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Evaluating the Ecological Performance of Recirculating Aquaculture Systems Under Variable Nutrient Loading

[1*] Florian Brandt, Hamburg Centre for Maritime Technology Training, Hamburg, Germany.

[2] Katharina Scholz, Hamburg Centre for Maritime Technology Training, Hamburg, Germany.

Abstract: Though RAS is considered a less impacting technology compared to open systems, there is little information on the ecological performance of RAS with changing feeding loads. This paper reports on experiments conducted on three replicate pilot-scale freshwater RAS with low, medium, high and shock feeding loads. An increase in the feeding load from low to high increased the total ammonia nitrogen from 0.18 to 0.71 mg L^{-1} and nitrate-nitrogen from 18 to 61 mg L^{-1} and decreased bottom-line dissolved oxygen from 6.8 to 5.6 mg L^{-1}. The efficiency of total nitrogen removal decreased from 68% to 54%, while effluent nitrogen discharge increased from 11.2 to 18.9 g N per kg of feed. Following a tripling of shock loading, ammonia reached its maximum value of 1.42 mg L^{-1} in 14 h before returning to baseline within 36 h, whereas nitrite took 60 h. There were strong correlations between feeding loading and ammonia, nitrate, and effluent nitrogen loading ($r > 0.94$). It is evident from these findings that RAS can handle moderate loadings quite well, although the discharge per unit of feeding loading increases with increased loading.

Keywords: Recirculating Aquaculture Systems; Nutrient Loading; Nitrogen Removal; Ecological Performance; Effluent Discharge; Aquatic Ecosystem Protection.

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I. Introduction

The field of aquaculture is among the fastest growing food-producing industries, and the fraction of total world production attributable to aquaculture has been growing (FAO, 2024). With this increasing rate of growth, there is an increase in the volume of feed as well as nutrients being input into the production system, and the nature of feeds can also affect the pressure exerted on wild fish populations (Cottrell et al., 2020). The recirculating aquaculture systems have been presented as a low impact alternative to the open and flow through systems owing to the way they use water as well as the collection of wastes and reduced nutrient discharges (Bergman et al., 2020; Ghamkhar et al., 2021). Life cycle assessments reveal that RAS can be run with little to no energy penalty, but the production of feed is still the major factor behind the environmental impacts (Bergman et al., 2020). They also show that burden shifting can occur as production intensity increases (Ghamkhar et al., 2021).

In reality, however, RAS do not always run under steady-state conditions. The loading of nutrients changes depending on feeding regimes, stocking rates, development phase of fish, and other related events. Variations in loading may have an effect on the quality of water, treatment processes, and the amount of nutrients discharged. Ecological performance of RAS under non-steady state conditions has been less researched compared to steady-state conditions. The purpose of this research is to investigate the ecological performance of RAS under variable nutrient loading, considering the quality of water, nutrient removal, loading of effluents, and system recovery from loading changes.

II. Related Works

Nitrogen Transformation and Biofilter Performance

Biological removal of nitrogen is key in terms of water quality in RAS, and much research has been done regarding the processes and bacteria that mediate nitrification and denitrification (Preena et al., 2021). Nitrifying biofilters utilize consortia that transform ammonia into nitrate, and their activity is highly affected by both the surrounding environment and the manner of their management (Ruiz et al., 2020).

Different biofilters exist for different water sources; hence, nitrifiers' salinity tolerance is affected by the water source (Hüpeden et al., 2020). The temperature has an effect on the ammonia and nitrite oxidizing bacteria populations (Li et al., 2022). The amount of organic material loaded into the system also affects the microbiome of the whole system, and lowering the fine particulate organic material leads to stability of the water quality and the microbiome (Fossmark et al., 2020).

Nitrogen Budgets and Effluent Treatment

The nitrogen budget analysis reveals that not all nitrogen that goes into the aquaculture system stays there; most of it is eliminated through water treatment systems or water exchange (Xu et al., 2022). It has been observed that electro-coagulation is effective for the removal of nitrogen from RAS and microalgae can recycle the waste nitrogen (Xu et al., 2022). Some other treatment schemes, for example, membrane aerated biofilm reactor, have demonstrated that turbidity, organic matter, and nitrogen can be removed without exceeding the required water quality standards for fish (Almeida et al., 2023).

Integrated Nutrient Recovery

Nutrient-acquiring biological organisms also provide another means for minimizing waste. Periphyton biofilters used in the RAS system help in removing a portion of the nitrogen and carbon that the fishes do not absorb, and their development is influenced by nutrient mass loading and hydrodynamics (Bell et al., 2023). The use of combined Ulva-periphyton biofilters has proved to be effective in removing nitrogen from mariculture wastewater (Shahar & Guttman, 2021). The frequency of harvest has a direct influence on the production of biomass and the removal of nutrients in attached algal cultures (Sutherland et al., 2020). In closed freshwater RAS, combined aerobic and anaerobic bioreactors have been developed to improve nitrogenous waste removal (Obondo et al., 2025).

Research Gap

Earlier studies have been conducted on the nitrification process, the microbial population, the technology used, and nutrient recovery in RAS systems, but these studies mostly consider the effect of the above factors while maintaining a stable operating condition. Limited research has been done in terms of how an RAS system performs ecologically as nutrients loading changes.

III. Materials and Methods

System Description

The three identical pilot-scale freshwater RAS systems had similar components. These were 1 m^3 culture tanks, solid-removal drum filters, moving-bed biofilters (nitrification), settling units, aeration units and a recirculating pump. The water was recirculated at a rate providing hydraulic retention time of 1 hour in the biofilter and the amount of daily make-up water was kept below 5% of the system volume. The Nile tilapia (Oreochromis niloticus) were stocked at a constant biomass of 20 kg m^{-3}. The temperature was maintained at 27 ± 1 °C. Key system characteristics are given in table 1.

Table 1: Characteristics of the Experimental RAS (Per System)

Component	Specification
Culture tank volume	1.0 m^3
Stocking biomass	20 kg m^{-3}
Mechanical filtration	Drum filter, 60 µm
Biofilter	Moving-bed, 0.4 m^3 media, 500 m^2 m^{-3} specific surface
Daily water exchange	5% of system volume
Temperature	27 ± 1 °C
Replicate systems	3 per scenario sequence

Nutrient Loading Scenarios

Nutrient loading was varied through alteration of daily feed loading rate. Each system underwent four consecutive cases in a sequence of 28 days with 7 days interval for each case: low case (40 g feed m^{-3} day^{-1}), medium case (80 g feed m^{-3} day^{-1}), high case (120 g feed m^{-3} day^{-1}) and shock case (base case of medium with three times increased load of 240 g feed m^{-3} day^{-1} for 2 days). The nature of feed (protein concentration) did not change for all cases.

Sampling and Analysis

Water samples were collected from the culture tank as well as the outlet of the biofilter on a daily basis. Parameters such as TAN, NO_2-N, NO_3-N, PO_4-P, TSS, and COD were determined through spectrophotometric and gravimetric analysis respectively. The parameters of temperature, pH, and DO concentration were measured using probes. In case of shock treatment, samples were collected every 6 hours for a period of 96 hours post-pulse. All fish handling was done according to institutional guidelines.

Ecological Performance Indicators

The four variables calculated were: (i) Efficiency of removal (%) = (Input Load – Effluent Load) / Input Load × 100 for TN and TP, where input load represented the nutrient load in the daily feed. (ii) Nutrient loading in the effluent, measured in grams of N or P released per kg of feed. (iii) Biofilter TAN removal efficiency from influent and effluent TAN. (iv) Recovery time defined as the time taken for TAN and NO_2-N to get back to 10% of their pre-shock values.

Statistical Analysis

Effects of scenarios on water quality and performance indices were determined using one-way analysis of variance on the means of the systems (n=3 for each scenario), followed by the Tukey test. Pearson correlation was conducted to determine the relationship between feed loading and water quality and performance indices in all the systems and scenarios (n=12).

IV. Results

Water Quality Under Different Loading Scenarios

The water quality was gradually degraded with increasing load (Table 2 and figure 1). The TAN increased from 0.18 ± 0.04 mg/L at low load to 0.71 ± 0.15 mg/L at high load, and the NO_3-N concentration increased from 18 ± 3 to 61 ± 8 mg/L. Differences among scenarios were significant for all variables (TAN: $F_{3,8} = 58.3$, $p < 0.001$; NO_3-N: $F_{3,8} = 71.6$, $p < 0.001$; DO: $F_{3,8} = 12.4$, $p < 0.01$). DO decreased from 6.8 to 5.6 mg L^{-1} but stayed above 5 mg L^{-1} in all cases except for the shock event period, which had a minimum value of 4.6 mg L^{-1}. The values for the shock event period are represented by the peak after the pulse for TAN and NO_2-N and by the scenario mean for the rest of the variables.

Table 2: Water Quality Under the Four Loading Scenarios (Mean ± SD, n = 3 Systems)

Variable	Low	Medium	High	Shock
TAN (mg L^{-1})	0.18 ± 0.04	0.34 ± 0.07	0.71 ± 0.15	1.42 ± 0.28 (peak)
NO_2-N (mg L^{-1})	0.05 ± 0.01	0.11 ± 0.03	0.29 ± 0.07	0.64 ± 0.12 (peak)
NO_3-N (mg L^{-1})	18 ± 3	36 ± 5	61 ± 8	44 ± 6
PO_4-P (mg L^{-1})	2.1 ± 0.4	4.3 ± 0.7	7.6 ± 1.1	5.1 ± 0.9
TSS (mg L^{-1})	12 ± 3	21 ± 4	38 ± 7	29 ± 6
DO (mg L^{-1})	6.8 ± 0.4	6.3 ± 0.4	5.6 ± 0.5	5.2 ± 0.6

The relationship between the 28-day change in total ammonia nitrogen (TAN) and nitrite nitrogen (NO_2-N) under low, medium, and high loading levels is shown in figure 1. For both the TAN and NO_2-N concentrations, the highest levels were recorded under the high loading level, where TAN varied from 0.44

to 0.86 mg L^{-1} and NO_2-N from 0.20 to 0.36 mg L^{-1}. Moderate levels were observed under medium loading conditions, whereas low loading levels resulted in stable and lower levels.

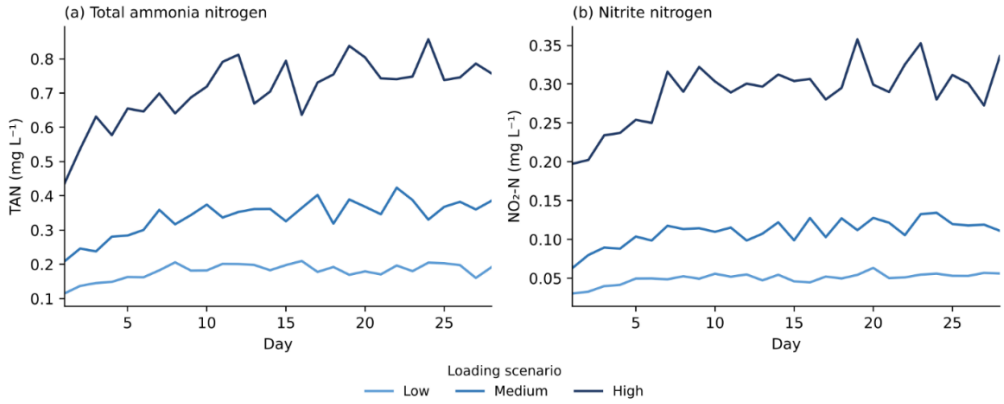


Figure 1: Daily TAN and Nitrite Concentrations Under Low, Medium and High Nutrient Loading

Nutrient Removal and Effluent Load

The removal efficiencies declined with an increase in the load (Table 3, figure 2). The removal of TN from 68% under the low-load scenario to 54% and 49% under the high load and shock load, respectively, while TP removal from 41% to 31% and 29%. The efficiency of TAN removal by biofilters showed similar trends from 92% to 84% and 78%. This resulted in an increase in the effluent nitrogen loading from 11.2 to 18.9 g N and 21.4 g N kg^{-1} feed, respectively, and effluent phosphorus loading from 3.1 to 4.4 and 4.8 g P kg^{-1} feed.

Table 3: Nutrient Removal and Effluent Load (Mean ± SD, n = 3)

Indicator	Low	Medium	High	Shock
TN removal (%)	68 ± 3	63 ± 3	54 ± 4	49 ± 5
TP removal (%)	41 ± 3	37 ± 3	31 ± 4	29 ± 4
Biofilter TAN removal (%)	92 ± 2	90 ± 2	84 ± 3	78 ± 4
Effluent N (g N kg^{-1} feed)	11.2 ± 0.9	13.6 ± 1.0	18.9 ± 1.4	21.4 ± 1.7
Effluent P (g P kg^{-1} feed)	3.1 ± 0.3	3.6 ± 0.3	4.4 ± 0.4	4.8 ± 0.4

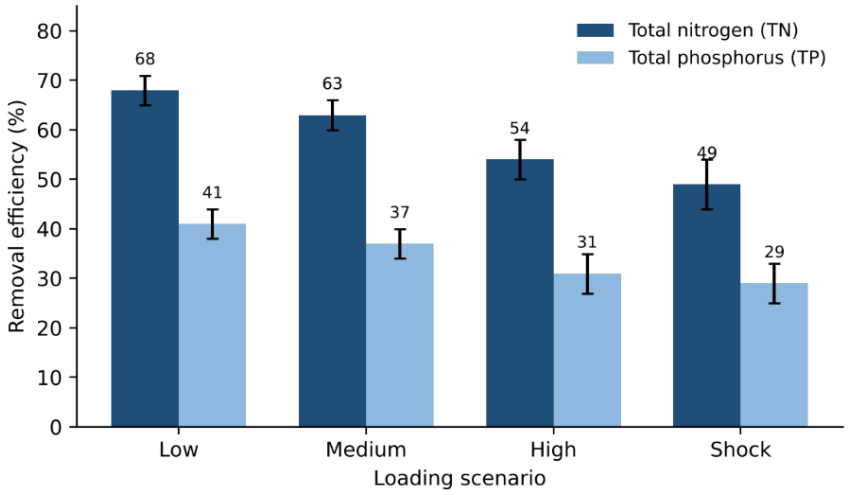


Figure 2: Total Nitrogen and Total Phosphorus Removal Efficiency Under the Four Loading Scenarios

Response to Shock Loading

Following the two-day pulse, TAN levels increased quickly and peaked at 1.42 ± 0.28 mg L^{-1} about 14 hours post initial pulse feeding, followed by an overall recovery to within 10% of pre-experiment levels within 36 hours. NO_2-N on the other hand peaked at 0.64 ± 0.12 mg L^{-1} at about 30 hours and took roughly 60 hours to recover from. The difference between peak times of TAN and NO_2-N is evidence that the latter is the slower process to recover in nitrification. Dissolved oxygen minimums were reached at 4.6 ± 0.5 mg L^{-1} during the pulse and recovered within 24 hours. There was no fish mortality observed in any experiment.

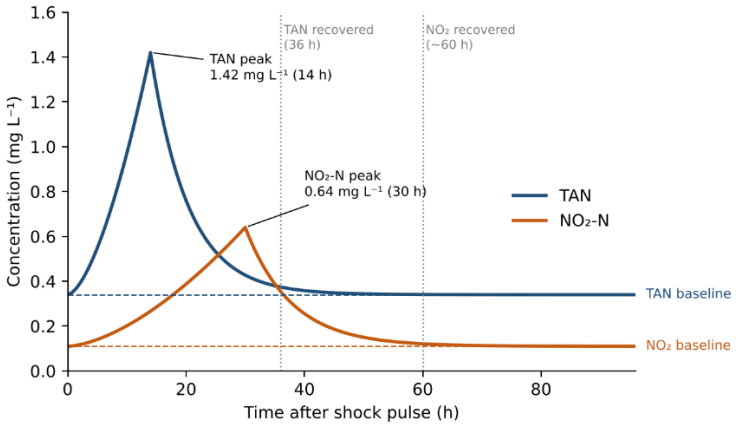


Figure 3: Recovery of TAN and Nitrite After a Three-Fold Shock Load

Figure 3 shows the time response of TAN and NO_2-N concentrations after a shock-loading disturbance. The maximum value of TAN was recorded at 14 h, where it attained a level of 1.42 mg L^{-1}, followed by a steady drop in its concentration down to the baseline of about 0.34 mg L^{-1} within 36 h. On the other hand, NO_2-N peaked at 30 h, attaining a value of 0.64 mg L^{-1}, before returning to its baseline of 0.11 mg L^{-1} after 60 h.

Relationships Between Loading and Performance

Feeding load showed strong significant association with water quality and performance parameters (Table 4). It had positive correlation with TAN, nitrate, TSS and nitrogen load in the effluent while having negative correlation with DO and TN removal efficiency.

Table 4: Pearson Correlation Between Feeding Load and Performance Variables (n = 12)

Variable	r	p
TAN	0.96	< 0.001
NO_3-N	0.97	< 0.001
TSS	0.94	< 0.001
Effluent N load	0.95	< 0.001
TN removal efficiency	−0.93	< 0.001
DO	−0.91	< 0.001

V. Discussion

System Response to Nutrient Loading

The increase in the level of TAN, nitrate and solids with respect to the increase in the feeding load reflects the role played by the nitrifying biofilters in water quality management in RAS (Preena et al., 2021; Ruiz et al., 2020). The drop in the removal rate of TAN in the case of high load can be interpreted as the biofilter approaching its treatment limits. In addition, the slower recovery of the nitrite following the spike

in load points to the second nitrification phase being the limited step under sudden spikes in load. Since the performance of biofilters is determined by the conditions in which the community is formed and since the different groups of nitrifiers react differently to environmental factors such as temperature and salinity, the threshold will vary from system to system (Hüpeden et al., 2020; Li et al., 2022). The relatively stable operation at low and medium loads also agrees with the observation that more stable organic matter levels favor stable water quality and microbial dynamics (Fossmark et al., 2020).

Ecological Implications for Receiving Waters

Ecologically, these findings are significant in relation to effluent loads. While the absolute amounts of removal were still quite high, the effluent loads of nitrogen and phosphorus per unit feed increased by about 70% and 40%, respectively, across the two load levels. The implication is that intensification reduces the effluent load benefits of RAS technology, just as in lifecycle assessments where environmental impacts may shift as a result of increased production intensity (Ghamkhar et al., 2021). Nonetheless, feed production still accounts for most of the impacts, hence improvement in feed efficiency is equally as vital as treatment efficiency (Bergman et al., 2020). In nitrogen budgets of other RAS, it has been found that much of the nitrogen inputs do not get retained in the fish but rather removed via the treatment systems and exchange water (Xu et al., 2022).

Management and Design Recommendations

These three recommendations are provided. Firstly, feeding should be scheduled and adjusted to prevent any sudden spikes because recovery from shock loading took 36-60 hours and led to increased levels of ammonia and nitrite. Secondly, treatment capacity should be designed to cover high load periods instead of mean load, and more systems may be introduced where the effluent requirements are stringent. This can be done using such approaches as electrocoagulation, membrane aerated biofilm reactors, hybrid aerobic/anaerobic bioreactors and biofiltration with algae or periphyton, which proved to provide higher nitrogen removal or nutrients recycling in RAS (Xu et al., 2022; Almeida et al., 2023; Bell et al., 2023). Thirdly, harvesting of biological nutrient recovery units needs to be arranged since removal and yield depend on the harvesting rate and load (Bell et al., 2023; Sutherland et al., 2020). Combined biofilter configurations can further improve nitrogen removal from effluent (Shahar & Guttman, 2021).

Limitations

The tests involved pilot-scale units where there is one species used, one type of feed and a certain time limit for each case, and therefore, adaptation to the environment and seasonality have been overlooked. Phosphorus removal has been done by conducting a mass balance, without measuring phosphorus that has been bound with the sludge.

VI. Conclusions

The impact of variable feeding load has a marked effect on the performance of RAS. An increase in the feeding load led to increased concentrations of ammonia, nitrate, phosphate, and solids, decrease in dissolved oxygen levels and efficiency of nutrient removal, and higher nitrogen and phosphorus discharges in the effluents from the system per unit of feed added. The shock feeding load was attenuated without causing any mortality among the fishes, although it took 36 and around 60 hours for ammonia and nitrite levels to return to the normal levels, respectively. The feeding load itself was responsible for explaining almost all variations in water quality and discharge parameters ($|r| > 0.91$). To protect receiving aquatic ecosystems, RAS should be designed and managed with attention to peak rather than average loading, avoidance of abrupt feed pulses and the use of complementary treatment and nutrient-recovery units.

References

[1] FAO, F. (2024). The state of world fisheries and aquaculture 2024: Blue Transformation in action. https://doi.org/10.4060/cd0683en

[2] Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M., & Froehlich, H. E. (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nature Food*, *1*(5), 301-308. https://doi.org/10.1038/s43016-020-0078-x

[3] Bergman, K., Henriksson, P. J., Hornborg, S., Troell, M., Borthwick, L., Jonell, M., ... & Ziegler, F. (2020). Recirculating aquaculture is possible without major energy tradeoff: life cycle assessment of warmwater fish farming in Sweden. *Environmental Science & Technology*, *54*(24), 16062–16070. https://doi.org/10.1021/acs.est.0c01100

[4] Ghamkhar, R., Boxman, S. E., Main, K. L., Zhang, Q., Trotz, M. A., & Hicks, A. (2021). Life cycle assessment of aquaculture systems: does burden shifting occur with an increase in production intensity? *Aquacultural Engineering*, *92*, 102130. https://doi.org/10.1016/j.aquaeng.2020.102130

[5] Preena, P. G., Rejish Kumar, V. J., & Singh, I. S. B. (2021). Nitrification and denitrification in recirculating aquaculture systems: the processes and players. *Reviews in Aquaculture*, *13*(4), 2053-2075. https://doi.org/10.1111/raq.12558

[6] Ruiz, P., Vidal, J. M., Sepúlveda, D., Torres, C., Villouta, G., Carrasco, C., ... & Urrutia, H. (2020). Overview and future perspectives of nitrifying bacteria on biofilters for recirculating aquaculture systems. *Reviews in Aquaculture*, *12*(3), 1478-1494.https://doi.org/10.1111/raq.12392

[7] Hüpeden, J., Wemheuer, B., Indenbirken, D., Schulz, C., & Spieck, E. (2020). Taxonomic and functional profiling of nitrifying biofilms in freshwater, brackish and marine RAS biofilters. *Aquacultural Engineering*, *90*, 102094. https://doi.org/10.1016/j.aquaeng.2020.102094

[8] Li, Q., Hasezawa, R., Saito, R., Okano, K., Shimizu, K., & Utsumi, M. (2022). Abundance and diversity of nitrifying microorganisms in marine recirculating aquaculture systems. *Water*, *14*(17), 2744. https://doi.org/10.3390/w14172744

[9] Fossmark, R. O., Vadstein, O., Rosten, T. W., Bakke, I., Košeto, D., Bugten, A. V., ... & Attramadal, K. J. (2020). Effects of reduced organic matter loading through membrane filtration on the microbial community dynamics in recirculating aquaculture systems (RAS) with Atlantic salmon parr (Salmo salar). *Aquaculture*, *524*, 735268. https://doi.org/10.1016/j.aquaculture.2020.735268

[10] Xu, J., Qiu, T., Chen, F., Zhou, L., Du, Y., & Sun, J. (2022). Nitrogen migration law and recycling strategy in an innovative recirculating aquaculture system: Enhancing performance through electrocoagulation. *Journal of Water Process Engineering*, *50*, 103275. https://doi.org/10.1016/j.jwpe.2022.103275

[11] Almeida, J. C. R., Bega, J. M. M., Leite, L. D. S., de Oliveira, J. N., Albertin, L. L., & Matsumoto, T. (2023). Membrane aerated biofilm reactor in recirculating aquaculture system for effluent treatment. *Environmental Technology*, *44*(26), 4071-4083. https://doi.org/10.1080/09593330.2022.2078674

[12] Bell, A. N., Guttman, L., Main, K. L., Nystrom, M., Brennan, N. P., & Ergas, S. J. (2023). Hydrodynamics of an integrated fish and periphyton recirculating aquaculture system. *Algal Research*, *71*, 103028. https://doi.org/10.1016/j.algal.2023.103028

[13] Shahar, B., & Guttman, L. (2021). Integrated biofilters with Ulva and periphyton to improve nitrogen removal from mariculture effluent. *Aquaculture*, *532*, 736011. https://doi.org/10.1016/j.aquaculture.2020.736011

[14] Sutherland, D. L., Burke, J., & Ralph, P. J. (2020). Increased harvest frequency improves biomass yields and nutrient removal on a filamentous algae nutrient scrubber. *Algal Research*, *51*, 102073. https://doi.org/10.1016/j.algal.2020.102073

[15] Obondo, C. O., Kagali, R. N., Njogu, P. M., & Kamau, J. N. (2025). Nitrogenous waste removal in closed freshwater recirculating aquaculture systems using an innovative DHS-USB bioreactor. *Journal of Agriculture and Food Research*, *19*, 101577. https://doi.org/10.1016/j.jafr.2024.101577