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WATER QUALITY STABILITY AND NUTRIENT DYNAMICS IN RECIRCULATING AND FLOW-THROUGH AQUACULTURE SYSTEMS

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ABSTRACT
The two types of aquaculture recirculating and flow-through have opposing water-management approaches which can affect environmental stability and nutrient buildup. This research compared water-quality conditions and nitrogen dynamics from repeated measurement data collected from two recirculating tanks and two flow-through tanks from 2023 to 2025. The dissolved oxygen, pH, temperature, alkalinity, ammonia, nitrite, and nitrate were analyzed for the samples in which no zero was coded. Descriptive statistics, coefficients of variation, matched-date Wilcoxon tests, the effect of rank-biserial, temporal trends, and Spearman correlations were used. Dissolved oxygen and pH were higher in recirculating tanks, and alkalinity was slightly higher in flow-through tanks and was more stable in temperature in flow-through tanks. The concentrations of ammonia, nitrite and nitrate were significantly higher in the recirculating systems, which signify greater nitrogen keeping and accumulation. In both, temperature was positively correlated with nitrate, while system-specific correlations were found for the relationships between dissolved oxygen and ammonia or nitrate. The results show that the recirculation system had the ability to enhance control of certain physicochemical parameters, although nitrogen management needs to be more carefully executed. The following measures are suggested for optimization of the system: Integrated monitoring, Adaptive aeration, Effective biofiltration, Calibrated water exchange, Nitrate removal.

Introduction

Aquaculture is playing an increasingly important role in providing global food for aquatics while the intensification of the culture process brings a lot of stress to the water resources and culture environment. Fish metabolism, fish welfare, fish growth, fish feed utilization, disease susceptibility and fish survival are directly affected by water quality. It is essential to have continuous monitoring of temperature, dissolved oxygen, pH, alkalinity and nitrogenous compounds to be able to manage the system effectively. Physicochemical monitoring and production practices must be coupled in water-quality management as much of the environmental deterioration can happen very quickly under intensive stocking and feeding condition (Yusoff et al., 2024). Recirculating aquaculture systems feature water treatment and reuse, which can be resource-efficient, but can also have unique management needs due to their technical complexity (Gupta et al., 2024).

Most production water is mechanically filtered, biologically treated by nitrification, aerated and biologically treated in other ways and retained in the recirculating aquaculture system. Flow through systems continuously pump in fresh water, and then pump out culture water, minimizing the time that dissolved metabolites spend in the system and resulting in higher water use and effluent production. The working principle of RAS is to keep biological treatment capacity equal to fish biomass, feed ration, oxygen requirement and metabolite generation (Waller, 2024). Water-quality monitoring is particularly important because variations in one variable can have an impact on multiple related water-process variables such as ammonia toxicity, microbial activity, and oxygen availability (Lindholm-Lehto, 2023). As observed during field assessments, RAS performance can be quite different depending on the local conditions and operation of the system (Nkoom & Ansobo, 2025).

Some of the most important indicators of system stability are dissolved oxygen, temperature, pH, and alkalinity. Dissolved oxygen is essential for respiration and microbial nitrification, temperature regulates metabolic rates, and affects oxygen solubility. The buffering capacity and the ratio of toxic unionized ammonia are controlled by the pH and alkalinity. The results from commercial rainbow trout production have proved that integrated monitoring is required to detect deviations before it becomes a problem to culture conditions (Pepe-Victoriano et al., 2025). The distribution of oxygen, waste transport, and ammonia excretion in culture tanks are also affected by flow conditions (Xiao et al., 2022). To minimize poorly mixed zones and enhance interactions between biological production and water-treatment components, hydrodynamic design can be used (Bell et al., 2023).

The challenge of nutrient management is the presence of uneaten feed, metabolic excretions and excrement (feces) in production water. Microbial nitrification of ammonia produced by fish metabolism results in nitrite and then nitrate. If treatment is inadequate, it can lead to ammonia or nitrite buildup, and repeated re-use of water can result in nitrate retention. The nutrient discharge from the feed depends on its composition and diets can be formulated specifically for recirculating production to reduce accumulation of nitrogen, phosphorus and zinc (Flo et al., 2024). Water quality and system output are also affected by protein-to-energy ratios and dietary phosphorus level (Fan et al., 2023). This study revealed that measured nutrient concentrations are related to feeding, fish metabolism, microbial conversion and water exchange.

Different spatiotemporal patterns of water quality can result from different system configurations. A direct comparison study of flow through, recirculation and bioremediation systems has shown differences in the level and extent of environmental conditions (Ismi et al., 2023). Hydrodynamic and water-quality models also demonstrate the spatial and temporal distribution of dissolved constituents is a function of circulation and transport processes (Badrzadeh et al., 2025). Another source of variation is biological, as microbial communities control the transformation of organic matter and conversion of nitrogen. The operation of RAS can shift the microbial communities, and water quality can also be impacted during specific productive phases (Lu et al., 2024). In addition, the design of the infrastructure will also affect the microenvironmental conditions by influencing circulation, aeration, solids retention and the biological treatment performance (Zhao et al., 2023).

Recent developments aim to enhance the environmental control with the help of integrated treatment, automation and resource recovery. Energy generation can be integrated with recirculating

production and microbial management (AquaCulture-Photovoltaic) as shown in aquaculture photovoltaic systems (Ruan et al., 2025). Automated flow-rate regulation can help optimize water quality, lower energy consumption and promote the growth of fish (Adoonsook et al., 2025). Coordinated water quality assessments for automated RAS also highlight the importance of linking water quality with production performance (Wu et al., 2025). In addition, the environmental control of the cultured fish should be assessed with regard to the nutritional quality and general value of the cultured fish in sustainable system. Other avenues to predict changes in water quality and optimize operation of the system exist through dynamic modelling and predictive control (Kamali, 2022).
Even with the progress that has been made, few direct comparisons of the stability of water quality and nutrient dynamics exist between recirculating and flow-through systems. The majority of investigations are conducted on a single RAS facility, treatment component, diet or fish species, and do not compare the two configurations using the same monitoring program. The lack of uniformity in sampling intervals and the different variables sampled also limit comprehension of the relationship between the patterns of ammonia, nitrite, and nitrate with their physicochemical counterparts. Comparative analysis based on repeated measurements from both the systems can help to elucidate the relationship between the water reuse and environmental stability, nutrient accumulation or system specific relationship between the monitored parameters. The research pursued three objectives:
To compare temporal stability of major water-quality parameters between recirculating and flow-through aquaculture systems
To quantify system-specific patterns in ammonia, nitrite, nitrate, and alkalinity across the monitoring period
To examine relationships between nutrient concentrations and physicochemical conditions within each aquaculture system

2. Methodology

2.1 Research Design

This study used a longitudinal comparative design to assess water-quality stability and nutrient dynamics of two aquaculture systems (Papadaki et al., 2025). Two flow-through units (G01 and G02) and two recirculating aquaculture system units (G03 and G04) were explored for repeated tank level measurements. A common temporal index was used as the date and within-system replication was preserved. Mean, median, mode and standard deviation were compared, as were the trends in time and cross-variable relationship s. The design facilitated observational comparisons to the existing operating state while avoided experimental manipulation and making no causal inference regarding system configuration.

2.2 Data Source

The measurements in this workbook spanned the time period of September 2023 to September 2025, and covered the parameters to the extent shown. All the dissolved oxygen, pH and temperature data were available for the longest time, and the nitrate and alkalinity monitoring started later. The measurements were planned in different parameter blocks in rows and four tanks in columns. The source clearly identified the flow-through tanks versus the recirculating tanks, so that the system could be consistently classified throughout the analysis.

2.3 Study Variables

Dissolved oxygen saturation (%), pH, surface temperature (°C), and alkalinity (mmol/L) were four physicochemical indicators used to reflect water-quality conditions. The dynamics of ammonia, nitrite and nitrate (mg/L) indicated successive stages of nitrogen transformations. Flow-through or recirculating was coded as the type of system, and the tank labels were preserved during preprocessing. The stability of water quality was operationalized as dispersion from the system means. Nutrient dynamics were evaluated based on the nutrient concentration distributions, temporal monotonic trends and relationships to the associated physicochemical conditions, and not on calculated nutrient loading or removal rates.
2.4 Data Preparation and Quality Control
The workbook was reshaped into longitudinal records at the tank level after standardization of dates

and parameter names.The workbook was reshaped to tank level longitudinal records after standardization of dates and parameter names. Undocumented missing-value coding was observed frequently across the temperature, pH, and dissolved oxygen levels, as well as for nutrients, with many zeros being reported in the same nutrient blocks. No values were imputed and all zero-coded entries were therefore not included in the primary analysis. Statistics were calculated using nonzero observations that were available. Only dates when both tanks of a system had a valid measurement for the parameter of interest were used for direct system comparisons. This method avoided the inclusion of placeholder zeros and dates of varying coverage, thereby not artificially lowering system means.

2.5 Stability and Temporal Assessment

Observation counts, means, standard deviations, medians, IQR and CV were computed for each parameter and system. Coefficients of variation were used to assess relative stability: lower CVs indicated greater stability; and standard deviations were used to describe variability in original measurement units. For each available date, the observations from each tank were averaged together prior to temporal and paired analysis. System-level means, variances, and Spearman correlations between concentration and monitoring elapsed time were summarized for nutrient dynamics. This method was used to obtain a capture of the direction change without making any assumptions about linearity or equal sampling times.

2.6 Statistical Analysis

Normality assumes even nutrient values and sampling times; this was not the case. Two-sided Wilcoxon signed-rank tests were used to test matched-date difference between recirculating and flow-through system means. The effect size and direction was quantified by rank-biserial correlation with positive values representing higher recirculating-system measurements. Spearman's non-parametric correlation coefficients were used to assess nutrient trends and nutrient-correlation with physicochemical parameters on common valid dates. The significance of the statistics was determined at the 0.05 level and p values were not rounded. The calculations were done at system-date level to minimize pseudoreplication among tanks.

3. Results

3.1 Data Coverage and Quality

Prior to the tank expansion, there were 1,585 parameter-date records, ranging from 115 alkalinity dates to 304 pH and temperature dates. The effects of removal of zero-coded entries were stronger for flow-through records than for RAS records. The flow-through tanks had an observation range of 136 to 399, while the RAS tanks had an observation range of 225 to 585. For the different parameters, 66–184 dates had full nonzero measurements in all four tanks. The records that were retained and the matched-date samples available for direct comparison are reported in Table 1.

Table 1. Data coverage and valid measurements following zero-code exclusion

Parameter	Recorded dates (n)	Flow-through valid observations (n)	RAS valid observations (n)	Flow-through zero codes (n)	RAS zero codes (n)	Matched dates (n)
Alkalinity	115	137	225	93	5	66
Ammonia	224	211	442	237	6	104
Dissolv	302	394	581	210	23	182

ed oxygen						
Nitrate	117	136	231	98	3	66
Nitrite	219	198	430	240	8	94
pH	304	399	585	209	23	184
Temperature	304	398	584	210	24	184

3.2 Water-Quality Conditions and Stability

The level and variability of physicochemical conditions were different for both systems. The mean dissolved oxygen in the RAS and flow-through tanks was 96.63% and 92.12%, respectively, and the mean pH for each tank was 7.93 and 7.53, respectively. The variability of temperature was significantly higher in RAS (CV = 11.00%) than in flow-through units (CV = 1.66%), while the mean temperature was comparable. Alkalinity was near, and there was significant relative variation in both systems for the operating conditions monitored. The full descriptive and stability statistics for the four water-quality indicators (Figure 2) are shown in Table 2.

Table 2. Descriptive statistics and stability of water-quality parameters

Parameter	**System**	**n**	**Mean**	**SD**	**Median**	**Q1**	**Q3**	**CV (%)**
Dissolved oxygen (%)	Flow-through	394	92.12	4.44	92.60	89.53	95.94	4.82
Dissolved oxygen (%)	RAS	581	96.63	3.24	97.30	94.50	98.90	3.35
pH	Flow-through	399	7.53	0.17	7.50	7.41	7.61	2.27
pH	RAS	585	7.93	0.19	7.91	7.79	8.06	2.46
Temperature (°C)	Flow-through	398	19.42	0.32	19.50	19.20	19.70	1.66
Temperature (°C)	RAS	584	19.58	2.15	19.60	18.70	21.20	11.00
Alkalinity	Flow-	13	3.72	1.	3.41	3.1	3.6	36.

(mmol/L)	through	7		36		3	3	56
Alkalinity (mmol/L)	RAS	225	3.63	1.74	3.11	2.82	3.42	48.03

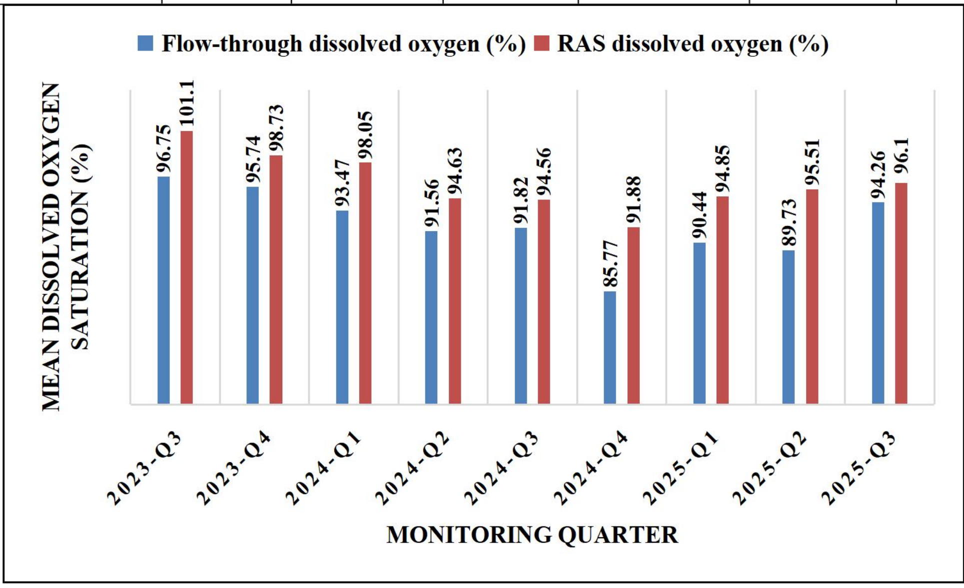

Figure 1. Quarterly Variation in Dissolved Oxygen Across Aquaculture Systems

3.3 Matched System Comparisons

Statistically significant higher values of dissolved oxygen, pH, ammonia, nitrite and nitrate were found by the matched-date testing, ranging from 0.865 to 0.980 rank biserial. RAS alkalinity was lower, thus resulting in a negative effect of −0.657. There was essentially no difference in temperature, with both systems having medians around 19.5°C with a median paired difference of −0.05°C and p = 0.933. The difference in all other contrasts was statistically significant for all water quality and nutrient parameters. The sample sizes, system medians, paired differences, Wilcoxon statistics, exact probabilities and effect estimates are shown in Table 3.

Table 3. Matched-date comparison between recirculating and flow-through systems

Parameter	**Matched dates (n)**	**Flow-through median**	**RAS median**	**Median difference (RAS − FT)**	**Wilcoxon W**	**p-value**	**Rank-biserial r**
Alkalinity (mmol/L)	66	3.383	3.073	−0.248	379.5	3.52×10^{-6}	−0.657
Ammonia	104	0.235	0.330	0.060	369.5	1.9	0.865

(mg/L)						3×10^{-14}	
Dissolved oxygen (%)	182	92.750	95.875	4.163	193.0	3.02×10^{-30}	0.977
Nitrate (mg/L)	66	1.600	2.875	1.400	24.5	5.00×10^{-12}	0.978
Nitrite (mg/L)	94	0.007	0.037	0.029	110.0	1.83×10^{-15}	0.950
pH	184	7.510	7.865	0.395	169.0	9.33×10^{-31}	0.980
Temperature (°C)	184	19.475	19.425	−0.050	7556.5	0.933	−0.007

3.4 Nutrient Dynamics

The concentrations of the nitrogen compounds were always higher in RAS, and in both systems there was a large range of concentrations. Mean ammonia, nitrite, and nitrate reached 0.357, 0.260, and 2.838 mg/L in RAS, compared with 0.235, 0.013, and 1.625 mg/L in flow-through tanks. The flow-through ammonia rose with time ($\rho = 0.616$), while the nitrate in the water decreased slightly ($\rho = -0.257$). There was a significant monotonic increase in RAS nitrate ($\rho = 0.262$), and no significant monotonic trends for RAS ammonia and nitrite. These concentration and temporal-pattern indicators are summarized in Table 4 for the entire observation period (Figure 2).

Table 4. Nutrient concentrations, variability, and temporal trends

Nutrient	System	Valid dates (n)	Mean (mg/L)	SD	Median (mg/L)	CV (%)	Temporal ρ	p-value
Ammonia	Flow-through	105	0.235	0.097	0.235	41.32	0.616	2.54×10^{-12}
Ammonia	RAS	219	0.357	0.401	0.295	112.28	0.087	0.202
Nitrite	Flow-through	95	0.013	0.039	0.007	306.85	0.215	0.037
Nitrite	RAS	212	0.260	0.379	0.044	145.88	−0.030	0.660
Nitrate	Flow-through	67	1.625	0.641	1.600	39.45	−0.257	0.036
Nitrate	RAS	114	2.838	1.107	2.850	39.00	0.262	0.005

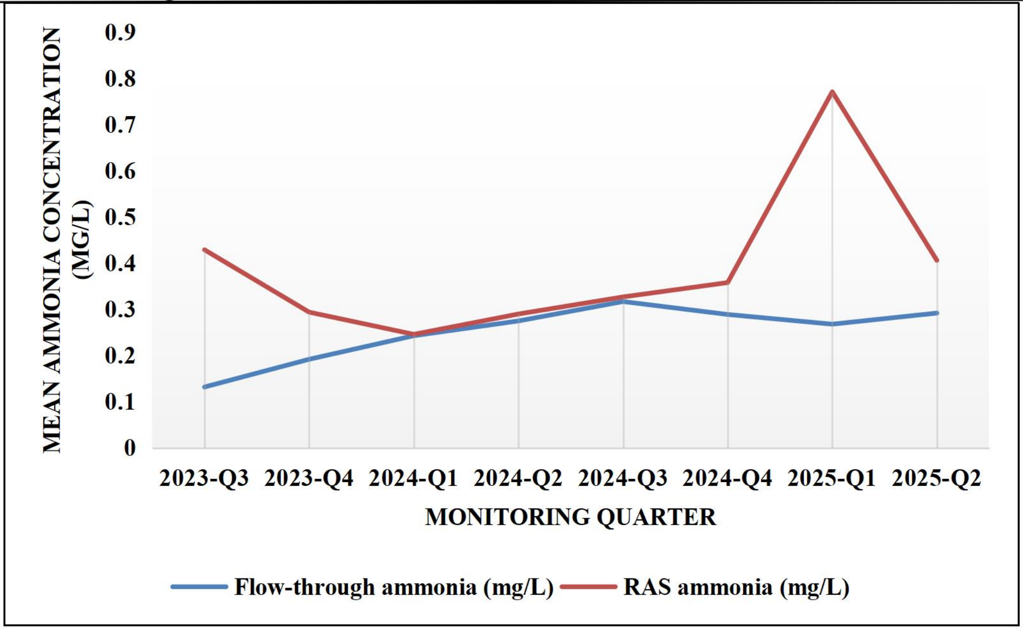

Figure 2. Quarterly Ammonia Dynamics Across Aquaculture Systems

3.5 Relationships Between Nutrients and Water Quality

Correlation patterns were quite different for different systems and for different nitrogen compounds. There was a negative correlation between flow-through ammonia and pH (ρ = −0.455) and dissolved oxygen (ρ = −0.507). The relationship between the temperature and the ammonia content of the water in the RWSD was positive (ρ = 0.278). The highest associations were for nitrate, with positive associations with temperature in the flow-through (ρ = 0.462) and in the RAS (ρ = 0.621) and negative associations with alkalinity in both systems. There was also a negative correlation between RAS nitrate and dissolved oxygen (DO) (ρ = −0.303). All statistically significant nutrient–water-quality relationships observed during monitoring are shown in Table 5 (Figure 3).

Table 5. Significant relationships between nutrients and physicochemical parameters

Nutrient	Water-quality parameter	System	Matched dates (n)	Spearman ρ	p-value
Ammonia	pH	Flow-through	102	−0.455	1.56×10^{-6}
Ammonia	Dissolved oxygen	Flow-through	103	−0.507	4.70×10^{-8}
Ammonia	Temperature	RAS	213	0.278	3.94×10^{-5}
Nitrite	Dissolved oxygen	Flow-through	94	−0.205	0.048
Nitrite	Temperature	RAS	209	0.138	0.046
Nitrate	Dissolved oxygen	RAS	112	−0.303	0.001
Nitrate	Temperature	Flow-through	67	0.462	8.15×10^{-5}

Nitrate	Temperature	RAS	112	0.621	2.93×10^{-13}
Nitrate	Alkalinity	Flow-through	67	−0.354	0.003
Nitrate	Alkalinity	RAS	110	−0.233	0.014

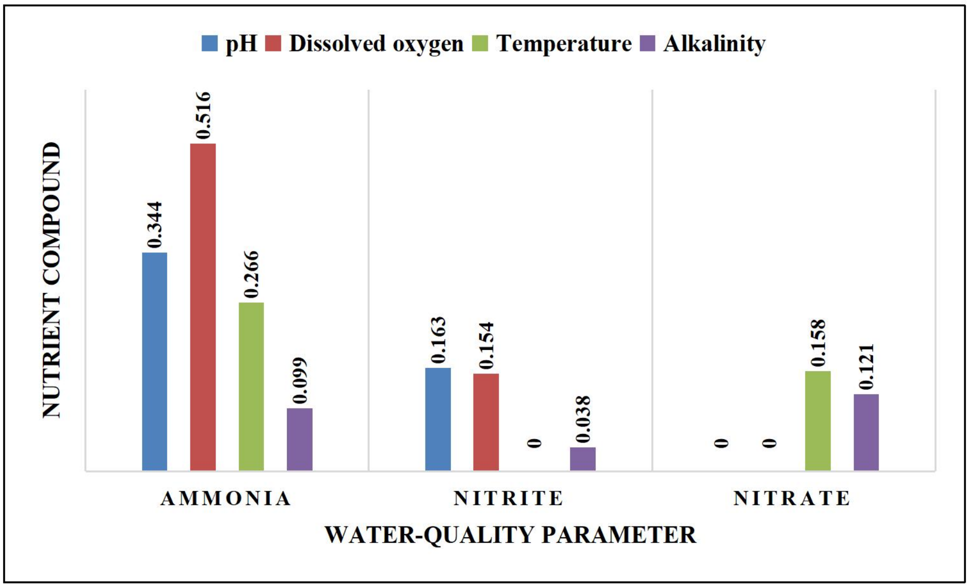

Figure 3. Differences in Nutrient–Water-Quality Correlations Between RAS and Flow-Through Systems

4. Discussion

Water-quality differences among the recirculating and flow-through aquaculture systems, as well as nitrogen dynamics. Significant rank-biserial effects showed that dissolved oxygen and pH were consistently higher in the RAS. Higher dissolved oxygen stability in RAS could be due to better aeration and water circulation control, and the higher pH may indicate variations in buffering, carbon dioxide removal and/or biological treatment. The alkalinity was slightly lower and variable in RAS, which could be due to the consumption of alkalinity during nitrification. Between systems, temperatures were very close to each other, although there was significantly more variation in the RAS, especially in several quarters of 2024. This result suggests that the water recirculation treatment did not result in homogeneous stability over all the physicochemical variables.

The best separation of the systems was obtained for the nitrogen compounds. The mean concentrations of ammonia, nitrite and nitrate were significantly higher in RAS, and the effect sizes of the matched date comparisons were large for ammonia, nitrite and nitrate. Water reuse leads to an increase of residence time of dissolved metabolites, and the accumulation of nitrogen compounds if they are not removed by biofiltration, denitrification, plant assimilation or water replacement. The higher nitrate concentration was in line with active nitrification as nitrate is the final product of the ammonia conversion. This biological process could be responsible for the higher dissolved oxygen found in RAS, but oxygen was insufficient to account for the nutrient patterns found. The same attention is given to the control of oxygen, pH and nitrogen compounds in RAS operations, using a model (dos Santos et al., 2022). The trend of the rising flow-through ammonia also indicates that deterioration does not always occur if the amount of metabolites produced are greater than the amount that can be removed by dilution or discharge even with continuous water replacement.

Results corroborated previous studies that stressed the need to look at feeding management together with environmental monitoring. Feed input influences the amount of nitrogen that enters into the aquaculture water and monitoring gives information needed to determine if the accumulation of nitrogen is safe and to make management adjustments (Aljehani et al., 2023). This is because the ammonia fluctuations that can be observed in a RAS can be quite large, calling for monitoring plans that recognize fluctuations over short timescales and not just long-term averages. Studies of integrated multi-trophic aquaculture have shown that the efficiency of nutrient retention can be enhanced if waste compounds are recovered by other organisms that belong to different trophic levels (Nederlof et al., 2022). Some of the reasons that the presence of nitrate and the episodic increases in ammonia and nitrite may remain in the systems examined here were due to the lack of recorded nutrient-recovery components.

These trends are set in the context of biological and engineered treatment methods described in the literature. Seaweed assisted treatment (SAT) has been studied to recover the dissolved nutrients from RAS wastewater and generate extra biomass. The differences showed that nutrient movement, retention and availability are also influenced by the treatment structure in flow-through and media-bed aquaponic systems (Abdissa et al., 2025). The present results confirm this by demonstrating system-specific differences between repeated ammonia, nitrite and nitrate measurements. Hybrid RAS designs have been suggested to improve solids removal and oxygen transfer as well as prediction of nitrogen transformations using a combination of ultrafiltration, diffused aeration, and nitrogen modelling (Assiddiqi et al., 2025). These are important because the peaks of nutrients measured in the RAS indicate that stable oxygen and pH do not always guarantee the full control of dissolved nitrogen.

Correlation analysis offered further understanding of processes that occurred in each system. There was an inverse relationship between flow-through ammonia and pH and dissolved oxygen, such that the lowest oxygen level and pH were associated with the highest ammonia concentration. There was a positive correlation between temperature and ammonia in the ground water of the RAS (RAS temperature) as expected due to higher microbial activity and metabolic activity in the warmer periods. Positive trends with temperature were observed with nitrate in both systems, with the highest coefficient observed in RAS. The negative correlation with alkalinity may be an indication of the use of buffering compounds in ammonia oxidation. This relationships are still associatives, but they are used to note down combinations of variables that should be monitored together. Therefore, coordinated thresholds for temperature, oxygen, pH, alkalinity, and nitrogen compounds should be considered by aquaculture managers rather than considering each parameter individually.

The results are applicable to system operation. RAS produced more and consistent DO but needed more attention on ammonia, nitrite, nitrate, alkalinity and temperatures. The flow-through systems had lower levels of nitrogen, but the oxygen pattern was decreasing, and the ammonia was increasing, suggesting that the exchange rates are adequate and that monitoring is required. However, there are several caveats to note. Only two tanks were sampled from each system and the sampling time was not uniform, with some observations having to be excluded due to being coded as a zero. The input of feed, biomass, flow rate, biofilter performance, and microbial measurement were not available. Future research efforts should integrate the continuous sensor data with operational data, use controlled replication and test nutrient removal interventions over similar production cycles.

5. Conclusion

Both recirculating and flow-through aquaculture systems had different physicochemical conditions and nitrogen profiles. The flow-through tanks had higher dissolved oxygen and pH while the recirculating tanks had slightly higher levels of alkalinity and significantly lower ammonia, nitrite and nitrate levels. Dissolved oxygen was relatively more stable in RAS, whereas the flow-through systems had a relatively higher temperature stability. The two configurations were thus not equally good everywhere in terms of water-quality indicators. Ammonia, nitrite (episodically) and nitrate (persistently) were more well retained in RAS. The continuous exchange resulted in an increase in flow-through ammonia with time, with only a slight decrease in nitrate, indicating that temporal water-quality risks were not eliminated by continuous exchange. These results can help with the comparison of aquaculture management approaches by highlighting the stability benefits of controlled recirculation versus the increased demands for nitrogen control. Instead of monitoring each of these variables separately, routine monitoring should incorporate dissolved oxygen, pH, alkalinity, temperature, ammonia, nitrite and nitrate. System optimization should be achieved in the future by a combination of automated sensing, adaptive aeration, calibrated water exchange, effective biofiltration, and nitrate removal. The study should be expanded to include feed input, biomass of stock, flow, microbial activity and replicated production cycles to establish the effect of operational controls on nutrient accumulation and long-term stability. This broader evidence would add to support system-specific operating thresholds and more resource efficient aquaculture production decisions.

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