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COMPARATIVE EVALUATION OF HOLLOW FIBRE TUBES AND PROCESSED NIPA PALM (*NYPA FRUTICANS*) STEM AS LOW-COST FILTRATION MEDIA FOR WASTEWATER REMEDIATION AND GROUNDWATER PROTECTION

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ABSTRACT

The high cost of conventional wastewater treatment technologies has increased the demand for sustainable and locally available filtration materials capable of supporting environmental remediation and water resource protection. This study comparatively evaluated the performance of hollow fibre tubes (HFT) and processed Nipa Palm stem (PNS) as low-cost filtration media for wastewater treatment and environmental remediation. Laboratory-scale filtration columns were constructed and operated under identical hydraulic conditions using synthetic municipal wastewater. The treatment efficiencies of both media were assessed based on turbidity, total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total dissolved solids (TDS), nitrate, phosphate, and microbial load reduction. A completely randomized design with triplicate analyses was employed, and statistical evaluation was performed using one-way analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$.The results revealed that HFT achieved significantly higher removal efficiencies for turbidity (94.8%), TSS (92.4%), BOD_5 (89.3%), COD (86.7%), and total coliforms (98.6%) than PNS, which recorded removal efficiencies of 82.1%, 79.5%, 71.8%, 68.2%, and 91.4%, respectively. However, PNS demonstrated comparable performance in nitrate and phosphate removal while exhibiting substantially lower operational costs. Statistical analysis indicated significant differences ($p < 0.05$) between the two filtration media for most physicochemical parameters. The findings suggest that hollow fibre tubes provide superior treatment efficiency, whereas processed Nipa Palm stem represents a cost-effective and sustainable alternative for decentralized wastewater treatment in resource-constrained communities. By reducing contaminant loads prior to environmental discharge, both filtration media contribute to environmental remediation and the protection of soil and groundwater systems from pollution.

KEYWORDS: Hollow fibre membrane, Nipa Palm stem, wastewater remediation, environmental protection, low-cost filtration, sustainable water treatment.

1.0 INTRODUCTION

Rapid population growth, urbanization, and industrialization have significantly increased the generation of wastewater globally, posing serious threats to environmental quality and public health. In many developing regions, inadequate wastewater treatment infrastructure results in the discharge of untreated effluents into surface water bodies and soils, increasing the risk of groundwater contamination. From a hydrogeological perspective, contaminants such as nitrates, phosphates, organic matter, and pathogenic microorganisms can infiltrate through soil layers and permeable geological formations into aquifers, thereby degrading groundwater quality, which serves as a major source of potable water for domestic and agricultural use (Ravindiran et al., 2023; Talabi & Kayode, 2019).

Conventional wastewater treatment technologies, including advanced membrane systems and physicochemical processes, are effective in pollutant removal but are often associated with high capital, operational, and maintenance costs. These limitations restrict their application in resource-constrained communities, particularly in rural and peri-urban areas. Consequently, there is increasing interest in low-cost, sustainable, and locally available filtration materials as alternatives for decentralized wastewater treatment systems. Such approaches not only reduce treatment costs but also contribute to environmental remediation and the protection of soil and groundwater systems (Bhatnagar et al., 2015;Banerjeeet al., 2016;Adowei et al.,2020).

Natural and biomass-derived materials have gained considerable attention due to their adsorption capacity, biodegradability, and availability. *Nypa fruticans* (Nipa palm), a mangrove-associated species common in tropical coastal environments, contains lignocellulosic structures that make it suitable for environmental applications. Processed Nipa Palm stem (PNS) has demonstrated potential for pollutant adsorption and water purification due to its porous structure and surface characteristics (Quoc et al., 2025; Meriatna et al., 2024; Bui, et al.,2014; Banerjee et al., 2016). These properties enable it to function as a low-cost filtration medium capable of reducing organic and inorganic contaminants in wastewater. In contrast, hollow fibre tubes (HFT), which are engineered membrane-based filtration materials commonly composed of polymeric substances, are widely recognized for their high efficiency in removing suspended solids, organic pollutants, and microorganisms. However, despite their superior performance, their relatively high cost may limit widespread adoption in low-income settings.

Untreated wastewater represents a major pathway for contamination of subsurface environments. The infiltration of polluted water into soils can lead to the transport of contaminants into groundwater systems, necessitating preventive remediation strategies to protect aquifers and maintain water quality (Talabi & Kayode, 2019). Therefore, effective wastewater treatment prior to environmental discharge plays a critical role in reducing pollutant loading and mitigating groundwater contamination risks.

Despite increasing research on alternative filtration media, comparative studies evaluating the performance of engineered and biomass-derived materials for wastewater remediation and groundwater protection remain limited. This study therefore comparatively evaluates hollow fibre tubes and processed Nipa Palm stem as low-cost filtration media for wastewater treatment. The findings are expected to provide insights into their suitability for decentralized wastewater treatment, environmental remediation, and the sustainable protection of groundwater resources in resource-limited communities.

2.0 MATERIALS AND METHODS

Study Design

A laboratory-scale experimental study was conducted to evaluate and compare the performance of two filtration media for wastewater treatment and environmental remediation.

The systems investigated were:

1. Hollow Fibre Tube (HFT) filter
2. Processed Nipa Palm Stem (PNS) filter

Both systems were operated under identical hydraulic conditions to ensure fair comparison. Each treatment was replicated three times, and a completely randomized experimental design was adopted to minimize bias and improve statistical reliability.

Preparation of Filtration Media

Hollow Fibre Tubes (HFT)

Commercial polypropylene hollow fibre membranes with an average pore size of 0.1 µm were used as the synthetic filtration medium. The membranes were rinsed with distilled water prior to use to remove manufacturing residues and conditioned under flow conditions to stabilize performance.

Membrane-based filtration systems are widely used in wastewater treatment due to their high efficiency in removing suspended solids and microorganisms (Shannon et al., 2008).

Processed Nipa Palm Stem (PNS)

Fresh stems of *Nypa fruticans* were collected from coastal wetland environments in Rivers State, Nigeria. The stems were processed as follows:

- Thorough washing to remove dirt and organic debris
- Cutting into 5–10 mm fragments
- Oven-drying at 105°C for 24 hours
- Carbonization at 450°C to enhance porosity and adsorption capacity
- Sieving to obtain uniform particle size (1–2 mm)

Thermal carbonization is a well-established method for improving the adsorption properties of biomass materials by increasing surface area and pore structure (Bhatnagar et al., 2015).

Wastewater Characteristics

Synthetic municipal wastewater was prepared to simulate typical domestic wastewater conditions. The influent was characterized prior to treatment to establish baseline conditions following standard analytical procedures.

Physicochemical and microbiological parameters were analyzed in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, & WEF, 2017).

The average influent characteristics were:

Parameter	Value
pH	7.42
Turbidity (NTU)	168
Total Suspended Solids (mg/L)	245
Biochemical Oxygen Demand (BOD_5) (mg/L)	198
Chemical Oxygen Demand (COD) (mg/L)	425
Total Dissolved Solids (mg/L)	612

Nitrate (mg/L)	28.4
Phosphate (mg/L)	11.5
Total Coliform (CFU/100 mL)	1.2×10^6

These parameters represent key indicators of organic pollution, nutrient loading, and microbial contamination relevant to groundwater protection and environmental remediation studies (Ravindiran et al., 2023).

Experimental Setup

Two vertical filtration columns (100 cm height × 10 cm diameter) were constructed for the experiment. Each column was packed with one of the filtration media (HFT or PNS) and operated under identical hydraulic conditions.

Operational parameters included:

- Flow rate: 2 L h^{-1}
- Hydraulic retention time (HRT): 4 hours
- Experimental duration: 30 days
- Flow configuration: Down-flow gravity filtration

Effluent samples were collected at regular intervals for physicochemical and microbiological analysis using standard methods (APHA et al., 2017).

Statistical Analysis

Experimental data were analyzed using descriptive and inferential statistics. Mean and standard deviation were used to summarize results. One-way Analysis of Variance (ANOVA) was used to test for significant differences between treatments, while Tukey's Honestly Significant Difference (HSD) post-hoc test was applied for pairwise comparisons. Statistical significance was set at $p < 0.05$.

Statistical analyses are commonly used in environmental engineering studies to validate treatment efficiency differences between filtration systems (Montgomery, 2013; Oliver et al.,2014).

3.0 RESULTS

Effluent Quality

Table 1. Mean Effluent Characteristics.

Parameter	Influent	HFT	PNS
Turbidity(NTU)	168	8.7	30.1
TSS(mg/L)	245	18.6	50.2
BOD_5 (mg/L)	198	21.2	55.8
COD(mg/L)	425	56.5	135.1
TDS(mg/L)	612	235	312
Nitrate(mg/L)	28.4	8.1	9.5
Phosphate(mg/L)	11.5	2.8	3.2
TotalColiform(CFU/100mL)	1.2×10^6	1.7×10^4	1.0×10^5

Fig. 1comparing influent, HFT, and PNS effluent quality.

Table2.RemovalEfficiency.(%)

Parameter	HFT(%)	PNS(%)
Turbidity	94.8	82.1
TSS	92.4	79.5
BOD_5	89.3	71.8
COD	86.7	68.2
TDS	61.6	49.0
Nitrate	71.5	66.5
Phosphate	75.7	72.2
TotalColiform	98.6	91.4

Fig 2. graphical representation of the removal efficiency comparison between HFT and PNS.

Table3. ANOVA Results.

Parameter	F-value	p-value
Turbidity	38.44	<0.001
TSS	29.61	<0.001
BOD_5	34.57	<0.001
COD	31.42	<0.001
TDS	8.56	0.012
Nitrate	2.34	0.087
Phosphate	1.87	0.124
Coliform	42.11	<0.001

4.0 DISCUSSION

Effluent Quality Performance

The influent wastewater exhibited a high pollution loading across all measured physicochemical and microbiological parameters (Table 1), with turbidity (168

NTU), total suspended solids (TSS) (245 mg/L), biochemical oxygen demand (BOD_5) (198 mg/L), chemical oxygen demand (COD) (425 mg/L), total dissolved solids (TDS) (612 mg/L), nitrate (28.4 mg/L), phosphate (11.5 mg/L), and total coliform (1.2×10^6 CFU/100 mL). These values indicate a heavily contaminated wastewater stream dominated by organic matter, suspended solids, nutrients, and pathogenic microorganisms, typical of untreated wastewater.

Such elevated pollutant concentrations reflect wastewater characteristics commonly associated with insufficiently treated effluents, where organic and microbial loading remain high due to limited treatment efficiency and inadequate sanitation systems (Metcalf & Eddy et al., 2014; WWAP, 2021). The elevated BOD_5 and COD values indicate a strong organic pollution load, suggesting the presence of both readily degradable and more complex organic compounds typical of mixed wastewater systems (Henze et al., 2008; Droste & Gehr, 2018).

Similarly, the high turbidity and TSS values indicate a substantial presence of suspended and colloidal particles. These particles contribute to reduced light penetration, increased pollutant transport, and potential shielding of microorganisms, thereby complicating treatment processes. High suspended solids are also known to negatively influence filtration performance by contributing to clogging and fouling in treatment systems (Le-Clech et al., 2006; Meng et al., 2017).

The elevated total coliform concentration (1.2×10^6 CFU/100 mL) confirms severe faecal contamination, indicating a high public health risk if discharged without adequate treatment. Such microbial loading significantly exceeds safe water quality thresholds and highlights the necessity for effective treatment prior to environmental discharge (World Health Organization, 2017).

Treatment System Performance

Following treatment, both the Hollow Fibre Tube (HFT) and Processed Nipa Palm Stem (PNS) systems achieved substantial reductions across all measured parameters (Table 2), confirming their effectiveness as filtration and polishing media. However, statistically significant differences between both systems (Table 3) indicate different removal efficiencies and mechanisms.

The HFT system consistently demonstrated higher performance across turbidity, TSS, BOD_5, COD, TDS, and total coliform removal. This improved efficiency is attributed to the engineered structure of membrane-based systems, which operate through:

- size-exclusion filtration via microporous membranes
- high surface area enabling enhanced pollutant contact
- biofilm formation contributing to biodegradation
- improved solid–liquid separation stability

Membrane bioreactor and hollow fibre systems are widely reported to achieve high removal efficiencies due to their combined physical and biological treatment mechanisms (Judd, 2011; Le-Clech et al., 2006). Their effectiveness in microbial removal is particularly notable due to membrane barrier properties that physically retain pathogens (Shannon et al., 2008; Wang et al., 2014).

In contrast, the PNS system achieved moderate but significant pollutant reductions across all parameters. Its performance is governed by the natural physicochemical properties of lignocellulosic biomass, which include:

- porous fibrous structure facilitating particle retention
- surface functional groups such as hydroxyl (–OH) and carboxyl (–COOH) enabling adsorption
- rough surface morphology supporting microbial attachment

Natural plant-based materials have been widely recognized as low-cost adsorbents capable of removing contaminants through combined adsorption and filtration processes (Bhatnagar et al., 2010; Crini, 2006; Kyzas et al., 2014). However, their efficiency is generally lower than engineered membrane systems due to larger pore sizes and weaker hydraulic control (Ali, 2010; Wang & Peng, 2010).

Comparative Interpretation

Generally, the observed trend (Influent >> PNS > HFT in reverse effluent quality) reflects two fundamentally different treatment mechanisms. The HFT system is dominated by engineered membrane separation and enhanced biological activity, while the PNS system relies on natural adsorption, sedimentation, and passive filtration processes.

Despite these differences, both systems significantly improved wastewater quality, demonstrating their potential for decentralized wastewater treatment applications. The high microbial reduction observed in both systems is particularly important for reducing health risks associated with wastewater discharge (World Health Organization, 2017).

Comparative Treatment Efficiency (HFT vs PNS)

Suspended Solids and Turbidity

The Hollow Fibre Tube (HFT) system achieved superior turbidity (94.8%) and total suspended solids (TSS) (92.4%) removal compared to the Processed Nipa Palm Stem (PNS) system, which recorded 82.1% and 79.5% respectively. This marked difference reflects the dominance of engineered membrane filtration mechanisms in HFT, particularly size exclusion, surface interception, and physical straining facilitated by its micro-porous fibre structure.

The removal efficiency (η) is expressed as:

$$\eta = (C_i - C_e) / C_i \times 100$$

where η represents removal efficiency, Ci is influent concentration, and Ce is effluent concentration.

The high performance of HFT is consistent with membrane filtration theory, where separation is governed primarily by pore size selectivity and the development of a dynamic cake layer that enhances particle retention over time. Membrane systems, particularly hollow fibre modules, are widely reported to achieve >90% removal of suspended solids due to these combined mechanisms (Le-Clech et al., 2006; Meng et al., 2017; Shon et al., 2020). In contrast, the PNS system relies on physical trapping within a natural fibrous matrix, which is less uniform and less efficient in controlling fine particulate passage.

Organic Load Removal (BOD_5 and COD)

For organic pollutant removal, HFT recorded higher efficiencies for BOD_5 (89.3%) and COD (86.7%) compared to PNS (71.8% and 68.2%). This indicates that HFT provides stronger retention of organic matter and promotes enhanced biodegradation within the system.

The improved organic removal in HFT can be attributed to the combined action of physical separation and biofilm development on membrane surfaces, which increases microbial activity and enhances breakdown of biodegradable organic compounds. This dual mechanism is a defining characteristic of membrane-based treatment systems.

These findings align with previous studies showing that membrane bioreactors and hollow fibre systems significantly improve organic load reduction through integrated filtration and biological degradation processes (Le-Clech et al., 2006; Wang et al., 2014; Meng et al., 2017). The lower performance of PNS reflects its reliance on passive adsorption and limited microbial colonization, which restricts sustained degradation of organic pollutants.

Nutrient Removal (TDS, Nitrate, Phosphate)

Total dissolved solids (TDS) removal was moderate in both systems, with HFT achieving 61.6% and PNS 49.0%. This lower efficiency reflects the inherent limitation of both systems in removing dissolved ionic species, as neither mechanism is specifically designed for ion exchange or advanced chemical separation.

Nitrate and phosphate removal showed no statistically significant difference ($p > 0.05$) (Table 3), suggesting that both systems rely on similar passive mechanisms for nutrient attenuation.

These mechanisms likely include:

- adsorption onto biomass or biofilm surfaces
- microbial assimilation into biomass
- limited nitrification–denitrification processes under low-energy conditions

Such behavior is typical of low-energy treatment systems, where nutrient removal is secondary and primarily biologically mediated rather than chemically driven. Similar observations have been reported in passive filtration and constructed wetland systems where nutrient removal depends heavily on microbial activity and contact time (Kadlec & Wallace, 2009; Vymazal, 2011; Vymazal, 2014;Rahman et al.,2021; Sutherland et al.,2020).

Microbial Removal (Coliform)

The HFT system achieved extremely high total coliform reduction (98.6%), significantly outperforming the PNS system (91.4%). This demonstrates the strong capability of membrane-based systems in pathogen removal due to physical size exclusion, where pore sizes are sufficiently small (<0.1 µm in many hollow fibre membranes) to retain bacteria and protozoa.

Membrane filtration is widely recognized as one of the most effective physical barriers for microbial removal, often achieving >4-log reductions in bacterial concentrations under optimized conditions. This performance is attributed to the combined effects of membrane sieving and biofilm-enhanced pathogen retention (Shannon et al., 2008; Meng et al., 2017;Thao et al.,2022). In contrast, PNS relies primarily on adsorption and entrapment mechanisms, which are less effective in consistently removing microorganisms, especially under variable hydraulic conditions.

In summary, the comparative performance clearly shows that:

- HFT system → dominated by engineered membrane separation + biofilm activity
- PNS system → dominated by natural adsorption + physical filtration

This explains the consistent superiority of HFT across all measured parameters, particularly for suspended solids, organic load, and microbial removal. However, PNS still demonstrates meaningful treatment potential, especially considering its low-cost, renewable, and locally available nature.

Statistical Validation (ANOVA Interpretation)

The ANOVA results (Table 3) confirm statistically significant differences between the treatment systems for most parameters.

- Highly significant differences ($p < 0.001$): turbidity, TSS, BOD_5, COD, and total coliform
- Moderate significance ($p = 0.012$): TDS
- Not significant ($p > 0.05$): nitrate and phosphate

These results indicate that the treatment systems differ substantially in their ability to remove suspended solids, organic matter, and microbial contaminants, while their performance in nutrient removal is comparatively similar.

The observed significance pattern suggests that physical and organic pollutant removal mechanisms vary strongly between the Hollow Fibre Tube (HFT) and Processed Nipa Palm Stem (PNS) systems, particularly due to differences in filtration structure, surface area, and retention capacity. In contrast, nutrient removal appears to be governed by similar passive processes, such as adsorption onto media surfaces, limited microbial uptake, and weak denitrification activity under low-energy conditions.

This statistical outcome supports the earlier findings in Sections 1.1 and 1.2, confirming that HFT performance is significantly superior for parameters dominated by physical separation and organic degradation, while both systems show comparable limitations in dissolved nutrient removal.

Performance Mechanism Interpretation

Hollow Fibre Tube (HFT)

The performance of the Hollow Fibre Tube (HFT) system is primarily driven by a combination of advanced physical and biological treatment mechanisms. These include:

- micro-porous membrane filtration
- surface cake layer formation
- biofilm-enhanced biodegradation
- high surface-area-to-volume ratio

Micro-porous membrane filtration enables effective size-based separation of suspended solids and microorganisms, while the gradual formation of a cake layer further improves particle retention by acting as an additional filtration barrier. In addition, biofilm development on the membrane surface enhances biodegradation of organic matter through microbial activity. The high surface-area-to-volume ratio of hollow fibre membranes further increases contact between pollutants and the treatment surface, improving overall efficiency.

Collectively, these mechanisms contribute to the high pollutant removal performance observed in the HFT system, particularly for turbidity, TSS, organic load, and microbial contaminants (Meng et al., 2017; Shon et al., 2020;Foo et al.,2010).

Processed Nipa Palm Stem (PNS)

The removal efficiency of the Processed Nipa Palm Stem (PNS) system is mainly attributed to its natural physicochemical and structural characteristics. These include:

- lignocellulosic adsorption sites containing functional groups such as hydroxyl (–OH) and carboxyl (–COOH)
- physical filtration through a fibrous matrix structure
- microbial colonization on rough surface textures

The lignocellulosic composition of Nipa Palm provides active adsorption sites that facilitate binding of organic and inorganic pollutants. Additionally, its porous fibrous structure allows for physical trapping of suspended particles, while the rough surface promotes microbial attachment, supporting limited biodegradation processes.

Natural plant-based materials have been widely documented as effective low-cost adsorbents for wastewater treatment, particularly for polishing applications where secondary removal of pollutants is required (Bhatnagar et al., 2015; Crini, 2006; Wang & Peng, 2010;Thao et al.,2022;Kurniawan et al.,2006;Negi et al.,2012).

Environmental and Economic Implications

Although the Hollow Fibre Tube (HFT) system demonstrates superior treatment performance across most water quality parameters, its practical application is limited by several operational and economic constraints. These include:

- high installation cost
- susceptibility to membrane fouling
- frequent maintenance requirements

The high capital and operational costs associated with membrane-based systems make them less suitable for low-income or decentralized wastewater treatment applications, particularly in rural and resource-limited settings. In addition, membrane fouling remains a persistent operational challenge that can reduce system efficiency and increase maintenance demands over time.

In contrast, the Processed Nipa Palm Stem (PNS) system presents several economic and environmental advantages, including:

- locally available biomass material
- low operational and maintenance cost
- sustainable waste valorization pathway

The use of agricultural waste such as Nipa Palm for wastewater treatment promotes resource recovery and reduces environmental burden associated with biomass disposal. This approach supports the transformation of waste materials into functional treatment media, thereby contributing to sustainable environmental management practices.

The comparative assessment highlights a clear trade-off between performance and affordability. While HFT provides higher treatment efficiency, PNS offers a more sustainable and cost-effective alternative for decentralized applications where advanced infrastructure is not feasible.

This approach aligns with global circular economy principles that encourage the reuse of agricultural residues and organic waste materials in environmental remediation processes, particularly in water and wastewater treatment systems (UNEP, 2022; FAO, 2020; WWAP, 2021).

5. CONCLUSION

This study evaluated the performance of Hollow Fibre Tube (HFT) and Processed Nipa Palm Stem (PNS) as alternative wastewater treatment media. The findings show that both systems significantly improved wastewater quality, although with clear differences in treatment efficiency.

The HFT system consistently demonstrated higher removal efficiencies across all measured parameters, including turbidity (94.8%), TSS (92.4%), BOD_5 (89.3%), COD (86.7%), TDS (61.6%), and total coliform (98.6%). This superior performance is attributed to membrane-based separation mechanisms involving size exclusion, cake-layer formation, and biofilm-assisted degradation. The high microbial and organic removal efficiencies indicate strong effectiveness in reducing health-related contaminants.

In contrast, the PNS system achieved moderate removal efficiencies ranging from 49.0% to 82.1%. Its performance is driven by adsorption onto lignocellulosic functional groups, physical filtration through fibrous structures, and limited microbial activity. Although less efficient than HFT, it still provides meaningful pollutant reduction suitable for low-intensity treatment applications.

Statistical analysis (ANOVA) confirmed significant differences between both systems for most parameters ($p < 0.05$), particularly for turbidity, suspended solids, organic load, and microbial content. Overall, the study highlights that HFT provides higher treatment efficiency, while PNS offers a more affordable and sustainable alternative for decentralized wastewater treatment applications and preventing sub-surface contamination.

3. Recommendations

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

1. Adoption of Hybrid Treatment Systems

Combining HFT and PNS is recommended to improve overall treatment efficiency, where PNS can function as a preliminary or polishing stage to reduce pollutant load.

2. Improvement of PNS Performance

Further research should focus on enhancing the adsorption capacity of Nipa Palm stem through physical or chemical modification such as activation or carbonization.

3. Long-Term Operational Studies

Extended performance evaluation is required to assess membrane fouling in HFT systems and structural stability of PNS under continuous wastewater flow conditions.

4. Field-Scale Application Testing

Pilot-scale implementation should be conducted to evaluate real-world performance under varying environmental and hydraulic conditions.

5. Economic Evaluation

A detailed cost–benefit analysis should be performed to determine the feasibility of large-scale adoption, especially for low-resource communities.

6. Improvement of Nutrient Removal

Since nitrate and phosphate removal were not significantly different between systems, additional treatment units may be required to enhance nutrient reduction efficiency.

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