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Two-year field performance of a full-scale ornamental constructed wetland treating university wastewater under tropical operating variability

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ABSTRACT

University wastewater may contain conventional pollutants and contaminants of emerging concern that are difficult to manage in decentralized settings. This two-year case study evaluated the seasonal performance of a full-scale subsurface-flow ornamental constructed wetland treating wastewater at the Granja Pericos campus, Universidad de Sucre, Colombia, and quantified tissue distributions of nitrogen, phosphorus, and triclosan. The limestone-bed system was planted with *Agapanthus* sp., *Alocasia* sp., *Canna hybrid*, *Cyperus papyrus*, and *Heliconia* sp. Weekly triplicate influent and effluent samples collected during 2024–2025 were analyzed using standardized physicochemical and microbiological methods; tissue triclosan was quantified by ultra-performance liquid chromatography–tandem mass spectrometry. A season × year factorial design was used to evaluate temporal associations. Removal of biochemical oxygen demand, chemical oxygen demand, and total suspended solids was higher during dry periods. Nitrogen removal did not differ significantly between seasonal categories, whereas total phosphorus retention decreased during wet periods. Performance for biochemical oxygen demand and bacterial indicators was higher in 2025. Visual morphological counts indicated greater than 90% apparent retention of putative microplastic particles, although polymer identity was not confirmed spectroscopically. Triclosan occurred predominantly in roots and rhizomes or bulbs and was below the detection limit in stems and leaves. Phosphorus was highest in rhizomes or bulbs, whereas nitrogen occurred in above- and belowground tissues. The results provide site-specific evidence that a full-scale ornamental wetland can contribute to university wastewater treatment under variable tropical field conditions; causal hydraulic interpretation is limited because operational flow and hydraulic retention time were not measured directly.

Keywords: constructed wetland, university wastewater, ornamental plant, seasonal variability, triclosan, microplastics.

INTRODUCTION

Emerging contaminants, also referred to as contaminants of emerging concern (CECs), are chemicals or materials detected in wastewater whose occurrence may pose risks to environmental and human health. Although many of these compounds have been used for decades, they are not completely removed by conventional wastewater treatment systems and, in many cases, remain unregulated. They include pharmaceuticals, illicit drugs, chemical residues, personal care products, pesticides, and other agrochemicals originating from diverse sources (Bhat et al., 2024).

Higher education institutions generate highly complex wastewater discharges characterized by a wide range of waste streams that differ substantially from conventional domestic effluents (Murcia et al., 2023). These aqueous matrices combine typical organic loads with increasing concentrations of contaminants of emerging concern derived from analytical procedures, the use of chemical reagents and personal care products, and polymer wash-off associated with laboratory activities and the cleaning of classrooms, restrooms, and cafeterias.

Globally, triclosan and microplastics are frequently detected in wastewater treatment streams, reflecting the widespread use of antimicrobial personal-care products and the release of synthetic polymer particles (Bakare and Adeyinka, 2022; Zoccali et al., 2025). The situation is especially challenging in developing regions. In Latin America, substantial gaps remain in safely managed sanitation and wastewater treatment, particularly in marginalized peri-urban and rural areas (World Bank, 2022). Moreover, many university campuses are located in peri-urban or rural areas far from municipal sewer networks. In the absence of adequate infrastructure, institutions frequently discharge effluents directly onto soil or into streams and rivers (Zurita and Sandoval-Herazo, 2026), increasing ecological stress in surrounding watersheds.

In response, constructed wetlands (CWs) have emerged as a robust, low-cost, and environmentally sustainable technology for the decentralized treatment of diverse wastewater streams (Vaudry et al., 2023; de Campos and Soto, 2024). Their performance depends on the integrated action of physical, chemical, and biological processes mediated by the substrate matrix, attached microbiome, and vegetation (Rahman et al., 2020). Over the past decade, increasing attention has been given to ornamental macrophytes, which perform essential structural and physiological functions: their roots release oxygen into the rhizosphere, provide extensive surface area for microbial biofilm development, and secrete exudates that contribute to pathogen suppression (Sandoval-Herazo et al., 2026).

Harvested biomass may provide a route for nutrient removal and potential recovery, thereby linking CW operation with circular-economy objectives. Whether this option is environmentally and economically beneficial depends on biomass yield, contaminant co-accumulation, processing requirements, and end-use safety, which require biomass-scaled mass balances and life-cycle assessment. More broadly, decentralized CW treatment may contribute to Sustainable Development Goals related to health, sanitation, sustainable communities, and climate action (SDGs 3, 6, 11, and 13, respectively).

Despite substantial advances in ecological engineering applied to CWs, important knowledge gaps remain regarding system performance under real-world operating conditions. Although numerous studies have demonstrated their effectiveness at laboratory and pilot scales, long-term studies of full-scale facilities remain relatively scarce, limiting the extrapolation of findings to practical applications (Vymazal, 2018). Such studies often use synthetic wastewater with known concentrations to facilitate experimental control. Moreover, many experiments are conducted over relatively short periods, which may constrain system maturation, root development, and the establishment of microbial communities.

Consequently, results obtained under these experimental conditions do not always reflect the behavior of CWs operated under real-world conditions, in which hydraulic, climatic, and biological variability produces processes that are difficult to reproduce at laboratory scale. This limitation is particularly relevant in tropical and subtropical regions. A systematic review by Sandoval-Herazo et al. (2026) identified a pronounced lack of long-term studies of full-scale ornamental CWs, thereby limiting understanding of their operational resilience to environmental conditions. Another unresolved issue concerns the interactions between the removal of conventional contaminants (organic matter and nutrients) and the fate of emerging contaminants within the biological system. Conventional treatment plants have been reported to achieve relatively low removal efficiencies (<72%) for antimicrobial compounds, facilitating their release into ecosystems; however, the effectiveness of ornamental species in wetlands for removing these recalcitrant compounds has not been conclusively demonstrated under long-term, real-world operating conditions (Sandoval-Herazo et al., 2026).

Despite these advances, major knowledge gaps remain regarding the tissue distribution of contaminants and nutrients among the organs of ornamental species (roots, rhizomes, stems, and leaves). The present study evaluated seasonal changes in the performance of a full-scale ornamental CW used to treat university wastewater and operated for two consecutive years (2024–2025). We analyzed spatiotemporal variations in the removal of conventional and emerging contaminants and quantified tissue-specific concentrations of nitrogen, phosphorus, and triclosan. The findings provide site-specific performance data and organ-level distribution patterns relevant to future evaluation of operational management, selective harvesting, and contaminant fate.

MATERIALS AND METHODS

Study area and full-scale system configuration

The study was conducted under real-world environmental conditions at the Granja Pericos campus of the Universidad de Sucre in Sincelejo, Colombia (Figure 1). The campus has a fluctuating population of approximately 450 users, including administrative staff, faculty, and students. The subsurface-flow constructed wetland (CW) was designed on the basis of the baseline wastewater generation associated with this population. The reported 4-day hydraulic retention time (HRT) is a nominal design target under steady-flow assumptions, estimated using the volumetric criteria described by Kadlec and Wallace (2008), rather than a measured operational residence time.

The full-scale system comprises a primary treatment stage consisting of an 11.50 m³ settling tank. The pretreated effluent flows by gravity into a treatment train of five interconnected cells with a combined effective volume of 39.59 m³. Limestone (12–25 mm particle size) was used as the principal filter medium to optimize porosity, facilitate hydraulic conductivity, and promote bacterial biofilm development. Plastic matrices such as PET were intentionally excluded to prioritize and evaluate the biological performance of common and economically accessible mineral substrates in full-scale systems (Sandoval-Herazo et al., 2023). The bed geometry replicated the shape of the institutional emblem to promote landscape integration and community ownership (Figure 2). The installed system did not include continuous flow metering or a tracer-based residence-time assessment. Consequently, operational flow, hydraulic loading rate, and actual HRT were neither controlled nor verified during the two-year monitoring period. Regional precipitation records were used only to contextualize the climatic classification of sampling campaigns and were not used as surrogates to calculate flow, hydraulic loading, or HRT. Therefore, the study cannot determine whether, or by how much, actual HRT changed during wet periods.

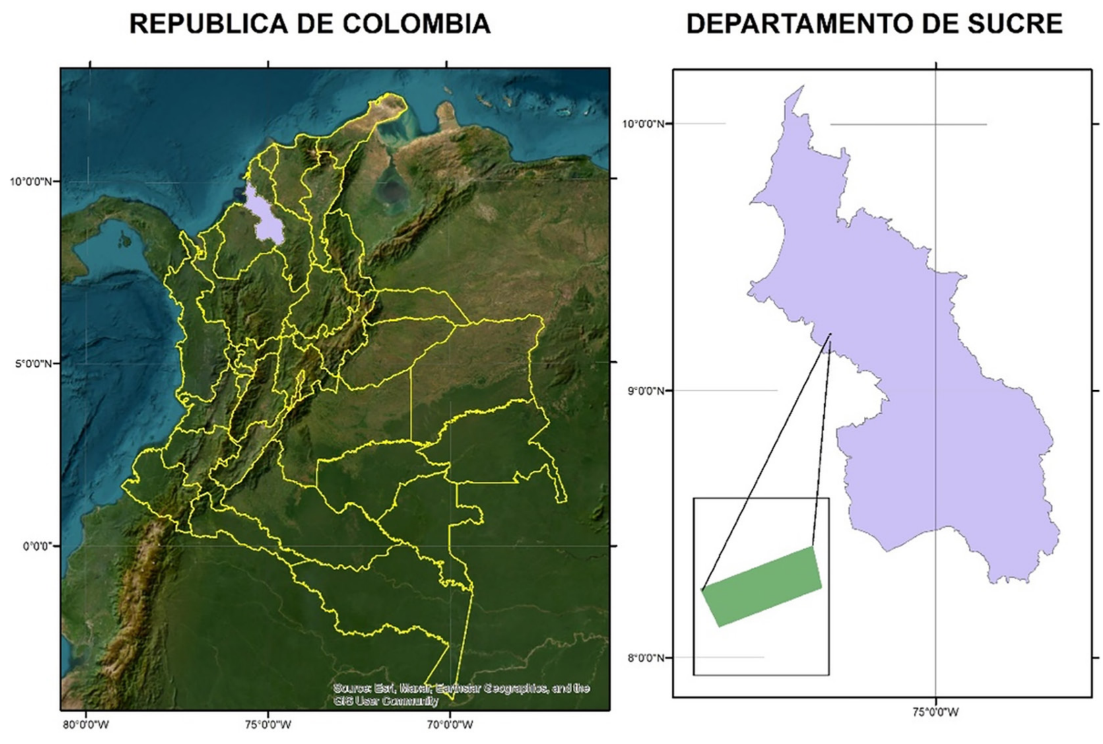

Figure 1. Location map of the study area (Granja Pericos campus)

Selection and acclimation of ornamental vegetation

A total of 205 individuals representing five ornamental macrophyte species adapted to the tropical climatic conditions of Colombia were used for phytoremediation (Lomeli et al., 2025): *Agapanthus* sp., *Alocasia* sp., *Canna hybrid*, *Cyperus papyrus*, and *Heliconia* sp. (Figure 2). Vegetative acclimation was conducted in situ under natural environmental conditions. For the first 20 days after planting, the CW was fed exclusively with tap water to mitigate acute physiological stress. The plants were then gradually acclimated for 40 days using a 50:50 (v/v) mixture of tap water and university wastewater. After this ontogenetic phase, the system was operated exclusively with undiluted wastewater influent. Unlike many controlled studies, the aqueous matrix was not spiked or artificially amended with synthetic compounds, ensuring that the reported performance reflected the actual organic and hydraulic fluctuations of the university community.

To preserve routine field operating conditions, the full-scale system was evaluated without artificial equalization of influent composition or hydraulic loading. This field-based design provides an ecologically relevant assessment of treatment performance under the variable operating conditions of a university campus. However, the absence of direct hydraulic measurements precluded flow-weighted mass balances and causal attribution of seasonal differences to hydraulic mechanisms; the results should therefore be interpreted as site-specific field performance rather than as controlled estimates of hydraulic response.

Spatiotemporal monitoring and treatment performance assessment

After the stabilization period, a systematic spatiotemporal sampling design was implemented to evaluate the performance of the full-scale system. Triplicate water samples were collected weekly at the inlet (influent) and outlet (effluent) over 24 consecutive months (January 2024–December 2025). Sampling campaigns were classified according to the regional climatic regime into dry (Dry) and wet (Wet) periods to compare treatment performance between temporal categories and operational years.

Figure 2. Full-scale ornamental constructed wetland

These labels describe meteorological categories and should not be interpreted as directly measured hydraulic states of the wetland.

Basic environmental parameters – pH, temperature, and dissolved oxygen (Table 1) – were measured in situ using calibrated portable multiparameter probes (Hanna HI98121 and HI9142; Hanna Instruments, Woonsocket, RI, USA).

In the Water and Soil Laboratory, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), ammonium (NH_4^+–N), nitrate (NO_3^-–N), total phosphorus (TP), and microbiological indicators (fecal and total coliforms) were quantified according to internationally standardized analytical protocols (APHA, 2017).

CW treatment performance for physicochemical contaminants was assessed by calculating removal efficiency (E) using Equation 1:

$$E\,(\%) = ((C_{inf} - C_{eff}) / C_{inf}) \times 100 \quad (1)$$

where: C_{inf} and C_{eff} are the mean analyte concentrations in the influent and effluent, respectively. Disinfection performance against microbiological indicators was expressed as log reduction units (LRU) using Equation 2:

$$LRU = \log_{10}(C_{inf}) - \log_{10}(C_{eff}) \quad (2)$$

Isolation and morphological quantification of microplastics

The collected volumetric aliquots were filtered and subjected to wet-oxidation digestion to remove interfering organic matter. Density separation was then performed using a saturated salt solution, and the supernatant was vacuum-filtered through glass-fiber membranes. Plastic particles were visually identified and counted by stereomicroscopy and classified into four predominant morphologies: fibers, fragments, films, and pellets. Concentrations were standardized and expressed as particles L^{-1} (Hidalgo-Ruz et al., 2012; Masura et al., 2015).

Tissue partitioning and bioaccumulation analyses (nutrients and triclosan)

A nondestructive sampling design using randomly placed quadrats (1 and 0.25 m^2) was implemented within the plant stands (Greenway and Woolley, 1999). Collected specimens were washed in situ with distilled and Milli-Q water to remove adhering sediment and biofilm (Wang and Kelly, 2017) and dissected into four anatomically and functionally distinct compartments: roots, rhizomes/bulbs, stems, and leaves. Analytical pretreatments were tailored to the chemical properties of each target analyte:

Macronutrients (N and P)

Plant tissues were oven-dried at 80 °C for 48 h and subsequently ground in a ring mill (Rocklab) (Ruiz and Velasco, 2010). Total nitrogen was analyzed using a stable-isotope mass spectrometer coupled to an elemental analyzer (Roboprep-CN). Total phosphorus was determined by the ascorbic acid colorimetric method (Murphy and Riley, 1962) after acid digestion of plant tissue (Jones, 2001).

Triclosan (TCS)

This compound was selected as a target emerging contaminant because of its use as

Table 1. Mean physicochemical parameters (± standard deviation) measured in situ in the system influent and effluent (2024–2025)

Parameter	Season	Influent	Effluent
pH	Dry	7.4 ± 0.3	6.2 ± 0.4
	Wet	7.2 ± 0.2	6.1 ± 0.3
Temperature (°C)	Dry	28.5 ± 1.2	27.8 ± 1.1
	Wet	26.2 ± 1.5	25.9 ± 1.4
Dissolved oxygen (mg/L)	Dry	1.8 ± 0.5	4.2 ± 0.8
	Wet	2.1 ± 0.6	3.8 ± 0.9
Redox potential (mV)	Dry	-120 ± 25	180 ± 40
	Wet	-140 ± 30	165 ± 35

Note: Values are the arithmetic means of all measurements obtained during the operational campaigns (n = 24 months).

an antimicrobial agent in liquid soaps on campus and its high persistence. To prevent thermal degradation of the xenobiotic, biomass was vacuum freeze-dried at −60 °C for 48 h, cryogenically milled under liquid nitrogen, and sieved to 2 mm. Extraction was performed using a Soxhlet apparatus (6 h; dichloromethane), with triclosan-d_3 as an internal recovery standard. The extracts were centrifuged (4.000 rpm, 8 min) to precipitate interfering material, reconstituted in methanol/water (50:50, v/v), and purified by C18 solid-phase extraction (SPE). The analyte was quantified by UPLC–MS/MS in multiple-reaction monitoring (MRM) mode. For quality assurance and quality control (QA/QC), the method was validated, yielding limits of detection (LOD) and quantification (LOQ) of 0.05 and 0.15 µg/kg dry weight, respectively.

Experimental design and statistical analysis

To evaluate associations of season and operational year with CW performance, a 2 × 2 factorial design was used, with season (Dry vs. Wet) and operational year (2024 vs. 2025) as independent factors. Two-way analysis of variance (ANOVA) was applied to continuous physicochemical variables that met the assumptions of normality and homoscedasticity, whereas the nonparametric Scheirer–Ray–Hare test was used for variables that deviated from normality (e.g., microplastic abundance). Tissue-concentration patterns among organs and species were evaluated by one-way ANOVA followed by Tukey's post hoc multiple-comparison test for means with homogeneous variances. Statistical significance was set at α = 0.05, and all numerical analyses were performed using IBM SPSS Statistics version 26.

RESULTS AND DISCUSSION

Removal efficiency for conventional contaminants and seasonal variation

Organic-matter and suspended-solids dynamics

Analysis of the full-scale constructed wetland (CW) showed that removal of organic matter and suspended solids differed significantly between the regional seasonal categories. Two-way ANOVA results (Table 2) indicated season effects for (BOD_5; $p < 0.00001$), (COD; $p = 0.00035$), and (TSS; $p = 0.00395$).

Removal efficiencies for organic matter and suspended solids were higher during the dry season and lower during the wet season (Figure 3). These observations describe seasonal associations; the study did not measure the hydraulic changes required to attribute the differences directly to contact time or loading.

Lower removal efficiencies during wet periods were temporally associated with the regional climatic category. Shorter contact time and increased hydraulic loading are plausible explanations because both processes can affect solids retention and organic-matter removal in constructed wetlands (García et al., 2010; Zhang et al., 2012); however, neither flow nor HRT was measured in the present study. Seasonal changes in influent concentrations and measured water temperature (Table 1) may also have influenced performance, whereas vegetation and attached-biofilm development could have changed between operational years but were not quantified. Consequently, the separate contributions of hydraulic conditions, influent composition, temperature, and biological maturation cannot be resolved, and the results should be interpreted as multifactorial temporal associations rather than evidence of a single seasonal mechanism. BOD_5 was the only organic parameter with a significant year effect ($p = 0.00564$).

Natural variation in influent concentrations, together with the absence of continuous flow measurements, increased uncertainty in the interpretation of hydraulic and mass-loading effects. Although this variability is representative of routine decentralized campus operation, it cannot by itself establish system resilience or define an operational limit. Instead, the two-year observations show that the wetland continued to provide treatment across the sampled seasonal conditions, while the lower organic-matter and TSS removal observed during wet periods indicates potential sensitivity to hydrological disturbance. Thus, the field design increases ecological relevance but limits mechanistic attribution. Continuous influent and effluent flow monitoring, event-based sampling, and flow-weighted mass balances are required to quantify robustness, identify performance thresholds, and determine whether hydraulic equalization or other management measures would improve performance.

Table 2. Factorial analysis (two-way ANOVA and Scheirer–Ray–Hare test) of treatment performance and seasonal and interannual variation (2024–2025)

Parameter	p-value (Season)	p-value (Year)	p-value (Interaction)
Organic matter (removal efficiency, %)			
BOD_5	< 0.00001 ***	0.00564 **	0.30593
COD	0.00035 ***	0.23968	0.93392
TSS	0.00395 **	0.52184	0.42334
Nutrients (removal efficiency, %)			
NH_4-N	0.12647	0.10024	0.45417
NO_3-N	0.63095	0.26233	0.07817
TN	0.2509	0.04140 *	0.79741
TP	0.00842 **	0.20979	0.97507
Microbiological indicators (log reduction units, LRU)			
CF	< 0.00001 ***	0.00003 ***	0.0555
CT	0.00002 ***	0.00052 ***	0.34782

Note: Bold values indicate statistically significant effects (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). The Season factor compares the regional dry and wet categories, whereas the Year factor compares the two operational years (2024 and 2025). The response variable for chemical parameters was percentage removal efficiency; microbiological indicators – fecal coliforms (CF) and total coliforms (CT) – were evaluated as log reduction units (LRU).

Seasonal variation in nitrogen and phosphorus removal

In contrast to organic matter, removal efficiencies for ammonium nitrogen (NH_4^+–N), nitrate (NO_3^-–N), and TN did not differ significantly between the sampled seasonal categories ($p > 0.05$; Table 2). Effluent concentration profiles were similar across the dry- and wet-season observations (Figure 4). This absence of a detected seasonal difference should not be interpreted as proof of climatic resilience beyond the system and period evaluated.

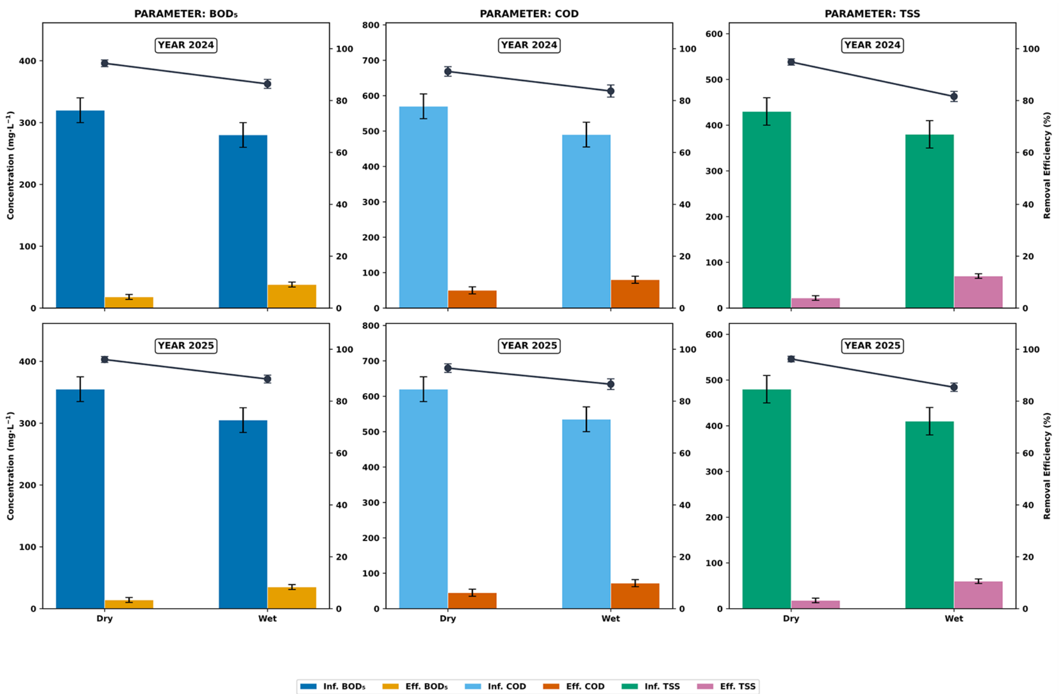

Figure 3. Seasonal dynamics and removal efficiencies for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total suspended solids (TSS) under tropical climatic conditions over two years of operation

The absence of significant seasonal differences for nitrogen is compatible with the persistence of both oxidizing and reducing microenvironments in the bed, which could support coupled nitrification and denitrification. Root oxygen release and deeper anoxic biofilms are plausible contributors, but the relevant microbial communities and pathway-specific rates were not measured in this study.

The observed pattern is consistent with literature showing that temperature, redox conditions, and wetland configuration influence nitrogen transformations (Vymazal, 2007) and with stable organic-matter and ammonium removal reported for a warm-climate hybrid CW (Ávila et al., 2013). Nevertheless, the present study did not measure microbial kinetics or pathway-specific nitrogen transformation rates.

Anaerobic ammonium oxidation (anammox) is another pathway that could contribute to nitrogen removal in CWs under suitable redox conditions (Mitsch et al., 2023). No functional genes, microbial communities, or pathway-specific rates were measured here; therefore, its contribution cannot be inferred from the observed seasonal pattern and should be tested in future mechanistic studies.

By contrast, TP differed significantly between seasonal categories ($p = 0.00842$), with lower retention during the wet season. Phosphorus retention in wetlands can involve adsorption to substrate binding sites and precipitation with calcium ions in limestone, whereas nitrogen can also be removed through gaseous loss as N_2. Arias et al. (2001) showed that phosphorus retention by sand media can vary with material properties and operating conditions. The present study did not measure sorption, precipitation, desorption, or porewater chemistry, so the mechanism underlying the seasonal difference remains unresolved.

Furthermore, under flowing and aerobic conditions, some insoluble phosphate precipitates in the oxygenated rhizosphere. Additional processes contributing to the decrease in total phosphorus include upward diffusion, anaerobic release, and microbial and plant uptake (Mitsch et al., 2023).

Microbiological disinfection performance

Fecal-coliform (CF) and total-coliform (CT) log reductions differed significantly between seasons and between operational years ($p < 0.0001$; Table 2). Log reduction units (LRU) were lower during the wet season (Figure 5). This pattern is compatible with changes in hydraulic conditions and contact time, but HRT was not measured directly and the underlying removal processes were not resolved.

Disinfection performance was higher in 2025 (CF, $p = 0.00003$; CT, $p = 0.00052$). This temporal pattern could reflect progressive establishment of rhizosphere and biofilm communities and/or other unmeasured operational changes. Because microbial community development was

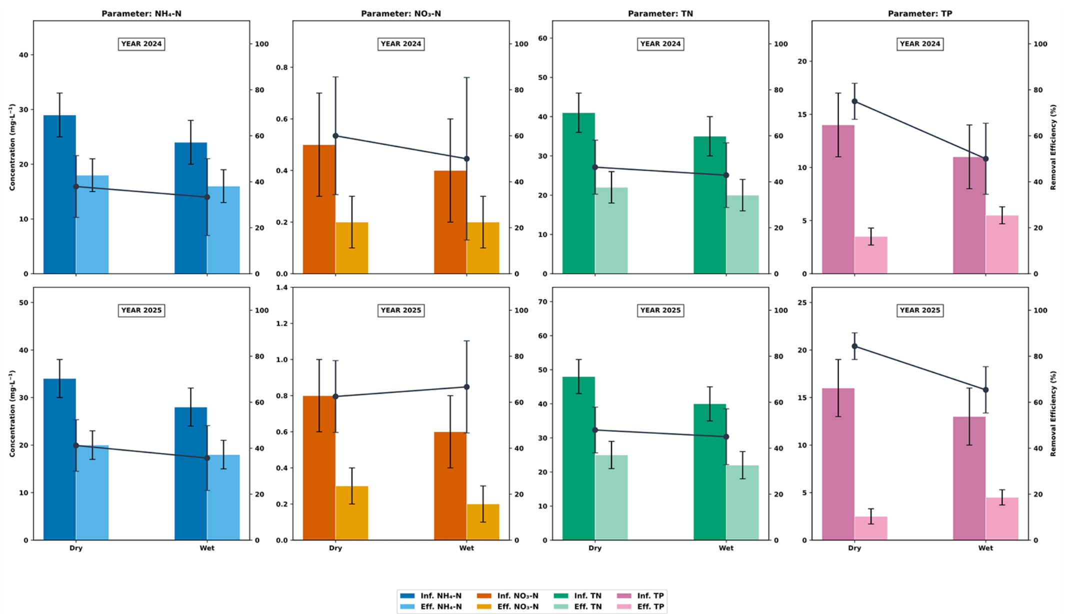

Figure 4. Spatiotemporal variation in nitrogen species (NH_4^+–N, NO_3^-–N, and TN) and total phosphorus (TP) concentrations and their corresponding removal efficiencies during the dry and wet seasons

not measured directly, maturation should be considered a plausible interpretation rather than a demonstrated mechanism.

Physical retention and seasonal dilution of microplastics

Visual examination showed that particles classified morphologically as putative microplastics were dominated by fibers, followed by fragments, films, and pellets (Figure 6). Polymer identity was not confirmed spectroscopically. Unlike the microbiological indicators, the statistical analysis found no significant year effect ($p = 0.24768$) on the total count of retained particles. Apparent retention based on visual counts remained high in both years and approached 100% for pellets and films during the dry season.

Season had a significant effect ($p < 0.01$) on influent MP concentrations. During wet periods

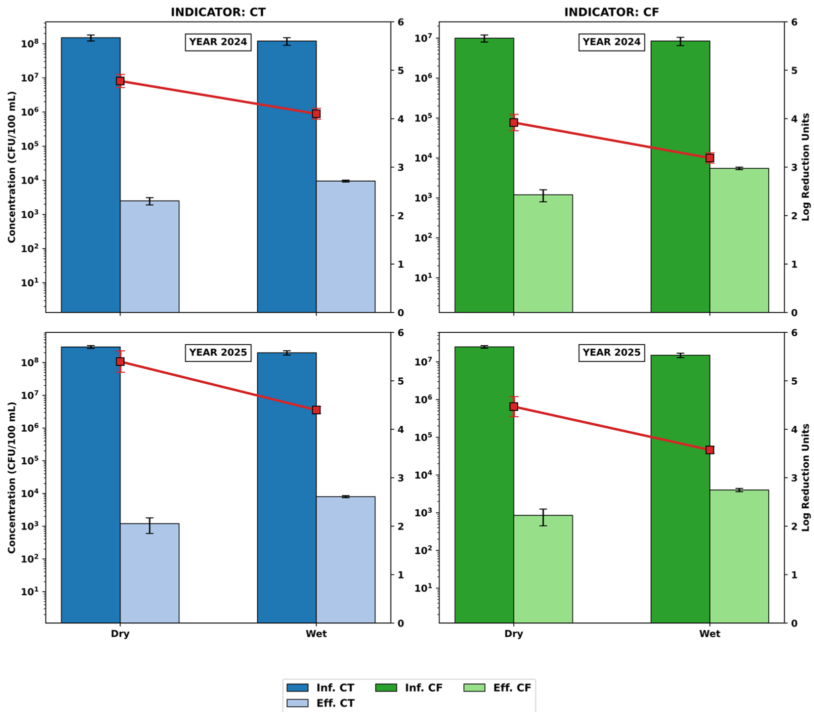

Figure 5. Disinfection performance and log reduction units (LRU) for total coliforms (CT) and fecal coliforms (CF)

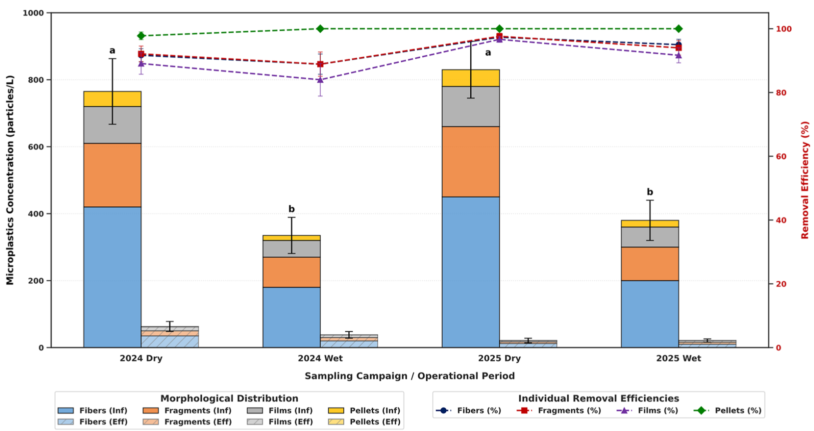

Figure 6. Seasonal and interannual variation in putative microplastic-particle counts and apparent retention efficiencies by morphology (2024–2025). Error bars represent standard deviations (n = 3); different letters indicate significant seasonal differences ($p < 0.01$) according to the Scheirer–Ray–Hare test and two-way analysis of variance

(2024 Wet and 2025 Wet), influent particle counts were lower than during dry periods, a pattern consistent with dilution, although stormwater inflow was not measured directly. High retention has also been reported in a full-scale free-water-surface polishing wetland, where approximately 95% of particles were retained and most removal occurred in settling and vegetated zones (Bydalek et al., 2023). Recent meta-analytic evidence further indicates that removal varies with treatment configuration and particle characteristics (Zoccali et al., 2025). These comparisons support physical interception as a plausible explanation for the present results, but they do not establish identical mechanisms across systems.

Anatomical partitioning and tissue-concentration patterns

Tissue distribution of nitrogen and phosphorus

Nitrogen (N) concentrations did not differ significantly among organs within the studied species (homogeneous Tukey grouping; Table 3), indicating a broad tissue distribution under the sampled conditions. Because uptake and translocation fluxes were not measured, this pattern does not directly demonstrate active translocation rates. Interspecific comparisons showed that roots of *Cyperus papyrus* and *Canna hybrid* had the highest observed N concentrations (up to 27.00 ± 4.50 mg g^{-1}); however, tissue concentration alone does not establish greater uptake efficiency or whole-plant accumulation.

Phosphorus (P) showed a contrasting tissue-distribution pattern ($p < 0.001$). Across the studied species, the highest P concentrations occurred in rhizomes/bulbs (4.50–9.80 mg g^{-1}; Table 4). This belowground concentration pattern identifies rhizomes/bulbs as candidate compartments for further nutrient-stock and harvesting studies, but it does not by itself demonstrate recoverable P mass or circular-economy benefits.

Tissue distribution of triclosan

Triclosan (TCS) concentrations differed markedly among tissues ($p < 0.0001$; Table 5). TCS was detected predominantly in roots (7.50–22.00

Table 3. Nitrogen concentrations (mg g^{-1} dry weight) in the organs of five ornamental macrophytes by season and operational year (2024–2025).

Period	Organ	*Agapanthus*	*Alocasia*	*C. hybrid*	*C. papyrus*	*Heliconia*
24-D	Leaf	15.50 ± 2.00 aA	16.50 ± 2.50 aA	18.50 ± 2.80 aA	18.00 ± 2.50 aA	15.00 ± 2.20 aA
24-D	Stem	9.80 ± 1.50 aA	10.50 ± 1.80 aA	11.80 ± 2.00 aA	11.20 ± 1.80 aA	9.50 ± 1.50 aA
24-D	Bulb	12.80 ± 1.80 aA	13.50 ± 2.20 aA	15.00 ± 2.50 aA	15.50 ± 2.80 aA	12.00 ± 2.00 aA
24-D	Root	12.50 ± 1.80 aB	12.50 ± 2.00 aB	16.50 ± 2.80 aA	20.50 ± 3.50 aA	13.50 ± 2.20 aA
24-W	Leaf	13.80 ± 1.80 aA	14.80 ± 2.00 aA	16.80 ± 2.50 aA	16.20 ± 2.20 aA	13.50 ± 1.80 aA
24-W	Stem	8.50 ± 1.20 aA	9.20 ± 1.50 aA	10.50 ± 1.80 aA	9.80 ± 1.50 aA	8.50 ± 1.20 aA
24-W	Bulb	11.50 ± 1.50 aA	12.00 ± 1.80 aA	13.50 ± 2.20 aA	14.00 ± 2.40 aA	10.80 ± 1.80 aA
24-W	Root	11.20 ± 1.50 aB	11.00 ± 1.80 aB	14.80 ± 2.50 aA	18.50 ± 3.00 aA	12.00 ± 1.90 aA
25-D	Leaf	20.20 ± 2.80 aA	22.00 ± 3.50 aA	24.50 ± 3.80 aA	23.80 ± 3.50 aA	19.50 ± 3.00 aA
25-D	Stem	13.00 ± 2.00 aA	13.50 ± 2.80 aA	15.50 ± 2.80 aA	15.00 ± 2.20 aA	12.80 ± 2.20 aA
25-D	Bulb	17.40 ± 2.60 aA	18.50 ± 3.50 aA	20.50 ± 3.50 aA	21.00 ± 3.80 aA	16.50 ± 2.80 aA
25-D	Root	17.20 ± 2.80 aB	16.80 ± 3.00 aB	21.50 ± 3.80 aA	27.00 ± 4.50 aA	18.00 ± 3.20 aA
25-W	Leaf	18.20 ± 2.50 aA	19.50 ± 3.20 aA	22.00 ± 3.50 aA	21.50 ± 3.00 aA	17.50 ± 2.80 aA
25-W	Stem	11.80 ± 1.80 aA	12.00 ± 2.50 aA	14.00 ± 2.50 aA	13.50 ± 2.20 aA	11.50 ± 2.00 aA
25-W	Bulb	15.60 ± 2.40 aA	16.50 ± 3.00 aA	18.50 ± 3.20 aA	19.00 ± 3.50 aA	14.80 ± 2.50 aA
25-W	Root	15.50 ± 2.50 aB	15.00 ± 2.50 aB	19.50 ± 3.50 aA	24.50 ± 4.20 aA	16.20 ± 3.00 aA

Note: 24-D/25-D = dry period; 24-W/25-W = wet period. Values are arithmetic means ± standard deviations of three independent replicates (n = 3). Different lowercase letters (a and b) within the same row indicate statistically significant differences among organs of the same plant (among-organ analysis) according to Tukey's post hoc test ($\alpha = 0.05$). Different uppercase letters (A, B) within the same row indicate statistically significant differences among plant species for the same organ (among-plant analysis) according to Tukey's multiple-comparison test ($\alpha = 0.05$). Units are mg g^{-1} dry weight for nitrogen (N).

Table 4. Phosphorus concentrations (mg g^{-1} dry weight) in the organs of five ornamental macrophytes by season and operational year (2024–2025)

Period	Organ	*Agapanthus*	*Alocasia*	*C. hybrid*	*C. papyrus*	*Heliconia*
24-D	Leaf	1.60 ± 0.30 cA	1.90 ± 0.40 cA	1.80 ± 0.30 cA	1.80 ± 0.30 bA	1.40 ± 0.30 cA
24-D	Stem	1.30 ± 0.20 dA	1.70 ± 0.30 dA	1.90 ± 0.40 bA	1.40 ± 0.20 cA	1.50 ± 0.30 bA
24-D	Bulb	5.50 ± 0.80 aA	5.80 ± 1.00 aA	6.80 ± 1.20 aA	5.20 ± 1.00 aA	5.20 ± 0.80 aA
24-D	Root	3.80 ± 0.60 bA	4.00 ± 0.80 bA	5.20 ± 1.00 bA	3.80 ± 0.60 bA	4.20 ± 0.80 bA
24-W	Leaf	1.40 ± 0.20 cA	1.60 ± 0.30 cA	1.50 ± 0.20 cA	1.50 ± 0.20 cA	1.20 ± 0.20 bA
24-W	Stem	1.10 ± 0.20 dA	1.40 ± 0.20 dA	1.60 ± 0.30 bA	1.20 ± 0.20 dA	1.20 ± 0.20 cA
24-W	Bulb	4.80 ± 0.70 aA	5.00 ± 0.80 aA	5.80 ± 1.00 aA	4.50 ± 0.80 aA	4.60 ± 0.70 aA
24-W	Root	3.20 ± 0.50 bA	3.50 ± 0.60 bA	4.50 ± 0.80 bA	3.20 ± 0.50 bA	3.80 ± 0.60 bA
25-D	Leaf	2.40 ± 0.50 bA	2.80 ± 0.60 bA	2.60 ± 0.60 cA	2.70 ± 0.60 bA	2.10 ± 0.50 cA
25-D	Stem	2.00 ± 0.40 cA	2.40 ± 0.60 cA	2.80 ± 0.60 bA	2.10 ± 0.50 cA	2.20 ± 0.50 bA
25-D	Bulb	7.80 ± 1.40 aA	8.50 ± 1.80 aA	9.80 ± 2.00 aA	7.50 ± 1.60 aA	7.80 ± 1.50 aA
25-D	Root	5.50 ± 0.90 bA	6.00 ± 1.20 bA	7.80 ± 1.60 bA	5.80 ± 1.20 bA	6.40 ± 1.40 bA
25-W	Leaf	2.10 ± 0.40 cA	2.40 ± 0.50 bA	2.20 ± 0.50 cA	2.30 ± 0.50 bA	1.80 ± 0.40 cA
25-W	Stem	1.70 ± 0.30 dA	2.10 ± 0.60 cA	2.40 ± 0.60 bA	1.80 ± 0.40 cA	1.90 ± 0.50 bA
25-W	Bulb	6.90 ± 1.20 aA	7.50 ± 1.50 aA	8.50 ± 1.80 aA	6.50 ± 1.40 aA	6.80 ± 1.30 aA
25-W	Root	4.80 ± 0.80 bA	5.20 ± 1.10 bA	6.80 ± 1.50 bA	5.00 ± 1.00 bA	5.50 ± 1.20 bA

Note: 24-D/25-D – dry period; 24-W/25-W – wet period. Values are arithmetic means ± standard deviations of three independent replicates (n = 3). Different lowercase letters (a, b, c, and d) within the same row indicate statistically significant differences among organs of the same plant (among-organ analysis) according to Tukey's post hoc test (α = 0.05). Different uppercase letters (A, B) within the same row indicate statistically significant differences among plant species for the same organ (among-plant analysis) according to Tukey's multiple-comparison test (α = 0.05). Units are mg g^{-1} dry weight for phosphorus (P).

μg g^{-1}) and secondarily in rhizomes/bulbs, whereas concentrations in stems and leaves were below the detection limit. This distribution is consistent with restricted translocation and root-associated retention under the conditions evaluated. However, tissue-concentration data alone do not distinguish internal plant uptake from adsorption to root surfaces or associated biofilms. Because flow-weighted influent and effluent TCS loads, total dry biomass by plant organ, substrate-associated TCS stocks, and transformation products were not quantified, a mass balance could not be constructed and the fraction of TCS removal from wastewater attributable to plant biomass cannot be determined. Accordingly, the findings demonstrate TCS occurrence and organ-level distribution but do not establish phytostabilization or any other system-level removal pathway.

The hydrophobicity of TCS provides a plausible basis for its association with root surfaces, tissues, and rhizosphere biofilms. Other CW studies have reported compartmentalization of hydrophobic organic contaminants within substrates and plant roots (Hijosa-Valsero et al., 2016). The present measurements, however, do not resolve adsorption, internal uptake, or microbial association as separate processes.

Tissue concentrations of N, P, and TCS were higher during dry than wet periods. Seasonal studies of wetland treatment have shown that the fate of emerging contaminants can vary with climatic and hydraulic conditions (Matamoros and Salvadó, 2012). In the present study, reduced dilution and greater evapotranspirative demand are plausible explanations for the observed pattern, but interstitial-water concentrations and plant water fluxes were not measured directly. These mechanisms should therefore be evaluated in future process-based studies.

The limestone medium used in this study can be classified as a reactive granular medium for CWs, and the system may therefore be considered a bioengineered wetland. Bioengineered wetlands are intensified systems in which operating conditions and wetland components are modified relative to conventional systems to improve treatment efficiency and overcome limitations in removing contaminants, including nitrogen, phosphorus, and other organic-matter constituents (Wu et al., 2014). Although the terms are sometimes used

Table 5. Triclosan concentrations (µg g⁻¹ dry weight) in the organs of five ornamental macrophytes by season and operational year (2024–2025)

Period	Organ	*Agapanthus*	*Alocasia*	*C. hybrid*	*C. papyrus*	*Heliconia*
24-D	Leaf	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND
24-D	Stem	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND
24-D	Bulb	3.40 ± 0.50 bA	2.50 ± 0.50 bA	4.50 ± 0.80 bA	3.80 ± 0.60 bA	3.20 ± 0.60 bA
24-D	Root	8.80 ± 1.50 aA	9.50 ± 1.80 aA	12.50 ± 2.20 aA	11.00 ± 2.00 aA	10.50 ± 1.90 aA
24-W	Leaf	0.00 ± 0.00 cND	0.00 ± 0.00 bND	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND
24-W	Stem	0.00 ± 0.00 dND	0.00 ± 0.00 bND	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND
24-W	Bulb	2.80 ± 0.40 bA	2.00 ± 0.40 aA	3.80 ± 0.60 bA	3.00 ± 0.50 bA	2.50 ± 0.50 bA
24-W	Root	7.50 ± 1.20 aA	8.00 ± 1.50 aA	10.50 ± 1.80 aA	9.20 ± 1.50 aA	8.80 ± 1.50 aA
25-D	Leaf	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND
25-D	Stem	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND
25-D	Bulb	7.00 ± 1.10 bA	5.50 ± 1.00 bA	9.20 ± 1.50 bA	7.50 ± 1.40 bA	6.40 ± 1.20 bA
25-D	Root	16.50 ± 2.80 aA	17.50 ± 3.00 aA	22.00 ± 3.50 aA	19.80 ± 3.50 aA	18.50 ± 3.20 aA
25-W	Leaf	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND	0.00 ± 0.00 cND
25-W	Stem	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND	0.00 ± 0.00 dND
25-W	Bulb	5.80 ± 0.90 bA	4.50 ± 0.80 bA	7.50 ± 1.20 bA	6.20 ± 1.10 bA	5.20 ± 1.00 bA
25-W	Root	13.80 ± 2.20 aA	14.50 ± 2.50 aA	18.50 ± 3.10 aA	16.50 ± 2.90 aA	15.80 ± 2.80 aA

Note: 24-D/25-D = dry period; 24-W/25-W = wet period. Values are arithmetic means ± standard deviations of three independent replicates (n = 3). Different lowercase letters (a, b, c, and d) within the same row indicate statistically significant differences among organs of the same plant (among-organ analysis) according to Tukey's post hoc test (α = 0.05). Different uppercase letters (A, B) within the same row indicate statistically significant differences among plant species for the same organ (among-plant analysis) according to Tukey's multiple-comparison test (α = 0.05). ND denotes values below the analytical detection limit with zero variance assigned for control. Units are µg g⁻¹ dry weight for triclosan (TCS).

interchangeably, all bioengineered wetlands are CWs, whereas not all CWs are bioengineered (Higgins et al., 2000). The latter involve active intervention in system conditions and processes, as in the present study, where an unconventional substrate and a polyculture of ornamental plants were used to enhance contaminant removal.

CONCLUSIONS

The two-year field evaluation showed that the full-scale ornamental constructed wetland contributed to the treatment of university wastewater under tropical conditions. Removal of biochemical oxygen demand, chemical oxygen demand, total suspended solids, and bacterial indicators varied between seasonal categories, with lower performance during wet periods. Nitrogen removal showed no statistically significant seasonal difference, whereas total phosphorus retention was lower under wet conditions. Performance for biochemical oxygen demand and bacterial indicators was higher in 2025 than in 2024. Because operational flow and hydraulic retention time were not measured directly, these patterns establish temporal associations but do not demonstrate hydraulic causation or generalized climatic resilience.

Visual counts indicated high apparent retention of putative microplastic particles, although polymer identity was not confirmed spectroscopically. Triclosan occurred primarily in roots and rhizomes or bulbs and was below the detection limit in stems and leaves, consistent with restricted translocation under the conditions evaluated. Phosphorus was concentrated mainly in rhizomes or bulbs, whereas nitrogen occurred in both above- and belowground tissues. Together, the results provide site-specific evidence on treatment performance and tissue partitioning in a full-scale ornamental wetland. Interpretation remains limited to the single monitored system and the analytical endpoints measured. The reported efficiencies should not be extrapolated as expected performance values for other tropical constructed wetlands. Nevertheless, these observations may inform hypothesis generation and monitoring design for systems with comparable wastewater, vegetation, substrate, and operating conditions; independent multi-site validation is required before broader generalization.

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REFERENCES

1. American Public Health Association (APHA), American Water Works Association (AWWA), & Water Environment Federation (WEF). (2017). *Standard methods for the examination of water and wastewater (23rd ed.)*. APHA Press. https://doi.org/10.2105/SMWW.2882
2. Arias, C. A., Del Bubba, M., Brix, H. (2001). Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. *Water Research*, *35*(5), 1159–1168. https://doi.org/10.1016/S0043-1354(00)00368-7
3. Ávila, C., Garfí, M., García, J. (2013). Three-stage hybrid constructed wetland system for wastewater treatment and reuse in warm climate regions. *Ecological Engineering*, *61*, 43–49. https://doi.org/10.1016/j.ecoleng.2013.09.048
4. Bakare, B. F., Adeyinka, G. C. (2022). Occurrence and fate of triclosan and triclocarban in selected wastewater systems across Durban Metropolis, KwaZulu-Natal, South Africa. *International Journal of Environmental Research and Public Health*, *19*(11), 6769. https://doi.org/10.3390/ijerph19116769
5. Benítez-Villalba, J. C., Dorival-García, N., Villalba-Villalba, N. M., Ferreira-Benítez, F. P., Rodríguez-Bonet, S., Vílchez, J. L. (2019). Kinetic study of triclosan and triclocarban degradation in agricultural soils amended with compost (in Spanish). *Reportes Científicos de la FACEN*, *10*(1), 37–48. https://doi.org/10.18004/rcfacen.2019.10.1.37
6. Bhat, S. A., Kumar, V., Li, F., Verma, P. (Eds.). (2024). *Detection and treatment of emerging contaminants in wastewater*. IWA Publishing. https://doi.org/10.2166/9781789063752
7. Bydalek, F., Ifayemi, D., Reynolds, L., Barden, R., Kasprzyk-Hordern, B., Wenk, J. (2023). Microplastic dynamics in a free water surface constructed wetland. *Science of the Total Environment*, *858*, 160113. https://doi.org/10.1016/j.scitotenv.2022.160113
8. de Campos, S. X., Soto, M. (2024). The use of constructed wetlands to treat effluents for water reuse. *Environments*, *11*(2), 35. https://doi.org/10.3390/environments11020035
9. García, J., Rousseau, D. P. L., Morató, J., Lesage, E., Matamoros, V., Bayona, J. M. (2010). Contaminant removal processes in subsurface-flow constructed wetlands: A review. *Critical Reviews in Environmental Science and Technology*, *40*(7), 561–661. https://doi.org/10.1080/10643380802471076
10. Greenway, M., Woolley, A. (1999). Constructed wetlands in Queensland: Performance efficiency and nutrient bioaccumulation. *Ecological Engineering*, *12*(1–2), 39–55. https://doi.org/10.1016/S0925-8574(98)00053-6
11. Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology*, *46*(6), 3060–3075. https://doi.org/10.1021/es2031505
12. Higgins, J. P., Hurd, S., Weil, C. (2000). The use of engineered wetlands to treat recalcitrant wastewaters. *Journal of Environmental Science and Health, Part A*, *35*(8), 1309–1334. https://doi.org/10.1080/10934520009377038
13. Hijosa-Valsero, M., Reyes-Contreras, C., Domínguez, C., Bécares, E., Bayona, J. M. (2016). Behaviour of pharmaceuticals and personal care products in constructed wetland compartments: Influent, effluent, pore water, substrate and plant roots. *Chemosphere*, *145*, 508–517. https://doi.org/10.1016/j.chemosphere.2015.11.090
14. Jones, J. B., Jr. (2001). *Laboratory guide for conducting soil tests and plant analysis*. CRC Press. https://doi.org/10.1201/9781420025293
15. Kadlec, R. H., Wallace, S. D. (2008). *Treatment wetlands (2nd ed.)*. CRC Press. https://doi.org/10.1201/9781420012514
16. Lomeli, J. S., Zamora-Castro, S. A., Zamora-Lobato, T., Sandoval-Herazo, E. J., Adame-García, J., Zurita, F., Monroy-Pineda, M. C., Aguilar-Cortés, G., Rivera, S., Sandoval-Herazo, M. (2025). Performance of large-scale ornamental wetlands for municipal wastewater treatment: A case study in a polluted estuary in the Gulf of Mexico. *Sustainability*, *17*(5), 2120. https://doi.org/10.3390/su17052120

17. Masura, J., Baker, J., Foster, G., Arthur, C. (2015). *Laboratory methods for the analysis of microplastics in the marine environment: Recommendations for quantifying synthetic particles in waters and sediments*. NOAA Technical Memorandum NOS-OR&R-48.
18. Matamoros, V., Salvadó, V. (2012). Evaluation of the seasonal performance of a water reclamation pond-constructed wetland system for removing emerging contaminants. *Chemosphere*, *86*(2), 111–117. https://doi.org/10.1016/j.chemosphere.2011.09.020
19. Mitsch, W. J., Gosselink, J. G., Anderson, C. J., Fennessy, M. S. (2023). *Wetlands (6th ed.)*. Wiley.
20. Murcia, J. E., Martinez, S., Martins, V., Herrera, D., Buitrago, C., Velasquez, A., Ruiz, F., Torres, M. (2023). Risk assessment and green chemistry applied to waste generated in university laboratories. *Heliyon*, *9*(5), e15900. https://doi.org/10.1016/j.heliyon.2023.e15900
21. Murphy, J., Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, *27*, 31–36. https://doi.org/10.1016/S0003-2670(00)88444-5
22. Rahman, M. E., Bin Halmi, M. I. E., Bin Abd Samad, M. Y., Uddin, M. K., Mahmud, K., Abd Shukor, M. Y., Sheikh Abdullah, S. R., Shamsuzzaman, S. M. (2020). Design, operation and optimization of constructed wetland for removal of pollutant. *International Journal of Environmental Research and Public Health*, *17*(22), 8339. https://doi.org/10.3390/ijerph17228339
23. Ruiz, M., Velasco, J. (2010). Nutrient bioaccumulation in *Phragmites australis*: Management tool for reduction of pollution in the Mar Menor. *Water, Air, & Soil Pollution*, *205*, 173–185. https://doi.org/10.1007/s11270-009-0064-2
24. Sandoval-Herazo, L. C., Marín-Muñiz, J. L., Alvarado-Lassman, A., Zurita, F., Marín-Peña, O., Sandoval-Herazo, M. (2023). Full-scale constructed wetlands planted with ornamental species and PET as a substitute for filter media for municipal wastewater treatment: An experience in a Mexican rural community. *Water*, *15*(12), 2280. https://doi.org/10.3390/w15122280
25. Sandoval-Herazo, L. C., Aguilar-Cortés, G., Martínez-Castellanos, G., Álvarez Month, A. E., Martínez-Reséndiz, G. (2026). Ornamental plants in constructed wetlands: A review. *Hydrobiologia*. https://doi.org/10.1007/s10750-026-06211-1
26. Vaudry, N., Sun, Y., Afolabi, O. (2023). Exploiting constructed wetlands for industrial effluent phytodesalination in Jing-Jin-Ji urban agglomeration, China. *International Journal of Phytoremediation*, *25*(7), 851–867. https://doi.org/10.1080/15226514.2022.2115005
27. Vymazal, J. (2007). Removal of nutrients in various types of constructed wetlands. *Science of the Total Environment*, *380*(1–3), 48–65. https://doi.org/10.1016/j.scitotenv.2006.09.014
28. Vymazal, J. (2018). Do laboratory-scale experiments improve constructed wetland treatment technology? *Environmental Science & Technology, 52*(22), 12956–12957. https://doi.org/10.1021/acs.est.8b05709
29. Wang, Q., Kelly, B. C. (2017). Occurrence, distribution and bioaccumulation behaviour of hydrophobic organic contaminants in a large-scale constructed wetland in Singapore. *Chemosphere*, *183*, 257–265. https://doi.org/10.1016/j.chemosphere.2017.05.113
30. World Bank. (2022). *Water matters: Resilient, inclusive and green growth through water security in Latin America*. https://doi.org/10.1596/37214
31. Wu, S., Kuschk, P., Brix, H., Vymazal, J., Dong, R. (2014). Development of constructed wetlands in performance intensifications for wastewater treatment: A nitrogen and organic matter targeted review. *Water Research*, *57*, 40–55. https://doi.org/10.1016/j.watres.2014.03.020
32. Zhang, D. Q., Gersberg, R. M., Hua, T., Zhu, J., Tuan, N. A., Tan, S. K. (2012). Pharmaceutical removal in tropical subsurface flow constructed wetlands at varying hydraulic loading rates. *Chemosphere*, *87*(3), 273–277. https://doi.org/10.1016/j.chemosphere.2011.12.067
33. Zoccali, A., Cantoni, B., Azzellino, A., Malpei, F. (2025). Removal of microplastics in wastewater treatment plants: Insights from a literature meta-analysis. *Journal of Environmental Chemical Engineering*, *13*(3), 116812. https://doi.org/10.1016/j.jece.2025.116812
34. Zurita, F., Sandoval-Herazo, L. C. (2026). Current situation of constructed wetlands in Latin America. *Current Opinion in Environmental Science & Health*, *51*, 100727. https://doi.org/10.1016/j.coesh.2026.100727