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Water Quality in Recirculating Aquaculture Systems for *Oreochromis Mossambicus* in Dzimauli Village, South Africa

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ABSTRACT

Low productivity in newly introduced household Recirculating Aquaculture Systems (RASs) in Dzimauli Village, Limpopo, has raised concerns regarding the suitability of the spring-derived groundwater used in these units. This study assessed water quality in two RASs stocked with Oreochromis mossambicus *to identify physicochemical constraints linked to suppressed growth. Over six months, temperature, pH, dissolved oxygen (DO), turbidity, electrical conductivity, major anions, chlorophyll-a (Chl a), and microcystins (MCs) were monitored. Temperatures (18.21-18.99 °C) were below the optimal >20 °C threshold, while turbidity periodically exceeded 120 NTU. DO fluctuated widely, often dropping below 5 mg/L. Although EC, pH, salinity and anions remained within acceptable ranges, elevated Chl-a (up to 265.54 µg/L) and the presence of* Microcystis *and* Lyngbya *indicated a potential CyanoHABs risk, despite low MCs (<0.12 µg/L). The interplay between turbidity, DO, and microbial activity suggests feedback loops that destabilise system performance. Operational observations further showed that pump deactivation to save electricity and unplanned outages likely exacerbated declines in DO and temperature. Overall, low temperature, high turbidity, and intermittent aeration loss were the primary*

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limitations, underscoring the need for more reliable, low-maintenance infrastructure and contingency measures for rural RAS operation.

Keywords: CyanoHABs, Microcystins, *Oreochromis Mossambicus*, Recirculating Aquaculture Systems (RAS), Water quality.

1. INTRODUCTION

Traditionally, *Oreochromis* (tilapia) culture has been practised in earthen ponds or cages under extensive and semi-extensive systems, typically characterised by low input and low productivity (Gullian-Klanian & Arámburu-Adame, 2017). In earthen pond systems, high stocking densities, coupled with the accumulation of uneaten feed and fish excreta, frequently lead to the deterioration of water quality, necessitating large volumes of water exchange with freshwater sources to maintain suitable rearing conditions (Sinha & Banerjee, 2025). With rising global demand for fish, aquaculture has emerged as one of the fastest-growing food production sectors, contributing significantly to food security and economic development (FAO, 2022). However, the intensification of conventional aquaculture practices has exacerbated environmental concerns, including eutrophication, habitat degradation, and excessive water use (Yusoff *et al*., 2024).

Several sustainable aquaculture technologies have emerged prominently in the last five years. Among them, Recirculating Aquaculture Systems (RAS) have become a key focus for sustainably intensifying tilapia production. RAS allows for water reuse after mechanical and biological filtration, reducing freshwater consumption and effluent discharge while improving biosecurity and environmental control (Badiola *et al*., 2018; Martins *et al*., 2010). RAS also offers year-round production potential, among the advantages that make it an attractive solution for aquaculture in urban, arid, or resource-limited settings (Ebeling & Timmons, 2010). However, high energy use and operational complexity limit their adoption, particularly in smallholder and rural contexts (Gupta *et al*., 2024).

Considering these technological advances, extensive studies have evaluated RAS and low-cost variants in rural and resource-limited settings. Such studies have highlighted both productivity improvements and operational challenges, including filtration efficiency, oxygen supply, and system adaptability to local conditions (Soma *et al*., 2025; Silva *et al*., 2025). This growing body

of literature underscores the importance of context-specific system design, reliable infrastructure, and capacity-building for the sustainable expansion of Tilapia farming through advanced aquaculture technologies.

Concerns also remain regarding the biological performance of fish cultured in RASs. Suboptimal water quality, resulting from the accumulation of metabolic waste products and limited dilution, can impair fish health, increase stress levels, and reduce growth rates compared to flow-through systems (Gupta *et al*., 2024). Moreover, high capital and operational costs pose a barrier to widespread adoption, particularly in low-income rural communities (Sinha & Banerjee, 2025).

In developing countries, RASs are not yet that popular, and a few recent studies have documented both promising successes and recurring constraints when RASs are implemented at small or rural scales for tilapia. In one such study, field pilots of affordable RAS (A-RAS) in Kenya demonstrated significant productivity and water-saving gains compared with traditional ponds (Soma *et al*., 2025). Among the limitations of the A-RAS reported by Soma *et al*. (2025) were insufficient filtration and oxygenation, as well as the need for further design optimisation to make the systems robust under rural conditions.

In South Africa, RAS technology for tilapia production remains in its developmental stages. In June 2022, the University of Venda launched a pilot project in Dzimauli Village, Limpopo Province, installing four household-scale RAS units supplied with water from nearby mountain springs. Each unit was stocked with approximately fifty *O. mossambicus* fingerlings. Despite the promise of the initiative, productivity has remained low, with host families reporting minimal growth and no substantial returns over the course of a year of operation.

The effectiveness of RASs depends heavily on maintaining optimal water quality. Key water quality parameters, including dissolved oxygen (DO), temperature, total dissolved solids (TDS), electrical conductivity (EC), salinity, pH, nitrates, phosphates, and the presence of harmful algal blooms (HABs), play a vital role in sustaining aquatic life and ensuring the physiological well-being and growth of cultured species (Mugwanya *et al*., 2022). Because water quality is one of the strongest determinants of fish performance in RAS, governing metabolism, stress tolerance, immune function, and overall growth (Mugwanya *et al*., 2022), evaluating the suitability of the

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spring-derived groundwater used in these units is a necessary first step toward diagnosing the causes of poor productivity.

The present study, therefore, focuses on assessing the physicochemical quality of water in two operational household RAS units in Dzimauli. The objective was to determine whether key water quality parameters in the spring-derived Dzimauli RASs, such as temperature, dissolved oxygen, turbidity, pH, and nutrient levels, fall within ranges required for healthy tilapia production. By foregrounding the local context, this study provides site-specific evidence necessary to enhance small-scale RAS performance in rural South Africa and to inform practical interventions for communities adopting groundwater-based aquaculture.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

Water samples were collected from two RASs located in two households in Dzimauli Village, situated in the Vhembe District of Limpopo Province, South Africa. Two of the four household-scale RAS units in Dzimauli Village were included, as they had been operational for at least six months at the start of the study, while the other two had only recently begun operation.

Figure 1 shows a map of the study area, highlighting the locations of the two households where the RASs are situated. The study area is generally hilly and dominated by shrub-like vegetation. The area is predominantly rural, and, as in many rural communities in South Africa, its inhabitants face numerous socioeconomic challenges, including limited income opportunities. RASs were introduced to households to promote integrated aquaculture. This enabled households to combine fish farming with other existing farming systems, diversifying their income, utilising their land more efficiently, and minimising environmental harm. Households mainly rely on groundwater from nearby perennial springs. Each household has arranged to channel water from the springs to a storage facility, from which it is then channelled into the household. Water being used in the RASs is thus derived from these springs, and Figure 2 (a & b) shows the two RASs at the sampled households.

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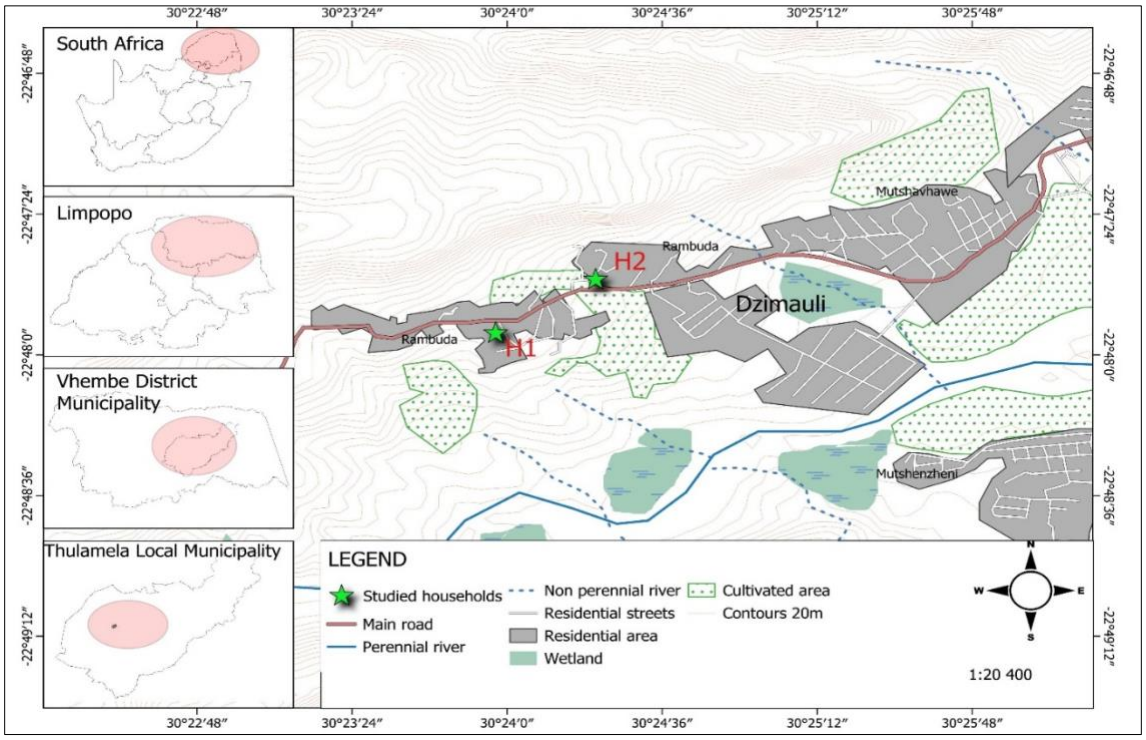

FIGURE 1: Map of the Study Area Showing the Location of the Two Households



FIGURE 2: The Two RASs at the Two Households Sampled

2.2. RAS Basic Configuration

The basic Recirculating Aquaculture System (RAS) configuration used in the two households in Dzimauli Village is shown in Figure 3. The system consists of a small-scale, household-level setup supplied with groundwater from nearby perennial mountain springs. Water is channelled from the

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springs to storage tanks and then into the RAS units. Each RAS was initially stocked with approximately fifty *Oreochromis mossambicus* (Mozambique tilapia) fingerlings. The RAS water treatment system comprises a multi-stage process designed to ensure optimal water quality for fish production. Water from the 10,000-litre fish tank is first directed to a mechanical sand filter, which removes suspended solids. It then flows into a 700 L biofilter equipped with 400 L of virgin bio-media, where biological filtration occurs, converting toxic ammonia into less harmful nitrate. A UV steriliser (55 W) follows, targeting microbial pathogens and reducing disease risk. The system is aerated using an LP100 blower with diffusers, ensuring adequate dissolved oxygen levels are maintained. Additionally, a side loop featuring two solar collectors is used to regulate water temperature, with manual valve adjustments allowing daytime heating. The entire system is supported by an electrical switchgear unit and interconnected piping to maintain a consistent water turnover rate of approximately one hour, supporting high stocking densities (40–65 kg/m³).

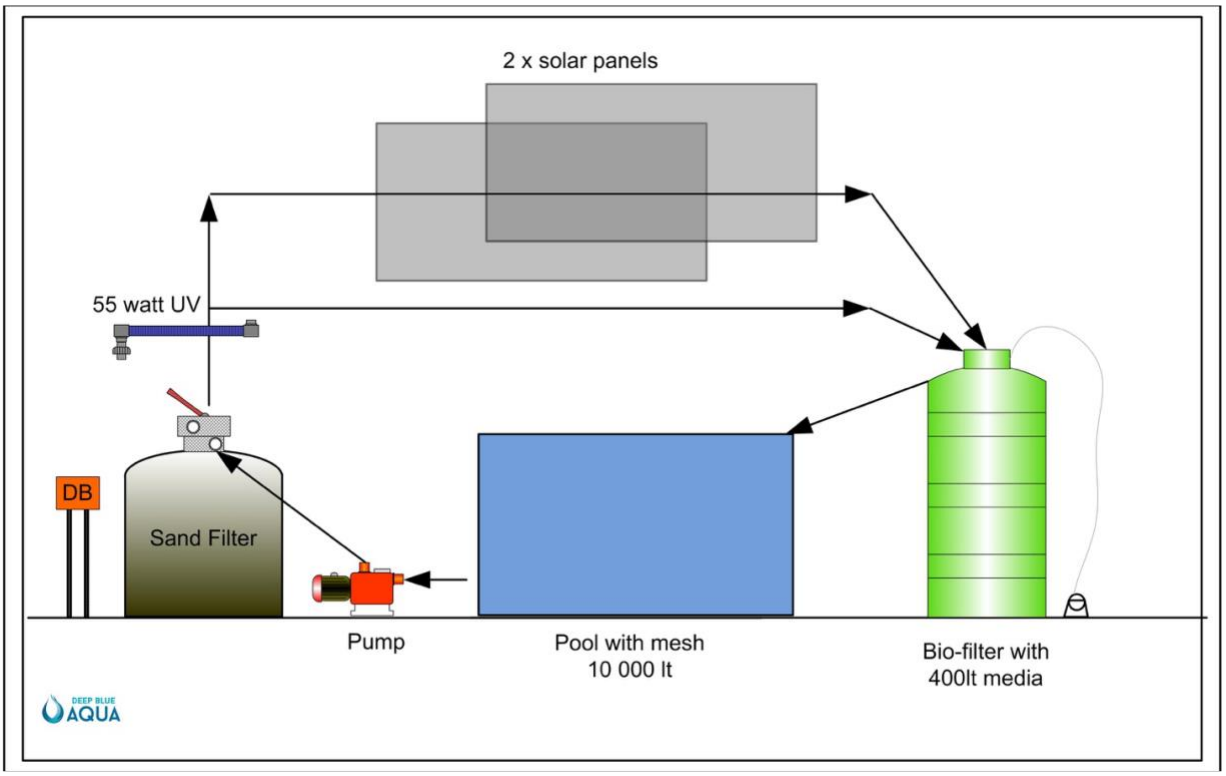

FIGURE 3: Flow Diagram of the RAS Plant (Adapted from the Manufacturer: Deep Blue Aqua, 2022)

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The systems are designed to operate as low-flow RAS units with partial daily water replacement (~10–15%), which is consistent with small-scale rural designs aimed at minimising water use while maintaining basic water quality. Each household fed commercial tilapia pellets (32% protein content) at an estimated rate of 3% of fish biomass per day during the initial three months, but this rate decreased over time due to poor growth performance.

Both RAS units required regular maintenance to maintain operational functionality, including weekly cleaning of the mechanical sand filter, backwashing the biofilter, and removing settled solids from tank bottoms. UV steriliser sleeves were cleaned biweekly to limit fouling, and blower diffusers were serviced monthly to maintain aeration efficiency. The solar heating loop was flushed approximately every two months to remove sediment buildup. Operational disruptions occurred approximately every six to eight weeks, primarily due to sand-filter clogging and short-term aeration interruptions caused by blower belt degradation. In addition, frequent local power outages caused intermittent system downtime ranging from several hours to over 24 hours, with a higher frequency during the colder months.

2.3. Sampling and Sampling Sites

Sampling was conducted in July, August, September, and November 2023, as well as in July and August 2024. Funding limitations and logistical challenges restricted the sampling plan for at least six consecutive months. Sampling involved monitoring physicochemical parameters (pH, temperature, turbidity, dissolved oxygen (DO), salinity, electrical conductivity (EC) and total dissolved solids (TDS) on-site and collecting water samples for *chlorophyll-a*, microcystins (MCs), nitrates (NO_3^{2-}), phosphates (PO_4^{2-}), fluoride (F^-), sulphates (SO_4^{2-}) and chloride (Cl^-) analysis in the laboratory at the University of Venda.

Water samples for microcystins (MCs) were collected in 100 mL Schott amber bottles, and samples for *chlorophyll-a* and anions were collected in 100 mL plastic HDPE bottles. A sampling rod was used to collect samples at approximately 1 m deep into the water column within the RAS. The sampling rod was rinsed thrice with the sample water before filling the various sampling bottles. The bottles were tightly closed and transported in a cooler filled with ice to the laboratory for analysis. Samples for MCs were kept at -20 °C, and those for *chlorophyll-a* and anions at 4 °C, and were analysed within 24 hours of sampling.

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2.4. Physicochemical Parameters Monitored In-Situ

A Thermo Scientific ORION portable multimeter (Singapore) was used to monitor pH, Electrical Conductivity (EC), Temperature, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), and salinity in situ. An Orbeco TB200 Turbidimeter was used for measuring turbidity. Both meters were first calibrated according to the manufacturer's protocols before use.

2.5. Determination of Fluoride, Chloride, Phosphate, Sulphate, and Nitrate Ions

Concentrations of anions (Nitrate, Phosphates, Fluoride, Sulphate and Chloride) were determined using a Metrohm 850 Professional Ion Chromatography (IC) system. The IC operating conditions were: flow rate of 0.7 mL per minute and pressure of 10.8 megapascals (MPa). The mobile phase was a mixture of 1.0 millimolar (mM) sodium bicarbonate and 3.0 mM sodium carbonate, and the column was a Metrosep a Supp5–250 250 mm column. All samples were first filtered through 0.2 µm syringe filters (Minisart NYLON with GF) prior to analysis. For quality control, certified reference materials and calibration standards were analysed alongside samples to verify instrument accuracy.

2.6. Identification of Cyanobacterial Harmful Algal Blooms

To identify Cyanobacterial Harmful Algal Blooms (CyanoHABs) that could be developing in the RASs, a Benchtop Flow-Cam (Model US-IV, Yokogawa Fluid Imaging Technologies, Maine, U.S.A) was used. A sample of water (5 mL) was passed through the instrument, and images of the particles were captured as the sample flowed through the flow cell. Images of different species of CyanoHABs captured were then identified using a guide by Huynh and Serediak (2006).

2.7. *Chlorophyll-a*

Phytoplankton biomass in the RAS water was estimated from *chlorophyll-a* measurements according to Lawton *et al*. (1999). In brief, chlorophyll was extracted with hot ethanol, and absorbance was measured using a UV/vis spectrometer (Spectrostar Nano, BMG LABTECH, 601-1106, Germany). Absorbency was recorded at 665 and 750 nm wavelengths, then second readings to correct for turbidity were taken after acidifying the samples with 10 µL of hydrochloric acid (1

mol/L) at the same wavelengths. Total *chlorophyll-a* was then calculated according to Lawton *et al*. (1999) using the following formula:

Correction for turbidity: absorbance 665*a* -750*a* = corrected 665*a* absorbance [1]

665*b* – 750*b* = corrected 665*b* absorbance [2]

$$Chlorophyll\text{-}a = \frac{29.62\ (665a - 665b)\ x\ Ve}{Vs\ x\ I}\ \mu g/L \quad [3]$$

Where: *Ve* = volume of ethanol extract (mL); *Vs* = volume of water sample (Litre); *I* = path length of cuvette (cm)

2.8. Microcystins Determination

Total MCs in the sample water were determined using the enzyme-linked immunosorbent assay (ELISA) using Microcystin Plate Kits (ENVIROLOGIX INC. (Kit Lot: 071499 Cat No: EP 022)). This assay uses antibodies specific to microcystins (MCs) to detect and quantify these toxins in water samples. A microplate reader Spectro-star Nano (BMG LABTECH, 601-1106, Germany) was used to read and quantify the MCs in the plates after the assay. Prior to conducting the assay, 5 mL of each water sample was filtered through 0.2 µm glass fibre syringe filters (Minisart) and 50 µL of the filtered sample was used for the assay.

2.9. Data Analysis

Data was captured and analysed using Microsoft Excel (2013). Data analysis involved calculating descriptive statistics, identifying monthly variations, and comparing the monitored parameters to the acceptable levels for tilapia aquaculture. To determine whether there were statistically significant differences between sampling sites (households), an unpaired *t*-test was performed using GraphPad Prism 3 (GraphPad Software, Inc., USA). Statistical significance was considered at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Physicochemical Parameters Monitored

The monthly trends of the monitored physicochemical parameters are in Figures 4 and 5. From July 2023 to July 2024, water quality varied seasonally and between sites. EC (Figure 4A) at H1 rose from 59.66 µS/cm (July 2023) to 179.20 µS/cm (June 2024), then dropped to 91.35 µS/cm

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(July 2024), while H2 remained lower (45.64–79.96 µS/cm). TDS (Figure 4C) followed similar trends, peaking at 88.33 ppm (H1, June 2024) and 39.70 ppm (H2, November 2023). Water temperatures (Fig.4B) ranged from 15.6 °C (H1, August 2023) to 24.5 °C (H2, November 2023). The water pH (Figure 4D) was predominantly alkaline, with extremes of 8.73 (H1, August 2023) and 6.77 (H1, June 2024).

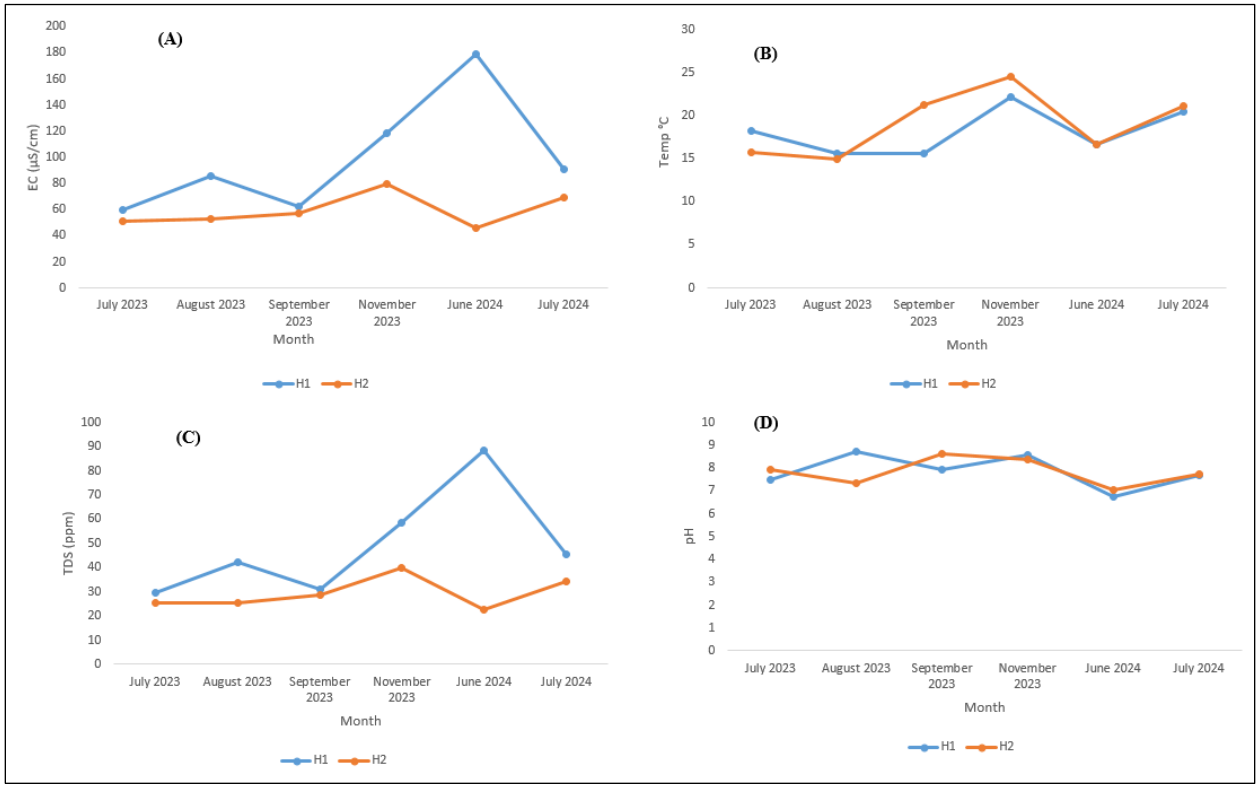

FIGURE 4: Physicochemical Parameters Trends Over the Monitored Period (A) Electrical Conductivity (B) Temperature (C) TDS & (D) pH

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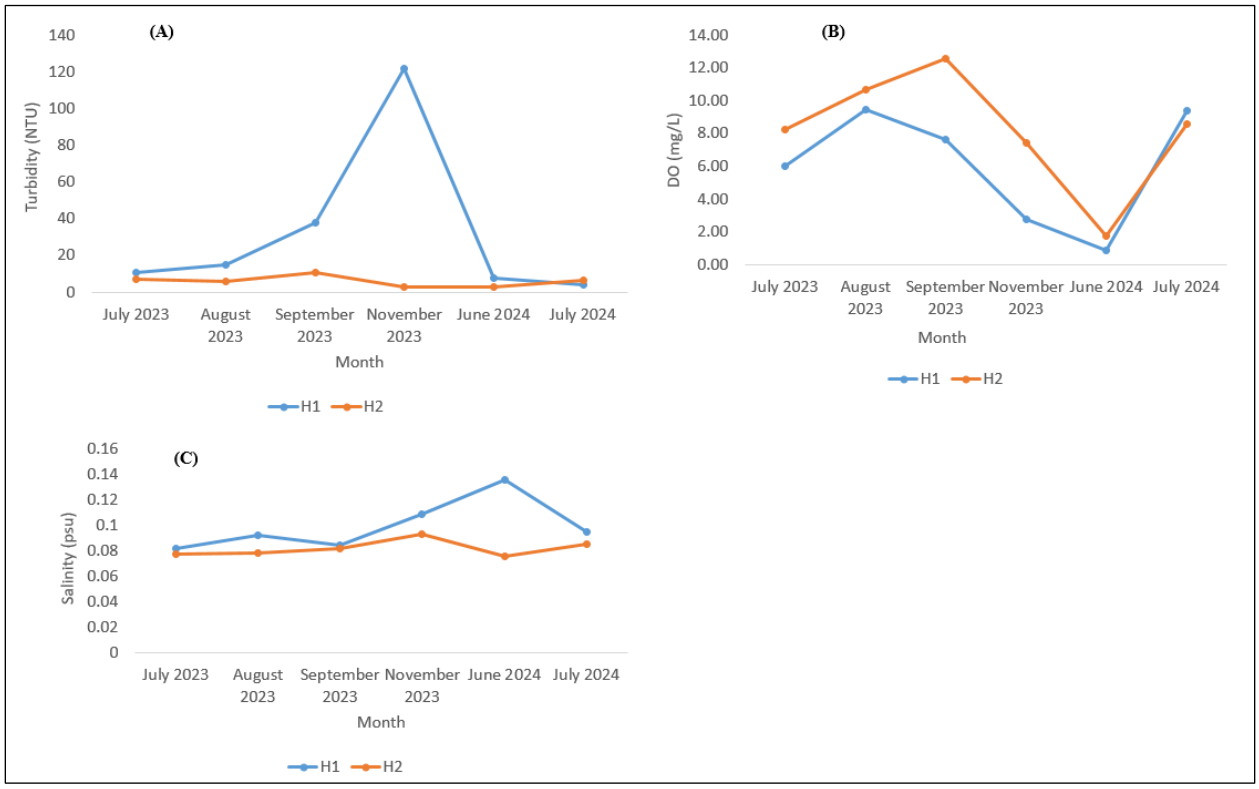

FIGURE 5: Physicochemical Parameters Trends Over the Monitored Period (A) Turbidity (B) DO (C) Salinity

Turbidity (Figure 5A) was highly variable, with a sharp peak at H1 in November 2023 (121.95 NTU) compared to only 2.57 NTU at H2. Dissolved Oxygen (Figure 5 B) fluctuated widely, reaching a minimum of 0.85 mg/L (H1, June 2024) and 7.45 mg/L (H2, November 2023), and a maximum of 9.40 mg/L (H1, July 2024) and 10.70 mg/L (H2, August 2023). Salinity (Figure 5C) remained low, with the highest at 0.1355 psu (H1, June 2024) and 0.093 psu (H2, November 2023). Seasonal hydrological changes and potential anthropogenic inputs are likely to drive these patterns. High turbidity at H1 in November 2023 was plausibly linked to poor maintenance of the RAS, and elevated EC/TDS in June 2024 suggested concentration effects from low flows.

The findings in Table 1 show statistically significant differences in water quality between H1 and H2 for EC, TDS, and salinity. The observed statistically significant differences between the two recirculating aquaculture systems (H1 and H2), despite utilising the same aquifer source water, are likely attributable to variations in system-specific operational factors. These include differences in

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water recirculation and exchange rates among households, which, in turn, affect water treatment and filtration processes, as well as biofilter and microbial activity. Additionally, the feed input and fish metabolism may also contribute to these discrepancies. Together, these factors influence the accumulation or dilution of dissolved ions and solids, resulting in the measured variations in EC, TDS, and salinity.

3.1.1. Water Temperature

The summary statistics for the monitored physicochemical parameters in the RASs are presented in Table 1. Over the six-month monitoring period, the mean water temperature was 18.21 °C (Table 1). This figure falls well below the optimal temperature for warm-water fish species such as O. mossambicus (tilapia), which generally thrive at around 28 °C (Santeri *et al*., 2021). The observed sub-optimal temperatures are primarily attributable to the study area's geographic and seasonal context. Located in a mountainous part of the Limpopo Province, the region experiences cooler climatic conditions, particularly during winter, with average air temperatures ranging from 9°C to 20 °C. Moreover, the sampling predominantly occurred during these colder months, further influencing the overall mean temperature.

While the maximum recorded temperature reached 22.10 °C during the warmer months (September and November), this remains below the preferred threshold for optimal tilapia growth. Furthermore, all measurements were taken during the daytime, which likely reflects peak daily temperatures and thereby underestimates the cooler nocturnal conditions. These findings suggest that the actual thermal environment within the RASs is likely even less favourable than the reported data indicate.

Water temperature plays a critical role in aquaculture because it directly influences key physiological processes in fish, such as metabolism, feeding behaviour, oxygen consumption, immunity, and reproductive performance (Ebeling, 2011; Marium *et al*., 2023). In the Dzimauli systems, consistently low water temperatures may have had direct, site-specific operational consequences. The deviations from the optimal thermal range can be a huge factor in the reduced growth rates, increased susceptibility to disease, and even mortality in extreme cases.

TABLE 1: Summary Statistics of Physicochemical Parameters of the Water in the Two RASs

Parameter	Points	H1	H2	Recommended
TEMP (°C)	Min	15.60	14.90	>20 °C (Ebeling, 2011)
	Max	22.10	24.50	
	Mean ± SD	18.21±2.48[a]	18.99±3.43[a]	
EC (µS/cm)	Min	59.66	44.97	-
	Max	180.20	79.96	
	Mean ± SD	108.39±47.47	58.89±12.63	
TDS (mg/L)	Min	29.73	22.74	<400 mg/L (Ebeling, 2011)
	Max	88.82	39.70	
	Mean ± SD	53.61±23.27[a]	29.26±6.26[b]	
pH	Min	6.55	6.93	6.5 – 9.0 (Ebeling, 2011)
	Max	7.69	8.60	
	Mean ± SD	7.71±0.73[a]	7.72±0.64[a]	
Turbidity (NTU)	Min	3.61	2.39	< 5 NTU (Santeri *et al*., 2021)
	Max	121.95	10.53	
	Mean ± SD	26.23±40.20[a]	5.64±2.73[a]	
DO (mg/L)	Min	0.85	1.75	>5 mg/L (Ebeling, 2011)
	Max	9.77	12.59	
	Mean ± SD	5.76±4.11[a]	7.34±4.17[a]	
Salinity (psu)	Min	0.08	0.08	<0.5 to 1 psu (Ebeling, 2011)
	Max	0.14	0.09	
	Mean ± SD	0.10±0.02[a]	0.08±0.01[b]	

Note: *Values with different superscript letters differ significantly at $p < 0.05$ (Unpaired 't' test).*

A key factor contributing to the stable, yet low temperature is the use of groundwater as the primary source for the RASs. Groundwater, because it is subterranean, tends to maintain a relatively constant temperature year-round, typically mirroring the region's mean annual air temperature (Boyd & Tucker, 2012). While this thermal stability might prevent sudden temperature fluctuations, it also limits the capacity for warming during cold seasons. Although the RASs

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include solar-powered heating components, their efficiency appears insufficient to raise water temperatures above the minimum threshold required for optimal tilapia production. This finding is consistent with studies, such as those by Rajesh *et al*. (2023), which highlight the inadequacy of passive solar heating in high-altitude or winter-prone aquaculture environments.

3.1.2. Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH, and Salinity

The mean TDS values recorded across the RASs (Table 1) remained within the recommended limit of 400 mg/L for freshwater aquaculture systems (FAO, 2015). Both EC and TDS levels are critical as they reflect the ionic strength and overall mineral content of the water, which can influence osmoregulatory function in fish (Verma *et al*., 2022). The pH and salinity levels were also within acceptable thresholds for tilapia farming, typically ranging from 6.5 to 8.5. The salinity levels recorded were all within the 5 psu range, optimal for tilapia health and growth (Bhatnagar & Devi, 2013). These results indicate that, despite suboptimal temperatures, the ionic and chemical quality of water in the RASs does not pose an immediate threat to fish health.

3.1.3. Turbidity

Turbidity levels in the RASs varied widely, ranging from 2.39 to 122.95 NTU, with a mean value of 26.23 NTU (Table 1). Although no universally accepted turbidity standards exist for aquaculture, studies suggest that levels below 5 NTU are ideal for maintaining water clarity and supporting optimal light penetration (Santeri *et al*., 2021).

Elevated turbidity can reduce photosynthetic activity by limiting light penetration, thereby suppressing dissolved oxygen production and affecting overall primary productivity. Low DO conditions thus create a feedback loop in which poor water clarity directly influences oxygen availability (Santeri *et al*., 2021; Rehman *et al*., 2023). Additionally, high turbidity can impair fish feeding efficiency and cause gill irritation or clogging. High turbidity also favours the proliferation of heterotrophic microbial communities that consume oxygen, further intensifying oxygen depletion (Rehman *et al*., 2023).

In particular, the RAS in H1 exhibited persistently high turbidity values, which may pose a risk to fish health. Ardjosoediro and Ramnarine (2002) found a direct correlation between increased turbidity and higher mortality rates among tilapia fingerlings, attributing the cause to impaired gill

function and reduced gaseous exchange. Schumann and Brinker (2020) also reported that elevated suspended solids in aquaculture systems led to increased ammonia levels and greater susceptibility to bacterial infections.

To reduce turbidity and the associated microbial oxygen demand in these systems, several practical management interventions are recommended. One way to achieve this is to install more efficient mechanical drum filters or swirl/radial settlers to reduce suspended particulates and organic loads (de Jesus Gregersen & Pedersen, 2025). More practical for the Dzimauli households will be the use of solar battery backups to reduce pump downtime, cut electricity costs, and maintain stable DO levels (Liu *et al*., 2024). Another practical solution for households is improving the feed management. By avoiding overfeeding and using smaller, more frequent feedings, the loading of fine particulates is reduced, as is the microbial oxygen consumption. Together, these interventions provide a feasible pathway to stabilise turbidity and improve water quality in these small-scale rural RAS.

3.1.4. Dissolved Oxygen (DO)

In Table 1, the mean DO concentration recorded across both RASs was slightly above the critical threshold of 5 mg/L necessary for optimal fish growth (Santeri *et al*., 2021; Ebeling, 2011). However, notable dips below this threshold were observed in June 2024 across both RASs, and in November 2023 in RAS H1. Such occurrences are concerning, given the importance of DO in supporting respiration, nutrient assimilation, and overall metabolic functioning in fish. Warm-water species, such as tilapia, have high oxygen demands, particularly during periods of active feeding and growth.

The primary cause of low DO concentrations appears to be groundwater's inherent oxygen-poor nature. As noted by Ebeling (2011), groundwater typically contains lower dissolved oxygen levels due to minimal surface agitation and biological activity in aquifer systems. Although mechanical aerators were installed, user behaviour, particularly the intermittent deactivation of pumps to conserve electricity, likely exacerbated DO depletion, especially during cooler months when solubility increases but biological oxygen demand remains elevated.

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Dissolved oxygen levels are also critical to microbial dynamics in the RAS biofilter. Fluctuating DO concentrations can negatively impact nitrifying bacteria, which convert toxic ammonia and nitrite into nitrate, thereby diminishing bio-filter efficiency (Rehman *et al*., 2023; Wicaksono *et al*., 2024). Low DO can also stimulate the growth of anaerobic and facultative pathogenic microbes, increasing disease risks in fish populations. These microbial shifts create a feedback mechanism in which impaired biofiltration further degrades water quality, reducing oxygen levels and amplifying stressors on aquatic organisms.

Comparative studies, such as that of Wicaksono *et al*. (2024), highlight the critical role of consistent aeration in maintaining DO levels in small-scale RASs. Their study (Wicaksono *et al*., 2024) reported a 25% reduction in fish growth and a significant increase in stress indicators when aeration was irregular or insufficient. This aligns with the current findings and underscores the need for continuous, reliable aeration strategies, especially when relying on groundwater inputs.

The interplay between turbidity, DO, and microbial activity underscores the complexity of managing water quality in RASs. High turbidity reduces light availability and oxygen production, while low DO conditions impair critical microbial processes and favour pathogenic growth, resulting in cyclical feedback loops that can destabilise system performance (Rehman *et al*., 2023). Effective RAS management thus requires integrated strategies that simultaneously target physical, chemical, and biological parameters to maintain system resilience and fish health.

The operational data collected during the study indicate that system configuration alone does not ensure optimal performance. Despite the presence of functional mechanical and biological filtration, periodic operational inconsistencies and lapses in routine maintenance likely contributed to the observed variability in turbidity, dissolved oxygen, and temperature. Regular pump deactivation to conserve electricity and unplanned electrical outages beyond operator control could have compounded, halting both aeration and heating and creating stress conditions that persisted beyond the outage itself.

A deeper socio-technical assessment shows that electricity outages, intermittent pump operation, and limited user maintenance capacity were central constraints affecting system stability. Frequent power interruptions halted aeration, heating, and filtration, creating stress conditions that persisted beyond each outage, an issue widely recognised in small-scale RAS literature (Gupta *et al*., 2024;

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Soma *et al*., 2025). Additionally, the operational complexity of filters, blowers, and heating components exceeded households' technical skills, consistent with findings that low-cost RAS designs often fail without reliable energy access and continuous training (Silva *et al*., 2025; Sinha & Banerjee, 2025). These socio-technical barriers likely contributed to the poor performance of the RASs and the measured water quality limitations. Such patterns highlight that improving RAS reliability in rural contexts will require not only technical optimisation but also investment in robust, low-maintenance components and contingency measures for power interruptions.

3.2. Anions

The monthly trends of the monitored anions are presented in Figure 6. Anion levels showed both site and parameter-specific patterns (Figure 6). Nitrate peaked in September 2023 for H1 (1.13 mg/L) and in July 2023 for H2 (1.28 mg/L). Phosphate remained low (<0.06 mg/L) except in July 2023 (0.89 mg/L in H1) and July 2024 (0.55 mg/L in H1). Fluoride was consistently higher in H2, notably in July 2023 (1.24 mg/L vs 0.028 mg/L in H1) and July 2024 (0.645 mg/L vs 0.019 mg/L in H1). Sulphate was highest in H2 in July 2023 (8.07 mg/L), while H1 recorded elevated values in August 2023 (0.66 mg/L) and July 2024 (0.783 mg/L). Chloride ranged from 0 to 9 mg/L, with maximums in August 2023 for H1 (8.99 mg/L) and July 2023 for H2 (8.04 mg/L), indicating no consistent seasonal trend.

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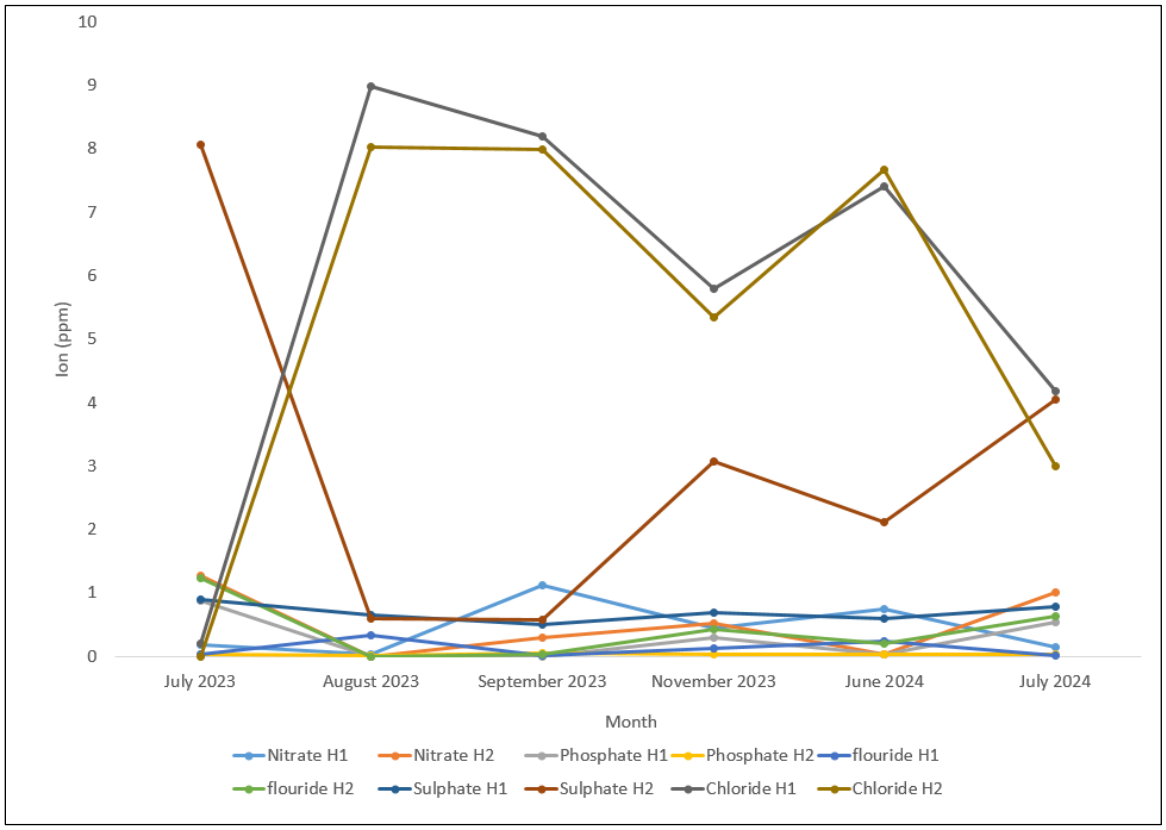

FIGURE 6: Monthly Trends for Anions Over the Monitored Period

The summary statistics of the monitored anions, chlorophyll *a*, and microcystins (MCs) in the recirculating aquaculture systems (RASs) are provided in Table 2. Monitoring these ions is critical not only for chemical characterisation of water quality but also for identifying emerging risks from ion accumulation, especially under intensive aquaculture operations.

Nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations in Table 2 were within the recommended safety thresholds for aquaculture systems as reported by Santeri *et al*. (2021), who emphasised that levels below 100 mg/L for nitrates and 5 mg/L for phosphates are considered non-toxic and conducive to fish health. Nitrate concentrations in RASs are typically elevated due to the breakdown of organic matter from uneaten feed and fish excreta by bacterial nitrification. This phenomenon is well-documented in earlier studies, including those by Ebeling (2011) and Ebeling and Timmons (2010), who noted that while nitrates are less toxic than nitrites and ammonia, they can still contribute to chronic stress and growth retardation in fish if not managed over time.

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Interestingly, phosphate levels remained low despite the potential for accumulation through feed inputs. This could be attributed to phosphorus precipitation or uptake by algal biomass within the system, a mechanism observed in studies such as Hawrot-Paw *et al*. (2019). Hawrot-Paw *et al*. (2019) demonstrated that algal growth in biofilm reactors could significantly reduce orthophosphate concentrations in aquaculture effluents.

Among the anions measured, fluoride and sulphate were found at low concentrations, reflecting either their low levels in the source water or efficient removal processes within the RASs. Fluoride typically originates from minerals like fluorite (CaF_2), apatite, and mica, and Sulphates usually come from gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite, or oxidation of sulphide minerals like pyrite (Brandl, 2002). The absence of these minerals in the aquifer rocks from which the source water for the RASs is derived means that the groundwater passing through them will not accumulate significant amounts of fluoride or sulphates, hence their low concentrations. Since the source water was untreated spring water, the anion analysis likely represents its original chemical composition. The region is part of the Soutpansberg geological formation, which is primarily composed of quartzitic sandstones and mudstones, with minimal occurrences of fluoride and sulphate-bearing minerals such as fluorite, gypsum, or anhydrite. This lithological context suggests a naturally low potential for fluoride or sulphate enrichment in groundwater (Brandl, 2002).

However, chloride (Cl^-) levels were relatively elevated across both systems. While typically the result of geological formations or groundwater weathering, as suggested by Egbueri *et al*. (2023), elevated chloride concentrations can be beneficial in aquaculture. Sodium chloride is frequently added to reduce nitrite (NO_2^-) toxicity through competitive inhibition at the gill interface, as reported by Kocour-Kroupová (2018). Therefore, naturally elevated chloride levels may provide a protective buffer against nitrite toxicity, provided nitrite concentrations remain within acceptable limits.

TABLE 2: Summary Statistics of the Anions, *Chlorophyll-a* & MCs Found in the RASs

Parameter	Points	H1	H2	Recommended
Nitrates (mg/L)	Min	0.03	0.00	0-400 mg/L or higher (Ebeling,
	Max	1.13	1.28	2011)

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	Mean ± SD	0.45±0.59	0.53±0.67	< 20 mg/L (Santeri *et al*., 2021)
Phosphates	Min	0.00	0.02	< 1 mg/L (Santeri *et al*., 2021)
(mg/L)	Max	0.89	0.06	
	Mean ± SD	0.30±0.51	0.04±0.02	
Fluoride (mg/L)	Min	0.02	0.00	-
	Max	0.34	1.24	
	Mean ± SD	0.13±0.18	0.42±0.71	
Sulphates (mg/L)	Min	0.51	0.59	-
	Max	0.90	8.07	
	Mean ± SD	0.69±0.20	3.08±4.32	
Chloride (mg/L)	Min	0.20	7.99	-
	Max	8.99	8.04	
	Mean ± SD	5.80±4.86	8.01±0.04	
Chlorophyll-a	Min	0.00	12.81	-
(µ/L)	Max	265.54	122.03	
	Mean ± SD	77.48±85.01	51.33±35.68	
MCs (µg/L)	Min	0.06	0.01	-
	Max	0.12	0.08	
	Mean ± SD	0.09±0.03	0.06±0.03	

NB: None of the parameters showed a statistically significant difference between H1 & H2 at p < 0.05 (Unpaired 't' test).

Despite these benefits, the continual conversion of ammonia and nitrites to less toxic forms is critical. The RAS biofilter plays a pivotal role in this conversion, as discussed by Ebeling (2011), who cautioned that nitrite accumulation remains possible due to fluctuations in system performance or organic loading rates. Therefore, although nitrate concentrations are currently within acceptable ranges, ongoing monitoring is necessary to detect potential system imbalances that could compromise fish health.

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3.3. *Chlorophyll-a* and Microcystins

Chlorophyll-a (Chl-*a*) is a widely accepted proxy for algal biomass and eutrophication levels. The monthly trends for Chl-*a* and the cyanotoxin microcystin are presented in Figure 7A and 7B. Chl-*a* concentrations varied markedly between months and sites. In H1, values rose from 112.56 µg/L in July 2023 to a peak of 265.54 µg/L in September 2023, then fell to 90.42 µg/L in November 2023 and reached a minimum of 7.99 µg/L in June 2024. Levels partially recovered to 48.58 µg/L in July 2024. H2 followed a similar pattern, increasing from 52.65 µg/L in July 2023 to 122.03 µg/L in September 2023, dropping to 12.81 µg/L in November 2023, and then rising again to 67.68 µg/L in July 2024.

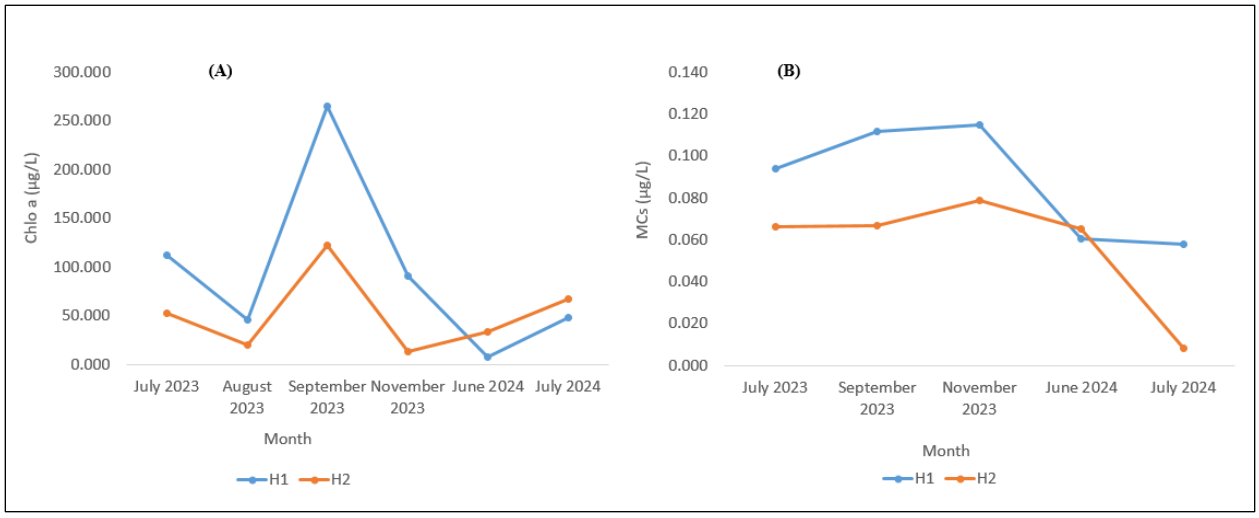

FIGURE 7: Monthly Trends for (A) Chl-*a* (B) Microcystins Over the Monitored Period

Microcystin concentrations remained consistently low (<0.12 µg/L) throughout the study. The highest values were recorded in November 2023 (0.115 µg/L in H1; 0.079 µg/L in H2), while the lowest were observed in July 2024 (0.0578 µg/L in H1; 0.0082 µg/L in H2). H1 generally recorded slightly higher concentrations than H2 (but there were no statistically significant differences).

In this study, Chl-*a* levels in both RASs in Table 2 exceeded 50 µg/L, a level considered considerably high. These values not only *et al*exceed the thresholds indicative of eutrophic conditions but also exceed the Chl-a concentrations reported by Zhao *et al*. (2023), who found mean levels of 35.6-38.4 µg/L in similar land-based RASs in China. The elevated Chl-*a*

concentrations observed here indicate substantial phytoplankton biomass, raising concerns about the potential for harmful algal blooms (HABs), even in closed systems such as RASs.

High Chl-*a* levels in RASs can compromise water quality, reduce light penetration, and interfere with system aesthetics and management. More importantly, they may indicate the proliferation of cyanobacteria, particularly those producing toxins. These findings are consistent with global trends highlighted by Li *et al*. (2024), who reported an increase in freshwater HABs due to anthropogenic nutrient enrichment and changing climatic conditions.

Flow-Cam imaging confirmed the presence of cyanobacterial genera *Microcystis* and *Lyngbya* in both RASs (Figure 8). *Microcystis* spp. are among the most frequently reported bloom-forming cyanobacteria in freshwater systems and are notorious for producing microcystins (MCs), a group of hepatotoxins harmful to both aquatic organisms and humans (Ballot *et al*., 2003). The genus *Lyngbya*, while sometimes non-toxic, can also produce a diverse range of cyanotoxins under optimal environmental conditions (Cheung *et al*., 2013). The co-occurrence of both genera in the RASs raises significant ecological and toxicological concerns, especially considering the potential for bloom proliferation in stagnant, nutrient-rich, and warm conditions typically found in poorly maintained systems.

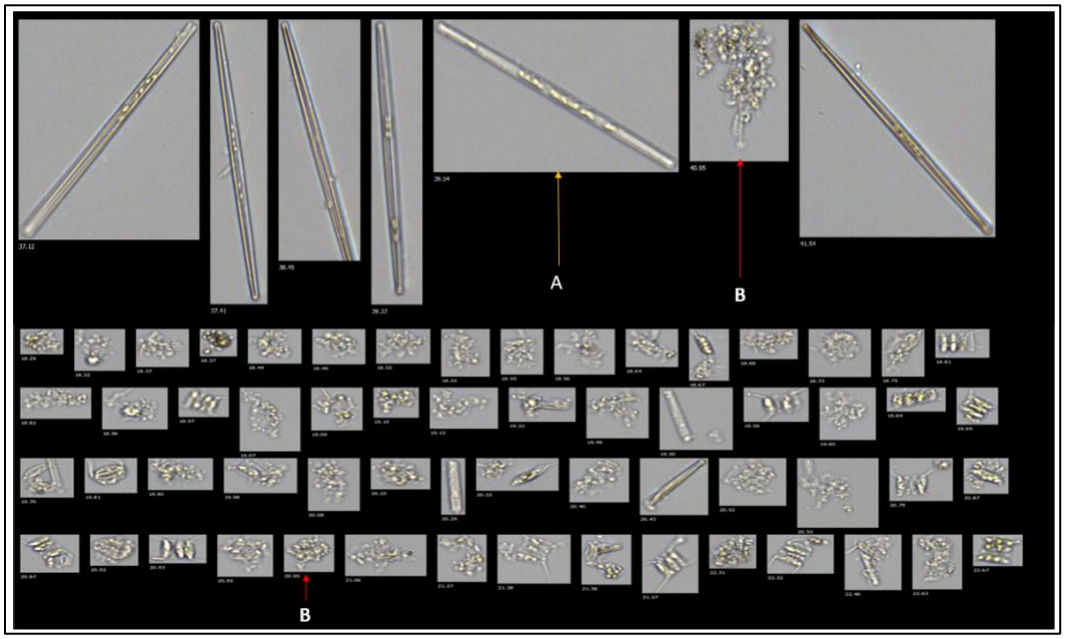

FIGURE 8: Flow-Cam Images of CyanoHABs Identified in the Two RASs (a) *Lyngbya Agardh ex Gomont* (b) *Microcystis Kutzing ex Lemmermann* Species Identified in the Samples

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Despite low nutrient levels reported in Table 2, the presence of these cyanobacteria suggests that other environmental factors, such as optimal temperature, pH, low water turnover, and light penetration, may have facilitated their growth. This supports the findings of Benayache *et al*. (2019), who demonstrated that nutrient levels are not the sole determinants of CyanoHABs development; physical and operational factors within aquaculture systems can also play a decisive role.

The findings in Table 2 indicate that microcystins were detected at trace levels in both RASs. While these concentrations do not currently pose an immediate threat, their presence is a strong indication of cyanobacterial activity and a potential precursor to larger blooms. Importantly, as emphasised by Chorus and Welker (2021), the absence of MCs does not guarantee the absence of all cyanotoxins. Other classes, such as cylindrospermopsin, anatoxin-a, and saxitoxins, may also be present and were not monitored in this study.

CyanoHABs pose ecological and toxicological risks beyond those posed by microcystins. Elevated *chlorophyll-a* signals high phytoplankton biomass, often reducing water clarity and causing hypoxia that impairs fish respiration and system health (Santeri *et al*., 2021). Cyanobacteria produce a diverse range of toxins, including anatoxins, cylindrospermopsins, saxitoxins, nodularins, and lipopolysaccharides, which affect nervous, hepatic, immune, and endocrine functions, leading to morbidity, mortality, and chronic impacts on growth and reproduction (Ndungu *et al*., 2025). Cyanotoxins can bioaccumulate and biomagnify, posing a threat to cultured organisms and to human consumers (Ndungu *et al*., 2025). Even non-toxic blooms can degrade water quality by increasing turbidity, limiting light availability, and irritating fish gills (Li *et al*., 2024). Li *et al*. (2024) thus recommend effective RAS monitoring that extends beyond microcystins, incorporating other toxin classes and ecological indicators, and using bio-optical, molecular, and chemical tools to facilitate early detection and management.

From a management perspective, these findings underscore the need for integrated monitoring frameworks that go beyond traditional nutrient surveillance. Regular assessments using bio-optical tools (e.g., Flow-Cam, fluorometers), coupled with toxin analysis, are essential for pre-emptively identifying and mitigating the risk of HABs in RASs. Moreover, comparisons with studies such as Zheng *et al.* (2022) highlight that while nutrient control remains vital, physical design and system

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maintenance also play equally critical roles in preventing HAB outbreaks in closed aquaculture systems.

While these management considerations emphasise the potential pathways for strengthening RAS performance and mitigating HAB risk, the extent to which such interventions can be fully evaluated in this study is constrained by several methodological and contextual limitations. This study was constrained by limited monitoring of key water quality parameters, such as ammonia, alkalinity, and carbon dioxide, due to resource limitations. The reliance on data that largely reflect mid-winter conditions, potentially underrepresenting dynamics during warmer seasons, is also a limitation. The absence of growth and feed-based metrics, including biomass increment, total feed applied, and Feed Conversion Ratios (FCR), also restricts the ability to directly link the observed water quality patterns to fish performance outcomes. In addition, data were collected from only two household RAS units, limiting replication and reducing the generalisability of the findings. While the measured parameters (temperature, DO, turbidity, and pH) still provide meaningful insight into chronic system constraints, the scope of inference remains narrow. The conclusions drawn here should be considered preliminary and system-specific and warrant validation across additional sites, seasons, and performance-based datasets.

4. CONCLUSION

Intensive Recirculating Aquaculture Systems (RAS) offer significant advantages, including the ability to control key water quality parameters and optimise fish growth rates. In the two RAS monitored in this study, water quality fell below the minimum recommended levels for critical parameters, including water temperature, turbidity, and dissolved oxygen (DO). These deficiencies have likely contributed to the low productivity observed in both households. Elevated *chlorophyll-a* (Chl-*a*) levels also raised the risk of harmful algal blooms (HABs), suggesting inadequate system maintenance. It is important to emphasise that these findings are specific to the two systems studied and should not be generalised to all RAS in the region without replication.

To improve system performance, implementing an alternative energy source could ensure continuous operation and enhance the water heating system's efficiency. This would support proper aeration of the groundwater used as source water and maintain the optimal culture temperature of approximately 28 °C for *Oreochromis mossambicus* (Mozambique tilapia). While

groundwater provides a relatively stable baseline for temperature, DO, and ion composition, the observations reported here remain system-specific, and extrapolation to other RASs requires caution and further replication. Future studies with continuous, year-round sampling are recommended to better capture seasonal dynamics.

5. AUTHOR CONTRIBUTIONS

Pindihama, G.K: Conceptualisation, methodology, data curation roles/writing - original draft, writing - review and editing, investigation, and methodology.

Mudzielwana, R: Conceptualisation, methodology, data curation roles, supervision, funding acquisition, investigation, resources, roles/writing - original draft, and writing - review and editing.

Rambaua, M.O. **and Mukwevho, S.N**: Methodology, data curation roles, investigation, and roles/writing - original draft.

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REFERENCES

ARDJOSOEDIRO, I. & RAMNARINE, I.W., 2002. The influence of turbidity on growth, feed conversion and survivorship of the Jamaica red tilapia strain. *Aquaculture.*, 212(1–4): 159–165. https://doi.org/10.1016/S0044-8486(01)00881-X

BADIOLA, M., BASURKO, O.C., PIEDRAHITA, R., HUNDLEY, P. & MENDIOLA, D., 2018. Energy use in recirculating aquaculture systems (RAS): A review. *Aqua. Eng.*, 81: 57–70. https://doi.org/10.1016/j.aquaeng.2018.03.003

BALLOT, A., FASTNER, J., LENTZ, M. & WIEDNER, C., 2003. First report of anatoxin-a-producing cyanobacterium *Anabaena flos-aquae* isolated from a temperate lake in Germany. *Toxicon.*, 42(3): 283–290. https://doi.org/10.1016/j.toxicon.2010.06.021

BENAYACHE, N.Y., NGUYEN-QUANG, T., HUSHCHYNA, K., MCLELLAN, K., AFRI-MEHENNAOUI, F.Z. & BOUAÏCHA, N., 2019. An overview of cyanobacteria harmful algal bloom (CyanoHAB) issues in freshwater ecosystems. In D. Gökçe (ed.), *Limnology: Some new aspects of inland water ecology*. OpenTech, pp. 13–37.

BHATNAGAR, A. & DEVI, P., 2013. Water quality guidelines for the management of pond fish culture. *Int. J. Environ. Sci.*, 3(6): 1980–2009. https://doi.org/10.6088/ijes.2013030600019

BOYD, C.E. & TUCKER, C.S., 2012. *Pond aquaculture water quality management.* Springer. https://doi.org/10.1007/978-1-4615-5407-3

BRANDL, G., 2002. *Geology of the Soutpansberg and Musina areas: Explanation of 1:250 000 scale geological sheets 2230 (Messina) and 2230 (Soutpansberg).* Council for Geoscience.

CHEUNG, M.Y., LIANG, S. & LEE, J., 2013. Toxin-producing cyanobacteria in freshwater: A review of their impacts, monitoring, and management. *Water Environ. Res.*, 85(6): 541–553. https://doi.org/10.1007/s12275-013-2549-3

CHORUS, I. & WELKER, M., 2021. *Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management.* https://doi.org/10.1201/9781003081449

DE JESUS GREGERSEN, K.J. & PEDERSEN, L.F., 2025. Effects of drum filters, swirl separators, and foam fractionation on water quality in pilot-scale recirculating aquaculture systems. *Aqua. Eng.*, 102593. https://doi.org/10.1016/j.aquaeng.2025.102593

DEEP BLUE AQUA., 2022. *Proposal for fully equipped small scale production unit RAS (recirculating aquaculture system) (RASV1).* Unpublished Company Proposal.

EBELING, J.M., 2011. *Water quality. Recirculating Aquaculture Systems Short Course. Aquaculture Systems Technologies, LLC.* Available from http://www.amphibianark.org/wp-content/uploads/2018/08/Water-Quality-Odum-Zippel-2011.pdf

EBELING, J.M. & TIMMONS, M.B., 2010. *Recirculating aquaculture. Cayuga Aqua Ventures.* Available from https://onlinelibrary.wiley.com/doi/10.1002/9781118250105.ch11

EGBUERI, J.C., AGBASI, J.C., AYEJOTO, D.A., KHAN, M.I. & KHAN, M.Y.A., 2023. Extent of anthropogenic influence on groundwater quality and human health-related risks: An integrated assessment. *Geocarto Int.*, 38(1): 2210100. https://doi.org/10.1080/10106049.2023.2210100

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO)., 2015. *Aquaculture.* FAO. Available from https://openknowledge.fao.org/handle/20.500.14283/I3587E

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO)., 2022. *The state of world fisheries and aquaculture 2022: Towards blue transformation.* https://doi.org/10.4060/cc0461en

GULLIAN-KLANIAN, M. & ARÁMBURU-ADAME, C., 2017. Performance of Nile tilapia *Oreochromis niloticus* fingerlings in a hyper-intensive recirculating aquaculture system with low water exchange. *Lat. Am. J. Aquat. Res.*, 41(1): 150–162. http://dx.doi.org/10.3856/vol41-issue1-fulltext-12

GUPTA, S., MAKRIDIS, P., HENRY, I., VELLE-GEORGE, M., RIBICIC, D., BHATNAGAR, A., SKALSKA-TUOMI, K., DANESHVAR, E., CIANI, E., PERSSON, D. & NETZER, R., 2024. Recent developments in recirculating aquaculture systems: A review. *Aqua. Res.*, 2024: 6096671. https://doi.org/10.1155/are/6096671

HAWROT-PAW, M., KONIUSZY, A., GAŁCZYŃSKA, M., ZAJĄC, G. & SZYSZLAK-BARGŁOWICZ, J., 2019. Production of microalgal biomass using aquaculture wastewater as growth medium. *Water.*, 12(1)**:** 106. https://doi.org/10.3390/w12010106

HUYNH, M. & SEREDIAK, N., 2006. *Algae identification field guide.* Environment Canada.

KOCOUR-KROUPOVÁ, H., VALENTOVÁ, O., SVOBODOVÁ, Z., ŠAUER, P. & MÁCHOVÁ, J., 2018. Toxic effects of nitrite on freshwater organisms: A review. *Rev. Aquac.*, 10(3): 525–542. https://doi.org/10.1111/raq.12184

LAWTON, L., MARSALEK, B., PADISÁK, J. & CHORUS, I., 1999**.** Determination of cyanobacteria in water. In I. Chorus & J. Bartram, J. (eds.), *Toxic cyanobacteria in water*. E & FN Sponpp, pp. 347–367.

LI, Z., YANG, X., ZHOU, T., CAI, S., ZHANG, W., MAO, K., OU, H., RAN, L., YANG, Q. & WANG, Y., 2024. Monitoring *chlorophyll-a* concentration variation in fish ponds from 2013 to 2022 in the Guangdong-Hong Kong-Macao Greater Bay Area, China. *Remote Sens.*, 16(11): 2033. https://doi.org/10.3390/rs16112033

LIU, Y., XU, X., XU, L., LIU, Y., YANG, N., JAWAD, S., LUO, Y., LIU, J. & HU, W., 2024. Collaborative water-electricity operation optimization of a photovoltaic/pumped storage-based aquaculture energy system considering water evaporation effects. *Renew. Energy.*, 237: 121886. https://doi.org/10.1016/j.renene.2023.121886

MARIUM, A., CHATHA, A.M., NAZ, S., KHAN, M.F.K.,SAFDAR, W. & ASHRAF, I., 2023. Effect of temperature, pH, salinity and dissolved oxygen on fishes. *J. Zool. Syst.*, 1(2): 1–12. https://doi.org/10.56946/jzs.v1i2.198

MARTINS, C.I.M., EDING, E.H., VERDEGEM, M.C.J., HEINSBROEK, L.T.N., SCHNEIDER, O., BLANCHETON, J.P., ROQUE D'ORBCASTEL, E. & VERRETH, J.A.J., 2010**.** New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aqua. Eng.*, 43(3): 83–93. https://doi.org/10.1016/j.aquaeng.2010.09.002

MUGWANYA, M., DAWOOD, M.A., KIMERA, F. & SEWILAM, H., 2022. A review on recirculating aquaculture system: Influence of stocking density on fish and crustacean behaviour, growth performance, and immunity. *Ann. Anim. Sci.*, 22: 873. https://doi.org/10.2478/aoas-2022-0014

NDUNGU, L., STUBNER, A., BEEMAN, S. *ET AL*., 2025. Scoping review of the effects of cyanobacterial toxins on human and animal health and potential role in mosquito control. *Discov. Environ.*, 3(1): 72. https://doi.org/10.1007/s44274-025-00261-3

RAJESH, M., KAMALAM, B.S. & SARMA, D., 2023. Recirculating aquaculture system for intensive fish farming in Indian Himalayan region: An overview. In P.K. Pandey, N. Pandey & S. Akhtar (eds.), *Fisheries and aquaculture of the temperate Himalayas*. Singapore: Springer, pp. 173–204.

REHMAN, A., SHARMA, B.K., OJHA, M.L., UPADHYAY, B. & KAUSHIK, M.K., 2023. Study of certain physico-chemical water quality parameters of different commercial RAS systems culturing *Pangasius pangasius* in Varanasi District, Uttar Pradesh. *Pharma Innov.*, 12(2): 2387–2390.

SANTERI, T., AMIN, M. & YULIWATI, E., 2021. Investigation of water quality in tilapia (*Oreochromis niloticus*) culture area with embedded net cages in Warkuk Ranau Selatan District, Indonesia. *AACL Bioflux.*, 14(1): 158–172.

SCHUMANN, M. & BRINKER, A., 2020. Understanding and managing suspended solids in intensive salmonid aquaculture: A review. *Rev. Aquac.*, 12(4): 2109–2139. https://doi.org/10.1111/raq.12425

SILVA, L., MARTINEZ-CORDERO, F.J., BAGANZ, G., BAGANZ, D., HERNÁNDEZ-PÉREZ, A., CORONADO, E. & PORTELLA, M.C., 2025. Advancing circularity in small-scale rural aquaponics: Potential routes and research needs. *Resources.*, 14(8): 119. https://doi.org/10.3390/resources14080119

SINHA, G. & BANERJEE, M., 2025. Water quality management in aquaculture: Trends and techniques. *Int. J. Environ. Sci.*, 11(14s): 2025. https://doi.org/10.64252/cm0zne05

SOMA, K., KANYUGUTO, C., VAN DER ZWAN, W. & BENNINGA, J., 2025. *Feasibility study: Affordable recirculation aquaculture systems (A-RAS): A-RAS hubs in Nyeri County, Kenya, 2023–2024.* Wageningen University and Research. https://doi.org/10.18174/684312

VERMA, D.K., SATYAVEER, N.K.M., KUMAR, P. & JAYASWA, R., 2022. Important water quality parameters in aquaculture: An overview. *Agric. Environ.*, 3(3): 24–29.

WICAKSONO, E.A., PRIYONO, S.B., LESTARI, P., SHIROT, M.J.S., FIRMANSYAH, P.Y., ISMAIL, A.Y., KRISTO, S., AISYAH, M., WIRAREDYA, S.D. & AWALIYAH, F., 2024. Nile tilapia (*Oreochromis niloticus*) productivity performance in small-scale recirculating aquaculture systems (RAS) with different biofilter media. *AACL Bioflux*, 17(4): 1471–1479.

YUSOFF, F.M., UMI, W.A., RAMLI, N.M. & HARUN, R., 2024. Water quality management in aquaculture. *Cambridge Prisms: Water.*, 2: e8. https://doi.org/10.1017/wat.2024.6

ZHAO, X.X., FANG, T., CHEN, J.L., GAO, N., CHEN, C. & LU, W.X., 2023. Characteristics of the phytoplankton community in a land-based container aquaculture system with recycling water. *J. Agro-Environ. Sci.*, 42(4): 869–878.

ZHENG, X.N., WU, D.X., HUANG, C.Q., WU, Q.Y. & GUAN, Y.T., 2022. Impacts of hydraulic retention time and inflow water quality on algal growth in a shallow lake supplied with reclaimed water. *Water Cycle.*, 3: 71–78.