# Nutrient Removal Efficiency of Constructed Wetlands Planted with Tropical Macrophytes: Implications for decentralised Wastewater Treatment at Aturukuku Sewerage works

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## Abstract

Constructed wetlands are increasingly seen as sustainable, low-energy wastewater treatment options, especially in areas with limited resources, but their nutrient removal varies by vegetation and design. This study tested nitrogen and phosphorus removal in lab-scale wetlands with selected plants under controlled conditions. Samples were analysed for ammonia and phosphorus by spectrophotometry, in accordance with ISO/IEC 17025 standards. Statistical tests showed significant reductions in nutrient levels from 6.99 mg/L to 2.22 mg/L for ammonia and from 17.47 mg/L to 3.05 mg/L for phosphorus. Wetlands with *Cyperus papyrus* achieved the highest removal rates, reducing ammonia by 82% and phosphorus by 76%. ANOVA confirmed plant type significantly affects nutrient removal ($p < 0.05$), and regression showed a strong link between plant biomass and nutrient uptake ($R^2 > 0.60$). These results suggest that selecting effective macrophytes, such as *Cyperus papyrus*, can improve wetland performance, especially in tropical regions like Uganda in East Africa, where they can enhance water quality, enable safe reuse, and support sustainable management.

## 1.0 Introduction

Constructed wetlands (CWs) are engineered, nature-inspired wastewater treatment systems that replicate the physical, chemical, and biological processes of natural wetlands to enhance water quality (Vymazal & Kröpfelová, 2020, p. 1). According to Sandoval-Herazo et al. (2018), CWs are engineered systems that mimic natural wetland functions, using wetland plants, porous substrates, and diverse microbial populations to remove pollutants through sedimentation, filtration, adsorption, microbial transformation, and plant uptake. Wu, S. et al. (2015, p.600) support this view, echoing earlier reports by Vymazal (2011) and Kadlec & Wallace (2009). Among sustainable wastewater treatment options, CWs are increasingly popular, particularly in decentralised and resource-limited areas, due to their low energy consumption, ease of operation, and ecological benefits. Stefanakis (2019) highlights their role as green infrastructure for sustainable urban water management, emphasising their multifunctional capacity to promote sustainability, resilience, and circular water practices.

Nitrogen (N) and phosphorus (P) in domestic wastewater are of major concern 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. Present evidence on eutrophication indicates that excessive nitrogen (N) and phosphorus (P) inputs, primarily from agricultural runoff, wastewater, and land-use change, still exceed what aquatic ecosystems can absorb. This leads to harmful algal blooms (HABs), hypoxia, and decreased biodiversity (Chislock et al., 2013; Li, 2020; Sonarghare et al., 2020). Recent key studies confirm that eutrophication is worsening globally due to combined human and climate-related factors, including increased nutrient runoff, greater hydrological connectivity, and faster biogeochemical processes driven by higher temperatures (Ji et al., 2024; Varis, 2026). These impacts are especially significant in tropical and sub-Saharan African ecosystems, where rising temperatures enhance microbial activity and nutrient cycling, speeding up eutrophication.

Recent research has made significant progress by recognising that nitrogen and phosphorus jointly contribute to eutrophication in freshwater and coastal areas, rather than acting independently. This understanding has led to a shift toward simultaneous management of both nutrients (Scott et al., 2025; Vasilakou et al., 2025), revealing the shortcomings of traditional single-nutrient control methods. In developing regions like Uganda, wastewater and diffuse agricultural runoff together release large amounts of N and P, causing ongoing eutrophication. This is consistent with findings from *"The Effect of Eutrophication on Drinking Water"* (Mishra, R. K., 2023), which link nutrient overload to excessive biomass growth and oxygen depletion, compromising drinking water quality and increasing treatment costs. Constructed wetlands offer a promising, nature-based solution to this complex, multi-source nutrient pollution. As Stefanakis (2019) notes, CWs function as green infrastructure, employing physical, chemical, and biological processes to remove nutrients and deliver ecosystem benefits. Their treatment mechanisms, such as sedimentation, plant absorption, microbial nitrification and denitrification, and phosphorus attachment, are particularly effective at reducing nitrogen and phosphorus under diverse hydraulic and environmental conditions. Tanner (2001) asserts that vegetation modifies hydraulic conditions and enhances treatment absorption efficiency (p. 14)

# 1.1 Aturukuku Sewerage Treatment Plant

The Aturukuku Sewerage Treatment Plant is situated about 1 Kilometre 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 (WSP) that uses natural processes, including 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, progressing through different stages. Meanwhile, wind continually sweeps across the surface, helping to dissolve and remove solids until optimal levels are reached. Aturukuku's capacity to simultaneously remove nitrogen and phosphorus directly supports the growing dual-nutrient management approach, in which nitrogen is primarily removed via microbial processes such as *nitrification–denitrification*, while phosphorus is retained through substrate adsorption, precipitation, and plant uptake. Recent research (Ricart S, & Rico-Amorós A, M., 2025; Chen et al., 2025) shows that CWs can regulate microbial communities and nutrient transformations even under changing hydrological conditions, highlighting their suitability for decentralised, climate-resilient wastewater treatment systems such as the Aturukuku wastewater treatment plant.

# 1.2 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) efficiently eliminate nutrients through advanced biological processes, chemical precipitation, and tertiary treatments. However, they often entail high capital and operational costs, consume significant energy, and are technically complex due to their dependence on electromechanical systems, continuous power, skilled labour, and chemicals. This limits their use in resource-limited settings (Vymazal, 2014; Verlicchi & Zambello, 2014). In many developing regions, especially sub-Saharan Africa, issues such as unreliable electricity, limited technical skills, and financial difficulties further impair performance and sustainability. Constructed wetlands (CWs), as natural treatment systems, present a low-cost, energy-efficient alternative suitable for these regions (Stefanakis, 2019; Dotro et al., 2017). However, their effectiveness depends on factors like hydraulic loading rates, design, and seasonal changes, and phosphorus removal can decrease over time as substrates saturate (Vymazal, 2018; Stefanakis, 2019). Recent research indicates that optimising CWs involves adaptive design strategies, such as using reactive or engineered substrates, hybrid vertical-horizontal flow systems, and staged configurations to improve nutrient removal (Wu et al., 2015; Langergraber et al., 2019). Additionally, incorporating CWs into broader watershed management frameworks is vital to address upstream and diffuse nutrient sources and ensure their long-term viability. Overall, these insights emphasise the importance of resilient, cost-effective, and locally tailored wastewater solutions that fit socioeconomic and environmental contexts and promote sustainable water management.

# 2.2 Advantages of the Aturukuku Constructed Wetland for Nutrient Removal

Nutrient removal relies partly on plant absorption and microbial activity (Tanner, 2001, p. 12). This is why constructed wetlands (CWs) offer a cost-effective, energy-efficient solution for nutrient removal by leveraging natural processes. Nitrogen and phosphorus elimination occurs through mechanisms such as sedimentation, substrate adsorption, microbial nitrification–denitrification, plant uptake, and long-term storage in biomass and sediments (Brix, 1997; Wu et al., 2015). These methods require minimal external energy, making CWs much less energy-dependent than conventional wastewater treatment facilities. Economically, Aturukuku CWs benefit from lower initial costs due to simpler infrastructure and locally sourced materials. They also require minimal operations and maintenance, as they do not require continuous aeration, chemicals, or specialised staff. In tropical regions like Uganda, CWs are especially advantageous higher temperatures enhance microbial activity and support plant growth, leading to more effective nutrient removal than in temperate regions. Von Sperling (2007) notes that waste stabilisation ponds are common natural wastewater treatment systems due to their simplicity, low operational costs, and pathogen removal efficacy, particularly in tropical and subtropical regions (P.2). Additionally, native plants such as *Cyperus papyrus* and *Phragmites mauritianus* are used to optimize nutrient absorption and improve system performance. Consequently, CWs are particularly suitable for projects such as the Aturukuku Wastewater Stabilisation Plant (WWSP), where their integration can greatly enhance effluent quality and reduce nutrient runoff into downstream ecosystems.

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). Constructed Wetlands (CWs) are currently one of the most promising techniques for wastewater treatment, having demonstrated their effectiveness.

## 3.0 Role of Constructed Wetlands in Achieving the Sustainable Development Goals

The Aturukuku constructed wetland (CW) system significantly advances Sustainable Development Goal 6 (Clean Water and Sanitation) by improving access to effective wastewater treatment and decreasing nutrient pollution in surface and groundwater. Recognised as a practical nature-based solution, constructed wetlands excel at nutrient removal and water quality enhancement, especially in low-resource areas (Stefanakis, 2019; Vymazal, 2018; Langergraber et al., 2019). Their cost-effectiveness, minimal operational demands, and decentralized design make them ideal for expanding sanitation services in underserved and rural communities across sub-Saharan Africa. Furthermore, CWs contribute notably to SDG 13 (Climate Action) by providing low-energy wastewater treatment options that emit fewer greenhouse gases than traditional systems, while also facilitating carbon sequestration in plant biomass and wetland sediments (Mander et al., 2017; Mitsch W.J, & Gosselink J. G., 2015). Additionally, the Aturukuku CW supports SDG 15 (Life on Land) by creating and maintaining wetland habitats that enhance biodiversity, ecological connectivity, and sustainable land-use practices. As Stefanakis (2019) notes, constructed wetlands serve as green infrastructure, integrating wastewater treatment with ecosystem restoration and offering multiple benefits, including habitat creation, landscape improvements, and ecological resilience. Recent research emphasises their potential to support biodiversity and ecosystem services while reducing nutrient pollution amid climate change (Wu et al., 2015). In summary, by integrating wastewater management with ecological functions, the Aturukuku constructed wetland offers a versatile, sustainable solution that simultaneously addresses water quality, climate resilience, and ecosystem preservation.

# 4.0 Factors Influencing Nutrient Removal and Implications for Safe Reuse

The nutrient removal efficiency of the constructed wetland (CW) at Aturukuku depends on a complex interplay of hydraulic, biological, and physicochemical factors, such as hydraulic retention time, loading rate, system design, substrate properties, temperature, dissolved oxygen, and plant species (Vymazal, 2018; Langergraber et al., 2019). Selecting appropriate macrophyte species is particularly crucial because wetland plants not only uptake nitrogen and phosphorus into their biomass but also enhance microbial processes. They do this by facilitating oxygen transfer through aerenchyma tissues, providing extensive root surfaces for biofilm growth, and stabilizing the rhizosphere environment (Brix, 1997; Wu et al., 2015; Stefanakis, 2019). Recent research indicates that plant diversity and growth patterns significantly influence nutrient removal efficiency and overall treatment performance, especially in tropical climates where elevated temperatures boost biological activity (Mashauri et al., 2016).

Despite these benefits, using treated wastewater with residual nutrients requires careful oversight. While nitrogen and phosphorus are crucial for crop growth, excessive levels in irrigation water can lead to nutrient leaching, soil salinisation, groundwater pollution, and a long-term decrease in soil fertility (Qadir et al., 2015; Drechsel et al., 2022). Additionally, unbalanced nutrient loads may alter soil physicochemical properties and reduce crop yields if application rates are poorly managed. Consequently, understanding nutrient removal mechanisms in constructed wetland (CW) systems is essential for safe reuse and protecting terrestrial and aquatic environments. This study investigates nitrogen and phosphorus removal in laboratory-scale constructed wetlands planted with different macrophyte species, focusing on how species-specific nutrient uptake and plant growth influence treatment performance and reuse potential.

## 5.0 Forms and Concentrations of Nitrogen in Domestic Wastewater and Challenges

Nitrogen in domestic wastewater exists in both inorganic and organic forms. Ammoniacal nitrogen ($NH_4^+/NH_3$) makes up about 60–70% of the total nitrogen, mainly due to rapid urea hydrolysis. Nitrogen removal in wastewater treatment relies primarily on biological processes, particularly nitrification and denitrification (Metcalf & Eddy, 2014). In the first stage, nitrification, aerobic microorganisms such as Nitrosomonas *and* Nitrobacter convert ammonia ($NH_3/NH_4^+$) into nitrate ($NO_3^-$). This process requires adequate dissolved oxygen and is influenced by temperature and pH. Subsequently, denitrification occurs under anoxic conditions, where heterotrophic bacteria reduce nitrate to nitrogen gas ($N_2$), which is released into the atmosphere. This step necessitates a carbon source and oxygen-free conditions, making system design and environmental control essential.

In systems such as constructed wetlands, these processes naturally occur in different zones: oxygen-rich zones support nitrification, while oxygen-poor zones promote denitrification. Combining these biological pathways effectively removes nitrogen, reducing eutrophication risks in water bodies. The remaining component is organic nitrogen (U.S. EPA, 2009). Ammonia is especially worrisome because it is toxic to aquatic life and its conversion during nitrification consumes oxygen, potentially causing dissolved oxygen depletion in receiving waters (Vymazal, 2018). Langergraber et al. (2019) agree. Organic nitrogen is a complex, varied mixture that includes particulate, colloidal, and dissolved forms, such as proteins, amino acids, urea derivatives, and resistant compounds, including chelating agents such as Ethylenediaminetetraacetic acid (EDTA), along with pharmaceutical residues (Pehlivanoglu-Mantas & Sedlak, 2006; Tran et al., 2016). Recent research shows that dissolved organic nitrogen (DON) can be particularly problematic because it is less effectively removed by standard treatments and can persist in effluents, leading to downstream eutrophication and the formation of nitrogenous disinfection by-products (Lee et al., 2020; Wang et al., 2022). Therefore, understanding the types, transformations, and fates of nitrogen species is essential to improve treatment efficiency and minimise environmental and health hazards.

In wastewater treatment systems targeting strict total nitrogen limits (e.g., ≤ 3.0 mg/L), dissolved organic nitrogen (DON) increasingly becomes the limiting component due to its resistance and difficulty of removal via standard biological methods. Recent research indicates that dissolved organic nitrogen can constitute about 20–50% of total nitrogen in the effluents of advanced treatment systems, compared to roughly 10% in traditional ones (Pehlivanoglu-Mantas & Sedlak, 2006; Lee et al., 2020; Wang et al., 2022). This highlights the need to understand nitrogen forms, their distribution, and transformation pathways to optimise treatment processes. In constructed wetlands (CWs), such as the Aturukuku system, nitrogen removal involves multiple mechanisms, including plant uptake, microbial nitrification–denitrification, ammonia volatilisation at high pH, and sedimentation of particulate nitrogen (Vymazal, 2018; Langergraber et al., 2019). Macrophytes are crucial as they supply oxygen to the rhizosphere through aerenchyma tissues, enhancing nitrification, while anoxic zones within the substrate support denitrification. This emphasises the importance of plant–microbe interactions in nitrogen cycling (Brix, 1997; Stefanakis, 2019). Recent studies also emphasise that the combined action of vegetation, microbial communities, and substrate media is key to improving the removal of complex nitrogen fractions, including dissolved organic nitrogen, in municipal and industrial wastewater treatment. Therefore, deepening our understanding of these interconnected processes is vital for optimising CW design and meeting stricter nitrogen discharge standards.

Research demonstrates that constructed wetlands (CWs) are effective at removing nutrients and a wide range of contaminants; however, their performance is heavily influenced by factors such as plant species selection, climatic conditions, hydraulic loading, and operational design (Vymazal, 2018; Langergraber et al., 2019). Sharma and Malaviya (2022) further emphasise that nutrient and contaminant removal in CWs is driven by key mechanisms, including adsorption, microbial biodegradation, and plant uptake. Despite these advances, in many developing regions, CWs are often established using locally available macrophytes without thorough evaluation of their treatment efficiency. This practice is primarily motivated by cost and accessibility considerations, but it introduces uncertainty in system performance. Notably, a significant knowledge gap persists regarding the comparative effectiveness of native macrophyte species in removing nitrogen and phosphorus under identical, controlled hydraulic and substrate conditions (Stefanakis, 2019). The absence of standardised, species-specific performance data limits optimisation, scalability, and reliability of CW systems for nutrient removal. Addressing this gap is therefore essential to improving the design, efficiency, and broader adoption of constructed wetlands, especially in resource-limited settings.

# 5.1.0 Policy Relevance for East Africa and Uganda

In East Africa, especially Uganda, rapid urbanisation, population growth, and agricultural intensification continue to strain water resources, worsening water quality and sanitation issues (Drechsel et al., 2022). The growing global water crisis emphasizes the critical need for sustainable and decentralized wastewater treatment methods, particularly in developing regions. Current evaluations indicate that efforts to achieve universal access to safe water and sanitation are still insufficient (United Nations World Water Assessment Programme, 2023, pp. 2–3). In this setting, nature-based solutions such as constructed wetlands offer a practical alternative due to their affordability, resilience, and adaptability to local conditions. Many municipalities and rural communities lack sufficient centralised wastewater treatment infrastructure, leading to untreated or partially treated effluent discharges into water bodies. National frameworks like Uganda Vision 2040, the National Development Plan (NDP III), the Water Policy, and the Water and Environment Sector Development Plan highlight sustainable sanitation, pollution control, climate resilience, and ecosystem conservation. Constructed wetlands support these goals by providing decentralised, low-energy, cost-effective wastewater treatment that can be implemented locally with available materials and knowledge (Stefanakis, 2019; Langergraber et al., 2019; Vymazal, 2018). They are particularly important for removing nutrients such as nitrogen and phosphorus, protecting sensitive water bodies such as Lake Victoria and Lake Kyoga, which are vital to fisheries, domestic water supply, and livelihoods (Mitsch et al., 2015). Combining constructed wetlands with wastewater reuse in agriculture also promotes climate adaptation and circular economy strategies by improving water reuse, reducing pollution, and enhancing soil fertility (Drechsel et al., 2022; FAO, 2021). These efforts directly support SDGs 6 (Clean Water and Sanitation), 13 (Climate Action), and 15 (Life on Land). Scaling up constructed wetlands offers a practical, policy-aligned, and environmentally sustainable way to enhance water quality, ecosystem services, and climate-resilient sanitation systems across Uganda and the East African region.

# 5.1.1 Governance and Implementation Challenges

Despite their known technological and environmental benefits, deploying constructed wetlands in Uganda and the wider East African region faces several governance, institutional, and financial hurdles. Land tenure issues, particularly in peri-urban areas with fragmented ownership and customary land systems, often hinder site acquisition and jeopardise project sustainability (Drechsel et al., 2022; UN-Habitat, 2020). Additionally, institutional fragmentation among water utilities, environmental agencies, local governments, and land authorities often results in unclear mandates and weak coordination in planning, operation, and maintenance of constructed wetlands (Langergraber et al., 2019; Stefanakis, 2019). Limited funding further restricts adoption: while CWs generally have low operational costs, their initial investment is seldom prioritised in municipal budgets, and access to climate finance and blended funding remains limited in many developing areas (World Bank, 2021; UNEP, 2022). Overcoming these challenges requires integrated planning, clear institutional roles, and innovative financing models that combine public funds, donor support, and community involvement. Currently, research primarily focuses on general wetland designs or single-species evaluations, with few comparative studies on locally adapted macrophytes under standardised hydraulic and substrate conditions (Vymazal, 2018). This study addresses this gap by experimentally assessing how different macrophyte species perform in nutrient removal under controlled flow, substrate, and hydraulic retention time conditions, providing evidence to support optimised, context-specific CW design and deployment.

## 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 $\alpha$ level of 0.05, in accordance with environmental engineering standards (Montgomery, 2017). Before analysis, data were tested for normality with the Shapiro–Wilk test and for 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 nutrient removal efficiency differed significantly among 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,

$\mu$ = overall mean,

$\alpha_i$ = effect of the $i^{th}$ macrophyte species,

$\epsilon_{ij}$ = 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,

$\beta_0$ = intercept,

$\beta_1$ = regression coefficient,

$\epsilon$ = 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 suggests that macrophyte growth plays a crucial role in enhancing nutrient removal in constructed wetlands. Wetland plants contribute directly by assimilating nitrogen and phosphorus into plant biomass and indirectly by stimulating rhizosphere microbial activity. Through their aerenchyma tissues, macrophytes transport oxygen to the root zone, creating aerobic–anaerobic microenvironments that support microbial processes such as nitrification–denitrification while also promoting phosphorus adsorption onto root-associated substrates and microbial biofilms (Kadlec & Wallace, 2009; Vymazal, 2013; Stefanakis, 2018).

The strong correlation observed indicates that macrophyte growth plays a crucial role in improving nutrient removal efficiency in constructed wetlands. Wetland plants contribute directly by assimilating nitrogen and phosphorus into their biomass and indirectly by stimulating microbial activity in the rhizosphere. Through specialised aerenchyma tissues, macrophytes enable oxygen transport to the root zone, creating dynamic aerobic–anaerobic microenvironments that support essential biogeochemical processes such as coupled nitrification–denitrification, while also enhancing phosphorus removal via adsorption onto root-associated substrates and microbial biofilms (Kadlec & Wallace, 2009; also mentioned in Vymazal, 2018). Recent studies further demonstrate that plant species selection, root architecture, and growth dynamics significantly influence oxygen transfer efficiency, microbial community structure, and overall nutrient transformation pathways, especially under tropical conditions where higher temperatures boost biological activity (Langergraber et al., 2019; Stefanakis, 2020). These findings highlight the vital role of plant–microbe–substrate interactions in optimising constructed wetland performance and emphasise the importance of selecting appropriate macrophyte species to enhance nutrient removal efficiency.

## 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 in Table 2.

i. 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.
ii. 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.
iii. 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 | i. Sustainable natural resource management<br>ii. Environmental protection and restoration<br>iii. to mitigate climate change impacts through sustainable agriculture, protection of wetlands (representing 13% of land area), and restoring forest cover to 21%<br>iv. Climate-resilient infrastructure<br>v. 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) | i. Water and Environment Programme<br>ii. Water for production (irrigation & livestock)<br>iii. Environmental restoration (restore wetlands and degraded lands)<br>iv. Pollution control and water quality improvement<br>v. Climate change adaptation and mitigation | 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) | i. Prote<br>ii. ction of water resources from pollution<br>iii. Regulation of wastewater discharge<br>iv. Enforc<br>v. ement 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 show that constructed wetlands effectively serve as engineered ecological systems that lower nitrogen and phosphorus in domestic wastewater. The reductions in ammonia (from 6.99 to 2.22 mg/L) and soluble phosphorus (from 17.47 to 3.05 mg/L) align with nutrient removal efficiencies reported in laboratory and pilot-scale CWs under controlled hydraulic conditions (Vymazal, 2018; Langergraber et al., 2019; Stefanakis, 2019). Ecologically, these decreases result from hydrological regulation, substrate-mediated adsorption, retention, and biological processes like plant uptake and microbial nitrification–denitrification within the Aturukuku system. Similar research suggests that these integrated processes are particularly effective in tropical climates, where higher temperatures boost microbial activity and nutrient cycling, thus enhancing treatment performance (Mashauri et al., 2016; Stefanakis, 2019). Overall, the findings confirm that the Aturukuku constructed wetland functions as intended and supports its role as a sustainable, nature-based solution for nutrient removal under controlled hydraulic conditions at the Aturukuku lagoon (Fig. 2). Mashauri et al. (2000) also note that constructed wetlands are generally seen as cost-effective systems suitable for developing countries (p. 1135) that need minimal energy and technical expertise.

The effluent nutrient concentrations approach thresholds recommended for restricted agricultural reuse, underscoring Aturukuku's dual role as both a treatment and resource recovery system. This multifunctionality is a core principle of ecological engineering, where systems are designed not only to meet regulatory standards but also to provide ecosystem services such as nutrient recycling and water reuse. Overall, integrating eutrophication research with CW performance shows that constructed wetlands are more than just treatment units; they operate as integrated ecological engineering systems that reduce nutrient pollution and enhance ecosystem resilience. Their adherence to green infrastructure principles and circular economy strategies highlights their significance for sustainable water management, especially in rapidly urbanising, resource-limited regions. Therefore, improving CW design, optimisation, and policy integration will be vital for the long-term control of eutrophication and the conservation of water resources.

# 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 below-ground biomass increases rhizosphere volume, promotes microbial colonisation, 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. Mitsch & Gosselink (2015) explain nutrient cycling in wetlands, emphasising complex interactions among microorganisms, vegetation, and substrates. They point out that nitrogen is mainly removed through nitrification and denitrification (pp. 603–605), while phosphorus is retained via sedimentation and adsorption processes. The findings are consistent with ecological engineering principles, which emphasise the use of structurally complex and highly productive plant species to enhance ecosystem resilience, functional redundancy, and overall treatment performance in engineered wetland systems. Such species contribute to system stability by supporting diverse microbial communities, increasing habitat heterogeneity, and maintaining nutrient removal processes under variable environmental conditions (Vymazal, 2013; Stefanakis, 2018; Wu et al., 2015).

# 8.1.2 Plant Biomass as a Driver of Nitrogen Transformation Processes

Regression analysis revealed a strong positive correlation between plant biomass and ammonia removal efficiency ($R^2 > 0.70$, $p < 0.01$), highlighting the important yet indirect role of vegetation in nitrogen cycling within constructed wetlands (CWs). Although direct plant uptake usually accounts for a small part of nitrogen removal, greater biomass improves rhizosphere conditions by increasing oxygen diffusion through aerenchyma tissues and supplying organic carbon substrates. This supports microbial processes such as nitrification and denitrification (Vymazal, 2018; Langergraber et al., 2019). Recent studies confirm that plant growth patterns, root architecture, and species-specific traits significantly influence microbial communities and nitrogen transformation pathways, especially in warm climates that enhance biological activity (Stefanakis, 2019). These findings align with ecological engineering principles, indicating that constructed wetland performance depends on complex interactions among hydrology, vegetation, substrate characteristics, and microbes, rather than on individual components. Mara (2004) states that nitrogen removal in pond systems occurs through processes such as ammonia volatilisation and biological transformations (p. 115), which are enhanced by algal-induced increases in pH (p. 117). Therefore, strategic vegetation management, including selecting suitable species, optimising planting density, and periodic harvesting, can effectively improve system stability and maintain high nitrogen removal efficiency 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 the

Aturukuku constructed wetland is driven by synergistic interactions between substrate sorption processes and biological assimilation.

However, consistent with previous ecological engineering studies, the phosphorus removal capacity of constructed wetlands often declines over long operational periods due to progressive saturation of adsorption sites within the substrate media (Vymazal, 2011; Vymazal, 2018; Li et al., 2020; Wang et al., 2021). Once the sorption capacity of the substrate is exhausted, phosphorus retention efficiency decreases, and in some cases, previously stored phosphorus may be released back into the water column. This limitation highlights the importance of adaptive design strategies, including the use of reactive or high-sorption substrates (e.g., slag, zeolite, or biochar), staged wetland treatment cells, and periodic substrate replacement or regeneration to maintain long-term phosphorus removal performance (Brix et al., 2011; Stefanakis, 2018; Dotro et al., 2022). Therefore, sustainable phosphorus management in the Aturukuku constructed wetlands requires balancing short-term biological uptake by macrophytes with long-term geochemical retention mechanisms within the wetland substrate.

# 8.1.4 Implications for Ecological Design and System Scalability

Assessing locally adapted macrophytes under standardised hydraulic and substrate conditions addresses a crucial gap in the design and optimisation of constructed wetlands in developing regions. The exemplary performance of *Cyperus papyrus* at the Aturuku treatment plant highlights its suitability as a functional component in engineered wetland systems, particularly where ecological compatibility, availability, and resilience to environmental changes are critical (Mashauri et al., 2016; Stefanakis, 2020). Indigenous macrophytes are increasingly appreciated for their better adaptation to local climates and their ability to maintain consistent treatment performance under varying loads (Vymazal, 2018; Langergraber et al., 2019). From a scalability perspective, results indicate that CWs like the Aturukuku system, designed with native species, can provide effective nutrient removal while remaining energy-efficient and simple to operate. These features are vital for decentralised and peri-urban wastewater management, where financial, technical, and infrastructural constraints often limit the use of conventional treatment methods (Drechsel et al., 2022; UN-Habitat, 2020). Thus, integrating locally adapted macrophytes into CWs enhances treatment efficiency and supports the broader adoption of sustainable, nature-based wastewater solutions in resource-limited areas.

# 8.1.5 Policy and Sustainable Development Goal Implications

The nutrient removal performance of *Cyperus papyrus*-based constructed wetlands at the Aturukuku plant has significant consequences for wastewater management policies and sustainable development plans. These wetlands can generate effluent nutrient levels suitable for limited agricultural reuse, supporting the safe integration of wastewater reuse in water-scarce, nutrient-poor farming systems. This improves water security and encourages a circular resource use (Drechsel et al., 2022; FAO, 2021). On a policy level, these findings back Sustainable Development Goals (SDGs) such as SDG 6 (Clean Water and

Sanitation) by promoting affordable, decentralized wastewater treatment; SDG 13 (Climate Action) through low-energy, climate-resilient treatment options; and SDG 15 (Life on Land) by reducing eutrophication caused by excess nutrients, thus safeguarding terrestrial and aquatic ecosystems (Stefanakis, 2019). The use of native macrophytes also supports national and regional strategies centered on nature-based solutions, ecosystem restoration, and locally suitable technologies (Langergraber et al., 2019; UNEP, 2022).

The global water crisis underscores the urgent requirement for sustainable, decentralised wastewater treatment solutions, particularly in developing areas. Current data indicate that efforts to achieve universal access to safe water and sanitation remain insufficient (United Nations World Water Assessment Programme, 2023, p. 2). In this regard, nature-based approaches such as constructed wetlands offer a practical alternative due to their affordability, resilience, and adaptability to local conditions. These systems align with the global demand for integrated, cooperative water management strategies (United Nations World Water Assessment Programme, 2023, p. 10).

Integrating CWs into national wastewater reuse policies and environmental management frameworks can improve regulatory adherence, increase system resilience, and support ecosystem-based management strategies. Additionally, this study highlights the need to incorporate species-specific performance criteria into CW design standards to enhance treatment reliability, optimise nutrient removal, and ensure sustainability under various operational conditions (Vymazal, 2018).

The long-term effectiveness of the Aturukuku system heavily relies on managing sludge buildup. If left untreated, accumulated settled solids can decrease treatment capacity and hydraulic efficiency. Regular desludging, depending on the rate of sludge accumulation, is vital. The removed sludge can be transferred to drying beds for dewatering and stabilisation, then safely reused as compost or a soil conditioner in agriculture. This process allows the recovery of valuable nutrients such as nitrogen, phosphorus, and organic carbon, supporting circular economy principles in wastewater management. Recent studies confirm that reusing treated sludge in agriculture is an environmentally sustainable approach, reducing dependence on landfills and enhancing soil fertility, structure, and carbon content (Collivignarelli et al., 2019; Semerci et al., 2019; Drechsel et al., 2022).

# 9.0 Conclusion

This study shows that the Aturukuku constructed wetland effectively and reliably reduces nitrogen and phosphorus levels in domestic wastewater. Its performance is strongly affected by the choice of macrophyte species. Macrophytes are essential because they enhance nutrient uptake and provide surfaces for biofilm growth (Vymazal & Kröpfelová, 2020, p. 93). Results indicate that CWs can significantly reduce nutrient levels when hydraulic conditions are well controlled, with *Cyperus papyrus* demonstrating the highest removal efficiency. A positive link between plant growth and nutrient removal emphasises the important role of vegetation in boosting system performance, both through direct nutrient uptake and by stimulating microbial activity in the rhizosphere (Vymazal, 2018; Langergraber et al., 2019). These findings advocate for the strategic use of locally adapted macrophytes to enhance the efficiency, resilience, and sustainability of constructed wetland systems.

Comparable nutrient removal efficiencies are commonly observed in constructed wetlands throughout tropical sub-Saharan Africa, where warm climates promote increased biological activity. Higher temperatures accelerate microbial processes, enhance macrophyte growth, and strengthen biogeochemical functions like nitrification, denitrification, and phosphorus sorption, leading to better treatment results than in temperate areas (Wu et al., 2015; Stefanakis, 2019; Vymazal, 2018; Wang et al., 2021; Dotro et al., 2022). Consequently, the performance of the Aturukuku CW system supports the broader understanding that tropical conditions create favourable environments for efficient nutrient removal in nature-based wastewater treatments.

Pilot-scale and field studies in East Africa show ammonia removal rates of about 60% to 85% in constructed wetland systems (Okurut et al., 2015; Wu et al., 2015; Vymazal, 2018). When operated with controlled hydraulic loading and retention times, these systems effectively and sustainably treat wastewater in tropical climates. Stefanakis (2019) notes that high performance is mainly due to warmer temperatures that boost microbial activity, especially nitrification and denitrification, and promote macrophyte growth, thereby increasing nitrogen removal. Langergraber et al. (2019) and Wang et al. (2021) also agree on this. These findings align with those from the Aturukuku system and support the suitability of CWs for nutrient removal in tropical environments. Lee et al. (2009) explain that nitrogen removal in constructed wetlands primarily occurs via microbial processes such as nitrification and denitrification (p. 12), with plant uptake playing a secondary role. Conversely, phosphorus removal mainly depends on physicochemical processes and generally diminishes over time due to substrate saturation (p. 16).

To advance nature-based solutions aligned with Sustainable Development Goals (SDGs) 6, 13, and 15, choosing the right macrophytes is vital for improving the effectiveness and sustainability of constructed wetlands (CWs). *Cyperus papyrus*, known for its excellent performance, is particularly suitable for decentralised wastewater treatment in Uganda and other tropical areas where ecological compatibility and local availability are important. Constructed wetlands provide a durable, cost-efficient method to meet national effluent standards and enable the safe reuse of treated water for agriculture, thereby enhancing water security and promoting circular resource management (Drechsel et al., 2022). By combining natural treatment with resource recovery, CWs contribute to sustainable water management, climate resilience, and ecosystem protection, directly supporting SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land). According to FAO (2021, pp. 21–23), increasing pressure on land and water resources worldwide worsens water scarcity and pollution. Agricultural runoff and untreated wastewater significantly increase nutrient loads in aquatic systems, causing eutrophication. The FAO highlights that sustainable water management strategies are crucial to mitigate these impacts (p. 109). Overall, nature-based solutions like constructed wetlands are increasingly recognised for their role in enhancing water quality and supporting ecosystem services (FAO, 2021, pp. 121–123).

## 9.1 Policy Recommendations for Overcoming Implementation Barriers

To enhance the adoption and effectiveness of constructed wetlands in Uganda and similar settings, planners and regulators should include locally appropriate macrophytes like *Cyperus papyrus* in national standards. This approach promotes sustainable, climate-resilient wastewater treatment solutions (Stefanakis, 2019; Vymazal, 2018). To resolve land tenure challenges, official recognition of CWs as essential public infrastructure for sanitation and environmental health is necessary. Such acknowledgement would support their prioritisation in national and local development plans and enable land allocation through mechanisms such as easements, community land agreements, and public land reservations. Rapid urbanization currently increases pressure on water and sanitation infrastructure in developing countries (UN-Habitat, 2020, pp. 12–14), and inadequate wastewater management significantly contributes to urban water pollution and environmental degradation (UN-Habitat, 2020, p. 56). Addressing these issues requires adopting sustainable and resilient infrastructure systems. Investing in wastewater treatment is crucial for environmental protection and offers economic and social benefits (World Bank, 2021, p. 35*)*. The World Bank emphasises that nature-based solutions, like constructed wetlands, are increasingly recognised as cost-effective wastewater management options, especially in low-income areas. Including CWs in municipal zoning and catchment management plans can reduce siting conflicts and improve long-term land security. Strengthening institutional coordination is equally vital. Establishing clear governance structures to define roles among water utilities, environmental agencies, local governments, and land authorities during planning, construction, and operation phases is essential. Creating inter-agency coordination platforms and integrating CWs into existing water and environmental sector groups can improve accountability, streamline permitting processes, and ensure consistent monitoring and performance evaluation (Langergraber et al., 2019). UNEP (2022, pp. 264–270) highlights the growing focus on sustainable, nature-based solutions such as constructed wetlands, which offer affordable, eco-friendly wastewater treatment options. The report also notes that improving policy frameworks and governance is key to fostering the wider adoption of these systems.

To address financing challenges, CWs should be clearly incorporated into national sanitation investment strategies and climate-resilient infrastructure plans. This inclusion can help unlock access to public funds, donor support, and climate finance options. Promoting blended financing approaches that combine municipal budgets, development partner grants, and community contributions, along with results-based financing and dedicated funding for nature-based solutions, is vital to expanding implementation (Drechsel et al., 2022). Moreover, enhancing local technical capacity in CW design, operation, and maintenance is essential to ensure these systems remain cost-effective and sustainable over the long term.

The Aturukuku Sewerage Treatment Plant is a cost-effective, nature-based solution designed for tropical municipal wastewater. Its long-term performance relies on proper hydraulic design, regular maintenance, and effective sludge handling. To maintain optimal treatment, ongoing monitoring and adaptive adjustments are essential. Future research should aim to enhance the efficiency and predictability of constructed wetland systems by investigating advanced substrate materials, such as phosphorus-sorbing media (PSMs), to better retain nutrients without requiring external carbon sources. Additionally, developing predictive kinetic models for key tropical plants, such as *Cyperus papyrus*, can help estimate areal rate constants ($K_a$) under different temperatures and loading conditions (Vymazal, 2018; Stefanakis, 2019). These improvements will increase the scalability, reliability, and cost-effectiveness of CWs for decentralised and high-load wastewater treatment.

# Declarations

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**AUTHORS CONTRIBUTIONS**

All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were carried out byTitus Bitek Watmon, Daniel Hector Ologe, Ezra Niringiyimana, Marcel Engiro, Brian Kasule, Guleson Ayat Tiko, Daniel Zirete, Alice Elizabeth Iramu, Moses Ogen, and John Ogire. The first draft of the manuscript was written by Ezra Niringiyimana, and all authors reviewed and approved the final manuscript.

**Ethical Approval:** Not applicable.

This study did not involve human participants, human data, or animal subjects. The research was conducted using municipal wastewater samples collected from the Aturukuku Sewerage Treatment Plant as part of routine environmental monitoring activities. All sampling and analytical procedures were carried out in accordance with applicable national environmental regulations and institutional guidelines governing wastewater and environmental research.

Permission to access the study site and collect samples was obtained from the relevant municipal authorities responsible for the management of the Aturukuku Sewerage Works. No personal, sensitive, or identifiable information was collected or used. The study posed no foreseeable risk to plant operators, the public, or the surrounding environment.

**Consent to Participate:** Not applicable.

**Consent to Publish:** Not applicable.

**Data Availability Statement:** This study's datasets were collected through field measurements, laboratory tests, and operational records, all of which were authorised by the National Water and Sewerage Corporation. Anonymised or aggregated data supporting the findings can be obtained from the corresponding author upon request, subject to the organisation's permission. Any additional data generated or analysed during the study are included within this published article.

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# Figures

**Figure 1**

Laboratory Tests in process

**Figure 2**

The Constructed Sewerage Treatment (plant) Lagoon at Aturukuku-Tororo

**Figure 3**

Wetlands planted with Cyperus papyrus at Tororo Aturukuku CW