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Assessment of Water Quality: A Case Study of Recirculation Aquaculture System

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ABSTRACT

Aquaculture's intensification requires water-saving systems to protect environmental quality. This study was designed to investigate the efficiency of a recirculating aquaculture system in the Department of Fisheries and Aquatic Resources Management in enhancing water quality. Five culture tanks were sampled before and a month after recirculation. Nutrient (ammonia, nitrate and phosphate) and physico-chemical parameters (conductivity, total dissolved solids, turbidity, pH) were analysed at the Water Research Institute Laboratory, Tamale. Our findings show that recirculation significantly improved water quality in general, with an average decrease of 66–96% in turbidity, total dissolved solids and conductivity. Also, nitrogenous and phosphorus fractions decreased markedly across all tanks, with ammonia reducing by >80% in almost all the samples and phosphate by >70%, which reflects excellent filtration capability. The variability in pH after recycling mirrored interactions between nitrification, carbon dioxide stripping and buffering, supporting the recommendation of precise pH control to reduce ammonia toxicity. One tank (E) consistently produced high ammonia, possibly owing to poor aeration, suggesting that site-specific operational optimization is needed. In summary, the recirculating aquaculture system significantly reduced nutrient loads, mitigated eutrophication risk and maintained water quality within WHO-recommended limits, progressing the sustainable fish production and water re-use. The operational recommendations were to reduce overfeeding, feed with precision and increase removal of solid waste to reduce organic inputs before filtration. These results illustrate the robustness of recirculating aquaculture system in nutrient removal and the control strategy for stable performance.

KEYWORDS: Water quality, Aquaculture, Ammonia, Nitrate, Phosphate.

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1.INTRODUCTION

Aquaculture, the regulated cultivation of aquatic creatures, is an expeditiously expanding source of fish and other aquatic commodities globally. This approach is frequently regarded as a viable solution to address the increasing need for protein while alleviating pressure on wild populations.

In many developing countries, aquaculture helps with livelihoods in the countryside, employment, food security, and alleviating poverty (Kashem et al., 2023). However, as output rises, so does the volume of wastewater (effluent) produce by aquaculture systems. If this effluent is inadequately treated or managed, it may adversely affect the ecosystems that receive it (Liu et al., 2024). Aquaculture effluents contain a variety of chemical and physical constituents from remnants of feed, excrement, metabolic byproducts, microbiological processes, and chemical additions such as fertilizers and buffering agents (Tom et al., 2021). Nitrogenous substances (such as ammonia, nitrite, and nitrate) and phosphorus (often in phosphate form) are frequently monitored for assessing effluent quality. High nutrients can lead to eutrophication, oxygen depletion, toxic algal blooms, and changes in aquatic biota (Cargnin and João, 2021; Turcios and Papenbrock, 2014). People take into consideration parameters such as the amounts of suspended solids, organic matter (commonly evaluated in the form of biochemical oxygen demand, BOD, or chemical oxygen demand, COD), pH, conductivity, and turbidity when making the assessment of water quality from aquaculture (Liu et al., 2024; Tom et al., 2021).

Evaluation of effluent from aquaculture plants is important to identify as well because wastewater quality has a significant influence on farm production (for instance, fish health, water reclamation) and environmental conservation especially in countries with weak regulatory monitoring or few resources. However, the amount and the distribution of these effluent components differ greatly according to the species cultured, stocking densities, feeding practices, water-exchange protocols, system composition (e.g., flow-through, ponds, and recirculating aquaculture systems), and the local environment (Kashem et al., 2023; Tom et al., 2021).

Freshwater Recirculating Aquaculture Systems are engineered, semi-closed systems used to cultivate fish or other aquatic organisms in an exceptionally controlled environment. They use a lot less freshwater and let out a lot less waste than traditional flow-through or pond systems. Recirculation Aquaculture System flows water through production tanks as well as a battery of treatment processes, such as mechanical filtration, biofiltration, gas exchange, solids removal, and disinfection. This way, the same water can be re-envisioned repeatedly, it can still be made good enough for intensive culture (Bartelme et al., 2017). Freshwater Recirculation Aquaculture Systems are resource efficient. They make less use of fresh water, release fewer nutrients, can produce at high yields over a limited area, and can be far-flung, or used in regions far from natural water bodies or in cities. Aided by these advantages, Recirculation Aquaculture System is particularly attractive for hatcheries as well as species with high market value and in particular for businesses requiring stringent biosecurity or production all year round. Yet such benefits can be accompanied by trade-downs in the complexity of operations, the price of money and energy, and the monitoring and regulation required to ensure that these systems are closely monitored and controlled (both in water chemistry and microbial communities) (Naylor et al., 2021).

The Freshwater Recirculating Aquaculture System culture tanks used by the Department of Fisheries and Aquatic Resource Management are made up of five parallel rows of rectangular cultivation tanks. A filtration system made of river sand, latex, and charcoal attached to the culture tanks. Municipal water is routed into de-chlorination tanks. An inlet valve directed the de-chlorinated water into the culture tanks. Degraded water from the culture tanks is discharged via an outlet valve into a treatment system, where it is filtered and pumped back into the culture tanks. Due to the poor monitoring and treatment facilities and significant environmental impact, the analysis of water quality in pond and tank systems (small-to medium-sized in underdeveloped countries like ours) is beneficial. Our study, investigating the levels of ammonia, nitrate, and phosphate alongside water quality parameters such as turbidity, pH, total dissolved solids, conductivity from aquaculture tanks will make an important contribution to literature in the areas of water quality assessment, comparison with health and the environment (e.g. WHO) based indicators and the effectiveness of the recirculation in reducing the nutrient loads.

2.0 METHODOLOGY

2.1 Description of the culture tank

The tanks operated by the Department of Fisheries and Aquatic Resources Management are also classified as a freshwater recirculating aquaculture system. They are next to the school library in Nyankpala, University for Development Studies (UDS). The Recirculation Aquaculture System consist of five rectangular cultivation tanks, which are situated parallel to one another. The size of each unit is approximately 84 m^2 while it is laid out with tarpaulin. The culture tanks are fitted with a filtration system composed of river sand, latex foam, and charcoal.

2.2 Sample collection

Water samples were collected in sterilized bottles to test the Recirculation Aquaculture System filtration efficiency. Samples were obtained from the five culture tanks. Before the sampling process, sample bottles were rinsed with water from the culture tanks. The containers were labeled A, B, C, D, and E; here, sample A is collected from tank 1, sample B from culture tank 2, sample C from culture tank 3, sample D from culture tank 4, and sample E from culture tank 5. All samples were preserved in an ice-box and sent to the Water Research Institute, Tamale for analysis. A total of 8 weeks was spent on sampling with a four-week interval after each sample batch was collected.

2.2.1 Analysis of Nitrate

Ten ml of the sample or an aliquot was carefully transferred into a test tube. 1.0 ml of 0.3 M NaOH was added and mixed lightly. 1.0 ml of the reducing mixture was added and mixed gently. The sample was heated to 60 °C for 10 min in a water bath. Then, the solution was allowed to reach room temperature, followed by the addition of 1.0 ml of color developing reagent. The mixture was agitated to allow for complete mixing and the absorbance was measured at 520 nm (American Public Health Association, 1995).

2.2.2 Analysis of Ammonia

The wastewater was allowed to settle and the supernatant was carefully pipetted into a 50 ml conical flask. Then, 1 to 5 ml of wastewater was pipetted and the volume was filled to 50 ml with ammonia-free water. The filtrate was subsequently screened for turbid compounds in the sample and analyzed. The initial portions of the filtrate were rejected. Rochelle salt (2 drops) was employed to dilute the sample. The sample underwent thorough mixing, followed by the addition of 2 ml of Nessler's reagent. A blank solution was prepared using 50 ml of ammonia-free water, to which 5 drops of Rochelle salt and 2 ml of Nessler reagent were added. The samples were allowed to rest for 10 min to promote the color development process and then were measured with a UV/VIS spectrophotometer at 410 nm (American Public Health Association, 1995).

2.2.3 Analysis of Phosphate

To a 100 ml sample containing uncolored and non-turbid samples, 1 drop of phenolphthalein indicator was added. The sample was then supplemented with 4 ml of molybdate reagent and 1 ml of another solution. The reagent containing 10 drops of stannous chloride was added carefully and mixed. The absorbance was measured at the wavelength of 690 nm using the spectrophotometer after 10 minutes but prior to 12 minutes. Using a blank solution prepared exactly the same as the samples but instead of the 100 ml sample, 100 ml distilled water was used for calibration of the spectrophotometer (American Public Health Association, 1995).

2.2.4 Data analysis

Microsoft excel was used to calculate the mean values of the culture tanks and also to generate the graphs.

3.0 RESULTS AND DISCUSSIONS

3.1 Physicochemical Parameters

This section evaluated physicochemical characteristics in aquaculture tanks before and after recirculation, employing four frequently observed indicators such as electrical conductivity, total dissolved solids (TDS), turbidity, and pH. In five tanks (A–E), recirculation resulted in substantial reductions in conductivity, total dissolved solids (TDS), and turbidity, whereas pH exhibited varying alterations at each location. The most prominent alterations were observed in tanks with a high concentration of solids and ions initially (such as A, D, and E). This indicates that the treatment system integrated into the Recirculating Aquaculture System was particularly effective in reducing both suspended and dissolved loads. The average conductivity decreased by almost 96%, the average TDS by around 85%, and the average turbidity by about 66% in comparison to pre-recirculation measurements. Conversely, pH responses varied, certain tanks showed increases corresponding with CO_2 removal and aeration, while others demonstrated decreases that may suggest nitrification and alkalinity depletion due to biofilter activity or other operational factors (Boyd and Tucker, 2012a; Timmons and Ebeling, 2013; Van Rijn, 2013).

3.1.1 Magnitude of Change

The conductivity decreased from approximately 7753 to 305 µS/cm, or a 96% reduction as shown in fig.1A. At the tank level, the drop percentages ranged from minimal (36% in B) to substantial (99.8% in A). In closed-loop Recirculation Aquaculture System utilizing solely mechanical and biofiltration, which do not directly eliminate inorganic ions, significant reductions in ionic strength are atypical. They likely refer to the substantial interchange of water with lower-conductivity make-up water and/or purification processes such as reverse osmosis, ion exchange, dilution blending, and/or foam fractionation aimed at removing dissolved organics (Lawson, 1994; Martins et al., 2010; Timmons and Ebeling, 2013).

TDS experienced an 85% reduction, decreasing from around 2155 mg/L to 321 mg/L. The reductions in tank levels ranged from 26% (B) to 98% (A) as shown in fig.1B. The correlation between TDS and conductivity reduction is logical, as specific conductance effectively quantifies the entire dissolved ionic load (Association, 2005; Hem, 1985).

In a completely closed system with minimal water exchange, conductivity and total dissolved solids often increase across production cycles due to feed inputs and the mineralization of metabolites (Martins et al., 2010; Van Rijn, 2013). The substantial reductions noted herein suggest either: considerable interaction with low-TDS makeup water or foam fractionation and activated carbon effectively removing a significant amount of dissolved organics (Lawson, 1994; Timmons and Ebeling, 2013). The majority of freshwater species can tolerate a broad spectrum of conductivity/TDS. Nevertheless, many producers target a range of 100–1500 µS/cm, contingent upon species and water supply (Boyd and Tucker, 2012a) . Post-recirculation indicates that approximately 300 µS/cm is within a typically acceptable range for freshwater.

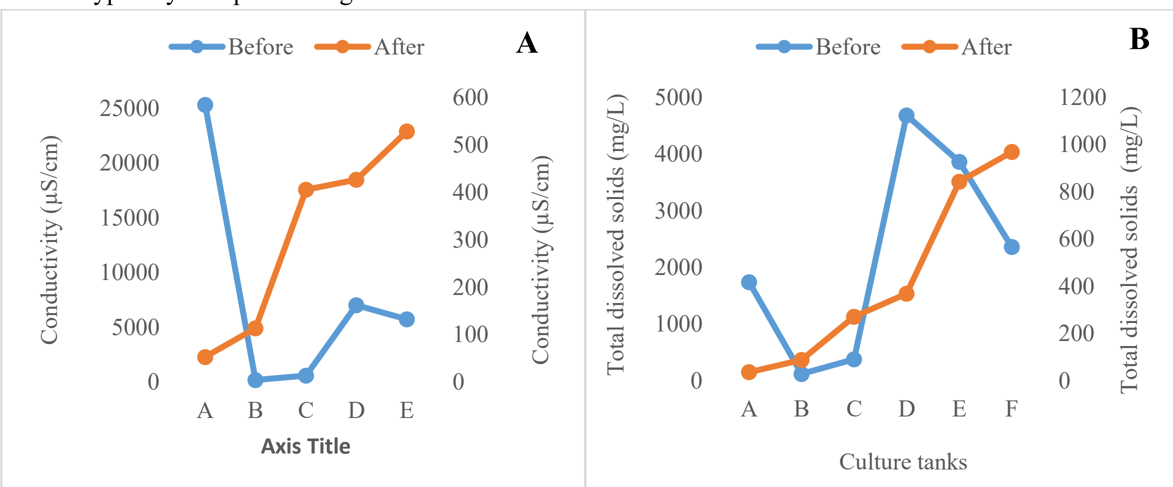

Figure 1: Concentrations of conductivity (A) and total dissolved solids (B) from the culture tanks

The turbidity decreased from 11.2 to 3.8 NTU, representing a reduction of 66%, whereas the tanks independently exhibited a decline of 50–91% as shown in fig.2A. This aligns with the fundamental procedures in Recirculation Aquaculture System design that effectively eliminate suspended solids thereby making the water clear (Dolan et al., 2013; Timmons and Ebeling, 2013). The continual decrease in turbidity (50–91%) corresponds with the implementation of filters to effectively retain primary solids, followed by settling and clarity, which are conventional practices in contemporary Recirculating Aquaculture Systems (Dolan et al., 2013; Timmons and Ebeling, 2013). Reduced turbidity enhances filtration efficacy and fish gill health by diminishing the particle load that causes gill abrasion and the oxygen demand of heterotrophic organisms (Boyd and Tucker, 2012a; Wedemeyer, 1996).

For Recirculation Aquaculture System, the principle of "as low as reasonably achievable" is optimal, levels below 5 NTU are frequently seen as beneficial for fish health and operational clarity (Timmons and Ebeling, 2013). Recirculation values ranging from 1 to 7 NTU are around this threshold. Nonetheless, tanks at the upper limit (7 NTU) might likely be enhanced by employing finer-screen drum filters, augmenting the frequency of backwashing, or incorporating polishing stages.

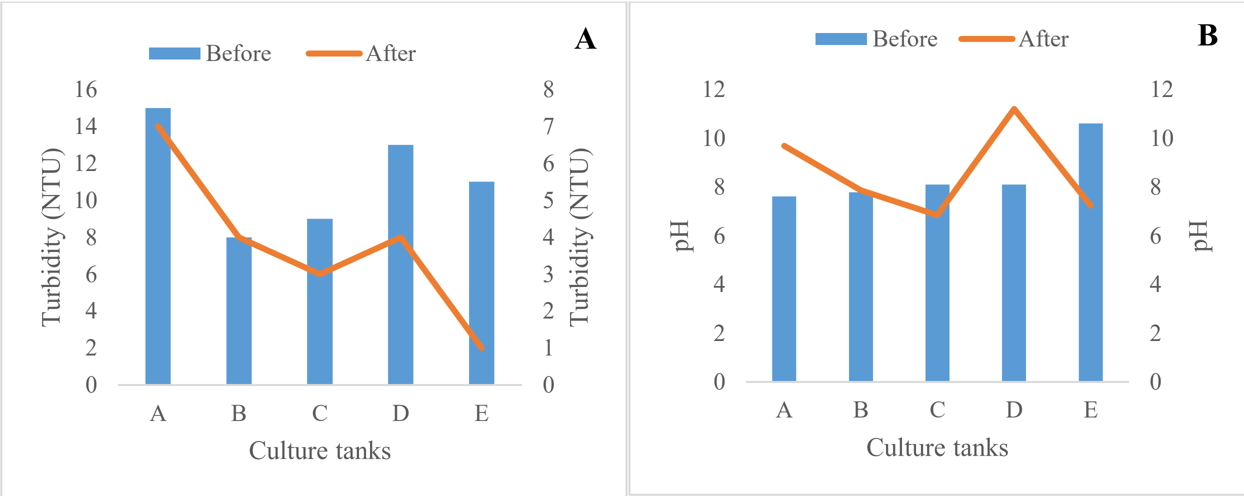

Figure 2: **Concentrations of turbidity (A) and pH (B) from the culture tanks**

The pH increased little, from 8.44 to 8.56, although the tank-level reactions varied. Tanks A and D increased (7.61 to 9.69 and 8.10 to 11.20), Tank B experienced a slight increase (7.78 to 7.86), while Tanks C and E decreased (8.10 to 6.84 and 10.60 to 7.23) as shown in fig.2B. The conflicting processes are mechanistically viable owing to the balance between nitrification (acidification), alkalinity supplementation (buffering), degassing/CO_2 removal (alkalization), and operational variations (e.g., water exchange rates) (Colt and Tomasso, 2001; Timmons and Ebeling, 2013; Van Rijn, 2013).

The post-recirculation pH of 11.2 in Tank D is excessively elevated for freshwater aquaculture and requires immediate rectification. The pH in Recirculating Aquaculture Systems quantifies the equilibrium between carbon dioxide accumulation and elimination, bicarbonate alkalinity, nitrification, which increases water acidity, utilizing approximately 7.07 mg of calcium carbonate for each milligram of total ammonia nitrogen nitrified, and any deliberate buffering agents such as sodium bicarbonate or calcium carbonate (Timmons and Ebeling, 2013; Van Rijn, 2013). Higher levels of A and D indicate more aggressive removal of CO_2 and/or base supplementation, whereas lower concentrations of C and E may indicate a high nitrification rate without adequate replenishment of alkalinity. pH levels at D (11.2) are much more complex, as it falls far outside the optimal range for freshwater (about 6.5–9.0 for most cultivated organisms). This can intensify un-ionized ammonia toxicity even at low total ammonia nitrogen concentrations (Boyd and Tucker, 2012a; Emerson et al., 1975; Wedemeyer, 1996). The goal of a number of species is to keep the pH around 6.5 to 8.5. Nevertheless, this level can be altered depending on the life stage (Wedemeyer, 1996).

3.2 Nutrients

The measurement of ammonia, nitrate, and phosphate concentrations before and after the water recycling procedure provides important information about the effectiveness of recirculating aquaculture system in improving water condition. Great decreases in every one of the parameters were obtained after the recirculation process which proved that the treatment technology and biological filter treatments made use of the system as intended. Yet, differences between culture tanks (A–E) highlight some of the fine changes in waste trapping, and input from the feed and in microorganisms that are necessary for the changing phase of nutrients in recirculating aquaculture system (Blancheton et al., 2013; Martins et al., 2011).

3.2.1 Variations in Ammonia concentrations

Before recirculation, ammonia concentrations also ranged from 1.045 to 23.55 mg/L, which can be further found in fig.3. The highest concentration was reached in culture tank E, which exceeded the WHO standard by close to 15x (1.5 mg/L). Increased levels of ammonia signal too much organic matter, not enough biofiltration or overfeeding (Gutierrez-Wing and Malone, 2006; Martins et al., 2010). Ammonia, which comes mostly from fish excretion and the breakdown of uneaten meals, is the single most harmful nitrogen to aquatic organisms (Boyd and Tucker, 2012b). In turn, the ammonia concentration dropped from 0.332 to 9.713 mg/L after recirculation. Culture tanks A, C and D had lower levels than the WHO value corresponding to nitrification and ammonia removal. The significant decrease in culture tank E (23.55 to 9.713 mg/L) is still above the recommended value however, and might indicate that oxidation processes continue to be incomplete or that the system is overloaded or is deprived of oxygen (Suriasni et al., 2023).

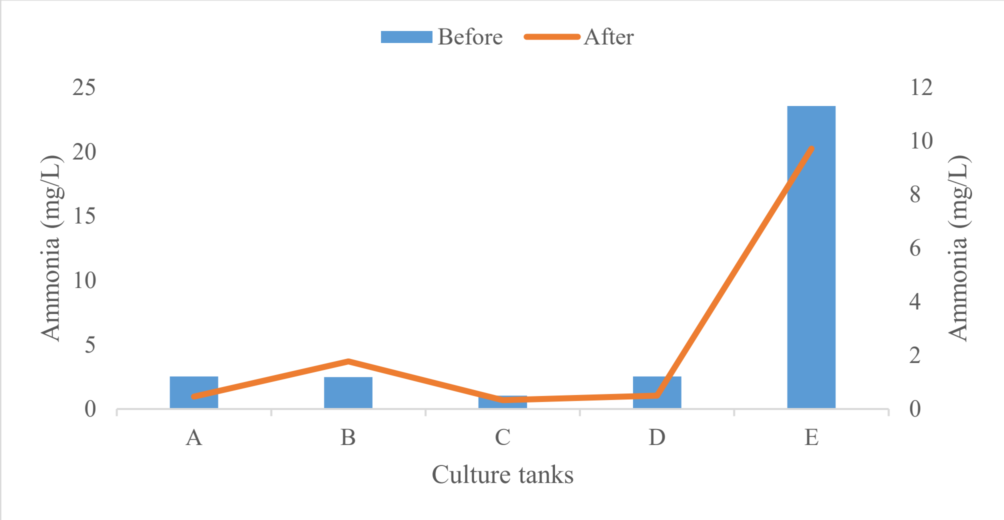

Figure 3: Concentrations of Ammonia from the culture tanks

Reduction efficiency was between 41% and greater than 80%, which is consistent with earlier work conducted by Lu et al. (2020) that showed similar removal efficiency with biological nitrification in recirculating aquaculture systems. Overall decline suggested effective functioning of biofilters and water exchange systems. However, these are still to be improved with respect to high-load zones, like culture tank E.

3.2.2 Variations Nitrate concentrations

Nitrate concentrations decreased from 1.109 to 5.683 mg/L prior to recirculation as illustrated in fig. 4, all within the WHO's permissible limit of ≤10 mg/L. A rise in nitrate relative to ammonia levels at some culture tanks (e.g., C and E) verifies the presence of active nitrification, an age in which ammonia is physiologically transformed into nitrate via nitrite intermediates (Martins et al., 2011). After recirculation, nitrate concentrations decreased to about 0.711–3.639 mg/L, corresponding to roughly a 30–50% reduction among the culture tanks. The decline also indicates the onset of nitrification and denitrification processes that likely take place in low-oxygen microenvironments of the biofilter, where nitrate is converted into gaseous nitrogen (van Rijn et al., 2006). This stable nitrate content under the given parameters reflects that the microbial population is matured through a sufficient time for nitrogen transformations to occur. Cao et al. (2007), showed similar reductions in nitrate levels after the treatment. This shows successfully constructed Recirculation Aquaculture Systems are capable of suppressing the deposition of nitrogen and preventing the eutrophication of downstream aquatic systems. The high nitrate content in culture tank E at (3.639 mg/L) post-recirculation may come from the ongoing oxidation caused by ammonia, which is present during biofiltration (Sitthi et al., 2024). Nitrifying bacteria perform prolonged activity, forming biofilms dense on biocarrier elements of biofiltration which lead to higher nitrate concentrations, and influence by the environmental conditions including temperature, pH, or nitrogen load (Spieck et al., 2017). Both environmental conditions and organic matter accumulation can be seen to play important roles in the evolution and functioning of these specialized microorganisms (Sahidhir et al., 2023). In addition, the excess of heterotrophic bacteria because of accumulation of organic matter can impair nitrifier activities and enhance the conversion of nitrate to nitrite (Rojas-Tirado et al., 2017; Spieck et al., 2017). Additionally, stable nitrate levels are usually reached when the excretion of nitrogen coincides with the removal of nitrogen via makeup water, establishing a situation of nitrogenous balance (Rojas-Tirado et al., 2017).

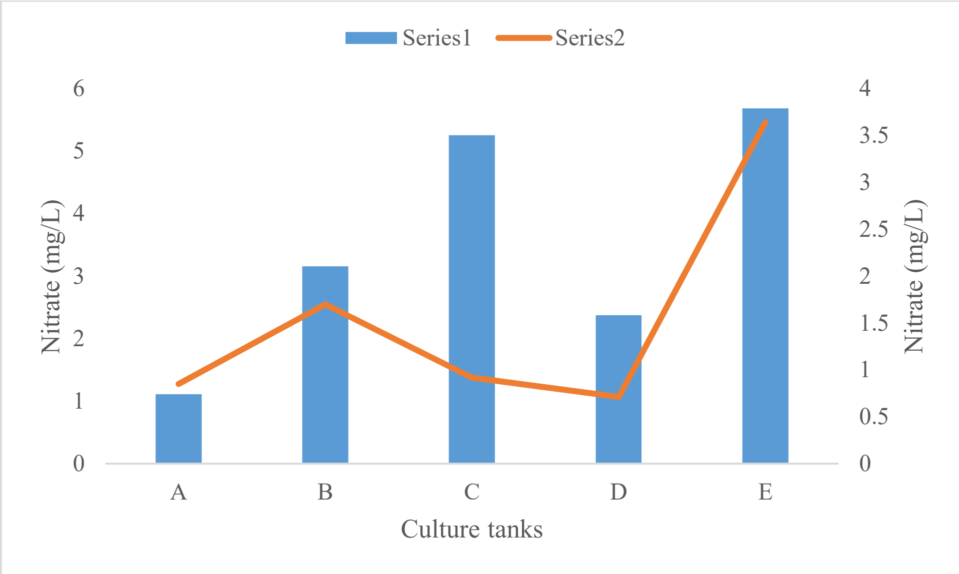

Figure 4: **Concentrations of nitrate from the culture tanks**

3.2.3 Variations in Phosphate concentrations

However, prior to recirculation phosphate concentrations were between 0.586 and 2.242 mg/L as shown in fig. 5, compared with the WHO guideline of an overall concentration of 0.005–0.05 mg/L. However, higher phosphate concentrations are expected because fish do not eat all of their feed, and phosphate in commercial diets is often poorly assimilated by fish (Yavuzcan Yildiz et al., 2017). Because of that, high levels of phosphate make the water prone to eutrophication, and even low levels of phosphate can be capable of causing algal blooms and reducing the amount of oxygen within the water area (Boyd and Tucker, 2012b). A significant decrease of phosphate values was observed at 0.001–0.786 mg/L after recirculation, implying that more than 70% phosphate content is avoided for almost all cases. The sharp drop of sample D (from 0.586 to 0.001 mg/L) which proves that filtering and microbial absorption were very effective. This improvement is pronounced, and all its post-recirculation ratios are well above WHO level, except for D. These results are consistent with Dauda et al. (2019) that optimized Recirculation Aquaculture System arrangement and biofilter media can have a positive impact in phosphorus depletion, which would enhance uptake and assimilation of the microbial biomass.

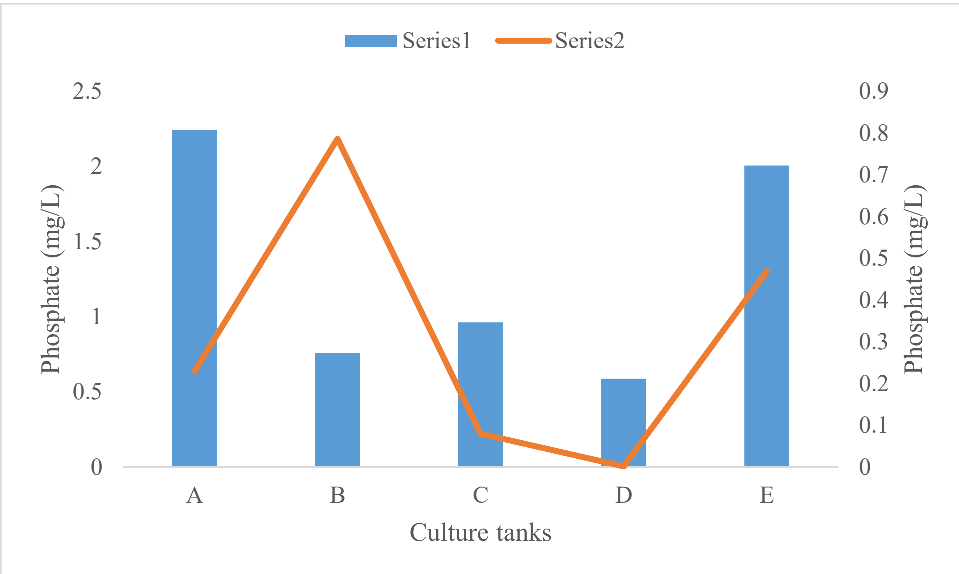

Figure 5: Concentrations of phosphate from the culture tanks

3.2.4 Recirculation Aquaculture System Efficiency and Environmental Significance

This work thus provides a concise empirical demonstration showing that recirculation in this facility reduces particle load (turbidity) and dissolved load (conductivity/TDS) at the same time while clarifying the complex functioning dependencies of pH. The results of this study are in step with classic Recirculation Aquaculture System theory and practices and emphasize the need for effective controls on pH level and ionic level for better and more stable fish production. In addition, comparisons of data before and after the recirculation indicate a general improvement in water quality. This demonstrates that the Recirculation Aquaculture System serves functions to diminish nutrient loads and improve effluent quality. The reduction of ammonia, nitrate and phosphate levels can reach up to 85%, 50%, and 90%, respectively, which confirms that the system is efficacious in reducing hazardous pollutants. However, the presence of high ammonia and phosphate concentrations in some particular tanks, notably Tank E, indicates the influence of operating differences and load pressures. These results are aligned with international observations, which showed that the Recirculation Aquaculture System efficiency relies on integrated feeding system, sufficient aeration, and biofilter capacity (Blancheton et al., 2013; Martins et al., 2010). Keeping nutrient concentrations below desired thresholds is a critical challenge for aquatic life and ecological health. Nutrient-laden effluents can induce hypoxia, harmful algal blooms, and decrease in the biodiversity of neighbouring ecosystems (Cao et al., 2007). The observed increase upon recirculation suggests that a well-managed Recirculation Aquaculture System can support sustainability of aquaculture by attenuating effluent effects and by complying with international water quality standards.

4 CONCLUSIONS

This study was carried out to assess the efficiency of recirculating aquaculture system used by the Department of Fisheries and Aquatic Resources Management. Recirculation increased the water quality and decreased dissolved loads in the tanks to a large extent. Reduction in turbidity, TDS, and conductivity are significant, ranging in average from 66 to 96%. After recirculation pH variations were associated with the interactions of nitrification, CO_2 stripping and buffering. The results imply that precise maintenance of pH is required to avoid variations related to ammonia toxicity, and uniformity of operational setpoints should be established in all tanks in order to obtain consistent results. This study proved that the recirculating aquaculture system could lead to improved effluent water quality by significantly minimizing the nitrogenous and phosphorus fractions. The ammonia, nitrate, and phosphate levels had significantly decreased in all sampling points with recirculation, suggestive of good filtration ability and removal. These high ammonia (more than 80% in a majority of the samples) and phosphate (above 70%) reduction rates demonstrated the high ability of the system to convert toxic wastes into more stable forms. Although it is better, a constant high concentration of ammonia in culture tank E indicates that in-site inefficient activities may occur due to inadequate aeration. Overall, the results support that a well-planned and controlled recirculating aquaculture system can effectively remove nutrients, diminish the risk of eutrophication, and maintain aquaculture production within the recommended boundaries by WHO. The existing systems provide a viable approach for sustainable fish farming and water reuse in areas that are increasingly faced with environmental and resource constraints. Overfeeding and excessive organic inputs should be minimized to control ammonia and phosphate accumulation. Adoption of precision feeding and solid waste removal mechanisms will help reduce nutrient buildup before filtration.

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