



Performance Evaluation and Design Analysis of Hybrid Constructed Wetlands for Aquaculture Effluent Treatment under Tropical Conditions

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Abstract

*Aquaculture wastewater discharge has become a significant environmental concern because of the release of nutrient-rich effluents into natural water bodies. This study evaluated the treatment performance and design efficiency of a laboratory-scale hybrid constructed wetland (HCW) system developed for aquaculture effluent treatment under tropical climatic conditions. The hybrid system consisted of horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) wetland units operated under planted and unplanted conditions using *Sacciolepis africana* as the test macrophyte. Aquaculture wastewater was collected from Musgola Fish Farm located in Minna, Niger State, Nigeria, and monitored over a 23-week experimental period. Physicochemical parameters including biological oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), total nitrogen (TN), sulphate (SO₄²⁻), and calcium (Ca²⁺) were analyzed using standard APHA methods. Hydraulic retention time, hydraulic loading rate, porosity, and wetland dimensions were incorporated into the wetland design calculations. Results showed that the planted VSSF unit recorded the highest pollutant removal efficiencies of 90.1% for BOD₅, 88.2% for COD, 77.7% for TSS, 58.2% for TDS, and 57.4% for TN. Statistical analysis using one-way ANOVA indicated significant differences ($p < 0.05$) between planted and unplanted systems. The study demonstrates that hybrid constructed wetlands provide an efficient, low-cost, and environmentally sustainable technology for aquaculture wastewater treatment in developing countries.*

Keywords: Hybrid constructed wetlands, aquaculture wastewater, horizontal subsurface flow, vertical subsurface flow, pollutant removal efficiency, sustainable wastewater treatment.

1.0 Introduction

Aquaculture is one of the fastest-growing sectors of global food production and contributes substantially to food security, employment generation, and economic development. According to the Food and Agriculture Organization [1], aquaculture currently contributes more than 50% of the global fish supply for human consumption. The continuous expansion of aquaculture activities, particularly in developing countries, has however resulted in increased generation of wastewater containing high concentrations of organic matter, nutrients, suspended solids, and dissolved contaminants [2][3].

Aquaculture effluents are primarily generated from uneaten feed, fish excreta, pond sediment disturbance, and metabolic by-products. When discharged untreated into receiving water bodies, these pollutants may cause eutrophication, dissolved oxygen depletion, excessive algal growth, and ecological imbalance. Elevated concentrations of nitrogen and phosphorus compounds in aquaculture wastewater have been identified as major contributors to environmental degradation and deterioration of aquatic ecosystems [3][4].

Conventional wastewater treatment technologies such as activated sludge systems, membrane filtration, and chemical treatment processes are often associated with high operational costs, intensive energy requirements, and complex maintenance procedures. These limitations reduce their applicability in rural and small-scale aquaculture systems commonly found in developing nations [5].

Constructed wetlands have emerged as sustainable and environmentally friendly alternatives for wastewater treatment because they utilize natural biological, physical, and chemical processes involving wetland plants, microorganisms, and porous substrates. Constructed wetlands are characterized by low energy consumption, ease of operation, reduced maintenance requirements, and effective pollutant removal performance [6][7].

Hybrid constructed wetlands combine two or more wetland configurations to improve treatment efficiency. In particular, the integration of horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) systems promotes both anaerobic and aerobic treatment processes. The HSSF unit enhances sedimentation and

denitrification under anoxic conditions, while the VSSF unit improves oxygen transfer, nitrification, and aerobic degradation of organic matter [6][8].

Aquatic macrophyte also play an important role in wetland treatment performance through nutrient uptake, oxygen transfer into the rhizosphere, sediment stabilization, and enhancement of microbial activity. The effectiveness of constructed wetlands is therefore strongly influenced by plant species selection, substrate characteristics, hydraulic design, and operational conditions [5].

Although several studies have reported the effectiveness of constructed wetlands for domestic and industrial wastewater treatment, limited information is available on the application of hybrid constructed wetlands for aquaculture effluent treatment under tropical climatic conditions in Nigeria.

1.1. Aim of the Study

The aim of this study was to evaluate the treatment performance of a hybrid constructed wetland system for aquaculture wastewater treatment.

1.2. Objectives of the Study

The specific objectives of the study were to:

1. Characterize the physicochemical properties of aquaculture wastewater.
2. Design and develop a laboratory-scale hybrid constructed wetland system.
3. Evaluate the pollutant removal efficiency of the hybrid wetland system.
4. Compare the treatment performance of HSSF and VSSF wetland units.
5. Assess the influence of vegetation on treatment efficiency.
6. Determine the compliance of treated effluent with recommended discharge standards.

2.0 Materials and Methods/Methodology

2.1 Study Area and Description of Wastewater Source

This study utilized aquaculture wastewater obtained from Musgola Fish Farm located in the Lapai-Gwari area of Minna, Niger State, Nigeria. The farm operates a semi-intensive aquaculture system of consisting earthen ponds used for fish production.

Wastewater generated from the ponds is periodically discharged into a nearby tributary of River Chanchaga without prior treatment. The effluent is typically characterized by high concentrations of organic matter, suspended solids, and nutrients originating from uneaten feed, fish excreta, and metabolic by-products.

The study area lies within the tropical savannah climatic zone, characterized by two distinct seasons: wet and dry seasons. Annual rainfall ranges between 1,100 mm and 1,600 mm, with average temperatures between 25°C and 35°C. These climatic conditions are favorable for biological treatment processes in constructed wetlands.

2.2 Design and Configuration of the Hybrid Constructed Wetland System

A laboratory-scale hybrid constructed wetland (HCW) system was designed and constructed to evaluate the treatment performance of aquaculture wastewater under controlled conditions.

The hybrid system consisted of two subsurface flow wetland units arranged in series:

1. **Horizontal Subsurface Flow Constructed Wetland (HSSF)**
2. **Vertical Subsurface Flow Constructed Wetland (VSSF)**

The configuration was selected to combine both anaerobic/anoxic and aerobic treatment processes, thereby enhancing pollutant removal efficiency.

Each wetland unit was constructed using rectangular plastic tanks with approximate dimensions suitable for laboratory-scale experimentation. The tanks were lined with impermeable materials to prevent leakage and ensure controlled hydraulic flow.

The system was divided into two treatment categories:

- **Planted Wetland Units (PW):** Vegetated with *Sacciolepis africana*
- **Unplanted Wetland Units (UW):** Control systems without vegetation

This design allowed for comparative evaluation of the effect of vegetation on treatment efficiency.

2.3 Hydraulic Design and Flow Pattern

The wastewater flow through the hybrid system followed a sequential treatment pathway:

- Influent wastewater → HSSF unit → VSSF unit → Effluent discharge

In the **HSSF unit**, wastewater flowed horizontally through the porous substrate below the surface, maintaining saturated conditions and promoting anaerobic and anoxic microbial processes such as denitrification.

In the **VSSF unit**, wastewater was intermittently applied to the surface and allowed to percolate vertically through the substrate. This promoted oxygen diffusion into the system, facilitating aerobic processes such as nitrification and organic matter oxidation.

The combination of these two systems ensured:

- Enhanced oxygen transfer
- Improved microbial diversity
- Efficient removal of both organic and inorganic pollutants

2.4 Wetland Substrate Materials and Preparation

The wetland beds were filled with locally sourced substrate materials arranged in stratified layers to enhance treatment performance.

Substrate Composition

- Bottom layer: Coarse gravel (20–40 mm) for drainage
- Middle layer: Medium gravel (10–20 mm) for structural support and root penetration
- Top layer: Fine sand (0.2–2 mm) for filtration and sedimentation

Preparation Procedure

All substrate materials were thoroughly washed with clean water prior to use to remove fine particles, clay, and organic impurities that could:

- Reduce hydraulic conductivity
- Cause clogging
- Interfere with treatment processes

The cleaned materials were then layered sequentially within each wetland unit to achieve optimal filtration and microbial attachment.

2.5 Selection and Establishment of Vegetation

The aquatic macrophyte *Sacciolepis africana* was selected for this study due to its:

- Adaptability to wetland conditions
- High tolerance to polluted environments
- Potential for nutrient uptake and pollutant removal

✓ Planting Procedure

Healthy plant shoots were collected from natural wetland environments and transplanted into the designated planted wetland units.

The plants were spaced uniformly within the substrate to ensure adequate coverage and optimal root development.

✓ Acclimatization Period

Following transplantation, the plants were allowed to acclimatize for a period before wastewater introduction. During this period:

- Clean water was used to maintain moisture
- Root systems were allowed to establish
- Microbial communities began to develop in the rhizosphere

This stabilization phase was critical to ensure effective performance during the treatment phase.

2.6 Design Calculations and Design Considerations

The hybrid constructed wetland system was designed using standard hydraulic and wetland design principles suitable for laboratory-scale wastewater treatment systems.

2.6.1 Hydraulic Retention Time (HRT)

Hydraulic retention time was determined using Equation (1):

$$\text{HRT} = (n \times L \times W \times d) / Q$$

where:

HRT = Hydraulic retention time (days)

n = Bed porosity (dimensionless)

L = Length of wetland bed (m)

W = Width of wetland bed (m)

d = Media depth (m)

Q = Flow rate (m³/day)

The designed hydraulic retention time ranged between 3 and 5 days to ensure adequate contact between wastewater, substrate media, microorganisms, and plant roots.

2.6.2 Hydraulic Loading Rate (HLR)

The hydraulic loading rate was calculated using Equation (2):

$$\text{HLR} = Q / A$$

where:

HLR = Hydraulic loading rate (m/day)

Q = Wastewater flow rate (m³/day)

A = Surface area of wetland bed (m²)

2.6.3 Wetland Porosity & Data Considerations

The effective porosity of the gravel media was estimated as 0.35–0.40 based on the particle size distribution of the substrate materials.

Design Considerations

The following design considerations were incorporated into the wetland system:

1. Prevention of hydraulic short-circuiting.
2. Adequate oxygen transfer in the VSSF unit.
3. Uniform wastewater distribution.
4. Prevention of media clogging.
5. Optimization of plant root development.
6. Enhancement of microbial attachment surfaces.
7. Maintenance of subsurface flow conditions to minimize odour and mosquito breeding.

The integration of HSSF and VSSF systems was intended to maximize both aerobic and anaerobic biological treatment mechanisms.

2.7 Wastewater Collection and Handling

Aquaculture wastewater was collected directly from the discharge point of Musgola Fish Farm before entering the receiving water body.

Collection Procedure

- Samples were collected using clean plastic containers
- Care was taken to avoid contamination
- Containers were rinsed with wastewater prior to sampling

Transportation and Storage

Collected wastewater was transported immediately to the laboratory and stored temporarily under controlled conditions to prevent significant physicochemical changes before use

2.8 Feeding Regime and Operational Conditions

Wastewater was introduced into the hybrid wetland system at controlled intervals to simulate real-life discharge conditions from aquaculture systems.

The feeding regime was designed to:

- Maintain consistent hydraulic loading
- Prevent overloading of the system
- Ensure adequate retention time for treatment processes

The system operated under batch/controlled flow conditions throughout the experimental period.

2.9 Monitoring Period and Sampling Frequency

The experimental system was monitored over a **23-week period**, during which influent and effluent samples were collected at regular intervals.

Sampling was conducted to:

- Track changes in water quality over time
- Evaluate system performance under varying conditions
- Assess treatment stability

2.10 Physicochemical Parameters and Analytical Methods

Water quality analysis was carried out to determine the effectiveness of the hybrid constructed wetland system.

Parameters Analyzed

- Dissolved Oxygen (DO)
- Turbidity
- Total Suspended Solids (TSS)

- Total Dissolved Solids (TDS)
- Biological Oxygen Demand (BOD₅)
- Chemical Oxygen Demand (COD)
- Total Nitrogen (TN)
- Sulphate (SO₄²⁻)
- Calcium (Ca²⁺)

Analytical Procedures

All analyses were conducted in accordance with standard methods recommended by the American Public Health Association (APHA).

- **DO:** Winkler titration method
- **BOD₅:** 5-day incubation method
- **COD:** Open reflux method
- **TSS:** Gravimetric method
- **TDS:** Digital conductivity probe
- **Nutrients:** Spectrophotometric methods

All instruments were calibrated prior to use to ensure accuracy and reliability of results.

2.11 Determination of Pollutant Removal Efficiency

The performance of the hybrid constructed wetland system was evaluated using pollutant removal efficiency.

$$\text{Removal Efficiency (\%)} = \frac{C_i - C_e}{C_i} \times 100$$

Where C_i = Influent Concentration

C_e = Effluent Concentration

This equation was applied to all measured parameters including BOD₅, COD, TSS, TDS, TN, sulphate, and calcium to quantify treatment effectiveness. Treatment reliability was evaluated by monitoring the consistency of pollutant removal over the 23-week operational period. The resulting effluent quality was compared with WHO and national discharge standards to assess the environmental suitability of the treated wastewater.

2.12 Statistical Analysis

Statistical analysis of the experimental data was performed to evaluate differences between treatment systems.

- One-way Analysis of Variance (ANOVA) was used
- Significance level was set at $p < 0.05$
- Mean values were compared using post-hoc tests where applicable

This analysis allowed for:

- Comparison between planted and unplanted systems
- Evaluation of differences between HSSF and VSSF units

2.13 Experimental Flow Description

The treatment process followed a sequential pathway:

1. Collection of aquaculture wastewater
2. Initial physicochemical characterization
3. Distribution into wetland units
4. Treatment through HSSF system
5. Treatment through VSSF system
6. Effluent collection and analysis
7. Determination of removal efficiency

3.0 Results and Discussion

3.1 General Performance of the Hybrid Wetland System

The hybrid constructed wetland system significantly improved the physicochemical quality of aquaculture wastewater during the experimental period. The integration of horizontal subsurface flow and vertical subsurface flow units enhanced the occurrence of both aerobic and anaerobic treatment mechanisms, resulting in effective pollutant reduction.

The planted wetland units consistently exhibited higher treatment efficiencies than the unplanted units. This improvement was attributed to nutrient uptake by *Sacciolepis africana*, enhanced oxygen transfer into the rhizosphere, and increased microbial activity around plant roots.

The observed treatment efficiencies confirm the effectiveness of hybrid constructed wetlands as sustainable treatment systems for aquaculture wastewater management.

3.2 Influent Characteristics and Variability

The raw aquaculture wastewater exhibited high variability in pollutant concentrations over the monitoring period, reflecting fluctuations in feeding intensity, pond management practices, and environmental conditions.

Table 1: Descriptive Statistics of Influent Wastewater Quality

| Parameter | Mean | Std. Dev | Min | Max | WHO Limit |
|-------------------------|--------|----------|-----|-----|-----------|
| BOD ₅ (mg/L) | 115.65 | — | — | — | 10–30 |
| COD (mg/L) | 218.30 | — | — | — | 40–60 |
| TSS (mg/L) | 142.91 | — | — | — | 30–50 |
| TN (mg/L) | 4.67 | — | — | — | 0.1–4.0 |

Source: Abari *et al.* (2026)

Discussion:

The influent exceeded permissible discharge limits, indicating the need for effective treatment. High BOD₅ and COD values confirm significant organic pollution, while elevated TSS suggests poor sedimentation within the fish pond system.

3.3 Comparative Performance of Wetland Configurations

Table 2: Comparative Removal Efficiency of Wetland Units (%)

| Parameter | Planted HSSF | Planted VSSF | Unplanted HSSF | Unplanted VSSF |
|------------------|--------------|--------------|----------------|----------------|
| BOD ₅ | 90.1 | 89.0 | 70.3 | 79.1 |
| COD | 84.9 | 88.2 | 66.4 | 77.4 |
| TSS | 60.7 | 77.7 | 60.2 | 76.9 |
| TDS | 44.9 | 58.2 | 32.2 | 37.5 |
| TN | 48.9 | 57.4 | — | — |

Source: Abari *et al.* (2026)

Discussion:

- The planted VSSF system showed the highest overall efficiency, particularly for COD and nitrogen removal.
- Vertical flow wetlands performed better due to improved oxygen transfer, enhancing aerobic degradation.
- Unplanted systems showed moderate performance, highlighting the importance of vegetation.

3.4 Removal of Organic Pollutants

The hybrid system achieved excellent removal of organic pollutants.

- BOD₅ removal: up to 90.1%
- COD removal: up to 88.2%

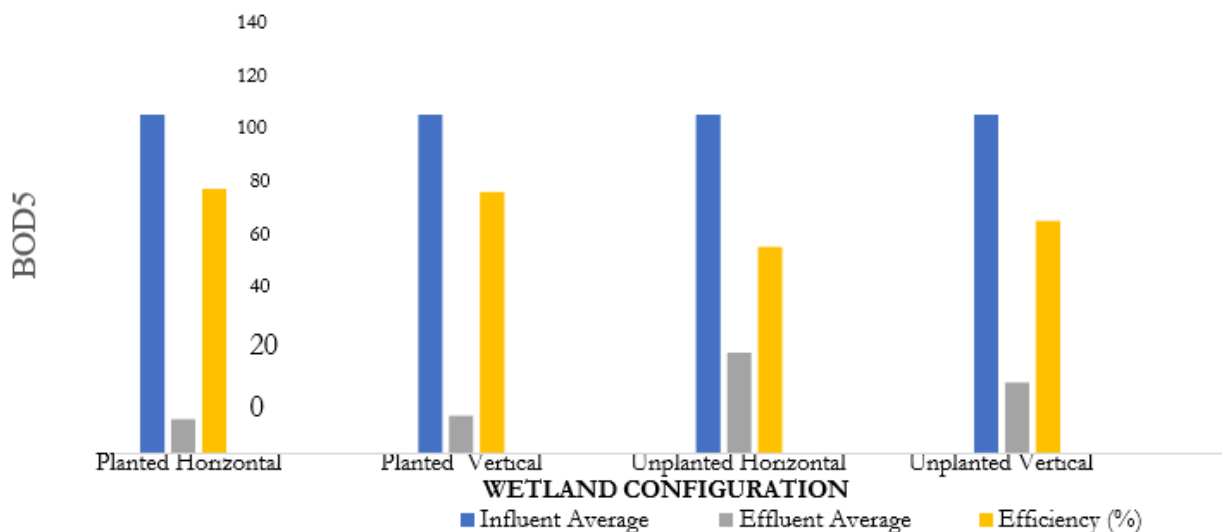


Figure 1: Influent, effluent average and efficiency of various wetlands configurations in treating biological oxygen demand (BOD₅)

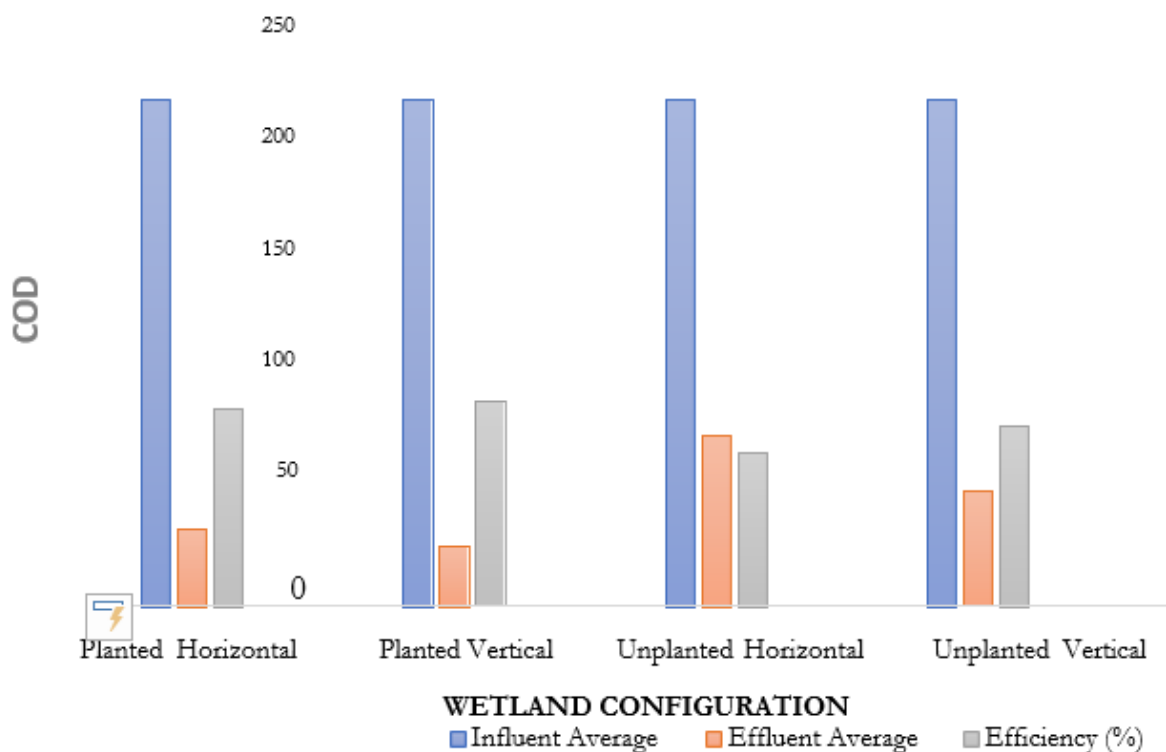


Figure 2: Influent, Effluent average and Efficiency of various wetlands configurations in treating chemical oxygen demand (COD)

Discussion:

The hybrid constructed wetland system demonstrated excellent removal performance for organic pollutants, particularly biological oxygen demand (BOD5) and chemical oxygen demand (COD).

The planted HSSF and VSSF systems achieved BOD5 removal efficiencies of 90.1% and 89.0%, respectively, while COD removal efficiencies reached 84.9% and 88.2%. In contrast, lower efficiencies were observed in the unplanted systems.

The high removal efficiencies recorded in the planted systems can be attributed to several interacting mechanisms including:

1. Aerobic biodegradation of organic matter in the VSSF unit.
2. Anaerobic and anoxic decomposition processes in the HSSF unit.
3. Enhanced microbial attachment on gravel and sand media.
4. Oxygen transfer through plant roots.
5. Increased microbial activity within the rhizosphere.

The superior performance of the VSSF unit indicates that oxygen availability significantly influenced organic matter degradation. Similar findings have been reported by previous studies on hybrid wetland systems.

3.5 Suspended and Dissolved Solids Removal

Table 3: Solids Reduction Performance

| Parameter | Best Performing Unit | Efficiency (%) | Dominant Mechanism |
|------------|----------------------|----------------|-------------------------------|
| TSS (mg/L) | Planted VSSF | 77.7 | Filtration & sedimentation |
| TDS (mg/L) | Planted VSSF | 58.2 | Adsorption & microbial uptake |
| TS (mg/L) | Planted VSSF | 63.1 | Combined processes |

Source: Abari *et al.* (2026)

- Vertical wetlands provided better solids removal due to improved filtration.
- Vegetation enhanced sediment trapping and reduced flow velocity.

3.6 Nutrient Removal Performance

Table 4: Nutrient Removal Efficiency

| Parameter | Planted HSSF (%) | Planted VSSF (%) | Removal Mechanism |
|----------------|------------------|------------------|-------------------------------|
| Total Nitrogen | 48.9 | 57.4 | Nitrification–denitrification |

| | | | |
|----------|------|------|----------------------------|
| Sulphate | 35.2 | 45.5 | Microbial reduction |
| Calcium | 46.4 | 57.1 | Precipitation & adsorption |

Source: Abari *et al.* (2026)

- Nitrogen removal was enhanced by hybrid design:
 - VSSF → nitrification (aerobic)
 - HSSF → denitrification (anaerobic)
- Plant uptake contributed significantly to nutrient reduction.

3.7 Statistical Analysis of Treatment Performance

Table 5: ANOVA Results for Treatment Efficiency

| Parameter | F-value | p-value | Significance |
|-------------------------|---------|---------|--------------|
| BOD ₅ (mg/L) | — | <0.05 | Significant |
| COD (mg/L) | — | <0.05 | Significant |
| TSS (mg/L) | — | <0.05 | Significant |

Source: Abari *et al.* (2026)

Discussion:

One-way analysis of variance (ANOVA) was conducted to determine whether significant differences existed among the treatment systems.

The results indicated statistically significant differences ($p < 0.05$) between planted and unplanted wetland units for major parameters including BOD₅, COD, and TSS.

The calculated F-values demonstrated that vegetation significantly improved treatment efficiency by enhancing biological and physicochemical pollutant removal processes.

These findings confirm that the presence of *Sacciolepis africana* positively influenced wastewater treatment performance in the hybrid wetland system.

3.8 Effect of Vegetation (*Sacciolepis Africana*)

Table 6: Influence of Vegetation on Removal Efficiency

| Parameter | Planted (%) | Unplanted (%) | Improvement (%) |
|-------------------------|-------------|---------------|-----------------|
| BOD ₅ (mg/l) | 90.1 | 70.3 | +19.8 |
| COD (mg/l) | 88.2 | 66.4 | +21.8 |
| TN (mg/L) | 57.4 | — | — |

Source: Abari *et al.* (2026)

The presence of *Sacciolepis africana* improved performance through:

- Nutrient uptake
- Oxygen diffusion into rhizosphere
- Enhanced microbial activity

3.9 Compliance with Discharge Standards

Table 7: Effluent Quality vs Regulatory Standards

| Parameter | Effluent Value | WHO Standard | Compliance |
|------------------|----------------|--------------|------------|
| BOD ₅ | ~11–13 mg/L | 10–30 mg/L | ✓ |
| COD | ~25–33 mg/L | 40–60 mg/L | ✓ |
| TSS | ~32 mg/L | 30–50 mg/L | ✓ |

Source: Abari *et al.* (2026)

Discussion:

The treated effluent met or approached acceptable discharge limits, demonstrating the system’s suitability for real-world application.

3.10 Overall Evaluation of the Treatment System

The hybrid constructed wetland system proved to be an effective and sustainable technology for aquaculture wastewater treatment. Key outcomes include:

- High removal efficiency for organic pollutants
- Significant reduction in suspended and dissolved solids
- Effective nutrient removal through combined biological processes
- Superior performance of planted systems compared to unplanted systems

The integration of HSSF and VSSF systems created optimal environmental conditions for pollutant removal, making the system suitable for practical application, particularly in resource-limited regions.

4.0 Conclusion and Recommendations

4.1 Conclusion

This study evaluated the performance of a hybrid constructed wetland system comprising horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) units for the treatment of aquaculture wastewater. The system was operated under planted and unplanted conditions using *Sacciolepis africana* as the test macrophyte.

The results revealed that aquaculture wastewater contained high concentrations of organic matter, suspended solids, and nutrients, with values exceeding recommended discharge limits. The hybrid constructed wetland system significantly improved wastewater quality by effectively reducing pollutant concentrations.

The planted hybrid wetland systems demonstrated superior performance compared to the unplanted units. Maximum removal efficiencies of approximately 90.1% for biological oxygen demand (BOD₅), 88.2% for chemical oxygen demand (COD), 77.7% for total suspended solids (TSS), and 57.4% for total nitrogen (TN) were achieved, particularly in the vertical subsurface flow units. The enhanced performance of planted wetlands was attributed to the combined effects of plant uptake, oxygen transfer, and increased microbial activity within the rhizosphere.

The hybrid configuration proved highly effective due to the integration of aerobic and anaerobic treatment processes. The vertical flow system promoted oxygenation and aerobic degradation, while the horizontal flow system facilitated denitrification and further pollutant removal. Statistical analysis confirmed that the differences between planted and unplanted systems were significant ($p < 0.05$), highlighting the importance of vegetation in wetland performance.

Furthermore, the treated effluent met or closely approached recommended discharge standards for key parameters such as BOD₅, COD, and TSS, demonstrating the suitability of hybrid constructed wetlands as an environmentally sustainable and cost-effective wastewater treatment technology for aquaculture operations. Overall, this study confirms that hybrid constructed wetlands planted with *Sacciolepis africana* offer a reliable, low-cost, and eco-friendly solution for aquaculture wastewater treatment, particularly in developing regions where conventional treatment systems may be economically or technically impractical.

4.2 Recommendation

Based on the findings of this study, the following recommendations are proposed:

1. **Adoption in Aquaculture Systems**
Hybrid constructed wetlands should be adopted as a sustainable wastewater treatment option in aquaculture farms, especially in developing countries where low-cost and low-maintenance technologies are required.
2. **Preference for Planted Wetlands**
The use of macrophytes such as *Sacciolepis africana* is strongly recommended, as planted systems demonstrated significantly higher pollutant removal efficiencies compared to unplanted systems.
3. **Optimization of System Design**
Future designs should prioritize vertical subsurface flow configurations within hybrid systems due to their superior performance in organic and nutrient removal.
4. **Scale-Up Studies**
Further research should focus on scaling up the hybrid constructed wetland system from laboratory scale to pilot and full-scale applications to assess long-term performance under real field conditions.
5. **Evaluation of Other Macrophyte Species**
Additional studies should investigate the performance of other locally available aquatic plants to identify species with higher pollutant removal potential and adaptability.
6. **Long-Term Monitoring**
Extended monitoring is recommended to evaluate seasonal variations, plant growth dynamics, and long-term system stability.
7. **Integration with Other Treatment Technologies**
Hybrid constructed wetlands may be combined with pre-treatment or post-treatment systems (e.g., sedimentation tanks or filtration units) to further enhance overall treatment efficiency.
8. **Policy and Regulatory Support**
Government agencies and environmental regulatory bodies should promote the use of nature-based

wastewater treatment systems by incorporating them into environmental management policies and guidelines.

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Appendix



Plate 1: Set-up of Unplanted hybrid constructed wetlands

Source: Abari et al. (2026)

Table A1: Plant parts, methods and frequency of data collection

| Plant Parts | Methods | Frequency Day 0 | Day 14 | Day 28 | Day 42 | Day 56 | Day 70 | Day 84 | Day 98 | Day 112 | Day 126 | Day 140 | Day 154 | Day 168 | |
|----------------------------|----------------------------|-----------------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|----|
| Plant Density H1 | Counting no stems of stems | 18 | 23 | 26 | 30 | 37 | 39 | 48 | 53 | 63 | 82 | 84 | 95 | 114 | |
| | | H2 | 18 | 27 | 33 | 39 | 43 | 49 | 51 | 62 | 67 | 70 | 76 | 81 | 85 |
| | | V1 | 8 | 21 | 27 | 29 | 30 | 33 | 35 | 39 | 43 | 44 | 47 | 51 | 53 |
| | | V2 | 8 | 22 | 25 | 27 | 31 | 36 | 38 | 39 | 47 | 52 | 54 | 56 | 60 |
| Plant Leaves H1 | Ruler to nearest CM | 9 | 13 | 15 | 24 | 30 | 44 | 46 | 47 | 51 | 52 | 55 | 57 | 61 | |
| | | H2 | 11 | 14 | 17 | 25 | 31 | 43 | 45 | 47 | 49 | 51 | 52 | 54 | 55 |
| | | V1 | 10 | 11 | 16 | 21 | 23 | 24 | 36 | 41 | 43 | 50 | 51 | 54 | 55 |
| | | V2 | 9 | 12 | 16 | 22 | 33 | 39 | 45 | 48 | 51 | 53 | 55 | 56 | 58 |
| Plants Stems H1 | Ruler to nearest CM | 4 | 6 | 7 | 11 | 14 | 16 | 19 | 22 | 25 | 29 | 30 | 32 | 33 | |
| | | H2 | 4 | 6 | 8 | 10 | 12 | 13 | 18 | 22 | 26 | 27 | 29 | 31 | 31 |
| | | V1 | 4 | 5 | 9 | 11 | 14 | 17 | 21 | 23 | 25 | 28 | 31 | 32 | 33 |
| | | V2 | 4 | 6 | 9 | 12 | 15 | 17 | 22 | 26 | 27 | 30 | 32 | 33 | 35 |
| Plants Roots H1 | Ruler to nearest CM | 5 | 7 | 8 | 10 | 12 | 14 | 15 | 19 | 21 | 22 | 23 | 25 | 27 | |
| | | H2 | 6 | 7 | 9 | 11 | 13 | 15 | 17 | 18 | 25 | 25 | 26 | 26 | 27 |
| | | V1 | 6 | 6 | 8 | 10 | 13 | 15 | 16 | 19 | 22 | 29 | 30 | 31 | 33 |
| | | V2 | 7 | 7 | 8 | 9 | 12 | 14 | 17 | 18 | 21 | 27 | 29 | 34 | 35 |

Source: Abari et al. (2026)