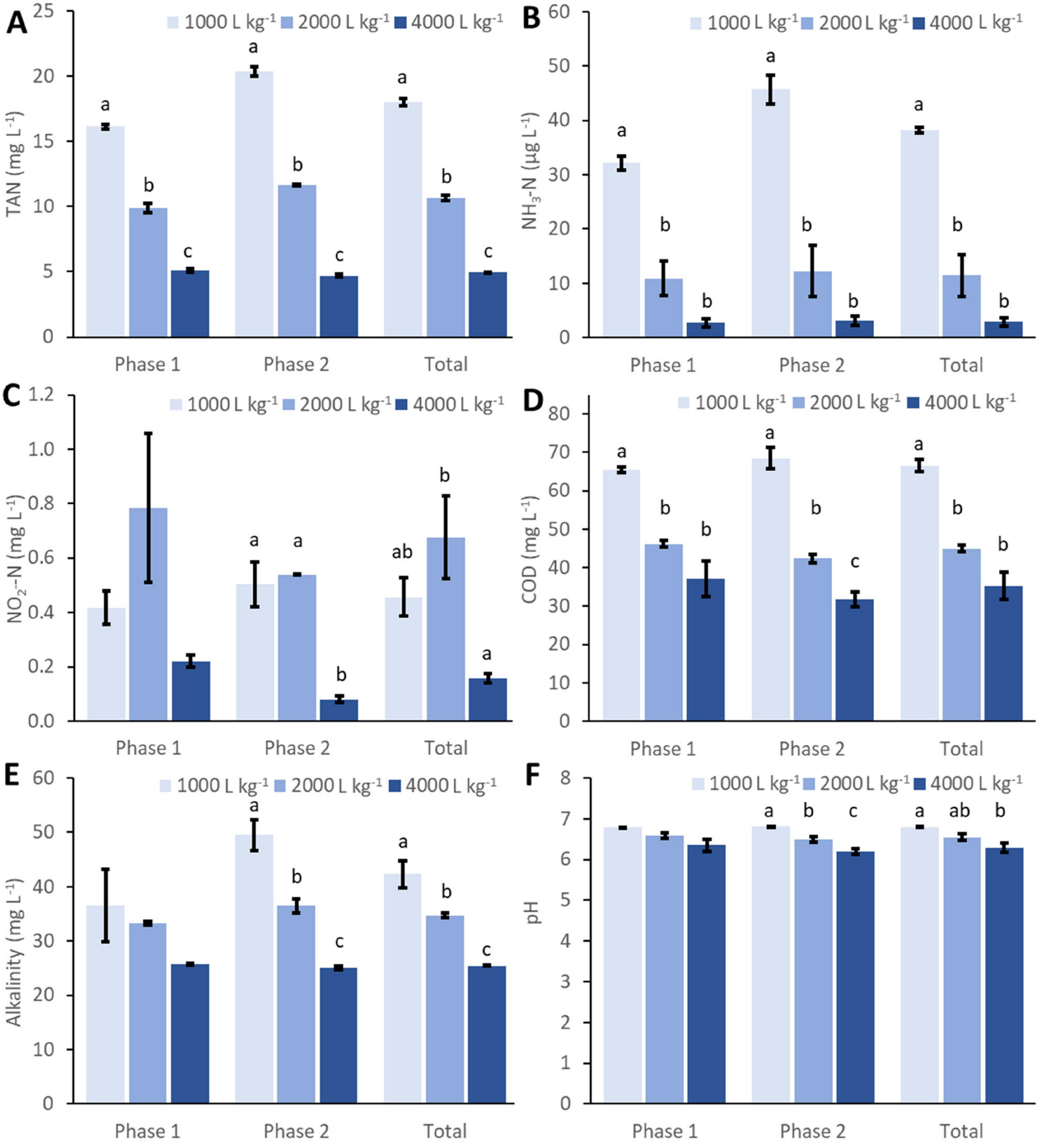

FIGURE 2 | Average concentrations (±SD) of (A) TAN, (B) unionized ammonia (NH_3—N), (C) NO_2—N, (D) chemical oxygen demand (COD), (E) alkalinity (expressed as $CaCO_3$) and (F) pH at different water renewal rates (1000, 2000 and 4000 L kg^{-1} feed, $n = 2$). Phase 1: the first 33 days of the experiment, Phase 2: the next 29 days of the experiment, total: the average of Phase 1 and Phase 2. The lowercase letters indicate statistically significant differences between treatments at each phase.

Increased concentrations of TAN and NO_2—N were observed at lower (2000 and 1000 L kg^{-1} feed) water exchange rates, both with statistical significance. At 1000 L kg^{-1} feed, the NH_3—N concentration was well above the recommended upper limit for salmonids (30 µg L^{-1}; Timmons et al. 2018). Highest mortality was observed in one of the lowest water use tanks (1000 L kg^{-1}, 8%) in the first phase of the experiment. High ammonia concentration may have affected the mortality, although there were no statistical differences between the systems. Twibell and Barron (2024) reported excellent survival of 100% in PRAS, while in this study, the average survival was 96%–100% and between 91% and 99% at 1000 L kg^{-1} feed.

Water quality plays a major role in the welfare of fish in all rearing systems, including PRAS. Lately, more debate has been raised about fish well-being among consumers, research communities

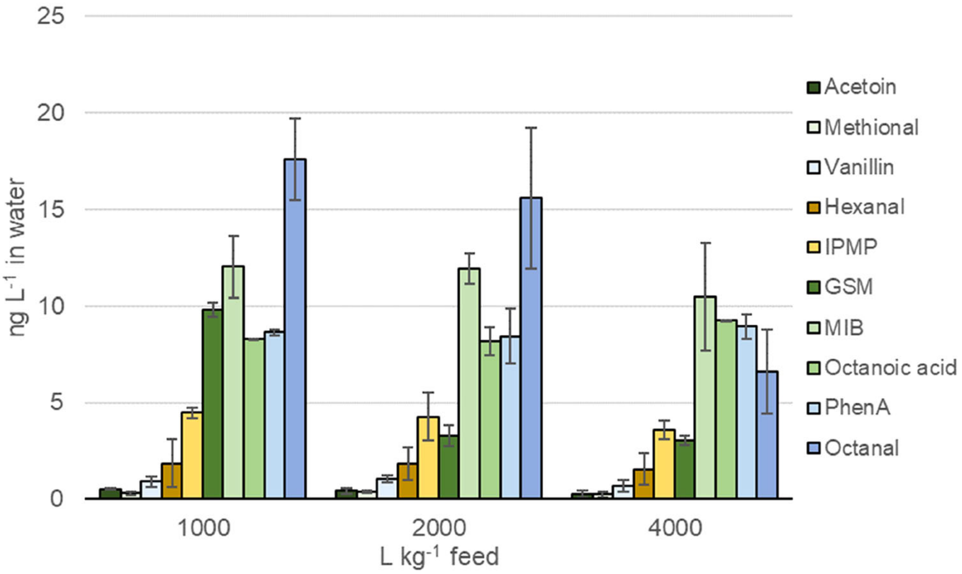

FIGURE 3 | Concentrations of 10 quantified off-flavour compounds in circulating water (ng L^{-1}, ±SD, $n = 2$) at replacement water of 1000, 2000 and 4000 L kg^{-1} feed after the experiment (April 30). GSM, geosmin; IPMP, 3-isopropyl-2-methoxypyrazine; MIB, 2-methylisoborneol; PhenA, phenylacetic acid.

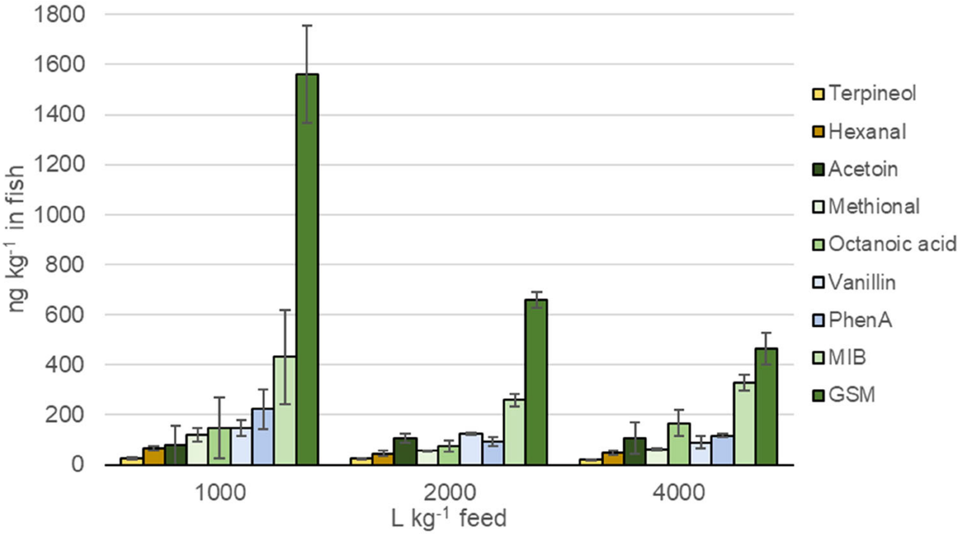

FIGURE 4 | Concentrations of quantified off-flavour compounds in rainbow trout muscle tissue (ng kg^{-1}, ±SD, $n = 2$) at replacement water of 4000, 2000 and 1000 L kg^{-1} feed after the experiment (May 2). GSM, geosmin; MIB, 2-methylisoborneol; PhenA, phenylacetic acid.

and decision-makers (Westerback et al. 2025). Consumers, in particular, want to be sure that the fish they eat has lived a good life (Seibel et al. 2020). In this study, however, any welfare parameters were not measured.

The highest levels of NO_2—N were measured in a tank at a water removal rate of 2000 L kg^{-1} feed (up to 1.4 mg L^{-1}), which is higher than the recommended concentration for salmonids (Kroupova et al. 2008; Timmons et al. 2018). To compare, NO_2—N remained below 0.01 mg L^{-1} and TAN ranged from 0.02 to 0.08 mg L^{-1} in the study of Twibell and Barron (2024). Both are much lower than those measured in this study (NO_2—N, 0.07–1.06 mg L^{-1}; TAN, 4.6–20.7 mg L^{-1}).

High NO_2—N levels indicate passive nitrification in the biofilm formed on the surfaces of the fish tank. Levels decreased as the experiment progressed, which is typical when the biofilm is new and the nitrite-oxidizing bacteria mature (Pulkkinen et al. 2018). However, it is unclear why nitrite concentration was highest in the 2000 L kg^{-1} water exchange group. It may be that high ammonia concentration in the lowest water exchange group stimulated complete nitrification start-up (Pulkkinen et al. 2018), and in the highest water exchange group, dilution kept nitrite concentration low. We did not measure NO_3—N during the experiment, so it was not possible to determine more precisely how nitrification was initiated or finished. NO_2—N accumulation should not be a problem in larger rearing tanks, where the surface area per volume is much less than in small experimental units (4.75 m^2 m^{-3}). High NO_2—N concentration in the two lowest water exchange treatment groups might have influenced the feed intake, as previously noticed by Roques et al. (2013) and Gutiérrez et al. (2019). Furthermore, this may have masked the potential benefits of a slightly elevated ammonium concentration. In Phase 2, when the NO_2—N concentration dropped in the 2000 L kg^{-1} water exchange group, the SGR was similar to that in the highest water exchange group.

In previous studies, basic water quality parameters of partial RASs have been measured (Summerfelt et al. 2004, 2009), but they monitored only the very basic parameters, such as pH, temperature, dissolved oxygen, TAN and CO_2. Here, besides the water quality parameters, feed use and fish growth, the accumulation of 14 different off-flavour compounds was monitored in water and in fish to determine if differences in water quality occurred due to different use of replacement water. Although a significant difference was found only for GSM between systems of 2000 and 1000 L kg^{-1} feed, the highest concentrations in water and in fish were found at systems with 1000 L kg^{-1} feed. This confirms that the formation of off-flavours occurred in the systems even without biofilters (Podduturi et al. 2017, 2020).

The effects of restricted water use were also observed as increased values of alkalinity, pH and COD. COD describes the amount of organic matter, particulate matter, or dissolved organic fraction in the system. Particulate matter is highly unwanted because it acts as a growth surface and substrate for bacteria (Rojas-Tirado et al. 2018), even for species producing off-flavours. In this study, the concentrations of COD remained relatively low, ranging from 30 to 65 mg L^{-1} and decreasing with a higher water removal rate. This is in accordance with the off-flavour results; lower concentrations were found at an increased water renewal rate. The residual H_2O_2 was higher for a water renewal rate of 4000 L kg^{-1} feed. In this case, the amount of particulate matter must have been lower, with less substance for H_2O_2 to react with.

Unexpectedly, pH and alkalinity increased when water use was reduced. This may be due to components in the fish feed, such as calcium, which increased the alkalinity. This shifted the ammonium balance towards the more harmful free ammonia. Thus, the difference in TAN values between the two units with the lowest water use was about twice the difference in unionized ammonia values. This highlights the risk of low water exchange, which must be considered when planning water use in a PRAS.

Overall, the concentrations of off-flavours were very low in the inlet water. This is a prerequisite for successful rearing and depuration without off-flavour-related issues. For GSM and MIB, a limit value of 10 ng L^{-1} has been suggested (Lindholm-Lehto and Vielma 2019), although any off-flavour in water affects accumulation in fish (Howgate 2004).

At the beginning of the experiment, octanoic acid, phenylacetic acid, MIB and IPMP showed higher values (6–10 ng L^{-1}) in the inlet water, but they decreased near their LODs by the end of the experiment. This is not exceptional because changes in microbe abundance can occur in nature in the spring and as the temperature of lake water changes (R. Wang et al. 2015). Only the concentrations of MIB and phenyl acetic acid remained at 8.7–9.1 ng L^{-1} in the inlet water. Overall, the concentrations in the circulating water remained at a low level (up to 18 ng L^{-1}), although concentrations above 10 ng L^{-1} induce a risk for off-flavour accumulation (Howgate 2004; Podduturi et al. 2017, 2021).

In fish flesh, MIB was found at 250–400 ng kg^{-1}, vanillin, PhenA and octanoic acid ranged from 100 to 220 ng kg^{-1}, while the concentrations of other compounds were below 70 ng kg^{-1}. The results are in line with the low concentrations found in the inlet and in circulating water. Additionally, the same compounds with the highest concentrations were found both in water and in fish. All this suggests that the inlet water was good in quality and the off-flavour compounds were mostly formed in the PRAS. The sensory detection limit of 700 ng kg^{-1} has been reported for MIB which is somewhat higher than the values found in this study (Grimm et al. 2004). In fish flesh, GSM was found 450–1600 ng kg^{-1} which were above the sensory threshold of 250 ng kg^{-1} (Grimm et al. 2004). Later, even a lower limit value of $\leq$100 ng GSM kg^{-1} for Atlantic salmon has been suggested (Davidson et al. 2023). However, the sensory limit values in fish flesh have not been determined for all the studied off-flavours (Lindholm-Lehto et al. 2023).

Oxidizing agents have been widely studied, aiming for reducing and removing the off-flavour compounds in RAS waters (Schrader et al. 2010; Klausen and Grønborg 2010; Rodriguez-Gonzalez et al. 2019; Pettersson et al. 2022), including the advanced oxidation processes (AOPs) which form very reactive hydroxyl radicals. In freshwater conditions, these agents do not form harmful byproducts. However, many oxidants react unselectively with all organic matter, not just off-flavour compounds.

The suitable concentration of H_2O_2 is relatively narrow to be used in RAS (Møller et al. 2010). Very low concentrations or short exposure times do not allow sufficient efficiency, while high doses may impair the beneficial microbial processes, for example, in biofilters. For example, Schwarz et al. (2000) reported severe inhibition by a H_2O_2 addition on nitrification in biofilters and reduced TAN removal at constant 100 mg L^{-1} dose. On the other hand, Møller et al. (2010) reported moderate inhibitory effect at 10–13 mg L^{-1} over 3 h, while in a study of Sortkjær et al. (2008), biofilters were unaffected at 30 mg H_2O_2 L^{-1} addition. However, as high as 30 mg H_2O_2 L^{-1} doses have been studied and observed that ammonium- and nitrite-oxidizing bacteria were able to recuperate quickly after a short exposure (Møller et al. 2010). Additionally, H_2O_2 reacts with NH_3 and oxidizes it to less harmful species. For example, H_2O_2 is commonly used in wastewater treatment to supplement the biofilter performance and nitrification, and NH_3 removal efficiency of 80% has been achieved (Jóźwiakowski et al. 2017).

In this study, 10 mg H_2O_2 L^{-1} was constantly added to all PRASs. Unlike in a RAS, the inhibitory effect on biofilters was not an issue, but any nitrification occurring in the biofilms may have been inhibited. The concentration used in this study remained below the upper limit safe for salmonids (70–100 mg H_2O_2 L^{-1}, Pedersen and Pedersen 2012). However, this H_2O_2 addition did not fully prevent the formation of off-flavours (mainly GSM) at the water use of 1000 L kg^{-1} feed. H_2O_2 was added via the inlet water directly to the rearing tanks, but at this level, it did not seem to affect the growth or well-being of the fish (Bögner et al. 2021). Any observed differences in growth and mortality of the fish were more likely caused by differences in water use and the accumulation of nitrogen species.

Summerfelt et al. (2009) observed that the circular bottom-drained tanks, similar to those used in this study, were not able to fully maintain mixing and even distribution in the water volume. This can be due to water flow dynamics and relatively low fish densities (9–16 kg m^{-3}; Summerfelt et al. 2009). In our study, the fish densities were higher (up to 50 kg m^{-3}), and a tank-specific aeration unit was used which allowed more homogeneous mixing through the water volume. This allows us to consider that the sampling was representative and the results of water quality were reliable.

5 | Conclusions

In this study, PRASs with three different water renewal rates (1000, 2000 and 4000 L kg^{-1} feed) and without biofilters were applied for rearing rainbow trout. The results showed that the overall water quality remained moderate or good in all systems. However, especially the unionized NH_3 concentrations were increased above the recommended limit values at the lowest water renewal rate. FCR and growth rates were good at all systems, but the growth was moderately reduced at the lowest water renewal rate. We did not observe that slightly elevated ammonium concentration improved fish growth, but high NO_2—N concentration may have masked the effect. Furthermore, the off-flavour concentrations were low or very low in all systems in water and in fish but, some compounds above their sensory detection limits were observed at the lowest water renewal rate.

Based on the results, water renewal rates of 4000 and 2000 L kg^{-1} feed seemed suitable for rearing rainbow trout in PRAS in terms of fish growth, feed use and minimizing off-flavours. At both water renewal rates, water quality remained good, suggesting sufficient conditions in terms of fish well-being, although any parameters of well-being were not monitored (besides visual inspection) in this study. Based on the results, the effects of H_2O_2 addition and the use of replacement water are difficult to separate. Overall, the results are a valuable addition when designing fish production in PRAS and selection suitable rearing conditions.

Author Contributions

Petra Lindholm-Lehto: methodology, chemical analyses and method development, writing -original draft. Kalle Sinisalo: conceptualizing, methodology. Jani T Pulkkinen: writing- review and editing. Tapio Kiuru: planning, conceptualizing.

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Ethics approval

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 authors declare 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.

Supporting Material: aff270080-sup-0001-SuppMat.docx