

Effects of Macrophyte Species and Seasonal Variation on Domestic Greywater Treatment in Free Water Surface Constructed Wetlands

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Abstract

This study evaluated the effects of macrophyte species and seasonal variation on greywater treatment performance in pilot-scale Free Water Surface (FWS) constructed wetlands operated under comparable hydraulic and operational conditions. Two parallel wetland channels planted with Duckweed (*Lemna minor*) and Vetiver (*Chrysopogon zizanioides*) were operated concurrently using greywater from the same source during dry and wet seasons. The systems were monitored over a 31-day treatment period, with sampling at three-day intervals. Removal efficiencies of biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), ammonium (NH₄⁺), total suspended solids (TSS), and Total Coliform were evaluated using two-way analysis of variance to determine the effects of macrophyte species, season, and their interaction. Mean removal efficiencies ranged from 41.7–68.2% during the dry season and 51.4–72.1% during the wet season for Duckweed, compared with 43.1–66.4% and 55.1–70.7%, respectively, for Vetiver. Macrophyte species had no significant effect on BOD₅ ($p = 0.704$), COD ($p = 0.851$), NH₄⁺ ($p = 0.776$), TSS ($p = 0.592$), or Total Coliform ($p = 0.836$). Season significantly affected BOD₅ removal ($F(1,40) = 4.251$, $p = 0.046$), but not COD, NH₄⁺, TSS, or Total Coliform. No significant macrophyte × season interaction was observed for any parameter. The findings indicate that Duckweed and Vetiver achieved comparable greywater treatment performance under the conditions investigated. The study recommends that macrophyte selection for decentralized FWS greywater treatment should consider local availability, establishment, maintenance requirements, and environmental suitability in addition to treatment performance.

1. Introduction

Water is an essential natural resource that supports human health, food production, industrial development and ecosystem sustainability. According to the World Health Organization (WHO), an individual requires approximately 50–100 L of water per day to satisfy basic domestic needs (United Nations - Office of the High Commissioner for Human Rights, UN-OHCH -UNHabitat-WHO, 2010). However, increasing freshwater demand resulting from rapid population growth, urbanization and industrialization has intensified pressure on available water resources, leading to widespread water scarcity in many regions of the world (Kiani & Abbasi, 2012; Anderson et al., 2014). Climate change, unsustainable water consumption and uneven geographical distribution of freshwater resources have further aggravated this challenge, threatening water security and sustainable socio-economic development (FAO, 2012; Vo et al., 2014).

To address the growing imbalance between water demand and supply, wastewater reclamation and reuse have become increasingly important components of integrated water resources management. Greywater, defined as domestic wastewater generated from showers, wash basins, laundries and kitchens but excluding toilet wastewater, constitutes a substantial proportion of household wastewater and offers considerable potential for non-potable reuse after appropriate treatment (Al-Isawi, 2016). Reusing treated greywater can significantly reduce potable water demand while minimizing the environmental impacts associated with untreated wastewater discharge.

Conventional wastewater treatment technologies are generally effective in removing contaminants but are often associated with high capital investment, energy consumption and operational costs, making them less suitable for decentralized applications, particularly in developing countries. Consequently, nature-based treatment systems such as constructed wetlands have attracted increasing attention because of their simplicity, low energy requirements, reduced maintenance costs and environmental sustainability (Muñoz, et al., 2015; Vymazal, 2007, 2011; Sehar et al., 2015). Constructed wetlands simulate the physical, chemical and biological processes occurring in natural wetland ecosystems to remove organic matter, suspended solids, nutrients and pathogenic microorganisms from wastewater (Al-Isawi, 2016).

The treatment efficiency of constructed wetlands is strongly influenced by design configuration, hydraulic loading rate, substrate characteristics, hydraulic retention time and vegetation type (Kadlec & Wallace, 2008). Wetland vegetation performs multiple ecological functions by facilitating oxygen transport to the rhizosphere, enhancing microbial activity, promoting nutrient uptake and providing surfaces for biofilm development. Previous studies have consistently reported high removal efficiencies for biochemical oxygen demand (BOD), chemical oxygen demand (COD) and suspended solids. In India for example Sharma, Gupta, & Kumar (2023) reported 85% reduction in biochemical oxygen demand (BOD) and a 78% reduction in total suspended solids (TSS), demonstrating its effectiveness for decentralized wastewater management, whereas nutrient removal is generally more variable depending on operational conditions and wetland design (Vymazal, 2007; Kadlec & Wallace, 2008).

Although numerous studies have demonstrated the effectiveness of constructed wetlands for wastewater treatment, comparatively few have evaluated the influence of different macrophyte species under contrasting tropical seasonal conditions (Kipasika, 2016). Seasonal variations influence plant growth, microbial activity and biochemical transformation processes, thereby affecting pollutant removal performance (Zulu, 2018). Understanding the combined influence of vegetation and seasonal variability is therefore essential for optimizing wetland performance and promoting sustainable greywater reuse under tropical environmental conditions (Ayanlade et al., 2021).

Accordingly, this study evaluates the treatment performance of Free Water Surface (FWS) constructed wetlands vegetated with Duckweed (*Lemna minor*) and Vetiver grass (*Chrysopogon zizanioides*) for domestic greywater treatment during the dry and wet seasons. The study compares the removal efficiencies of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium (NH_4), total suspended solids (TSS) and Total Coliform, and further assesses the influence of plant species, season and their interaction on treatment efficiency using two-way analysis of variance.

2. Materials and Methods

2.1 Study Area

The study was conducted at the residential quarters of the National Water Resources Institute (NWRI), Kaduna, Nigeria. Greywater generated from domestic activities including bathing, laundry and kitchen operations was collected and conveyed into a retention basin before entering the treatment units see

2.2 Greywater Collection and Experimental Setup

A pilot-scale batch-operated Free Water Surface constructed wetland system consisting of two treatment channels was designed and constructed. One channel was planted with Duckweed (*Lemna spp.*), while the second channel was planted with Vetiver grass (*Chrysopogon zizanioides*). Gravel, sand and topsoil were used as substrate materials.

2.3 Analytical Procedures

Water quality monitoring was conducted over a 31-day treatment period during both wet and dry seasons. Parameters analysed included pH, electrical conductivity (EC), total suspended solids (TSS), total dissolved solids (TDS), turbidity, biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), nutrients, selected heavy metals and microbiological indicators. Laboratory analyses followed the procedures outlined in Standard Methods for the Examination of Water and Wastewater (APHA, 2017).

Removal efficiency was calculated using:

$$RE (\%) = \frac{C_i - C_e}{C_i} \times 100 \dots\dots\dots Eq. 2.1$$

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

2.4 Statistical analysis

The treatment removal efficiencies of biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), ammonium (NH₄⁺), total suspended solids (TSS), and total coliform were analysed using R statistical software (Version 4.6.1; R Core Team, 2025). Prior to statistical analysis, descriptive statistics and boxplots were used to examine the distribution of the data and identify potential outliers.

A two-way analysis of variance (ANOVA) was performed separately for each water quality parameter to evaluate the effects of plant species (Duckweed and Vetiver), season (dry and wet), and their interaction on removal efficiency. Where significant differences were detected (p < 0.05), Tukey's Honestly Significant Difference (HSD) test was applied for pairwise comparison of treatment means using the estimated marginal means (emmeans) package.

3. Results

3.1 Descriptive Statistics of Treatment Efficiency

The constructed wetland systems demonstrated progressive improvements in greywater quality throughout the experimental period. Overall treatment efficiencies were generally higher during the wet season than during the dry season. However the highest pollutant reductions were observed for COD

and microbial indicators. Vetiver consistently demonstrated superior treatment performance compared with Duckweed under both seasonal condition see Table 3.1. The distribution of pollutant removal efficiencies under different plant species and seasonal conditions is illustrated in Figs. 3.1 to 3.5."

Table 3.1
Descriptive statistics of treatment efficiency (%) for the constructed wetland under different plant species and seasons.

Parameter	Plant	Dry Mean $\pm$ SD	Wet Mean $\pm$ SD
BOD ₅	Duckweed	41.7 $\pm$ 21.9	58.5 $\pm$ 28.1
	Vetiver	45.6 $\pm$ 22.9	60.4 $\pm$ 28.2
COD	Duckweed	68.2 $\pm$ 27.9	72.1 $\pm$ 27.9
	Vetiver	66.4 $\pm$ 28.0	70.7 $\pm$ 28.3
NH ₄	Duckweed	41.2 $\pm$ 22.7	54.9 $\pm$ 27.9
	Vetiver	43.7 $\pm$ 23.2	56.9 $\pm$ 27.8
TSS	Duckweed	39.2 $\pm$ 21.1	51.4 $\pm$ 24.6
	Vetiver	43.1 $\pm$ 22.0	55.1 $\pm$ 25.1
Total Coliform	Duckweed	56.8 $\pm$ 28.3	67.1 $\pm$ 30.3
	Vetiver	58.9 $\pm$ 28.3	68.7 $\pm$ 30.0

The boxplots (Figs. 3.1–3.5) illustrate the distribution of removal efficiencies for BOD₅, COD, NH₄, TSS, and total coliform in the Duckweed- and Vetiver-based constructed wetlands during the dry and wet seasons. Overall, both wetland systems demonstrated appreciable pollutant removal, with removal efficiencies generally higher during the wet season than during the dry season. For most parameters, the wet season exhibited higher median removal efficiencies and a slight upward shift in the interquartile range, indicating improved treatment performance under wetter environmental conditions. Although Vetiver tended to show marginally higher median removal efficiencies than Duckweed for several parameters, the overlap in the interquartile ranges suggests that the differences between the two plant species were relatively small.

Among the evaluated parameters, COD and total coliform exhibited the highest removal efficiencies, with median values generally exceeding 70% in both treatment systems, whereas NH₄ and TSS showed comparatively lower and more variable removal efficiencies. The presence of a few low-value observations, particularly for COD, BOD₅, and total coliform, indicates occasional reductions in treatment performance under certain sampling conditions. Nevertheless, the overall distributions demonstrate consistent pollutant removal by both constructed wetland systems, with seasonal variation appearing more pronounced than differences between plant species. These visual patterns are further examined using the two-way ANOVA presented in Table 3.3.

3.2 Effects of Plant Species and Season

The interaction plots showed higher mean removal efficiencies during the wet season for several parameters, particularly BOD₅, NH₄⁺, and TSS. However, the absence of statistically significant plant × season interactions indicates that the seasonal response did not differ significantly between Duckweed and Vetiver.

Table 3.2
Two-way ANOVA results for the effects of macrophyte species, season and their interaction on pollutant removal efficiency.

Parameter	Effect	F(1,40)	p-value	Decision
BOD ₅	Plant species	0.147	0.7039	NS
	Season	4.251	0.0458	Significant
	Plant × Season	0.016	0.8993	NS
COD	Plant species	0.036	0.851	NS
	Season	0.232	0.633	NS
	Plant × Season	0.000	0.984	NS
NH ₄ ⁺	Plant species	0.082	0.7757	NS
	Season	3.045	0.0886	NS
	Plant × Season	0.001	0.9738	NS
TSS	Plant species	0.292	0.592	NS
	Season	2.961	0.093	NS
	Plant × Season	0.000	0.991	NS
Total Coliform	Plant species	0.044	0.836	NS
	Season	1.302	0.261	NS
	Plant × Season	0.001	0.980	NS

Note: NS = not significant at $\alpha = 0.05$; significant = $p < 0.05$. Plant and season were treated as fixed factors. Residual degrees of freedom = 40 for each parameter.

The two-way ANOVA results are presented in Table 3.3. Macrophyte species had no significant effect on the removal efficiency of any of the evaluated parameters ($p > 0.05$). Season significantly affected BOD₅ removal efficiency, $F(1,40) = 4.251$, $p = 0.0458$, whereas seasonal effects were not statistically significant for COD, $F(1,40) = 0.232$, $p = 0.633$; NH₄⁺, $F(1,40) = 3.045$, $p = 0.0886$; TSS, $F(1,40) = 2.961$, $p = 0.093$; or Total Coliform, $F(1,40) = 1.302$, $p = 0.261$.

Although NH_4^+ and TSS exhibited higher mean removal efficiencies during the wet season, these differences were not statistically significant at the 5% significance level. No significant interaction between macrophyte species and season was observed for BOD_5 , $F(1,40) = 0.016$, $p = 0.8993$; COD, $F(1,40) = 0.000$, $p = 0.984$; NH_4^+ , $F(1,40) = 0.001$, $p = 0.9738$; TSS, $F(1,40) = 0.000$, $p = 0.991$; or Total Coliform, $F(1,40) = 0.001$, $p = 0.980$. These results indicate that the effect of macrophyte species on pollutant removal efficiency did not vary significantly between seasons for any of the evaluated parameters.

3.4 Post hoc comparison of BOD_5 removal efficiency

Table 3.3

Tukey-adjusted pairwise comparisons of estimated marginal means for BOD_5 removal efficiency.

Comparison	Mean difference (percentage points)	Adjusted p-value	Interpretation
Duckweed (Dry) vs Vetiver (Dry)	-3.91	0.7202	Not significant
Duckweed (Wet) vs Vetiver (Wet)	-1.96	0.8576	Not significant
Duckweed (Dry) vs Duckweed (Wet)	-16.80	0.1295	Not significant
Vetiver (Dry) vs Vetiver (Wet)	-14.80	0.1790	Not significant

Note: Mean differences are based on estimated marginal means. p-values are Tukey-adjusted; statistical significance was assessed at $\alpha = 0.05$.

Following the two-way ANOVA, Tukey-adjusted pairwise comparisons were conducted to examine differences among the estimated marginal means for BOD_5 removal efficiency. No significant difference was observed between Duckweed and Vetiver within either the dry season (mean difference = - 3.91 percentage points, $p = 0.7202$) or the wet season (mean difference = - 1.96 percentage points, $p = 0.8576$). Seasonal comparisons within individual macrophyte treatments were also not statistically significant for Duckweed (mean difference = - 16.80 percentage points, $p = 0.1295$) or Vetiver (mean difference = - 14.80 percentage points, $p = 0.1790$).

These pairwise results should be interpreted alongside the significant main effect of season identified by the two-way ANOVA, $F(1,40) = 4.251$, $p = 0.0458$. The ANOVA indicated a significant overall effect of season on BOD_5 removal efficiency, whereas the Tukey-adjusted pairwise comparisons did not identify significant differences within either individual macrophyte treatment. The absence of a significant plant $\times$ season interaction further indicates that the seasonal response did not differ significantly between Duckweed and Vetiver. Thus, season had a significant overall effect on BOD_5 removal, but the magnitude of the seasonal response did not differ significantly between macrophyte species.

4. Discussion

4.1 Effect of Plant Species on Treatment Performance

The present study demonstrated that both Duckweed (*Lemna minor*) and Vetiver (*Chrysopogon zizanioides*)-based Free Water Surface (FWS) constructed wetlands achieved appreciable removal of the evaluated greywater pollutants under both dry- and wet-season conditions. Although Vetiver generally produced slightly higher mean removal efficiencies for BOD₅, NH₄⁺, TSS, and Total Coliform, the two-way ANOVA showed that macrophyte species did not have a statistically significant effect on the removal efficiency of any of the evaluated parameters ($p > 0.05$). Thus, the observed numerical differences between the two macrophytes should not be interpreted as evidence of superior treatment performance by Vetiver. Rather, under the controlled hydraulic and operational conditions of the present experiment, Duckweed and Vetiver exhibited statistically comparable treatment performance.

This finding is important because macrophyte selection is only one component of a complex constructed-wetland treatment system. Constructed-wetland performance is influenced by the combined effects of vegetation, substrate characteristics, microbial communities, wastewater characteristics, hydraulic conditions, temperature, hydraulic residence time, and pollutant loading (Wu et al., 2023). Consequently, vegetation effects should be interpreted within the broader hydraulic, biological, and environmental context of the wetland rather than considered independently.

The comparable performance of Duckweed and Vetiver observed in the present study may therefore reflect the contribution of treatment processes common to both wetland units, including sedimentation, filtration, adsorption, microbial degradation, and plant-associated processes. Recent evidence emphasizes that constructed-wetland treatment results from interactions among plant species, substrate characteristics, microbial communities, wastewater dosing, and operational conditions, with microbial processes playing important roles in pollutant transformation and removal (Rani et al., 2024). However, because microbial activity, oxygen transfer, and individual removal mechanisms were not independently measured in the present study, their relative contributions cannot be established directly from the experimental data.

The absence of a significant plant-species effect is also consistent with the broader evidence that different macrophytes can provide substantial treatment without necessarily producing statistically distinct removal efficiencies under all experimental conditions. For example, Justin and Olukanni (2024) evaluated three macrophytes, including *Lemna minor*, in pilot-scale constructed wetlands in Ota, Nigeria. Although differences in pollutant removal were observed among the macrophytes, the study demonstrated the treatment potential of *L. minor*, supporting its applicability as a macrophyte for decentralized wastewater treatment. This suggests that differences in macrophyte performance may depend partly on the characteristics and operating conditions of the treatment system.

Similarly, Ali et al. (2024) reported substantial removal of BOD, COD, TSS, ammonia, and other pollutants in a Free Water Surface constructed wetland planted with *Pistia stratiotes*, with treatment performance

varying with hydraulic retention time. Their findings reinforce the importance of considering hydraulic and operational conditions when interpreting differences in macrophyte-based treatment performance.

An important implication of the present finding is that macrophyte selection may provide some flexibility in decentralized greywater treatment when hydraulic and operational conditions are appropriately controlled. Since neither Duckweed nor Vetiver produced a statistically superior response across the evaluated parameters, selection between the two species may also consider practical factors such as local availability, establishment, maintenance requirements, biomass management, and adaptability to local environmental conditions. This interpretation is consistent with the broader understanding that constructed-wetland performance arises from interacting biological, hydraulic, chemical, and environmental processes rather than vegetation identity alone (Wu et al., 2023; Rani et al., 2024).

Importantly, the present study does not establish that Duckweed and Vetiver are universally equivalent. Rather, the findings demonstrate that, under the specific hydraulic, operational, wastewater, and seasonal conditions investigated, macrophyte species did not significantly differentiate treatment performance. This distinction is important because differences between macrophytes reported in previous studies may partly reflect differences in wetland configuration, hydraulic retention time, loading conditions, substrate, wastewater characteristics, or climate. The controlled comparison adopted in the present study therefore provides a more robust basis for evaluating the contribution of vegetation independently of major hydraulic differences and helps distinguish macrophyte effects from those arising from contrasting operational conditions.

4.2 Influence of Seasonal Variation

Seasonal variation influenced treatment performance to varying degrees across the evaluated water-quality parameters. Although mean and median removal efficiencies were generally higher during the wet season, the two-way ANOVA showed that season had a statistically significant effect only on BOD₅ removal efficiency, $F(1,40) = 4.251$, $p = 0.0458$. Seasonal effects on COD, NH₄⁺, TSS, and Total Coliform were not statistically significant ($p > 0.05$). Therefore, the generally higher wet-season removal observed descriptively should not be interpreted as evidence of a statistically significant seasonal effect for all pollutants.

The significant seasonal effect observed for BOD₅ suggests that the removal of biodegradable organic matter was more responsive to seasonal environmental conditions than the other parameters evaluated. Constructed-wetland treatment is influenced by environmental and hydraulic conditions, with temperature, hydraulic residence time, and pollutant loading identified among the important factors contributing to variability in treatment performance (Wu et al., 2023). In addition, microbial communities are central to organic-matter degradation and nutrient transformation in constructed wetlands, and their composition and activity can respond to seasonal changes in environmental conditions, wastewater characteristics, vegetation, and system configuration (Rani et al., 2024).

The higher wet-season BOD₅ removal observed in the present study may therefore be associated with more favourable conditions for biological degradation. However, this interpretation should be treated as a plausible mechanism rather than a directly demonstrated causal relationship because microbial activity, dissolved oxygen dynamics, and temperature were not independently evaluated as explanatory variables in the present study. A recent study specifically examining constructed wetlands treating greywater under natural seasonal temperature variation reported that seasonal changes in temperature and microbial activity can influence treatment performance, supporting the importance of environmental conditions when interpreting seasonal responses in greywater treatment systems (Mazières et al., 2024).

The absence of significant seasonal effects for COD, NH₄⁺, TSS, and Total Coliform indicates that these parameters were comparatively less responsive to the seasonal conditions represented in the present experiment. Although NH₄⁺ ($p = 0.0886$) and TSS ($p = 0.0930$) showed higher removal during the wet season, these differences did not reach the predefined significance level of $\alpha = 0.05$. They should therefore be regarded as descriptive seasonal patterns rather than statistically confirmed seasonal effects. This distinction is important because constructed-wetland responses can differ among pollutants depending on their dominant removal mechanisms and the interaction between biological, physicochemical, hydraulic, and environmental processes (Wu et al., 2023; Rani et al., 2024).

The finding that BOD₅ was the only parameter significantly affected by season may indicate that biodegradable organic-matter removal was particularly sensitive to seasonal changes in biological treatment conditions in the present FWS system. In contrast, COD removal may have been supported by a combination of biological and physicochemical processes, while TSS removal is strongly associated with physical processes such as sedimentation and filtration. Similarly, Total Coliform removal involves multiple mechanisms, including sedimentation, filtration, adsorption, natural die-off, predation, and environmental stress. Consequently, the response of each parameter to seasonal variation need not be uniform.

From an operational perspective, the results suggest that seasonal variability should be considered when assessing the reliability of decentralized FWS constructed wetlands for greywater treatment. However, the relatively limited number of statistically significant seasonal responses also indicates that the system maintained treatment capacity across both seasons. This is particularly relevant for tropical applications, where seasonal changes may be less extreme than those experienced in temperate climates but can still influence temperature, rainfall, organic loading, and biological activity. The present findings therefore suggest that seasonal conditions should be considered as an important contextual factor rather than assumed to be the dominant determinant of treatment performance.

4.3 Removal Performance of Individual Water Quality Parameters

Among the evaluated parameters, COD exhibited the highest mean removal efficiencies under both macrophyte species and across both seasons. This indicates substantial attenuation of oxidizable

organic matter within the Free Water Surface (FWS) constructed wetlands. Organic matter removal in constructed wetlands is achieved through a combination of biological, physical, and physicochemical processes, including microbial degradation, sedimentation, filtration, adsorption, and plant-associated processes. The relative contribution of these mechanisms depends on wetland configuration, substrate characteristics, hydraulic conditions, wastewater composition, and environmental conditions (Wu et al., 2023; Wang et al., 2024).

The relatively high COD removal observed in the present study may therefore reflect the combined action of these processes rather than the effect of either macrophyte species alone. This interpretation is consistent with recent evidence that constructed-wetland treatment results from interactions among vegetation, substrates, microbial communities, wastewater characteristics, and operational conditions. Microbial processes are particularly important in the transformation and degradation of organic pollutants within constructed wetlands (Rani et al., 2024). However, because microbial activity, dissolved oxygen dynamics, and individual removal pathways were not directly measured in the present study, the contribution of specific mechanisms cannot be quantified.

Total Coliform also showed relatively high removal efficiencies compared with NH_4^+ and TSS. The removal of microbial indicators in constructed wetlands can occur through a combination of physical and biological processes, including sedimentation, filtration, attachment to substrates and biofilms, natural die-off, and biological interactions within the wetland environment. The effectiveness of these processes is influenced by hydraulic conditions, environmental factors, substrate characteristics, and wetland configuration (Wu et al., 2023; Rani et al., 2024). Although the present study demonstrated substantial Total Coliform reduction, the individual contributions of these mechanisms were not independently evaluated. Therefore, the observed reduction should be interpreted as the overall treatment performance of the wetland rather than being attributed to a particular removal mechanism.

NH_4^+ and TSS exhibited comparatively moderate removal efficiencies. Ammonium removal in constructed wetlands involves several interacting processes, including microbial nitrification and subsequent nitrogen transformations, plant uptake, and interactions with the substrate. The relative importance of these pathways depends on oxygen availability, microbial communities, substrate properties, hydraulic conditions, and wastewater characteristics (Rani et al., 2024; Wu et al., 2023). Because nitrification rates, microbial community composition, and nitrogen transformation pathways were not measured in this study, the observed NH_4^+ removal cannot be assigned to a single mechanism.

TSS removal is primarily associated with physical retention processes, particularly sedimentation and filtration, although adsorption and interactions with biofilms and wetland vegetation may also contribute. The effectiveness of these processes depends strongly on substrate properties, hydraulic conditions, particle characteristics, and wetland configuration (Wang et al., 2024). In the present study, TSS removal was lower than COD and Total Coliform removal under most treatment conditions. Although wet-season mean removal was higher for both macrophytes, the seasonal effect was not statistically significant

($F(1,40) = 2.961, p = 0.093$). Thus, the higher wet-season values should be regarded as a descriptive pattern rather than evidence of a statistically confirmed seasonal effect.

The differences in removal efficiencies among the investigated parameters highlight the pollutant-specific nature of constructed-wetland treatment. COD and Total Coliform showed relatively high removal, whereas NH_4^+ and TSS showed comparatively lower removal. This variation is expected because different pollutants are controlled by different combinations of physical, chemical, and biological processes. Consequently, overall wetland performance should be evaluated across multiple water-quality indicators rather than using the removal of a single parameter as an indicator of system effectiveness (Wu et al., 2023; Wang et al., 2024).

Importantly, high removal efficiency should not be interpreted as evidence of a statistically significant treatment-factor effect. In the present study, COD and Total Coliform achieved relatively high mean removal efficiencies, but the two-way ANOVA showed that neither macrophyte species nor season significantly affected their removal efficiencies ($p > 0.05$). Similarly, although NH_4^+ and TSS showed higher mean removal during the wet season, the corresponding seasonal effects were not statistically significant. These results demonstrate that the magnitude of pollutant removal and the statistical significance of plant or seasonal effects represent different aspects of system performance and should be interpreted separately.

Overall, the results indicate that pollutant removal was parameter-specific and resulted from the integrated functioning of the FWS wetland rather than from a statistically demonstrable advantage of either macrophyte species.

4.4 Implications for Sustainable Greywater Management

The findings of this study have practical implications for decentralized greywater management in water-stressed and resource-constrained settings. Both Duckweed (*Lemna minor*) and Vetiver (*Chrysopogon zizanioides*) wetlands achieved appreciable removal of the investigated pollutants, while the two-way ANOVA detected no statistically significant effect of macrophyte species on BOD_5 , COD, NH_4^+ , TSS, or Total Coliform removal. Under the hydraulic and operational conditions investigated, macrophyte species did not significantly differentiate treatment performance. Consequently, vegetation selection for similar decentralized systems may consider additional factors such as local availability, establishment characteristics, maintenance requirements, biomass management, and environmental suitability, rather than treatment efficiency alone. This interpretation is consistent with the broader understanding that constructed-wetland performance results from interactions among vegetation, substrates, microorganisms, hydraulic conditions, wastewater characteristics, and environmental factors (Wu et al., 2023; Rani et al., 2024).

Constructed wetlands are particularly relevant to decentralized wastewater management because they can provide treatment using relatively simple infrastructure and rely on natural physical, chemical, and biological processes. Reviews of greywater treatment have identified constructed wetlands as promising

treatment options for decentralized applications and water recycling, although their ability to consistently achieve microbiological reuse standards may require additional treatment or disinfection depending on the intended end use (Abdel-Halim et al., 2018; Wu et al., 2023). The present study therefore supports the use of FWS constructed wetlands as a treatment component within decentralized greywater-management systems, rather than suggesting that wetland treatment alone will necessarily make greywater suitable for unrestricted reuse.

The potential contribution of the system to water-resource conservation is particularly relevant where treated greywater can be safely used for appropriate non-potable purposes. Reuse of treated greywater can reduce dependence on freshwater sources and contribute to more circular urban water-management approaches. Recent research on nature-based solutions for circular urban water systems highlights their potential to reclaim water from non-conventional sources and contribute to water-scarcity management and resource recovery (Tsatsou et al., 2023). However, the suitability of the treated effluent for a particular reuse application should be determined by comparing measured effluent quality with the applicable national or international reuse standards. Because the present study did not undertake a formal risk assessment or comprehensive compliance assessment against a specific reuse standard, the results should not be interpreted as demonstrating unrestricted reuse safety.

The findings are also relevant to Sustainable Development Goal 6, particularly Target 6.3, which promotes improved water quality, reduction of pollution, increased wastewater treatment, and safe water reuse. The potential role of constructed wetlands in decentralized wastewater treatment therefore aligns with broader efforts to improve water-quality management and promote sustainable approaches to wastewater treatment. Nevertheless, implementation at larger scales would require consideration of land requirements, hydraulic loading, maintenance, pathogen control, effluent standards, seasonal performance, and long-term operational reliability.

Overall, the findings indicate that FWS constructed wetlands using either Duckweed or Vetiver show potential as decentralized greywater-treatment systems under the tropical seasonal conditions investigated in Kaduna, Nigeria. The practical value of the study lies not in demonstrating that one plant is universally superior, but in showing that comparable treatment performance was achieved by two contrasting macrophyte functional types under controlled hydraulic conditions. This provides useful evidence for vegetation selection and decentralized greywater-management planning in tropical and resource-constrained settings.

4.5 Study Limitations and Future Research

The experimental comparison comprised two concurrently operated pilot-scale wetland channels, with one channel planted with Duckweed and the other with Vetiver. Both channels received greywater from the same source and were operated under comparable hydraulic and operational conditions. Water-quality monitoring was conducted at three-day intervals, resulting in 11 sampling observations for each parameter per channel during each experimental period. This design enabled repeated assessment of treatment performance under comparable operating conditions; however, each macrophyte treatment

was represented by a single physical wetland channel. Thus, the sampling observations represent repeated measurements over time rather than independent replicated wetland units. Future studies should incorporate multiple independent wetland units per macrophyte treatment to strengthen experimental replication and statistical inference.

Conclusions

This study evaluated the treatment performance of Duckweed (*Lemna minor*) and Vetiver (*Chrysopogon zizanioides*) in pilot-scale Free Water Surface (FWS) constructed wetlands treating domestic greywater under dry- and wet-season conditions. The two wetland channels were operated concurrently using greywater from the same source and under comparable hydraulic and operational conditions, enabling a controlled comparison of the two macrophyte types.

Both wetland systems achieved substantial reductions in BOD₅, COD, NH₄⁺, TSS, and Total Coliform over the experimental period. Although Vetiver generally produced slightly higher mean removal efficiencies for several parameters, the two-way ANOVA detected no statistically significant effect of macrophyte species on the removal efficiency of any of the evaluated parameters. Thus, under the specific hydraulic, operational, wastewater, and seasonal conditions investigated, no statistically significant treatment advantage of Vetiver over Duckweed was demonstrated.

Season significantly affected BOD₅ removal efficiency, whereas no statistically significant seasonal effects were detected for COD, NH₄⁺, TSS, or Total Coliform. Furthermore, no significant plant × season interaction was observed for any of the evaluated parameters, indicating that the seasonal response did not differ significantly between the two macrophyte treatments. The observed higher wet-season removal efficiencies for several parameters should therefore be interpreted as descriptive patterns rather than statistically confirmed seasonal effects where $p > 0.05$.

Overall, the findings indicate that macrophyte identity was not a major differentiating factor in pollutant removal under the controlled conditions of this pilot study. The comparable performance of the two contrasting macrophyte types suggests that vegetation selection in decentralized FWS greywater-treatment systems may provide some flexibility, allowing practical considerations such as local availability, establishment, maintenance, biomass management, and environmental suitability to be considered alongside treatment performance.

The substantial pollutant reductions observed also demonstrate the potential of FWS constructed wetlands as nature-based treatment components for decentralized greywater management. However, the present study did not constitute a comprehensive assessment of treated-effluent compliance or health risk for reuse. Therefore, suitability for a particular non-potable reuse application should be established by comparing the treated effluent with the relevant water-quality and reuse standards.

Because the experiment involved one physical channel for each macrophyte treatment, the findings should be interpreted within the conditions investigated rather than as evidence of universal equivalence

between *L. minor* and *C. zizanioides*. Future studies should incorporate replicated wetland units, longer monitoring periods, and multiple seasonal cycles, while explicitly accounting for treatment time, hydraulic loading rate, hydraulic retention time, influent variability, and climatic conditions. Further investigation of nutrient transformation pathways, microbial communities, plant nutrient uptake, pathogen removal, life-cycle impacts, and economic feasibility would strengthen the evidence base for scaling decentralized constructed wetlands for sustainable greywater management.

Declarations

Conflict of Interest

The authors declare no conflict of interest.

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Author Contribution

Conceptualization: Hadiza Nuhu Ajoge; Methodology: Hadiza Nuhu Ajoge; Investigation: Hadiza Nuhu Ajoge; Formal analysis: Ibrahim Muhammad Abubakar; Data curation: Hadiza Nuhu Ajoge; Writing original draft: Hadiza Nuhu Ajoge; Writing, review and editing: Ibrahim Muhammad Abubakar.

Data Availability

My data sets are readily available on request

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Figures

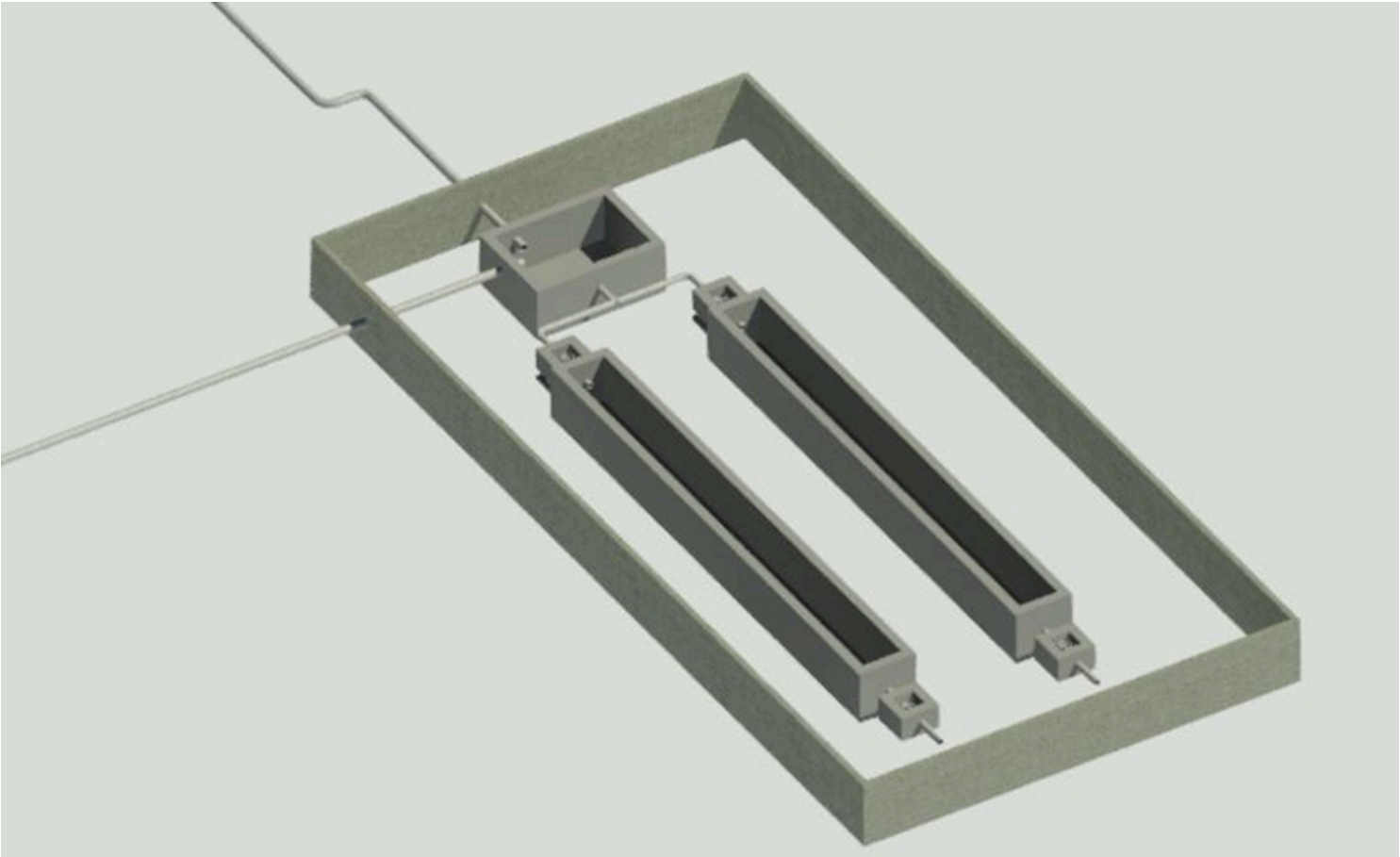


Figure 1

2.1: 3D Model of the Study Area

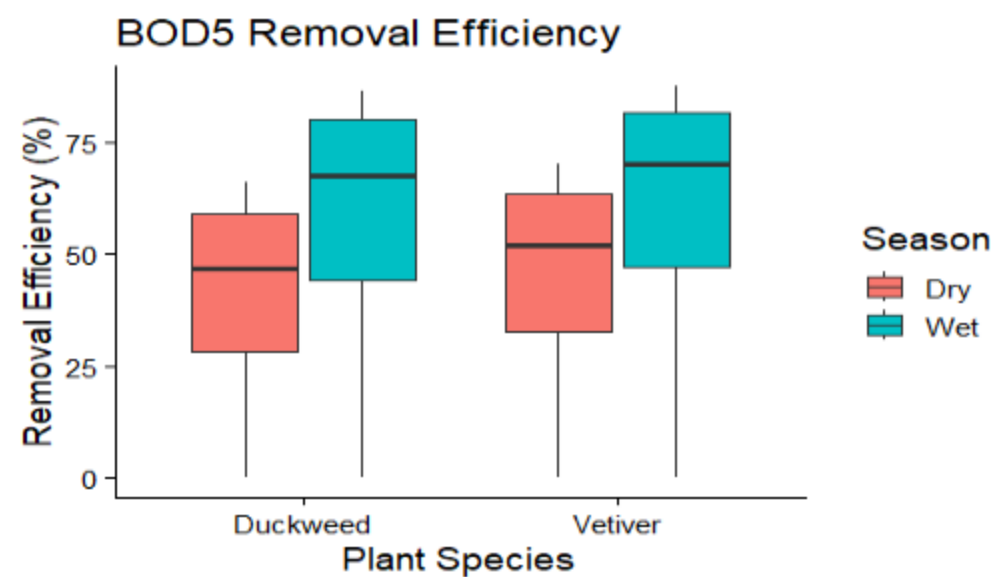


Figure 2

3.1. BOD₅ removal efficiency of Duckweed and Vetiver under dry and wet seasons.

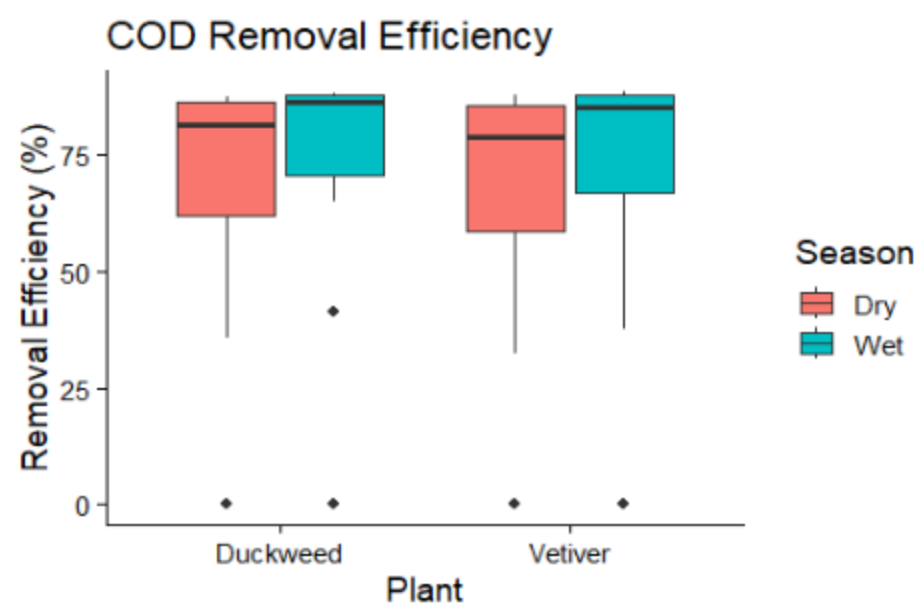


Figure 3

3.2. COD removal efficiency of Duckweed and Vetiver under dry and wet seasons.

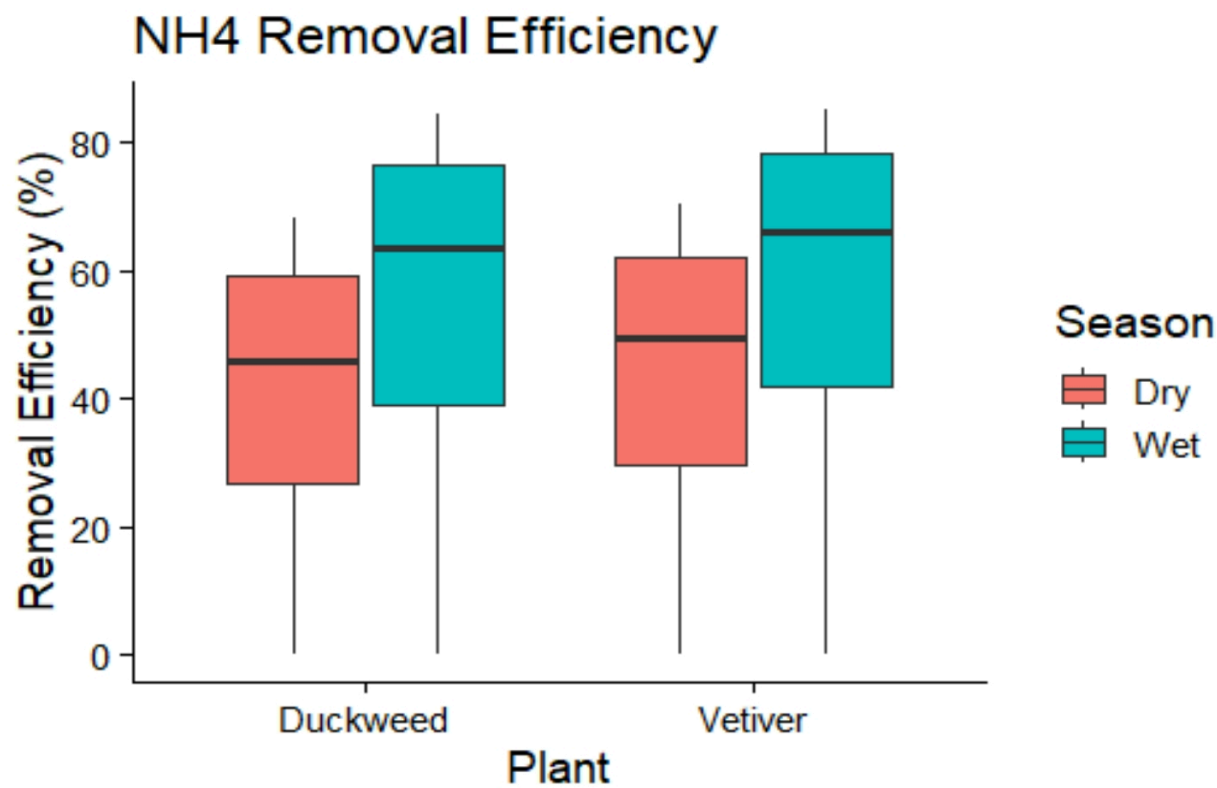


Figure 4

3.3. NH_4^+ removal efficiency of Duckweed and Vetiver under dry and wet seasons.

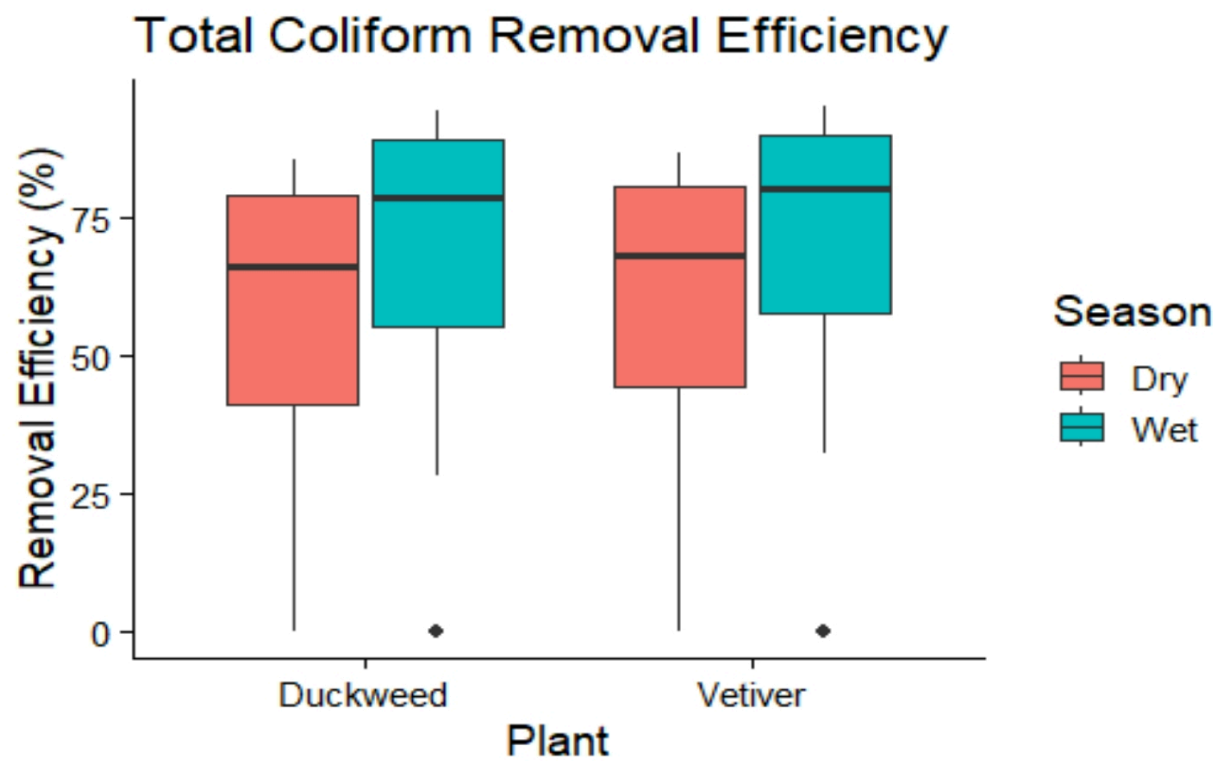


Figure 5

3.4. Total Coliform removal efficiency of Duckweed and Vetiver under dry and wet seasons.

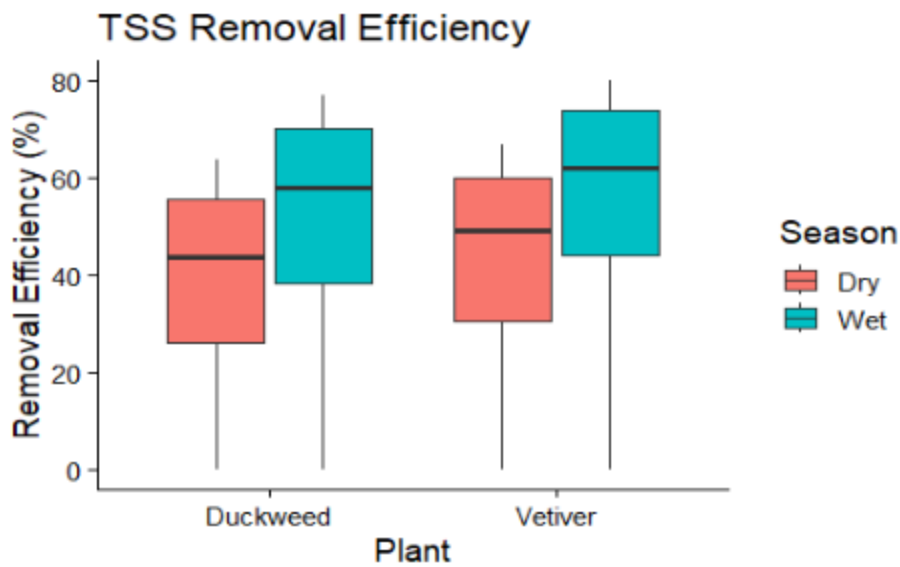


Figure 6

3.5. TSS removal efficiency of Duckweed and Vetiver under dry and wet seasons.

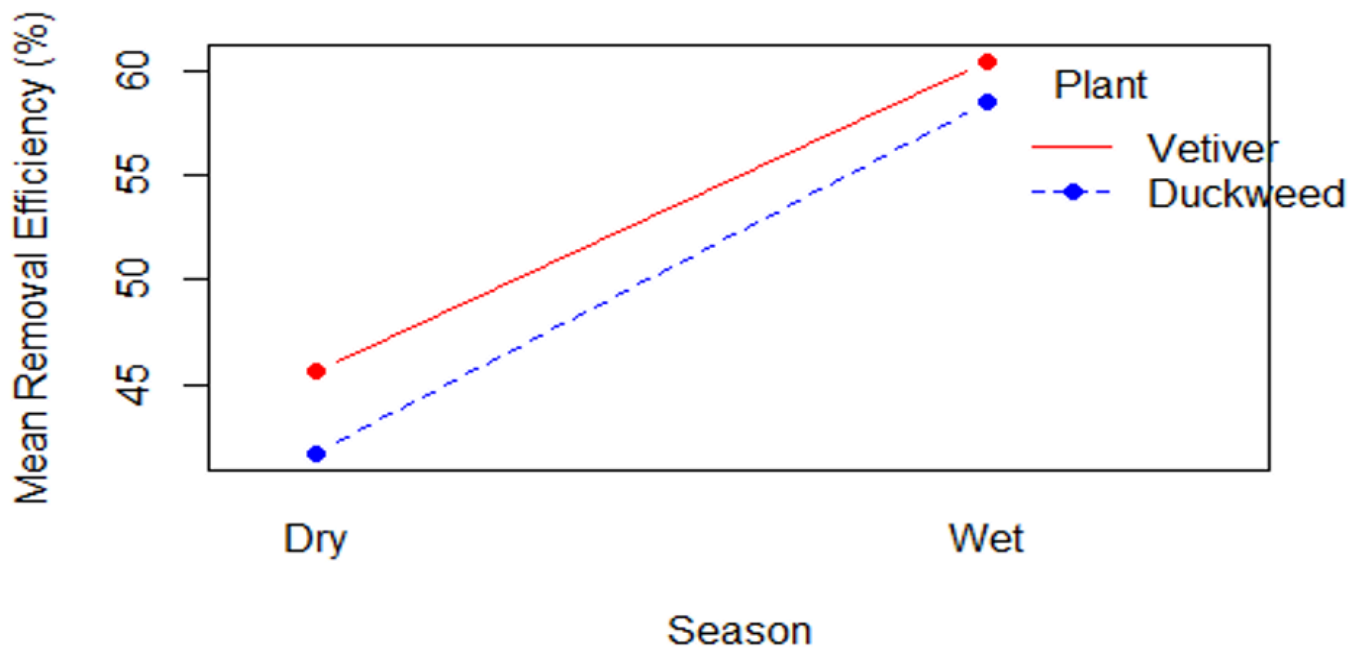


Figure 7

3.6. Interaction plot showing the effects of plant species and season on mean removal efficiency.

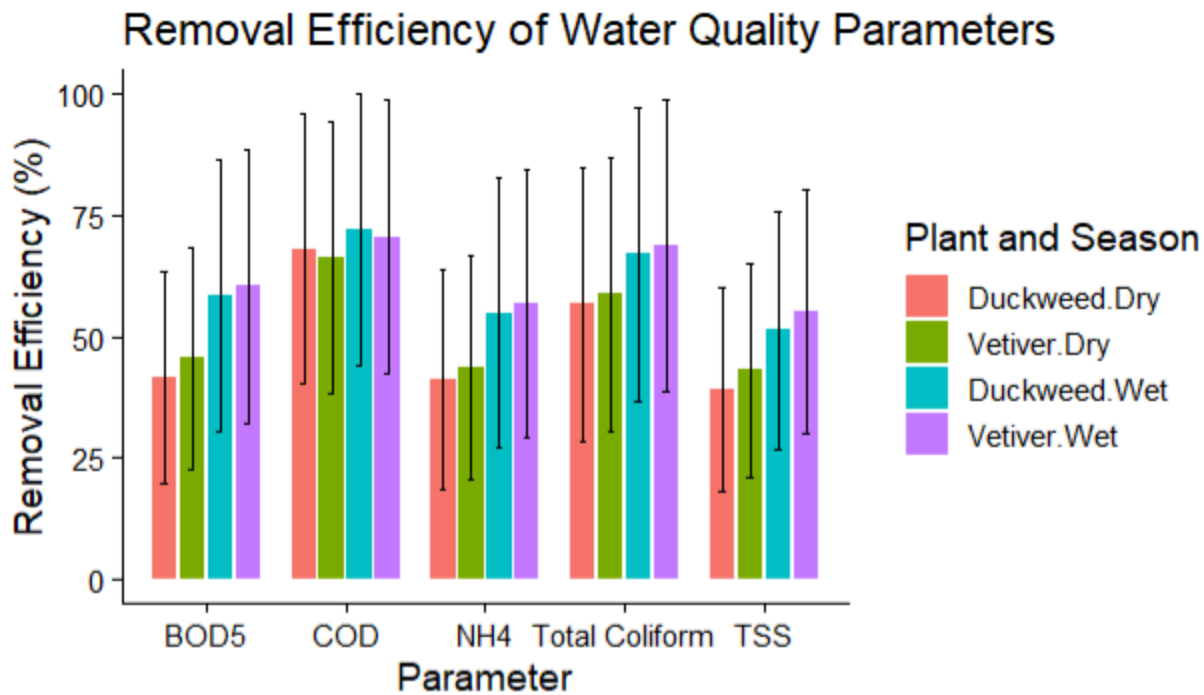


Figure 8

3.7. Mean ($\pm$ SD) removal efficiencies of selected water-quality parameters under different macrophyte species and seasonal conditions.