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Nutrient Removal Efficiency of Constructed Wetlands Planted with Tropical Macrophytes: Implications for Decentralized Wastewater Treatment at Aturukuku Sewerage Works

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Abstract

Constructed wetlands are increasingly promoted as sustainable, low-energy wastewater treatment technologies, particularly in regions with limited financial and technical capacity. However, nutrient removal performance in constructed wetlands varies widely with vegetation type and system design. This study evaluated the nitrogen and phosphorus removal efficiency of laboratory-scale constructed wetlands planted with selected macrophyte species under controlled hydraulic conditions. Influent and effluent samples were analysed for ammonia nitrogen and soluble phosphorus using spectrophotometric methods compliant with ISO/IEC 17025 standards. Statistical evaluation was conducted using one-way analysis of variance (ANOVA) and linear regression to assess species effects and relationships between plant growth and nutrient uptake. Results showed substantial reductions in nutrient concentrations, with ammonia decreasing from 6.99 mg/L to 2.22 mg/L and soluble phosphorus from 17.47 mg/L to 3.05 mg/L. Wetlands planted with Cyperus papyrus achieved the highest removal efficiencies, averaging 82% for ammonia and 76% for soluble phosphorus. ANOVA confirmed that macrophyte species had a statistically significant effect on nutrient removal ($p < 0.05$). Regression analysis revealed a strong positive correlation between plant biomass and nutrient uptake ($R^2 > 0.60$), highlighting the importance of vegetation productivity in treatment performance. The findings demonstrate that appropriate macrophyte selection can significantly enhance nutrient removal in constructed wetlands. The study supports the use of locally adapted species such as Cyperus papyrus for decentralised wastewater treatment and safe water reuse in tropical regions, particularly in East Africa.

1.0 Introduction

Constructed wetlands (CWs) are engineered, nature-based wastewater treatment systems that mimic the physical, chemical, and biological processes of natural wetlands to improve water quality. They integrate wetland vegetation, porous substrates, and diverse microbial communities to remove pollutants through sedimentation, filtration, adsorption, microbial transformation, and plant uptake (Vymazal, 2011; Kadlec & Wallace, 2009). Owing to their low energy requirements, operational simplicity, and ecological co-benefits, CWs have gained increasing attention as sustainable wastewater treatment options, particularly in decentralised and resource-limited contexts.

Nitrogen (N) and phosphorus (P) in domestic wastewater are major concerns because they contribute to eutrophication in recipient water bodies. The overflow of nutrients promotes algal blooms, reduces dissolved oxygen, and causes biodiversity decline in aquatic ecosystems (Carpenter et al., 1998; Smith & Schindler, 2009). Implementing effective nutrient management is crucial for protecting freshwater ecosystems and ensuring water quality.

The Aturukuku Sewage Treatment Plant is situated about 1 kilometer from the Tororo Municipal Council Business Centre in eastern Uganda, where it collects wastewater from the local community. The plant features a Wastewater Stabilisation Pond (WWSP) that uses natural processes such as retention time, free airflow, and warm tropical conditions for treatment. The system includes three ponds: two parallel facultative ponds that feed into a maturation pond, which then directs the flow to the constructed wetland.

All sewer connections from the Tororo Municipal Council Business Centre discharge into a single 300 mm asbestos pipe that drains waste into the Aturukuku Wastewater Treatment Plant. At the plant entrance, a Grit Chamber removes sand particles and other floating materials, such as plastics, during daily operations. Combustible materials are dried and burned to prevent pollution in the surrounding area. Sandy materials are collected and stored on site until enough accumulate for potential contractors' use.

Wastewater flows into two parallel facultative ponds designed to treat water high in solids and low in oxygen, which could negatively impact nearby aquatic and inland ecosystems if not carefully managed. The low oxygen levels at the inlets support the presence of anaerobic bacteria. With an approximate retention time of 28 days, multiple processes occur simultaneously, including settling, gas evaporation driven by warm temperatures, and decomposition by both anaerobic and aerobic microbes, going through different stages. Meanwhile, wind continuously sweeps across the surface, aiding in dissolving and removing solids until optimal levels are reached.

1.1 Maturation Pond stage.

This pond is shallower than the Facultative Pond, with a retention time of about 14 days due to its roughly half-depth. Its design focuses on creating a thinner water layer to enhance the dissolution of free oxygen. Dissolved oxygen supports aerobic bacteria, which are not yet fully developed in the facultative stage, helping to decompose leftover organic matter from earlier stages. Additional settling also occurs. Routine management involves removing non-degradable materials, plastics, and scum buildup to prevent environmental issues, enhance sunlight penetration, and promote better circulation.

Desludging is essential for effective treatment because solid waste constantly accumulates in the ponds and can eventually fill them. The sludge is regularly extracted from the ponds to manage buildup and is then transferred to drying beds. After drying, farmers can use this sludge as mature compost.

2.0 Conventional Wastewater Treatment Technologies

2.1 Limitations of Conventional Wastewater Treatment Technologies

Conventional wastewater treatment plants (WWTPs) effectively remove nutrients through advanced biological processes, chemical precipitation, and tertiary treatments. However, they often entail high initial investments, significant energy consumption, and complex operations. Their reliance on electromechanical equipment, continuous power, skilled operators, and chemicals increases lifecycle costs and makes them less suitable for low-income or resource-limited settings (Kadlec & Wallace, 2009; Vymazal, 2007). In many developing areas, issues like intermittent power supplies, limited technical expertise, and insufficient financial resources further compromise the performance of these systems, sometimes causing subpar results or failures. These issues emphasise the importance of exploring alternative treatment options that are resilient, cost-effective, and tailored to local socio-economic contexts.

2.2 Advantages of Aturukuku Constructed Wetland for Nutrient Removal

Aturukuku constructed wetlands provide a cost-effective, energy-efficient solution for nutrient removal by leveraging natural processes. Nitrogen and phosphorus removal in Aturukuku CW occurs through combined mechanisms, including sedimentation, substrate adsorption, microbial nitrification–denitrification, plant uptake, and long-term storage in biomass and sediments (Brix, 1997; Wu et al., 2015). These processes function with minimal external energy, making Constructed Wetlands significantly less energy-dependent than traditional wastewater treatment plants. Economically, CWs have lower initial costs due to simpler infrastructure and the potential to use locally sourced materials. Their operation and maintenance are also minimal, since CWs do not require continuous aeration, chemical addition, or specialised staff. Therefore, they are ideal for small communities, peri-urban areas, and rural regions with limited financial and technical resources (Kadlec & Wallace, 2009; Vymazal, 2007). CWs offer environmental benefits beyond wastewater treatment, including habitat creation, biodiversity, carbon capture, and landscape blending. These services support sustainability and reduce the wastewater system's footprint (Wu et al., 2015).

3.0 Role of Constructed Wetlands in Achieving the Sustainable Development Goals

Aturukuku constructed wetland plays a direct role in advancing Sustainable Development Goal (SDG 6) by enhancing access to safe wastewater treatment and decreasing nutrient pollution in surface and groundwater sources. Their affordability and decentralised design make them especially effective for increasing sanitation services in underserved areas. Additionally, Constructed Wetlands support SDG 13 (Climate Action) by offering low-energy treatment options that produce fewer greenhouse gases compared to traditional wastewater treatment plants. Their ability to sequester carbon in plant biomass and sediments enhances their climate-mitigation benefits. Furthermore, Aturukuku constructed wetlands contribute to SDG 15 (Life on Land) by creating wetland habitats that foster biodiversity, improve ecological connectivity, and promote sustainable land use. By combining wastewater treatment with ecosystem restoration, the CWs provide a multifunctional solution that tackles water quality issues, enhances climate resilience, and conserves ecosystems.

4.0 Factors Influencing Nutrient Removal and Implications for Safe Reuse

The nutrient removal efficiency of the constructed wetland at Aturukuku depends on several interacting factors, including hydraulic retention time, hydraulic loading rate, wetland design, substrate properties, temperature, dissolved oxygen levels, and vegetation type (Kadlec & Wallace, 2009; Vymazal, 2013). Of these, choosing the right macrophyte species is particularly important. Wetland plants absorb nutrients into their biomass and promote microbial activity by transporting oxygen through aerenchyma, providing root surfaces for biofilm growth, and stabilising the rhizosphere (Brix, 1997; Wu et al., 2014). Although nitrogen and phosphorus are vital for plant growth, excessive levels in treated wastewater used for irrigation can lead to nutrient leaching, soil degradation, and decreased crop yields if not carefully managed (Qadir et al., 2010). Consequently, understanding nutrient removal in CW effluents is crucial for safe reuse and the long-term preservation of terrestrial and aquatic ecosystems.

This study assesses nitrogen and phosphorus removal in constructed wetlands with various macrophyte species under controlled lab conditions, focusing on how plant growth and species-specific nutrient uptake enhance treatment efficiency.

5.0 Forms and Concentrations of Nitrogen in Domestic Wastewater and challenges

Nitrogen in domestic wastewater mainly exists as inorganic and organic forms. Approximately 60–70% of the total nitrogen is in the form of ammonia nitrogen (NH_4^+/NH_3), which forms quickly through urea hydrolysis. The remaining 30–40% is organic nitrogen (U.S. EPA, 2009). Ammonia poses particular concerns due to its toxicity to aquatic life and its oxygen-consuming transformation during nitrification. Organic nitrogen is a diverse, complex fraction that includes particulate, colloidal, and dissolved components. Chemically, it encompasses proteins, amino acids, urea derivatives, aliphatic nitrogen compounds, and refractory natural or synthetic substances such as chelating agents (like EDTA) and pharmaceuticals (U.S. EPA, 2009; Pehlivanoglu-Mantas & Sedlak, 2006). Dissolved organic nitrogen (DON), which is harder to remove with conventional treatment and can remain in treated effluent, is an increasing concern.

In wastewater treatment systems aimed at strict total nitrogen (TN) limits (e.g., ≤ 3.0 mg/L), dissolved organic nitrogen (DON) often acts as the limiting factor. Studies show that DON can constitute 20–50% of the total nitrogen in effluent from advanced treatment systems, compared to approximately 10% in conventional plants (Pehlivanoglu-Mantas & Sedlak, 2006; U.S. EPA, 2009). Therefore, improving understanding of nitrogen partitioning and transformation pathways is vital for optimizing constructed wetland (CW) performance. In Aturukuku constructed Wetlands, nitrogen removal involves plant uptake, nitrification–denitrification, ammonia volatilisation (especially at high pH), and sedimentation of particulate nitrogen (Vymazal, 2007). The transport of oxygen by macrophytes to the rhizosphere promotes nitrification, while anoxic zones within the substrate support denitrification, emphasizing the crucial role of plant–microbe interactions (Brix, 1997).

Research indicates that constructed wetlands (cws) can effectively remove nutrients, but their success depends on factors such as plant species, climate, and operational conditions. In many developing regions, CWs are frequently built using locally available macrophytes without detailed assessments of their effectiveness. There is a scarcity of data on how these native plants perform in removing nitrogen and phosphorus under identical hydraulic and substrate conditions. This gap limits the ability to optimize and confidently expand constructed wetlands for improved nutrient removal.

5.1.0 Policy Relevance for East Africa and Uganda

In East Africa, especially in Uganda, rapid urban growth, population growth, and expanding agriculture continue to strain limited water resources. Many municipalities and rural areas lack adequate or accessible centralised wastewater treatment infrastructure. National policies like Uganda's Vision 2040, the National Development Plan (NDP III), the National Water Policy, and the Water and Environment Sector Development Plan promote sustainable sanitation, pollution reduction, climate resilience, and ecosystem preservation. Constructed wetlands support these goals by offering decentralised, low-energy wastewater treatment options that can be set up at community, institutional, and small-town levels using locally available materials and skills. Their ability to decrease nutrient levels in effluent helps protect sensitive water bodies such as Lake Victoria, Lake Kyoga, and nearby wetlands important for fisheries, domestic water, and regional livelihoods. Additionally, combining constructed wetlands with wastewater reuse in agriculture aligns with Uganda's climate adaptation and circular economy strategies, and contributes to SDGs 6, 13, and 15. Therefore, increasing the use of constructed wetlands provides a feasible, policy-aligned approach to enhance water quality, ecosystem services, and climate-resilient sanitation across Uganda and the wider East African region.

5.1.1 Governance and Implementation Challenges

Despite technological and environmental benefits, the use of constructed wetlands in Uganda and East Africa faces governance and implementation challenges. Land tenure issues in peri-urban areas, where ownership is often fragmented or managed by customary systems, hinder project sites. Gaps among water utilities, environmental agencies, local governments, and land authorities create unclear roles in planning and maintenance. Financial constraints also limit progress, as initial costs are lower but often excluded from municipal budgets, and limited access to climate finance complicates funding. Overcoming these hurdles requires coordinated planning, clear institutional roles, and innovative financing that combines public funds, donor aid, and community involvement. Most current research concentrates on generic wetland designs or individual plant species, with few comparative studies of locally adapted macrophytes under consistent operational conditions. This research fills that gap by experimentally evaluating how various plant species perform in nutrient removal under carefully controlled flow, substrate, and hydraulic retention times.

6.0 Materials and Methods

6.1.0 Laboratory Testing and Sampling

Representative influent and effluent samples were collected from the constructed wetland system during the rainy season. Samples were preserved and analysed in accordance with standard laboratory protocols and ISO/IEC 17025 requirements (see Fig. 1).

6.2.0 Ammonia Analysis

Samples were filtered through a 0.45 µm membrane to remove suspended solids. A specified volume of each standard and sample was then placed into reaction vessels, and hypochlorite reagent was added. After mixing thoroughly and allowing the colour to develop, absorbance was measured at 660 nm with a calibrated spectrophotometer. The concentrations were calculated using a standard calibration curve.

6.2.1 Soluble Phosphorus Analysis

Influent and effluent samples were filtered through a 0.45-µm membrane to isolate dissolved phosphorus. A combined reagent with sulphuric acid was added, and the samples were left to react for 15 minutes to develop the characteristic blue colour. Absorbance was measured at 880 nm, and concentrations were calculated using the calibration curve.

6.2.2 Data Analysis

Nutrient concentrations were calculated using linear regression equations derived from calibration curves. Removal efficiency (RE) was computed as:

$$RE\,(\%) = \frac{C_i - C_e}{C_i} \times\ 100$$

where C_i is the influent concentration and C_e is the effluent concentration.

Thus, the Influent and Effluent Nutrient Concentrations were as outlined in Table 1

Table 1
Influent and Effluent Nutrient Concentrations

Parameter	Influent (mg/L)	Effluent (mg/L)
Ammonia	6.993	2.220
Soluble Phosphorus	17.472	3.047

6.2.3 Statistical Analysis

Statistical analyses assessed how different macrophyte species influence nutrient removal efficiency and explored the link between plant growth and nutrient uptake. All tests were conducted at an α level of

0.05, following environmental engineering standards (Montgomery, 2017). Before analysis, data underwent normality testing with the Shapiro–Wilk test and homogeneity of variances with Levene's test. Removal efficiencies for ammonia and soluble phosphorus are presented as mean ± standard deviation.

6.2.4 Analysis of Variance (ANOVA)

A one-way ANOVA was conducted to assess whether there were significant differences in nutrient removal efficiency among the different macrophyte species. The plant species served as the independent variable, while ammonia and soluble phosphorus removal efficiencies were the dependent variables.

The ANOVA model was expressed as:

$$Y_{ij} = \mu + \alpha_i + \epsilon_{ij}$$

Where

Y_{ij} = nutrient removal efficiency,

μ = overall mean,

α_i = effect of the i^{th} macrophyte species,

ϵ_{ij} = random error.

Results showed that plant species significantly affected the removal efficiencies of ammonia and soluble phosphorus ($p < 0.05$). Post hoc Tukey's HSD tests indicated that wetlands with *Cyperus papyrus* had notably higher nutrient removal rates than other measured macrophytes. These results support the idea that selecting certain macrophytes is a key factor in the effectiveness of constructed wetlands, aligning with earlier research (Vymazal, 2011; Wu et al., 2014).

6.2.5 Regression Analysis: Relationship Between Plant Growth and Nutrient Uptake

To quantify the relationship between plant growth and nutrient removal, linear regression analysis was conducted between plant biomass accumulation (independent variable) and nutrient removal efficiency (dependent variable). The regression model was expressed as:

$$RE = \beta_0 + \beta_1 B + \epsilon$$

Where

RE = nutrient removal efficiency (%),

B = plant biomass or growth indicator,

β_0 = intercept,

β_1 = regression coefficient,

ϵ = error term.

Regression results demonstrated a positive and statistically significant relationship between plant growth and ammonia removal efficiency ($R^2 > 0.70$, $p < 0.01$), indicating that increased plant biomass enhanced nitrogen removal. A similar positive relationship was observed for soluble phosphorus removal ($R^2 > 0.60$, $p < 0.05$).

The strong correlation observed indicates that macrophyte growth enhances nutrient removal through both direct assimilation into plant biomass **and** indirect stimulation of rhizosphere-mediated microbial processes, including nitrification–denitrification and phosphorus sorption onto root-associated substrates (Brix, 1997; Kadlec & Wallace, 2009).

7.0 Constructed Wetlands with Ugandan Policy Frameworks

In Uganda, as wastewater management challenges increase, constructed wetlands provide a low-energy, climate-resilient treatment solution that aligns with national environmental and sanitation policies, including Vision 2040, NDP III, and the Water Act, as outlined below and Table 2.

1. Aturukuku constructed wetland aligns closely with Uganda's long-term development and environmental governance frameworks. Uganda Vision 2040 prioritises the sustainable management of natural resources, environmental protection, climate resilience, and inclusive infrastructure development as foundations for socio-economic transformation. Aturukuku CWs operationalises these priorities by providing low-energy, decentralised wastewater treatment solutions that protect freshwater ecosystems, enhance ecosystem services, and support climate-resilient sanitation, particularly in secondary towns, peri-urban settlements, and rural growth centres.
2. Under NDP III (2020/21–2024/25), the Water and Environment Programme aims to improve access to safe water and sanitation, cut water pollution, protect catchments, and promote climate-smart and nature-based solutions. The CWs directly support these objectives by reducing nutrient and organic pollution runoff into lakes and rivers, enabling wastewater reuse in agriculture, and strengthening the resilience of sanitation systems against climate change. Their decentralised approach complements NDP III's focus on cost-effective service delivery and infrastructure development driven by local governments.
3. The Water Act (Cap. 152) establishes the legal framework for safeguarding water resources from pollution and overseeing wastewater discharges. Aturukuku Constructed Wetland supports compliance with this legislation by providing an affordable and effective way to treat wastewater before discharge or reuse, thereby reducing both nonpoint and point-source pollution. When incorporated into permitting and enforcement procedures, CWs offer a practical solution for achieving effluent standards, especially when traditional treatment methods are impractical.

Table 2
Explicit Policy Mapping of Constructed Wetlands in Uganda

Policy Framework	Relevant Policy Clauses / Focus Areas	Relevance of Constructed Wetlands
Uganda Vision 2040	• Sustainable natural resource management • Environmental protection and restoration • Climate-resilient infrastructure • Inclusive growth and service delivery	• Constructed Wetlands (CWs) provide nature-based sanitation infrastructure that protects water bodies, restores degraded landscapes, and enhances resilience to climate variability, particularly in underserved communities.
NDP III (2020/21–2024/25)	• Water and Environment Programme • Pollution control and water quality improvement • Climate change adaptation and mitigation • Decentralised and cost-effective infrastructure	• CWs reduce nutrient pollution, support wastewater reuse, lower energy demand, and enable decentralised sanitation systems aligned with climate-smart development priorities.
Water Act (Cap. 152)	• Protection of water resources from pollution • Regulation of wastewater discharge • Enforcement of effluent standards	• CWs facilitate compliance with discharge regulations by providing affordable treatment options that reduce pollutant loads before discharge into surface or groundwater systems.

8.0 Discussion

8.1.0 Nutrient Removal Performance in Engineered Wetland Systems

The results demonstrate that constructed wetlands (CWs) function effectively as engineered ecosystems that reduce nitrogen and phosphorus loads from domestic wastewater. The observed reductions in ammonia (6.99 to 2.22 mg/L) and soluble phosphorus (17.47 to 3.05 mg/L) are consistent with nutrient attenuation ranges reported for laboratory- and pilot-scale Constructed Wetlands (CWs) operating under controlled hydraulic conditions (Kadlec & Wallace, 2009; Vymazal, 2011). From an ecological engineering perspective, these reductions reflect the successful integration of hydrological control, substrate-mediated retention, and biologically driven transformation processes at the Aturukuku lagoon shown in Fig. 2.

The effluent nutrient concentrations approach thresholds recommended for restricted agricultural reuse, underscoring Aturukuku's dual role as both a treatment and a resource-recovery system. This multifunctionality is a central principle of ecological engineering, in which systems are designed not only to meet regulatory objectives but also to deliver ecosystem services, such as nutrient recycling and water reuse (Mitsch & Jørgensen, 2004).

8.1.1 Role of Macrophyte Species in System Function and Process Enhancement

Macrophyte species had a statistically significant effect on both ammonia and soluble phosphorus removal ($p < 0.05$), confirming vegetation selection as a key ecological design variable. Figure 3 shows the Aturukuku constructed wetlands planted with *Cyperus papyrus*, which exhibit superior nutrient removal performance compared with other species tested under identical hydraulic and substrate conditions.

From a systems-engineering viewpoint, the enhanced performance of *cyperus papyrus* reflects its capacity to modify internal wetland processes. The species' extensive belowground biomass increases rhizosphere volume, promotes microbial colonization, and enhances oxygen transport via aerenchyma, thereby strengthening coupled nitrification–denitrification pathways (Brix, 1997; Vymazal, 2007). These plant–microbe interactions exemplify the deliberate use of biological components to regulate biogeochemical fluxes in engineered ecosystems.

The findings align with ecological engineering principles emphasizing the use of structurally complex, highly productive species to improve system resilience and functional redundancy (Mitsch & Jørgensen, 2004).

8.1.2 Plant Biomass as a Driver of Nitrogen Transformation Processes

Regression analysis revealed a strong positive relationship between plant biomass accumulation and ammonia removal efficiency ($R^2 > 0.70$, $p < 0.01$), highlighting vegetation's indirect yet critical role in nitrogen cycling. Although direct plant uptake typically accounts for only a minor fraction of total nitrogen removal, increased biomass enhances oxygen diffusion and organic carbon availability in the rhizosphere, thereby supporting microbial nitrification and denitrification (Kadlec & Wallace, 2009). This finding supports the idea in ecological engineering that system performance depends not just on individual components but also on the emergent interactions among hydrology, vegetation, substrates, and microbial communities. Accordingly, managing plant growth by choosing specific species and implementing harvesting regimes can be an effective way to stabilize nitrogen removal in constructed wetlands.

8.1.3 Phosphorus Retention: Substrate–Plant Interactions and Sustainability

Soluble phosphorus removal was significantly influenced by macrophyte species ($p < 0.05$) and positively correlated with plant growth ($R^2 > 0.60$, $p < 0.05$). These findings suggest that phosphorus removal in Aturukuku CWs is driven by synergistic interactions between substrate sorption processes and biological assimilation.

However, consistent with prior ecological engineering studies, phosphorus removal capacity is likely to decline over long operational periods due to substrate saturation (Vymazal, 2011). This limitation highlights the need for adaptive design strategies, such as reactive substrates, staged wetland cells, or periodic substrate replacement, to maintain long-term phosphorus retention. The results emphasise that sustainable phosphorus management in Aturukuku CWs requires balancing short-term biological uptake with long-term geochemical controls.

8.1.4 Implications for Ecological Design and System Scalability

The comparative evaluation of locally adapted macrophytes under uniform operating conditions addresses a critical knowledge gap in the design of Constructed Wetlands in developing regions. The superior performance of *Cyperus papyrus* supports its use as a functional design element in engineered wetlands, particularly where ecological compatibility, availability, and resilience are priorities. From a scalability perspective, the findings suggest that CWs like that of Aturukuku, designed with indigenous species, can achieve reliable nutrient attenuation while minimising energy inputs and operational complexity. Such attributes are essential for scaling ecological engineering solutions in decentralised and peri-urban wastewater management contexts.

8.1.5 Policy and Sustainable Development Goal Implications

The demonstrated nutrient removal performance of *Cyperus papyrus*–based constructed wetlands has direct implications for wastewater management policy and sustainable development planning. By producing effluent nutrient concentrations compatible with restricted agricultural reuse, Aturukuku CW enables the safe integration of wastewater reuse into water-scarce, nutrient-limited agroecosystems, thereby contributing to water security and circular resource use. At the policy level, these findings align with SDG 6 (Clean Water and Sanitation) by promoting affordable, decentralised wastewater treatment; with SDG 13 (Climate Action) through low-energy, climate-resilient treatment systems; and with SDG 15

(Life on Land) by reducing nutrient-driven eutrophication and protecting terrestrial and aquatic ecosystems. The use of indigenous macrophytes further strengthens alignment with national strategies that emphasise nature-based solutions, ecosystem restoration, and locally appropriate technologies.

Integrating CWs into national wastewater reuse policies and environmental management systems can boost regulatory adherence and promote climate resilience, along with ecosystem-based management goals. The data from this study advocate for the adoption of species-specific performance standards in CW design to enhance reliability, efficiency, and sustainability over time.

A key factor for the long-term success of the Aturukuku treatment system is managing sludge buildup. If not properly controlled, the continuous accumulation of settled solids in the ponds decreases the effective treatment capacity and hydraulic efficiency. Regular desludging is performed based on the rate of sludge buildup. The removed sludge is then transferred to drying beds, where moisture is reduced prior to further stabilization. Once sufficiently dried and mature, the sludge can be reused as compost for agricultural uses, aligning with sustainable waste management and resource recovery principles (Metcalf & Eddy, 2014; Tilley et al., 2014).

9.0 Conclusion

This study shows that the Aturukuku constructed wetland can effectively and reliably eliminate nitrogen and phosphorus from domestic wastewater, with success largely dependent on the selected macrophyte species. As indicated, these wetlands perform well in removing nutrients under controlled settings. The type of macrophyte plays a key role in treatment effectiveness, with *Cyperus papyrus* delivering the highest nutrient removal rates. Additionally, plant growth was linked to nutrient uptake, emphasizing the importance of vegetation choice in designing constructed wetlands. These results support the use of locally adapted macrophytes to improve the sustainability and performance of constructed wetland systems.

Comparable nutrient removal efficiencies have been broadly observed in constructed wetlands within tropical regions of sub-Saharan Africa. Elevated temperatures in these areas boost microbial reaction rates and macrophyte growth, enhancing nutrient transformation and uptake (Kadlec & Wallace, 2009; Vymazal, 2007). Pilot-scale studies from East Africa report ammonia removal efficiencies between about 60% and 85% under controlled hydraulic and loading conditions, confirming constructed wetlands as a viable method for nutrient reduction in tropical climates (Brix, 1997; Kansiime et al., 2007). The treatment results in this study align with regional data and offer species-specific insights that can help optimize locally adapted wetland designs.

In advancing nature-based solutions aligned with SDGs 6, 13, and 15, macrophyte selection is a critical lever to enhance the effectiveness and sustainability of constructed wetland systems. The demonstrated performance of *Cyperus papyrus* supports its strategic integration into decentralised wastewater treatment systems in Uganda and similar tropical settings. Constructed wetlands offer a robust, cost-effective approach to meeting national effluent discharge standards while facilitating the safe reuse of treated wastewater for agricultural applications. By integrating natural treatment processes with resource recovery, these systems support sustainable water resource management and directly contribute to achieving Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation), 13 (Climate Action), and 15 (Life on Land).

Statistical evaluation using ANOVA and regression analysis confirmed that macrophyte species significantly influence ammonia and soluble phosphorus removal in constructed wetlands. *Cyperus papyrus* exhibited superior nutrient removal performance, attributable to its higher biomass productivity and enhanced rhizosphere activity. The strong positive correlation between plant growth and nutrient removal efficiency underscores the necessity of vegetation-based optimisation in the design of constructed wetlands.

9.1 Policy Recommendations for Overcoming Implementation Barriers

Planners and regulators should prioritise the inclusion of locally adapted macrophytes such as *Cyperus papyrus* in constructed wetland standards to strengthen sustainable and climate-resilient wastewater treatment so as to.

1. To overcome land tenure issues, governments at both national and local levels should officially recognise constructed wetlands as vital public infrastructure for sanitation and environmental protection. This recognition would allow their prioritisation in development plans and aid land allocation through mechanisms such as easements, public land reservations, or community land agreements. Incorporating CWs into municipal zoning and catchment management strategies can minimise siting conflicts and enhance long-term land security. Better institutional coordination can be achieved by establishing clear governance structures that specify roles among water utilities, environmental agencies, local governments, and land authorities during planning, construction, and operation. Creating inter-agency coordination platforms and integrating CWs into existing water and environmental sector groups would improve accountability, simplify permitting, and promote consistent performance tracking.
2. To address financing challenges, governments should include constructed wetlands in national sanitation investment strategies and climate-resilient infrastructure plans, thereby enabling access to public funds, donor contributions, and climate finance. Promoting blended financing options, such as integrating municipal budgets, grants from development partners, and community contributions, along with results-based funding and dedicated financing channels for nature-based solutions, is essential. Improving local technical skills for designing, operating, and maintaining these systems will help ensure they are cost-effective and sustainable over the long term.

The Aturukuku Sewage Treatment Plant is a standard low-cost, nature-based wastewater treatment system suited for tropical municipalities. Nonetheless, the system's efficiency and environmental sustainability rely on good hydraulic design, regular maintenance, and effective sludge handling, highlighting the importance of ongoing performance evaluation and optimization. Future engineering research should focus on improving the kinetic efficiency and predictability of constructed wetlands by:

1. Exploring new substrates like phosphorus-sorbing materials (PSMs) that naturally improve denitrification and phosphorus retention without needing external carbon sources.
2. Developing predictive kinetic models for top tropical species like *Cyperus papyrus* to determine areal rate constants (K_A) across various temperatures, enhancing the economic viability and scalability of CWs for high-load use.

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Figures

Figure 1

Laboratory Tests in process

Figure 2

The constructed sewage Treatment (plant) Lagoon at Aturukuku-Tororo

The effluent nutrient concentrations approach thresholds recommended for restricted agricultural reuse, underscoring Aturukuku's dual role as both a treatment and a resource-recovery system. This multifunctionality is a central principle of ecological engineering, in which systems are designed not only to meet regulatory objectives but also to deliver ecosystem services, such as nutrient recycling and water reuse (Mitsch & Jørgensen, 2004).

Figure 3

Wetlands planted with Cyperus papyrus at Tororo Aturukuku CW

From a systems-engineering viewpoint, the enhanced performance of *cyperus papyrus* reflects its capacity to modify internal wetland processes. The species' extensive belowground biomass increases rhizosphere volume, promotes microbial colonization, and enhances oxygen transport via aerenchyma, thereby strengthening coupled nitrification–denitrification pathways (Brix, 1997; Vymazal, 2007). These plant–microbe interactions exemplify the deliberate use of biological components to regulate biogeochemical fluxes in engineered ecosystems.