Aquatic Ecosystems and Environmental Frontiers, Volume 4, Issue 4, December 2026 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V4I4/AF260420

Nutrient Recovery Efficiency of Constructed Wetland Systems Treating Small-Scale Aquaculture Wastewater

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Abstract: Nitrogen and phosphorus found in aquaculture wastewater have been cited to be a source of eutrophication and ecologically detrimental. The current study seeks to analyze the effectiveness of constructed wetland systems in removing these nutrients and the suitability of constructed wetlands for small-scale aquaculture wastewater treatment. Quantitative secondary data analysis based on experimental results from pilot-scale constructed wetlands with Salicornia bigelovii for marine aquaculture effluents at low, medium, and high total ammonia nitrogen loadings was performed. The removal efficiencies of ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, and phosphate phosphorus have been analyzed to observe the specific response of nutrients to treatments. It was found that the removal efficiency of ammonia nitrogen has reduced from 58.51% at low loading to 26.21% at high loading. The removal efficiency of nitrite nitrogen has reduced from 96.07% to 27.93%, showing a decrease of 68.14 percentage points. The removal efficiency of nitrate nitrogen has reduced from 52.03% to 29.69%, while that of phosphate phosphorus has been observed to be very limited, i.e., between 1.87% and 8.20%. It can be inferred that with an increase in nutrient loading, nitrogen treatment efficiency decreases significantly, especially for nitrite. Constructed wetlands are a sustainable method of wastewater treatment; however, better hydraulic design, vegetation, substrate, and additional phosphorus removal are required.

Keywords: Constructed Wetlands; Aquaculture Wastewater; Nutrient Removal; Nitrogen; Phosphorus; Ecological Engineering.

(Submitted: September 04, 2026; Revised: October 06, 2026; Accepted: November 23, 2026; Published: December 30, 2026)

I. Introduction

Background

Wastewater from aquaculture facilities is rich in undigested feed, fish waste, suspended solids, dissolved organic compounds, and nutrients, especially nitrogen and phosphorus. The indiscriminate release of these contaminants into nearby water sources increases eutrophication, promotes algae bloom, lowers dissolved oxygen levels, and impacts the health of the aquatic environment negatively. Small scale aquaculture facilities encounter difficulties in utilizing conventional wastewater treatment techniques due to lack of funding and technological know-how. For this reason, sustainable, economic, and eco-friendly treatment options are becoming increasingly necessary. The use of constructed wetlands is a nature-based approach that makes use of aquatic plants, microorganisms, and filter media to clean pollutants by means of sedimentation, filtration, adsorption, uptake by plants, and biological transformation (Blandford et al., 2024; Xu et al., 2024). Constructed wetlands are usually grouped according to their classification into free-water surface wetlands, horizontal subsurface flow wetlands, vertical flow wetlands, and hybrid wetlands. Each type of system offers different flow and treatment principles, facilitating proper nutrient management in aquaculture facilities (Wu et al., 2023; Li et al., 2022).

Research Problem

Wetlands do not necessarily treat all nutrients in the same way. For example, ammonia, nitrate, nitrite, and phosphorus are treated differently by wetlands. Nutrient loading can affect the biological removal process, since phosphorus binding sites can be saturated.

Objectives and Contributions

Objectives include comparison of efficiency of nutrient removal from published data under different loading rates; difference between ammonia, nitrite, nitrate and phosphate removal efficiency; operation limitations; and recommendation for small-scale aquaculture. In this experiment, field observation was not done but data were obtained through traceable secondary source.

II. Literature Review

Wetland Treatment of Aquaculture Effluent

A constructed wetland mimics certain processes of a natural wetland via settling, filtration, adsorption, and microorganism activity. Pilot-scale planted systems have shown the potential of treatment of aquaculture wastewaters, albeit with varying results according to pollutant loads and operating conditions (Ma et al., 2018; Nabi et al., 2025).

Nitrogen Transformation

Nitrogen transformations take place through ammonification, nitrification, and denitrification in different oxygen levels. There is an extra nitrogen retention process through plant absorption and microbial assimilation. System integration will ensure the efficient management of nitrogen due to oxygen variation (Zhao et al., 2023; Hu et al., 2024).

Phosphorus Retention

Phosphorus can be removed through adsorption, precipitation, sedimentation, microbial uptake and plant uptake. The long-term removal will depend on the chemical nature of the substrate and the management of stored phosphorus, while removal will depend on capturing it in a recyclable state (Kamilya et al., 2022; Truong et al., 2024).

Operating Conditions and Gap

Retention time, loading rates, substrate composition, and vegetation may influence the treatment effects. This study evaluates the response to nutrients through one documented experiment without making any causal relationship between other wetlands (Imron et al., 2024; Zhao et al., 2024).

III. Materials and Methods

Study Design and Source

The study has been carried out through quantitative secondary data analysis of the peer-reviewed pilot scale study titled “Characterization of Microbial Communities in Pilot-Scale Constructed Wetlands with Salicornia for Treatment of Marine Aquaculture Effluents” (Ma et al., 2018). In the original study, treatment of saline effluent from an Atlantic salmon recirculating aquaculture system has been analyzed at three TAN loadings.

Experimental Variables

The experimental conditions employed in the assessment of nutrient removal efficiency in constructed wetlands at three loading levels of total ammonia nitrogen (TAN) are outlined in table 1. There is an increment in TAN concentrations in the influent, where the values go from 0.75 mg/L at low loading to 2.31 mg/L at medium loading and 7.23 mg/L at high loading. Salicornia bigelovii was employed in all treatments as the wetland vegetation, where there were three replicates reported per treatment. The monitored nutrients were TAN, NO_2-N, NO_3-N, and PO_4-P.

Table 1: Published Experimental Loading and Monitoring Conditions

Parameter	Low	Medium	High
Influent TAN (mg/L)	0.75	2.31	7.23
Vegetation	Salicornia bigelovii	S. bigelovii	S. bigelovii
Reported replicates	3	3	3
Monitored nutrients	TAN, NO_2-N, NO_3-N, PO_4-P	Monitored nutrients	TAN, NO_2-N, NO_3-N, PO_4-P

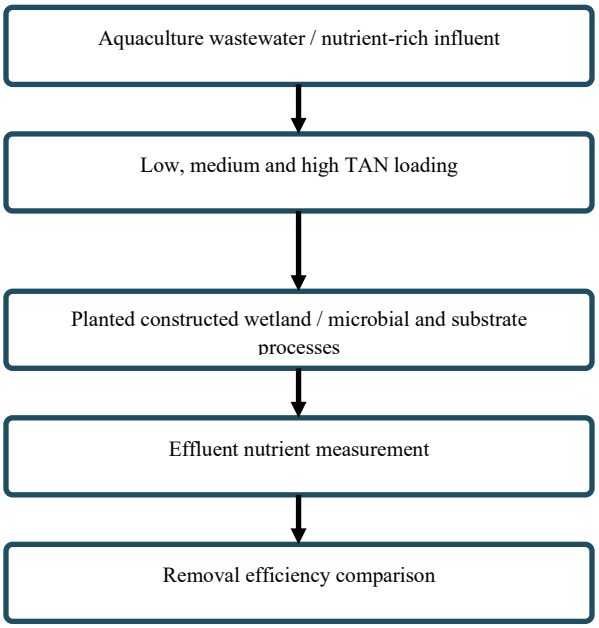


Figure 1: Secondary-Analysis Framework for Constructed Wetland Nutrient Removal

The methodical approach for assessing nutrient removal efficiency in constructed wetlands for treatment of aquaculture wastewater is depicted in figure 1. First, nutrient-rich effluent from aquaculture is put under low, medium, and high levels of total ammonia nitrogen (TAN) loading. Next, the wastewater goes into constructed wetlands with plants where microbial activity, plant absorption and interaction with substrate are key mechanisms in the removal of nutrients. Further, the level of nutrients in the effluent is assessed. Lastly, the comparison of removal efficiency of nutrients for different loadings is made.

Calculation of Removal Efficiency

Removal efficiency was defined as Equation (1):

$$RE_{\mathrm{i}} = [(C_{\mathrm{i}}, in - C_{\mathrm{i}}, out) / C_{\mathrm{i}}, in] \times 100 \ (1),$$

Where C_{i}, in and C_{i}, out are influent and effluent concentrations of nutrient i.

Differences between high and low loading were computed as equation (2):

$$\Delta RE_{\mathrm{i}} = RE_{\mathrm{i}}, high - RE_{\mathrm{i}}, low \ (2)$$

Concentration-based removal is not equivalent to a complete nutrient mass balance or recoverable fertilizer yield.

Analytical Approach

The mean efficiencies for published works were described in comparison to each other and percent changes calculated. Replicate level data from original publications was not recalculated, therefore no statistical significance is claimed.

IV. Results and Discussion

Nutrient Removal Efficiencies

Table 2 shows the removal efficiencies of nutrients in constructed wetlands in low, medium, and high loads. Removal of TAN was reduced from 58.51% in low load to 26.21% in high load, and removal of nitrite nitrogen was significantly reduced from 96.07% to 27.93%. Removal of nitrate nitrogen was also reduced from 52.03% to 29.69%. Phosphate phosphorus showed very low removal efficiencies of between 1.87% and 8.20%. This implies that high loads resulted in poor removal efficiencies of nitrogen, especially nitrite nitrogen, but not of phosphorus (Ma et al., 2018).

Table 2: Reported Mean Nutrient Removal Efficiencies Across Loading Conditions

Nutrient	Low (%)	Medium (%)	High (%)
TAN	58.51	29.46	26.21
Nitrite-N	96.07	59.26	27.93
Nitrate-N	52.03	51.38	29.69
Phosphate-P	1.87	8.20	6.88

Removal efficiencies of nitrites were 96.07% for low loading and 27.93% for high loading, while ammonia removal efficiencies were 58.51% for low loading and 26.21% for high loading. However, phosphate removal efficiency was less than 10%, regardless of the loadings used (Ma et al., 2018).

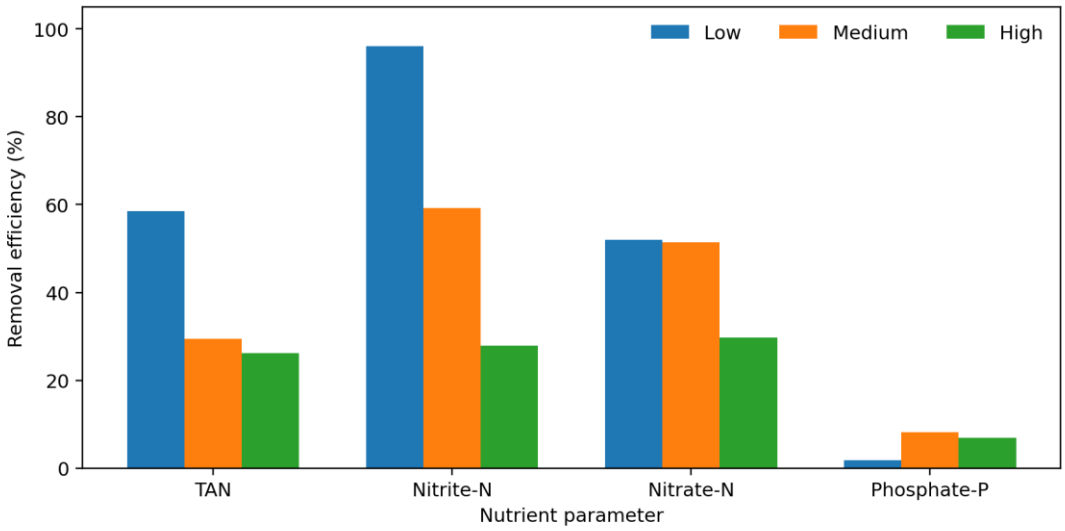


Figure 2: Nutrient Removal Efficiency Across Low, Medium and High Loading

Nutrient removal efficiencies for constructed wetlands with respect to low, medium, and high loading conditions have been depicted in figure 2. The highest nutrient removal efficiency was recorded for nitrite nitrogen with 96.07% efficiency under low loading conditions, while TAN and nitrate nitrogen removed at 58.51% and 52.03%, respectively. However, removal efficiencies reduced to 27.93%, 26.21%, and 29.69% for nitrite nitrogen, TAN, and nitrate nitrogen, respectively, under high loading. Removal of phosphate phosphorus remained consistently low with efficiency values varying between 1.87% to 8.20%.

Residual Effluent Concentrations

Table 3: Published Final Effluent Concentrations

Nutrient (mg/L)	Low	Medium	High
TAN	0.020	0.773	3.510
NO_2-N	0.008	0.006	0.013
NO_3-N	1.348	1.145	0.675
PO_4-P	0.420	0.398	0.356

The TAN effluent concentration also showed a marked increase with increased loading, attaining an average value of 3.510 mg/L. Nitrate concentration was found to be lesser in the case of the high-loading treatment, proving that effluent concentration cannot be used instead of influent concentration and nitrogen transformation details (table 3).

Loading Sensitivity

The percentage change in nutrient removal efficiency between low and high loading was indicated in table 4. The nutrient with the highest decrease in efficiency was nitrite nitrogen with a percentage decrease of 68.14%, followed by TAN at 32.30% and nitrate nitrogen at 22.34%. On the other hand, phosphate phosphorus removal was only slightly improved at 5.01%. Nevertheless, the efficiency of removing this nutrient was still lower than 10%. The results showed that there was significant decrease in efficiency of nitrogen removal under high loading conditions (Ma et al., 2018).

Table 4: Calculated Changes in Nutrient Removal Efficiency Between Low and High Loading Conditions

Nutrient	Low (%)	High (%)	Change (pp)
TAN	58.51	26.21	-32.30
Nitrite-N	96.07	27.93	-68.14
Nitrate-N	52.03	29.69	-22.34
Phosphate-P	1.87	6.88	+5.01

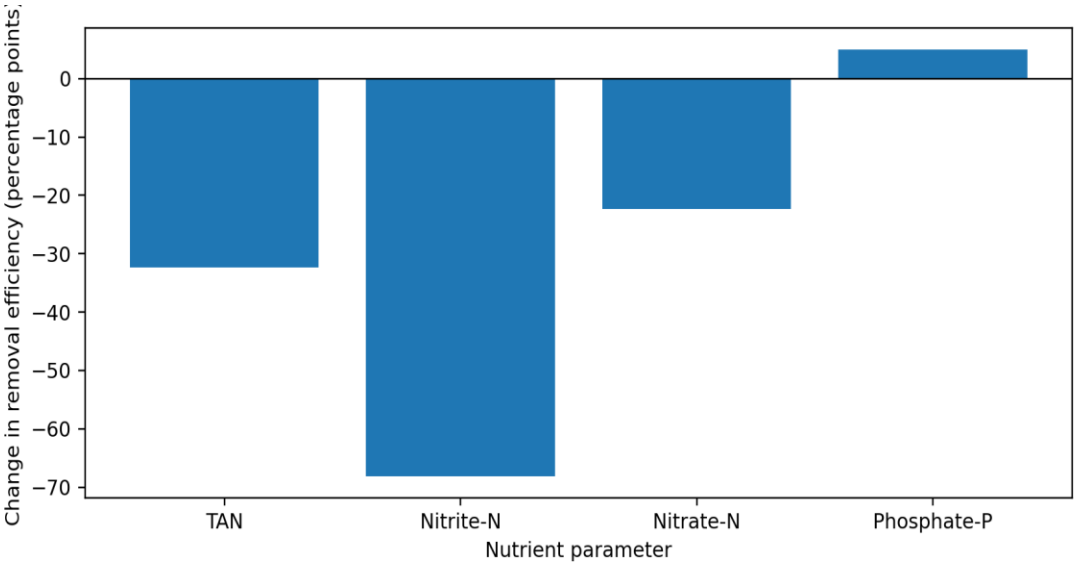


Figure 3: Change in Removal Efficiency Between High and Low Loading, Calculated From (Ma et al., 2018).

The figure 3 presents the biggest decline was noted in nitrite reduction (−68.14 percentage points), followed by ammonia (−32.30) and nitrate (−22.34). While phosphate rose by 5.01 percentage points, its level stayed relatively low. This trend highlights the importance of evaluating each nutrient individually, as opposed to calculating one efficiency rate for all nutrients.

Comparison with Literature

However, commercial wetland treatment of aquaculture wastewater has shown removal of total nitrogen and total phosphorus at other operating conditions (Li et al., 2022). The wetland literature shows that the hybrid systems can have complementary processes involved, but due to variation in the nature of the influents, HRT and parameters analyzed for comparison, comparison is not possible (Wu et al., 2023) (Kamilya et al., 2022).

Implications for Small-Scale Aquaculture

Flow equalization, solids conditioning, phased wetlands, and nutrients monitoring may be important for small-scale operations. The nitrite loading rate response suggests that the design will be able to accommodate the maximum load rather than the average flow rate. For phosphorus removal, reactive media, vegetative removal, or capture systems may be required. In addition, nutrient recovery claims should measure the nutrient capture/recovery and suitability for reuse.

Environmental and Operational Considerations

Long-term use must consider clogging, hydraulic short-circuiting, substrate exhaustion, seasonal plant dynamics, and potential nutrient mobilization. Measurement of flow, pH, dissolved oxygen, total ammonia nitrogen (TAN), nitrate, nitrite, phosphate, and sediment is needed. Nature-based treatment can have co-benefits for the ecology, but these need to be evaluated separately.

Assessment of Residual Nutrient Fractions Under Different Loading Conditions

In addition to measuring the effectiveness of the treatment process in terms of the percentage of nutrient removal, it could be possible to measure the effectiveness of the constructed wetlands by estimating the residual percentage of nutrients in the water body. In particular, it is vital to estimate the residual percentage of nutrients in aquaculture wastewater treatment because the lack of treatment for such nutrients as nitrogen and phosphorus may impact the quality of water in the receiving water even after wastewater discharge. Specifically, the wetland may be effective in removing one type of nitrogen, but not another type. Therefore, it is necessary to assess the effectiveness based on the efficiency of the certain type of nutrient removal and the percentage of residuals (Wu et al., 2023; Kamilya et al., 2022).

$$RNF_i = 100 - RE_i \quad (3)$$

Where RNF_i represents the residual nutrient fraction (%) and RE_i denotes the reported removal efficiency (%) of nutrient i. This is calculated based on the assumption that the percentage removal cited refers to concentration change from one set of influent and effluent conditions to another. This yields the percentage of the initial concentration of the nutrient left after the treatment process equation (3).

Table 5: Calculated Residual Nutrient Fractions Across Different Loading Conditions

Nutrient parameter	Low loading (%)	Medium loading (%)	High loading (%)
Total ammonia nitrogen (TAN)	41.49	70.54	73.79
Nitrite nitrogen	3.93	40.74	72.07
Nitrate nitrogen	47.97	48.62	70.31
Phosphate phosphorus	98.13	91.80	93.12

The range of the fraction of residual nutrients in the three treatment levels shown in table 5 is very different. In the case of low loading, 3.93% of the nitrite level remains unreacted. In contrast, at medium and high loadings, the percentages are 40.74% and 72.07%, respectively (table 5). Also, an increasing trend is seen in the fraction of residual TAN. Although only 41.49% remained in the case of low loading, the fraction increased up to 73.79% in the case of high loading. In terms of nitrate, the difference between low and medium loadings was less compared to other nutrients; however, the fraction was 70.31% in the case of high loading. In the case of phosphate phosphorus, a completely different trend was observed. The residual fractions were always higher than 90%, no matter what the loading was. This fact means that the

suggested wetland system is not effective enough for removal of phosphate from the aquaculture effluent. This point is especially important because of the ability of phosphorus to lead to eutrophication despite the efficient treatment of nitrogen.

The distinctions between the forms of nutrients suggest that a single characteristic of the total treatment efficiency can overlook specific limitations in relation to certain pollutants. For example, effective nitrite reduction at low loading level does not guarantee the efficiency of phosphorus treatment. Besides, reduced nitrate level does not mean nitrogen treatment as nitrogen can change its chemical forms. Therefore, evaluation of wastewater treatment requires a number of indicators.

The analysis of residual fractions is highly important for small scale aquaculture enterprises, which may differ from each other by the properties of their effluents, depending on such factors as the intensity of feeding, the density of stocking, the rate of water exchange, and production cycles. When the amount of feed is large, the effluent loading may exceed the treatment capacity of the wetland system. The residual nutrient fractions will help to reveal such cases, pointing out the need for hydraulic and other treatment measures. On the other hand, currently, the analysis is descriptive only.

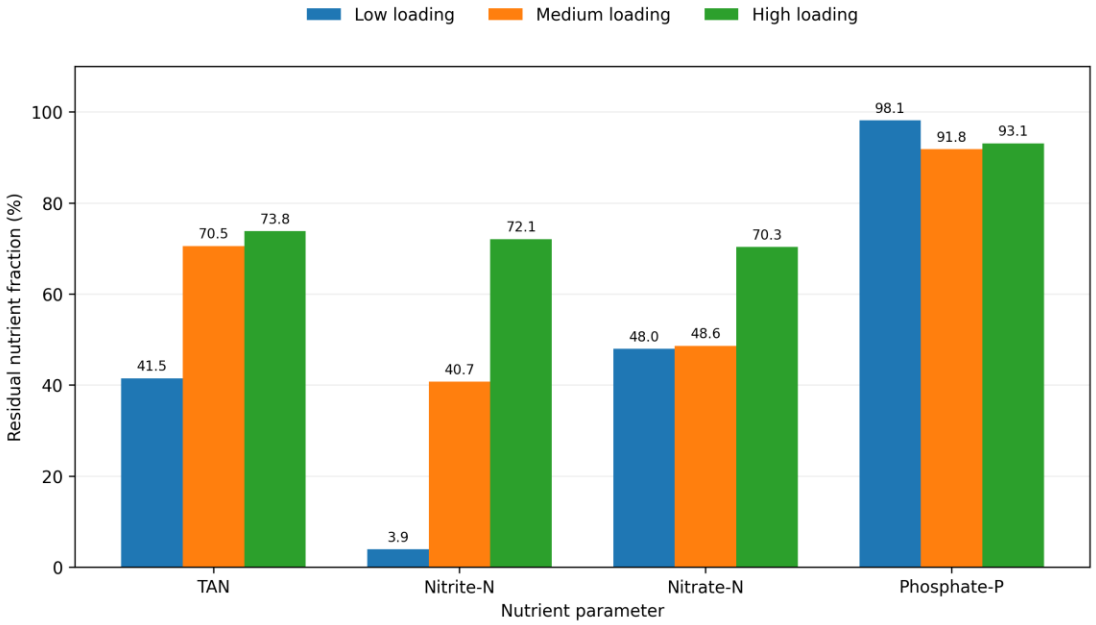


Figure 4: Comparison of Residual Nutrient Fractions Under Different Loading Conditions

Figure 4 above shows different residual nutrients fractions for low, medium, and high loading levels. Residual TAN fraction changed from 41.49% at low loading level to 73.79% at high loading level, and nitrite nitrogen also rose considerably from 3.93% to 72.07%. Nitrate nitrogen also showed increase from 47.97% to 70.31%. On the other hand, residual phosphate phosphorus fractions were higher for all the three loading levels, varying between 91.80% and 98.13%. It is evident that there is need for nutrient specific management, hydraulic loading control, and additional phosphorus retention mechanisms in constructed wetlands (Ma et al., 2018).

Comparative Analysis of Nutrient Removal Stability

Treatment stability is an important consideration in the long-term operation of constructed wetlands. Aquaculture facilities frequently experience fluctuations in wastewater production, nutrient concentration, and hydraulic loading. A treatment system that performs efficiently under low loading may not maintain comparable removal efficiency when influent conditions change. Therefore, evaluating the relative retention of treatment performance across different loading conditions can provide useful information about

operational reliability. This assessment is particularly relevant to small-scale aquaculture systems, where advanced flow-control and nutrient-regulation equipment may be unavailable (Xu et al., 2024; Imron et al., 2024).

For the present secondary analysis, the relative efficiency retention ratio was calculated using equation (4):

$$ERR_i = \frac{RE_{i,H}}{RE_{i,L}} \times 100 \quad (4)$$

Where ERR_i represents the efficiency retention ratio (%), $RE_{i,H}$ denotes removal efficiency under high loading, and $RE_{i,L}$ represents removal efficiency under low loading. An efficiency retention ratio of 100% indicates that the removal percentage

Table 6: Relative Efficiency Retention and Loading-Associated Performance Changes

Nutrient parameter	Low removal (%)	High removal (%)	Efficiency retention ratio (%)	Change (percentage points)
TAN	58.51	26.21	44.80	−32.30
Nitrite-N	96.07	27.93	29.07	−68.14
Nitrate-N	52.03	29.69	57.06	−22.34
Phosphate-P	1.87	6.88	367.91	+5.01

Table 6 demonstrates that nitrate nitrogen retention ratio was about 57.06% of the removal efficiency in the case of high loading, whereas TAN ratio was 44.80% and nitrite nitrogen ratio was 29.07%. The extremely low retention ratio of nitrite nitrogen proves that there has been considerable change in the removal percentage of nitrite during high and low loadings. This proves that nitrite treatment needs special consideration for constructed wetlands when exposed to changing wastewater load from aquaculture operation.The high retention ratio of phosphate phosphorus (367.91%) should not be considered an indicator of good removal performance of phosphorus. The reason is that the phosphate phosphorus removal percentage at low loading was 1.87%, which increased up to 6.88% at high loading; however, the actual percentage of removal efficiency was less than 10%.

Biological processes of nitrogen removal in constructed wetlands include ammonia oxidation, nitrite oxidation, nitrate reduction, microbial assimilation, and plant absorption. These processes may have different responses to changes in dissolved oxygen, organic carbon, and nutrient loading. Thus, any changes in one of these nitrogen compounds can affect another one. The decrease in nitrite removal efficiency noted at high loading rates can indicate different microbial processes or other factors, but the existing secondary data cannot quantify the effects of the individual process. The findings indicate that treatment facilities should be built with enough flexibility for handling changes in influent properties. Flow equalization, multistage wetland cells, and additional treatment processes could help overcome the effect of rapid changes in loading on the process operation, but their effectiveness needs experimental proof first. In case of small aquaculture, the goal of treatment system design is to achieve stable performance in each cycle, rather than optimal removal efficiency at a particular set of conditions.

V. Sustainable Wetland Management

Hydraulic Loading

Controlled storage and flow rate can prevent load spikes. Modular wetland cells may be a viable choice for irregular production cycles, but design according to local hydraulics is essential.

Phosphorus Capture

The phosphorus binding media as well as the biomass produced can be a source of nutrient recovery but their efficiency and frequency of replacement need to be determined first.

Monitoring and Maintenance

A workable monitoring system must set baseline levels for influent and effluent, as well as flow volumes and inspection schedules. The operator will need to monitor the system's performance during each cycle and maintain vegetation and distribution systems.

VI. Conclusion and Future Research

The nutrient removal capacity of the constructed wetlands system used for the treatment of aquaculture effluent was quantitatively analyzed by using published pilot studies. The effectiveness of nutrient removal for ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, and phosphate phosphorus at different levels of nutrient loading was compared in this study. Under low loading, efficiencies for ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen removal were 58.51%, 96.07%, and 52.03%, respectively. For high loading, efficiencies reduced to 26.21%, 27.93%, and 29.69%, respectively. Nitrite nitrogen removal was most affected, recording a decline of 68.14 percentage points. Efficiency of phosphate phosphorus removal remained relatively low throughout, varying between 1.87% and 8.20%. This suggests poor phosphorus retention by the tested wetland system. The above results stress the need for different approaches depending on nutrient types, hydraulic loading rates, appropriate vegetation, and substrate choice. Coupling of constructed wetlands with phosphorus retention media and additional treatment methods can enhance wastewater treatment in small-scale aquaculture operations. However, the study has been based on literature values for marine aquaculture and does not provide the amount of recoverable nutrients. Future work should focus on validation of results, seasonal performance testing, nutrient mass-balance calculations, and cost evaluation to achieve a viable wastewater treatment technique This analysis employs means of treatments obtained from previous literature and does not involve experiments that could provide a basis for mass balance and cause-and-effect relationship studies regarding loading. The saline pilot scale system does not necessarily represent freshwater ponds. Further work is needed to examine field-scale hydraulic conditions, seasonal impacts, nutrient retention in media and vegetation, and costs.

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