Indonesian Journal of Environmental Management and Sustainability
e-ISSN:2598-6279 *p*-ISSN:2598-6260

Research Paper

Performance of Free Water Surface Constructed Wetlands (FWS-CWs) using Water Jasmine (*Echinodorus palaefolius*) in Removing COD and TDS from Domestic Wastewater

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Abstract
This study evaluated the reduction of chemical oxygen demand (COD) and total dissolved solids (TDS) in domestic wastewater using water jasmine (*Echinodorus palaefolius*) in a free water surface constructed wetland (FWS-CW) system. We characterized the influent wastewater, assessed the acclimatization of *E. palaefolius* to undiluted domestic wastewater, and quantified the effects of plant density and observation time on COD and TDS removal. The experimental campaign comprised wastewater sampling, reactor fabrication, plant acclimatization, batch treatment, and analyses of COD and TDS. Removal efficiencies were computed and the data analyzed by two-way ANOVA followed by Tukey's HSD post-hoc test. The initial wastewater contained 275.88 mg/L COD and 286 ppm TDS. *Echinodorus palaefolius* adapted successfully to the wastewater and reached maximum removal efficiencies of 86.04% for COD and 12.41% for TDS in the 12-plant reactor on Day 12. The two-way ANOVA showed significant main effects of plant density and observation time on both parameters ($p < 0.05$), and Tukey HSD indicated that the presence of *E. palaefolius* significantly improved TDS removal compared with the unplanted control, although differences among the 4-, 8-, and 12-plant reactors were not statistically significant. These findings indicate that even moderate plant densities are effective for reducing COD and TDS in tropical domestic wastewater treated with FWS-CWs.

Keywords
Domestic Wastewater, Constructed Wetlands, *Echinodorus palaefolius*, COD, TDS

Received: 11 March 2026, Accepted: 1 June 2026
https://doi.org/10.26554/ijems.2026.10.3.214-227

1. INTRODUCTION

Domestic wastewater is a significant contributor to environmental pollution and demands effective, sustainable management (Kim et al., 2014; Sané et al., 2022). According to the Indonesian Environmental Statistics Report (2020), 57.42% of households discharge their wastewater directly into drainage channels or rivers, and a further 18.71% release it directly onto the ground (Badan Pusat Statistik, 2020). When unmanaged, these practices accelerate environmental degradation and pose serious public-health risks, including waterborne diseases, parasitic infections, odor nuisance, and localized flooding (Kamaruzaman et al., 2023; Khan et al., 2022). Domestic wastewater is typically composed of about 99% water and 1% organic and inorganic pollutants from household activities such as bathing, washing, and cooking, and accounts for 50–70% of urban freshwater consumption (Chu and Liao, 2024; Yang et al., 2021). Untreated discharges raise the chemical oxygen demand (COD) and total dissolved solids (TDS) of receiving waters, depress dissolved oxygen levels, and disrupt photosynthesis in aquatic ecosystems (Sai Krishna et al., 2023).

Conventional treatment methods such as adsorption and filtration have long been used to reduce organic and inorganic loads, but they have well-known limitations. Activated-carbon adsorption is constrained by limited capacity and high regeneration costs (Sangeetha et al., 2023), while filtration units are prone to clogging, require frequent maintenance, and are poorly suited to long-term community-scale operation (Koul et al., 2022). These shortcomings motivate the search for cost-effective, low-maintenance, and environmentally benign alternatives. Constructed wetlands (CWs) are one such alternative, integrating physical, chemical, and biological processes to remove a broad range of pollutants.

Among the available CW configurations, free water surface constructed wetlands (FWS-CWs) have been widely applied to domestic wastewater. In a FWS-CW, wastewater flows over the substrate surface and interacts directly with aquatic plants, sediment, and microbial communities, all of which contribute to pollutant removal (Vishwakarma and Dharmendra, 2024). Compared with subsurface-flow systems, FWS-CWs are simpler to construct and operate and perform well for organic-matter removal from high-strength domestic wastewater (Gunes et al., 2012). A recent systematic review of decentralized CW treatment of domestic wastewater (2015–2024) confirms that surface-flow configurations remain a cost-effective and widely adopted option in tropical and developing contexts (Domínguez-Solís et al., 2025), and a recent meta-analysis of FWS-CWs identifies plant coverage and hydraulic retention time as the two design factors most strongly associated with nutrient removal (Gaballah et al., 2024).

Plant selection is a critical determinant of FWS-CW performance. Water jasmine (*Echinodorus palaefolius*) is a strong candidate because of its adaptability to tropical climates, ornamental value for landscape integration, and demonstrated capacity to remove pollutants. Previous studies report that *E. palaefolius* can achieve COD removals of up to 95% and TDS removals of as much as 85%, underscoring its potential for domestic wastewater treatment (Ayuningtyas et al., 2023; Perdana et al., 2018; Qomariyah et al., 2021). More recently, Ratnawati et al. (2024) showed that *E. palaefolius*, used together with other macrophytes for landfill-leachate treatment, effectively reduced TSS, total nitrogen, and several heavy metals, further confirming its versatility as a phytoremediator under tropical conditions. Its resilience and rapid vegetative growth also help sustain removal efficiency over extended operation periods.

Despite the broad use of CWs for domestic wastewater, few studies have specifically examined *E. palaefolius* in FWS-CWs, and even fewer have addressed plant-density optimization. Most existing work reports pollutant-removal performance in general terms without resolving how density modulates COD and TDS removal under tropical conditions. The present study addresses this gap by characterizing the adaptability of *E. palaefolius* and quantifying its effectiveness in removing COD and TDS across three planting densities. Its contribution lies in linking plant-density variation to removal efficiency in FWS-CWs and translating the results into practical guidance for community-scale wastewater treatment in tropical settings.

The findings are intended to support community-scale wastewater treatment initiatives, particularly in developing regions where cost-effective and low-maintenance solutions are most needed. They also align with the Sustainable Development Goals (SDGs), notably Goal 6 (Clean Water and Sanitation), Goal 3 (Good Health and Well-being), and Goal 11 (Sustainable Cities and Communities). More broadly, this work contributes to sustainable and environmentally friendly practices for domestic wastewater management that can be adapted for wider deployment in tropical urban areas.

2. EXPERIMENTAL SECTION

2.1 Materials

Domestic wastewater was collected from household drainage channels in the PEMDA residential area of Way Huwi, Jati Agung District, South Lampung Regency. Samples were taken during peak domestic-activity hours (06:00–08:00 a.m.) and not during or immediately after rainfall to avoid dilution by stormwater. The wastewater was subsequently used in the FWS-CW reactors to assess COD and TDS removal. The sampling location is shown in Figure 1. Samples were collected with plastic jerry cans directly from the drainage channels carrying household effluent. Because the study draws on a single source on a single sampling day, the resulting characterization should be interpreted as a snapshot rather than a representative profile of seasonal or inter-household variability.

Water jasmine (*Echinodorus palaefolius*) was selected as the treatment plant because of its tolerance to waterlogged conditions and its well-developed root system, both of which support pollutant uptake during phytoremediation (Syamlal et al., 2024). The reactor medium comprised a bottom layer of gravel (mean grain diameter ≈0.5 cm) for drainage, overlain by a layer of sand (mean grain diameter ≈0.1 cm) that served as the primary filtration medium; the layer thicknesses are reported in Section 2.2. The sand was first sieved through a No. 100 mesh screen to ensure a uniform grain-size distribution. The sand, gravel, and *E. palaefolius* used in the study are shown in Figure 2.

Four FWS-CW units were fabricated: one control reactor (no plants) and three planted reactors. Each unit had a rectangular geometry, was built from transparent plastic, and was configured to allow free-surface flow with an outlet at the upper section; all units were operated in batch mode. To investigate the effect of planting density on COD and TDS removal, the three planted reactors were stocked with 4, 8, and 12 plants, respectively. A schematic diagram and photographs of the reactors are shown in Figure 3.

All chemicals were of analytical grade. The COD assay used potassium dichromate ($K_2Cr_2O_7$), concentrated sulfuric acid (H_2SO_4), mercury(II) sulfate ($HgSO_4$), and silver sulfate (Ag_2SO_4); potassium hydrogen phthalate ($KHC_8H_4O_4$) was used as the COD calibration standard. Potassium permanganate ($KMnO_4$) was used to prepare organic-free water, and distilled water was used for cleaning and dilution. All reagents were stored under standard laboratory conditions and prepared according to the Indonesian standard for water quality testing (SNI 6989.2–2019).

2.2 Methods

The experiment was carried out at laboratory scale and comprised five stages: (1) collection and initial characterization

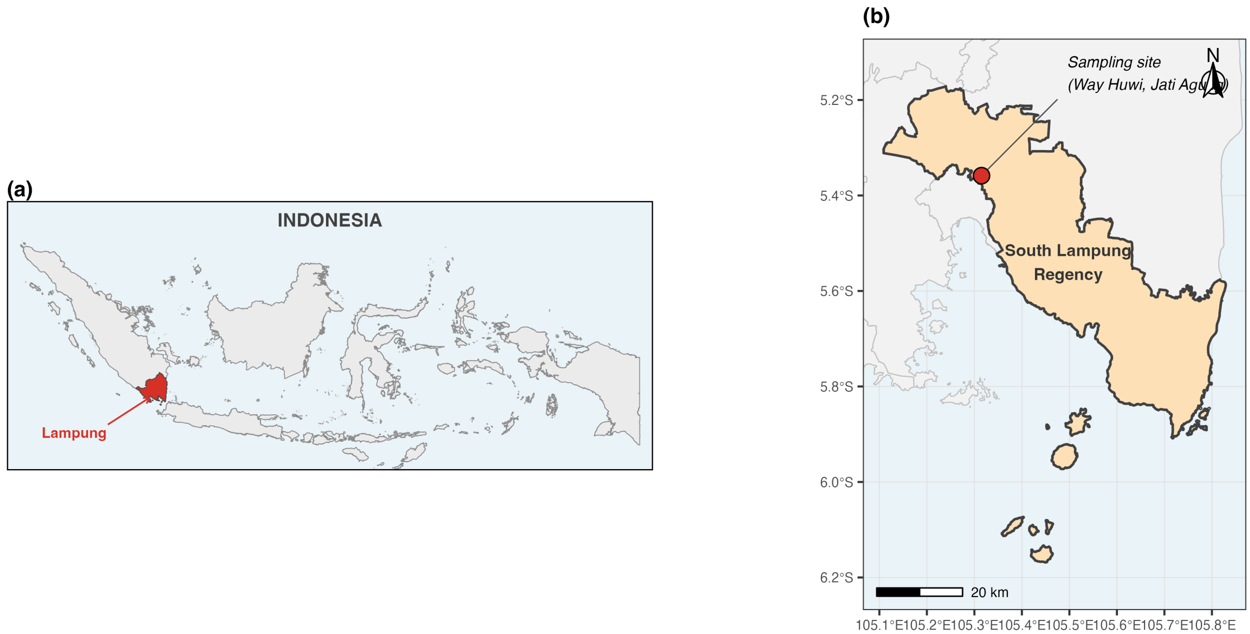

Figure 1. Location and Sampling Point of Domestic Wastewater in the PEMDA Residential Area, Way Huwi, South Lampung

Figure 2. (a) Sand, (b) Gravel, and (c) *Echinodorus palaefolius* (Water Jasmine)

of the domestic wastewater, (2) preparation of media and plants, (3) reactor assembly, (4) operation of the FWS-CW system at varying planting densities, and (5) analysis of COD and TDS.

Echinodorus palaefolius was acclimatized to the domestic wastewater over seven days by stepwise dilution. The plants were exposed sequentially to four wastewater compositions: 25%, 50%, 75%, and finally 100% domestic wastewater (the remainder being clean water at each step).

The reactor medium consisted of two layers: a 7 cm gravel layer (mean grain diameter ≈0.5 cm) at the bottom, overlain by a 5 cm sand layer (mean grain diameter ≈0.1 cm). The sand was sieved through a No. 100 mesh, washed, and air-dried at room temperature before use.

Each reactor had internal dimensions of 45 cm × 32 cm × 25 cm (length × width × height), giving a working volume of approximately 20 L, and was equipped with an upper outlet that maintained the water level at about 15 cm. After the media and plants were arranged in the predetermined layer sequence, domestic wastewater was added until the target water level was reached. The system was then operated in batch mode for the duration of the experiment, with regular checks to compensate for evaporation and leakage. Each density treatment was run in duplicate. No fertilizers or external aeration were applied, in order to simulate field conditions as closely as possible.

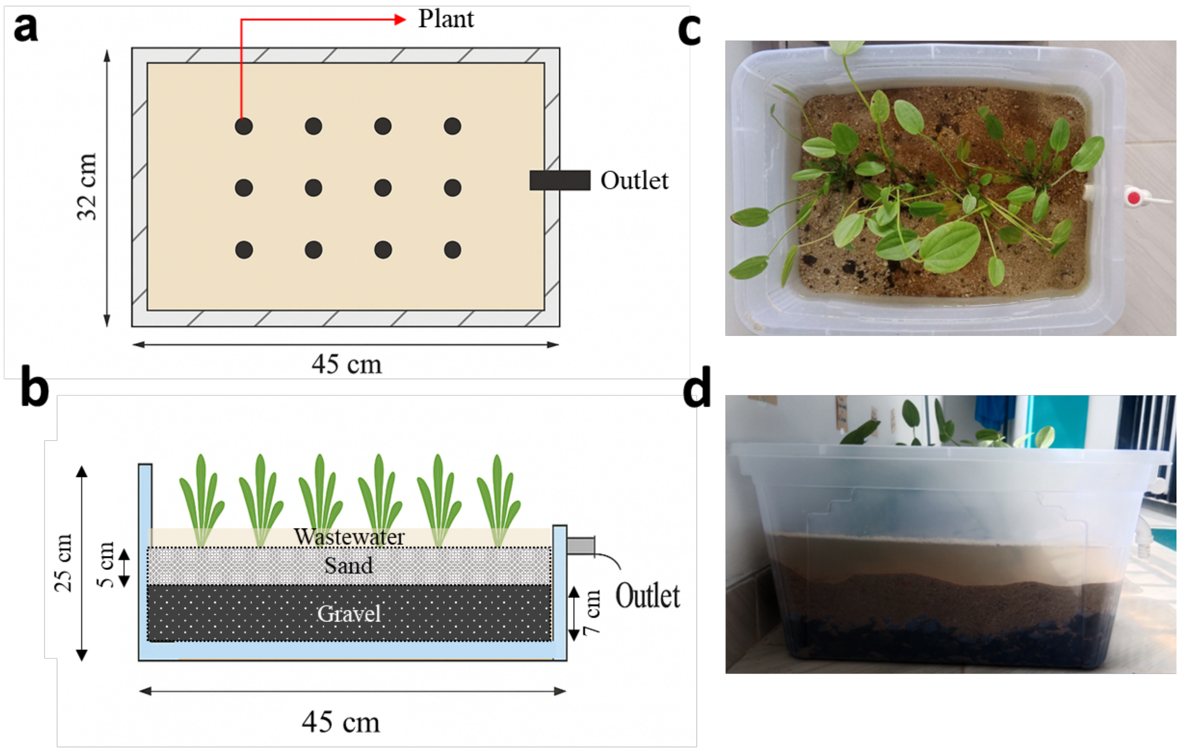

Figure 3. Schematic Design of the Laboratory-Scale FWS-CW Reactor: Top View (a), Side View (b), Reactor Used-Top View (c), and Side View (d)

The primary parameters evaluated were COD and TDS. COD was determined by the closed-reflux dichromate method (SNI 6989.2:2019), with absorbance read at 600 nm on a UV–Vis spectrophotometer. TDS was measured with a digital TDS meter (Hanna Instruments) after filtration through a 0.45 μm membrane. Water temperature was monitored daily and remained stable at 25 °C across all reactors. We acknowledge that this parameter set is deliberately narrow: complementary indicators such as BOD_5, TSS, dissolved oxygen, pH, and key nutrients (NH_3-N, NO_3^-, PO_4^{3-}) were not measured in this campaign and are flagged as priorities for follow-up work.

Samples for analysis were collected at the beginning (day 0) and end (day 12) of the treatment period, with intermediate samples on days 3, 6, and 9. Removal efficiency was calculated as the percentage difference between the initial concentration (C_{in}) and the concentration at the sampling time (C_{out}) using Equation (1):

$$RE = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (1)$$

The data were analyzed by two-way ANOVA, with plant density and observation day as independent variables and COD or TDS concentration as the dependent variable. Type II sums of squares were used. Where the omnibus ANOVA indicated significant main effects, Tukey's HSD test was applied for pairwise comparisons. Partial eta-squared (η_p^2) values were also reported as effect-size measures. Initial computations were performed in IBM SPSS Statistics 27, and the final analysis was independently reproduced using `statsmodels` (Python) on the raw replicate-level data; both pipelines yielded identical results.

3. RESULTS AND DISCUSSION

3.1 Characteristics of Domestic Wastewater Samples

The initial characteristics of the domestic wastewater are summarized in Table 1. The measured COD substantially exceeded the 100 mg/L discharge limit set by Indonesian Regulation P.68/2016 on Domestic Wastewater Quality Standards, whereas the TDS was well below the 2,000 ppm threshold for Class I receiving waters under PermenLH No. 5 of 2014. Together, these values indicate a strongly organic but only weakly mineralized wastewater, consistent with the typical signature of residential domestic effluent.

The elevated COD level is consistent with domestic activities in the surrounding area. Muoghalu et al. (2023) reports that elevated COD in domestic wastewater can arise from urine, cleaning agents, washwater, nutrients (nitrogen and phosphorus), metal-bearing detergents (Pb, Hg, Mn,

Table 1. Initial Characteristics of the Domestic Wastewater Sample

Parameter	Unit	Initial Value	Quality Standard	Remarks
COD	mg/L	275.88	100 mg/L	Exceeded
TDS	ppm	286	2000 ppm	Within standard

Fe), personal-care products, and pathogenic bacteria including *Escherichia coli*, *Legionella pneumophila*, *Leptospira* spp., *Salmonella* spp., and *Shigella* spp. Conversely, the low TDS indicates that the dissolved-ion load (K^+, Cl^-, Na^+) was within acceptable limits for discharge to receiving waters (Dwi Putri et al., 2021).

3.2 Adaptation Ability of Water Jasmine (*Echinodorus palaefolius*)

The adaptation ability of *Echinodorus palaefolius* was assessed through an acclimatization process prior to the treatment phase. Based on observations, changes were observed in the plant's condition, including variations in leaf color and stem condition, as shown in Figure 4.

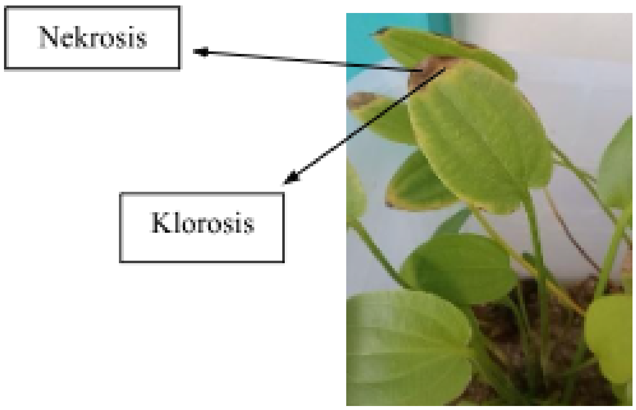

Figure 4. Condition of *Echinodorus palaefolius* (Water Jasmine) During the Acclimatization Process, Showing Chlorosis and Necrosis

The yellowing of *Echinodorus palaefolius* leaves was identified as chlorosis, a condition that arises when leaf formation is disrupted due to exposure to pollutants. In contrast, the browning of leaves was classified as necrosis, which results from the gradual degradation of chlorophyll, leading to leaf desiccation and browning (Shen et al., 2017; Ur Rahman et al., 2024). These effects were likely a result of pollutants present in the domestic wastewater that the plants absorbed. Observations across various wastewater compositions revealed that *Echinodorus palaefolius* could adapt to different concentrations of domestic sewage, showcasing a successful acclimatization process. Consequently, a 100% domestic wastewater composition was chosen for use during the treatment phase. The condition of the plants on the first and last days of acclimatization (day 1 and day 7) is depicted in Figure 5.

The number of leaves, new shoots, and plant height of *Echinodorus palaefolius* during the acclimatization process are shown in Figure 6.

The acclimatization stage demonstrated that *Echinodorus palaefolius* adapted well to varying concentrations of domestic wastewater. From day 0 to day 7, the number of leaves gradually increased across all treatments, with the highest growth observed in the 25% and 75% treatments, reaching 41–45 leaves, respectively. The number of new shoots also increased up to day 7, with a total of 12–15 additional shoots per clump at concentrations of 25–75%, indicating optimal vegetative activity. Plant height increased from 15–22 cm to 15–23 cm, suggesting that moderate organic loading levels (50–75%) did not inhibit vertical growth but rather stimulated new tissue formation. Meanwhile, in the 100% wastewater treatment, although mild stress symptoms (chlorosis and leaf tip browning) were observed, the plants remained viable and exhibited positive growth. *Echinodorus palaefolius* exhibited high tolerance to changes in wastewater composition and was able to recover rapidly, consistent with the findings of Saha et al. (2025); Parab et al. (2025), who reported that plants play a crucial role in pollutant removal within constructed wetland systems.

3.3 COD and TDS Removal Performance

The mean COD and TDS concentrations measured in each reactor at the four sampling time points are summarized in Table 2, and the corresponding removal efficiencies are shown in Figure 7. COD declined from an initial 275.88 mg/L to 77.20 mg/L in the unplanted control and to 38.52 mg/L in the 12-plant reactor by Day 12, while TDS decreased from 286 ppm to 267 ppm in the control and to 250.5 ppm in the 12-plant reactor over the same period.

The highest COD removal was observed in the 12-plant reactor (≈86%), followed by the 8-plant (≈78%) and 4-plant (≈77%) reactors (Figure 7(a)). These efficiencies are in line with the 95% COD removal reported by Ayuningtyas et al. (2023) after four weeks in a subsurface-flow CW, indicating that the present 12-day FWS-CW system already approaches the upper-end performance reported for the same plant species under longer retention. The improvement seen in the planted reactors reflects the combined contributions of phytoremediation and rhizosphere-associated microbial activity: a larger number of plants provides a greater root surface area for interaction with the wastewater, which

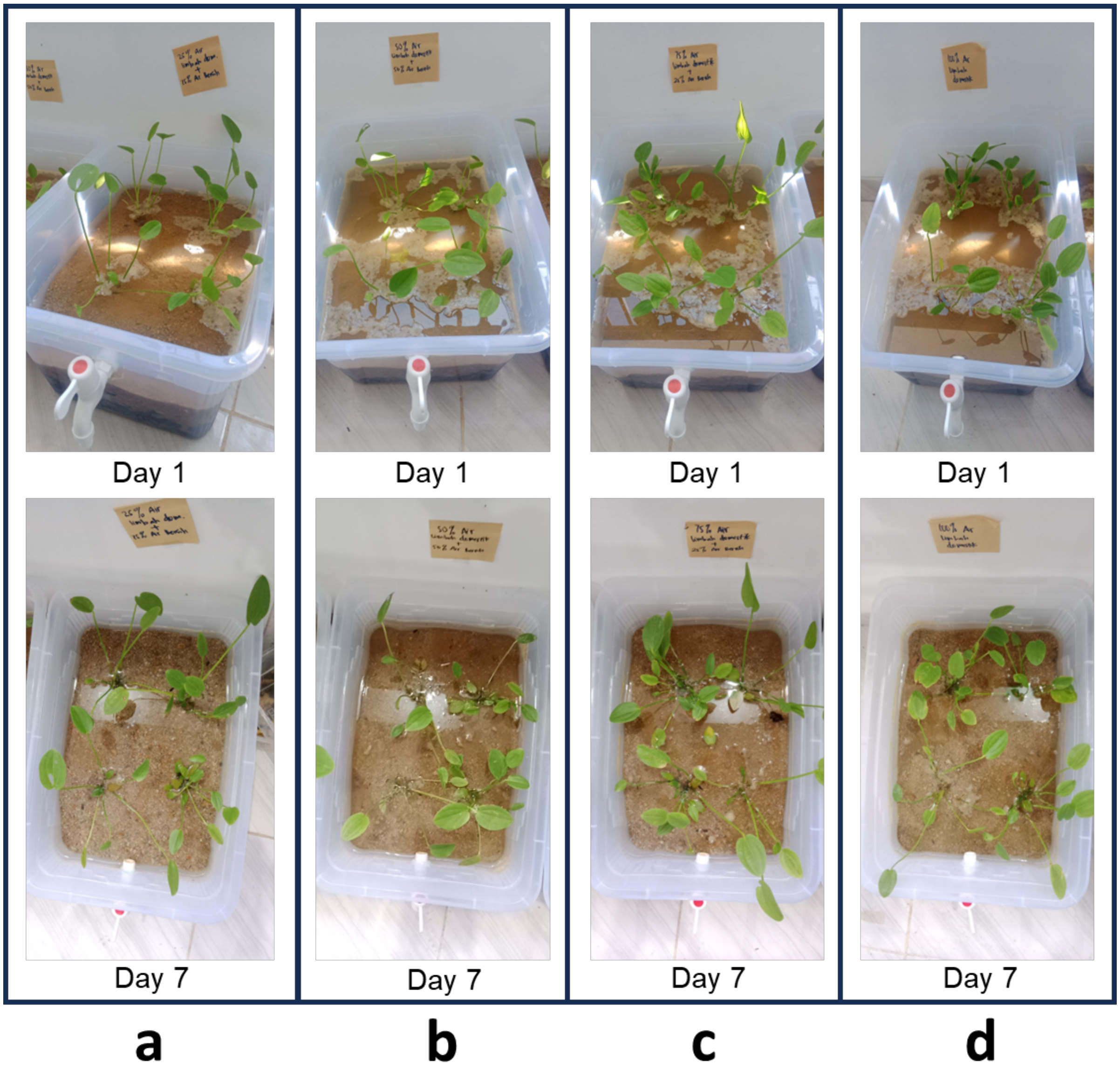

Figure 5. Condition of *Echinodorus palaefolius* on the First (Day 1) and Last (Day 7) Days of Acclimatization: (a) 25% Domestic Wastewater + 75% Clean Water, (b) 50% Domestic Dastewater + 50% Clean Water, (c) 75% Domestic Wastewater + 25% Clean Water, and (d) 100% Domestic Wastewater

in turn promotes adsorption, microbial colonization, and oxidation of dissolved organic compounds.

Substantial COD reduction was observed in all four reactors, including the unplanted control (Panrare et al., 2016). In the control reactor, the decline in COD is attributable to physical filtration of fine particles and colloids by the gravel and sand media and to sedimentation (Dissanayaka and Gunasekara, 2022); this non-biological pathway is, however, less effective than the planted systems.

The strongest COD reduction occurred in the 12-plant reactor, which is consistent with the expectation that higher plant density provides more root biomass and a more favorable environment for microbial decomposition of organic matter (Al Kholif and Diah Indah Pratiwi, 2021). *Echinodorus palaefolius* also transfers atmospheric oxygen from the leaves and stems to the roots, enriching the rhizosphere with oxygen and supporting aerobic microbial degradation of organic pollutants (Panrare et al., 2016). This radial oxygen loss (ROL) mechanism has been shown to create vertically structured oxic–anoxic micro-zones around the roots that simultaneously sustain aerobic COD oxidizers and anaerobic denitrifiers, thereby maximizing the treatment capacity of planted constructed wetlands (Sun et al., 2024). The rhizosphere bacterial community - typically dominated by

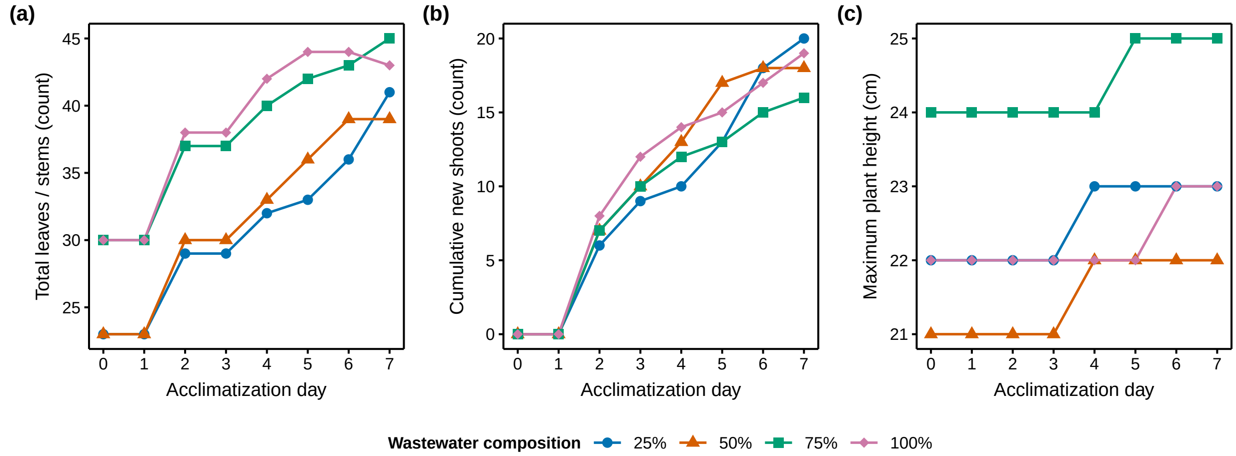

Figure 6. Growth Response of *Echinodorus palaefolius* During the 7-Day Acclimatization Process Under Four Wastewater Compositions (25%, 50%, 75%, and 100% Domestic Wastewater): (a) Total Number of Leaves/Stems, (b) Cumulative New Shoots, and (c) Maximum Plant Height

Table 2. Mean ± Standard Deviation of COD (mg/L) and TDS (ppm) Concentrations Measured in Each Reactor at the four Sampling Time Points. Each Cell Represents the Mean of Two Analytical Replicates ($n = 2$)

Reactor	Day 3	Day 6	Day 9	Day 12
COD (mg/L)				
Control	119.58 ± 6.74	93.62 ± 0.00	93.10 ± 12.73	77.20 ± 30.72
4 plants	118.00 ± 16.48	92.04 ± 5.24	84.09 ± 7.50	62.90 ± 19.48
8 plants	103.69 ± 24.72	87.79 ± 29.22	66.08 ± 7.49	59.72 ± 8.99
12 plants	94.15 ± 0.75	85.15 ± 7.50	65.54 ± 8.24	38.52 ± 0.00
TDS (ppm)				
Control	278.0 ± 0.00	275.0 ± 0.00	271.0 ± 0.00	267.0 ± 0.00
4 plants	269.0 ± 0.00	264.0 ± 0.00	262.0 ± 0.00	261.0 ± 0.00
8 plants	267.0 ± 0.00	264.5 ± 4.95	263.0 ± 0.00	256.0 ± 0.00
12 plants	264.0 ± 0.00	262.5 ± 2.12	257.0 ± 0.00	250.5 ± 2.12

Note: Several TDS cells show SD = 0 because the two analytical replicates yielded identical readings on the digital TDS meter (Hanna Instruments, ±1 ppm resolution); this should be regarded as within-instrument precision rather than zero variability.

Proteobacteria– has been shown to be the dominant contributor to organic-matter and nitrogen turnover in subsurface- and surface-flow CWs, with its composition strongly modulated by hydraulic retention time and plant species (Wang et al., 2024).

TDS removal also varied across reactors, although the absolute changes were smaller than for COD (Figure 7(b)). TDS concentrations declined steadily over the 12-day operation, from an initial 286 ppm to 267 ppm in the unplanted control and to a minimum of 250.5 ppm in the 12-plant reactor. The TDS removal efficiency ranged from 2.80% to 12.41% across all reactor configurations and sampling days, with the maximum (12.41%) reached on Day 12 in the 12-plant reactor.

The gradual TDS decline indicates a stable but lower-rate removal of dissolved inorganic and organic constituents, consistent with the combined contributions of filtration, adsorption, and biogeochemical processes occurring in the rhizosphere. Plant density had a measurable effect on TDS removal: at Day 12 the 12-plant reactor reached 12.41% removal, followed by the 8-plant (10.49%) and 4-plant (8.74%) reactors, while the unplanted control reached only 6.64%. The denser plantings provided more root surface area for adsorption of inorganic ions and dissolved colloids; in addition, *E. palaefolius* took up dissolved species as nutrients, and the gravel–sand media further promoted sedimentation, together yielding the observed TDS reduction (Novita et al., 2021; Thakur et al., 2023).

3.4 Removal Kinetics and Areal Removal Rates

To quantify the influence of plant density on the rate of pollutant removal, the temporal evolution of COD and TDS

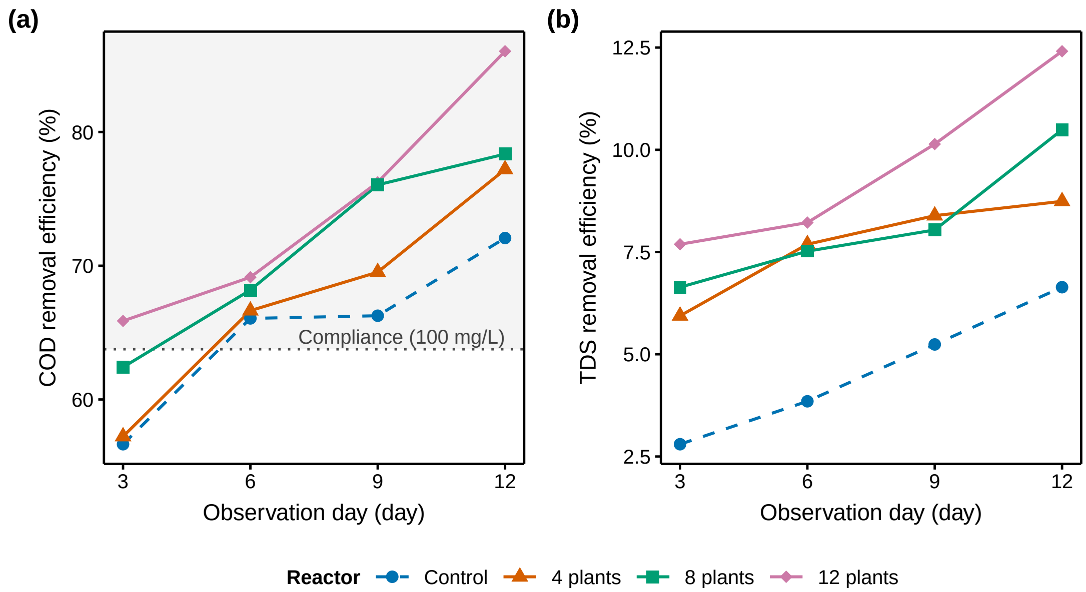

Figure 7. Removal Efficiency of (a) COD and (b) TDS During the 12-Day Operation of the FWS-CW System Across the Four Reactor Configurations (Control, 4, 8, and 12 *Echinodorus palaefolius* plants). The Dotted Line and Shaded Region in (a) Mark the Removal Efficiency (∼63.75%) at Which the Effluent COD Reaches the 100 mg/L Discharge Limit Set by Indonesian Regulation P.68/2016. The TDS Panel Has No Compliance Threshold Because the Initial Concentration (286 ppm) is Already Well Below the 2,000 ppm Regulatory Limit

concentrations was fitted to a first-order kinetic model:

$$\ln\left(\frac{C_t}{C_0}\right) = -k\,t, \tag{2}$$

where C_0 and C_t are the initial and time-t concentrations (mg/L), respectively, and k is the apparent first-order removal rate constant (day^{-1}). Linear regression of $\ln(C_t/C_0)$ against t yielded the rate constants and corresponding half-lives ($t_{1/2} = \ln 2/k$) listed in Table 3, and the model fits are shown in Figure 8.

For COD, the rate constant increased monotonically with plant density, from 0.096 day^{-1} in the unplanted control to 0.144 day^{-1} in the 12-plant reactor- a 49% improvement. The corresponding half-life decreased from 7.2 days to 4.8 days. A similar trend was observed for TDS, where k increased from 0.0054 day^{-1} (control) to 0.0097 day^{-1} (12 plants), shortening the half-life from 128 days to 71 days. Although the absolute magnitude of k_{TDS} is more than an order of magnitude smaller than k_{COD}, the relative enhancement attributable to *Echinodorus palaefolius* is even larger for TDS (+80% versus +49% for COD), reflecting the greater dependence of dissolved-solids removal on plant-mediated uptake and rhizosphere processes. Coefficients of determination ranged from 0.73 to 0.97, confirming that the first-order model adequately describes the observed concentration profiles within the 12-day operating window. We caution, however, that the 12-day window captures only the early-to-mid kinetic phase; longer-term phenomena such as microbial community succession, biofilm maturation, plant senescence, and substrate saturation cannot be inferred from these short-term constants and should be investigated in extended-duration experiments (≥ 28 days).

To support the design implications of these results, the areal mass-removal rate (g m^{-2} day^{-1}) was calculated for each reactor based on the working volume of 20 L, the surface area of $0.45 \times 0.32 = 0.144$ m^2, and the 12-day operation period (Table 4). The hydraulic loading rate (HLR) was 0.012 m day^{-1} for all reactors. The 12-plant reactor achieved areal removal rates of 2.75 g COD m^{-2} day^{-1} and 0.41 g TDS m^{-2} day^{-1}, representing increases of 19% and 87% respectively over the unplanted control. These values are within the range typically reported for tropical FWS-CW systems treating low-strength domestic wastewater and provide a basis for scaling the system to community-level applications. For comparison, Ali et al. (2024) reported COD, TSS, and TDS removals of 81–83% in a five-reactor FWS-CW treating domestic wastewater with *Pistia stratiotes* at an optimum HRT of 30 days, indicating that the present 12-day window represents an early-stage benchmark with substantial headroom for further improvement under longer retention times.

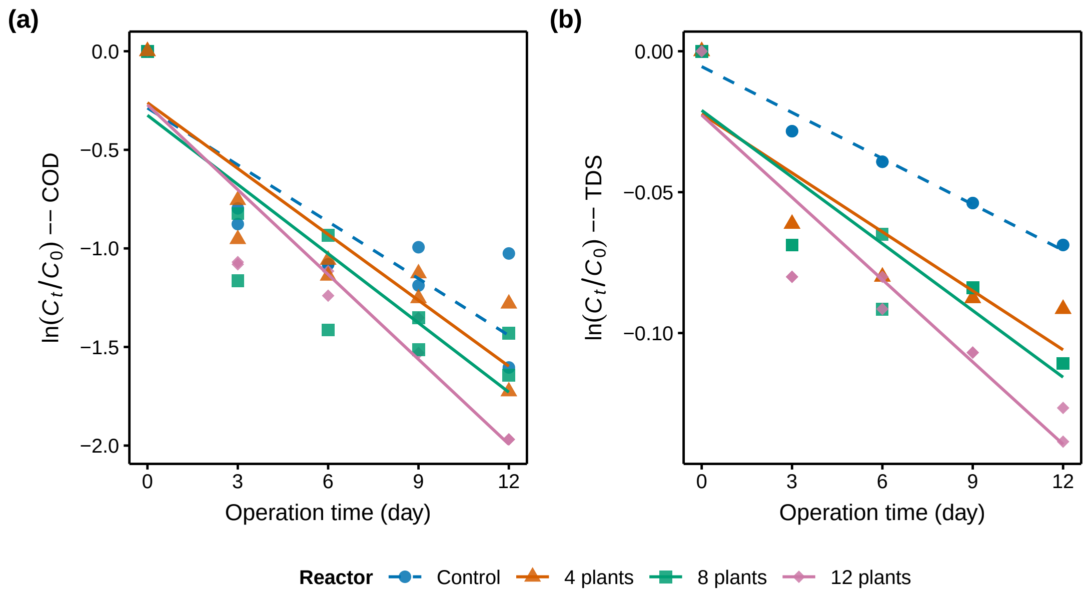

Figure 8. First-Order Kinetic Plots of (a) COD and (b) TDS Removal Showing $\ln(C_t/C_0)$ Versus Operation Time for Each Reactor Configuration. Solid and Dashed Lines Represent Linear Fits According to Equation (2)

Table 3. First-Order Kinetic Parameters and Half-Lives for COD and TDS Removal in Each Reactor Configuration. All Fits Were Statistically Significant ($p < 0.005$)

Parameter	Reactor	k (day^{-1})	$t_{1/2}$ (day)	R^2	p-value
COD	Control	0.0961	7.21	0.727	0.002
	4 plants	0.1114	6.22	0.821	<0.001
	8 plants	0.1171	5.92	0.768	<0.001
	12 plants	0.1435	4.83	0.884	<0.001
TDS	Control	0.0054	127.58	0.971	<0.001
	4 plants	0.0070	99.35	0.772	<0.001
	8 plants	0.0079	87.84	0.802	<0.001
	12 plants	0.0097	71.22	0.854	<0.001

Table 4. Mass Balance and Areal Removal Rates Over the 12-Day Operation Period. Working Volume = 20 L; Surface Area = 0.144 m^2; HLR = 0.012 m day^{-1}.

Reactor	COD		TDS	
	Removed (g)	Areal rate (g m^{-2} d^{-1})	Removed (g)	Areal rate (g m^{-2} d^{-1})
Control	3.97	2.30	0.38	0.22
4 plants	4.26	2.47	0.50	0.29
8 plants	4.32	2.50	0.60	0.35
12 plants	4.75	2.75	0.71	0.41

3.5 Condition of Plants During the Treatment Process

The condition of the plants served as one of the indicators of treatment performance in the FWS-CWs system. The condition of *Echinodorus palaefolius* during the 12-day treatment period is shown in Figure 9.

During the treatment phase, plant development showed a positive correlation with plant density. The 12-plant reactor

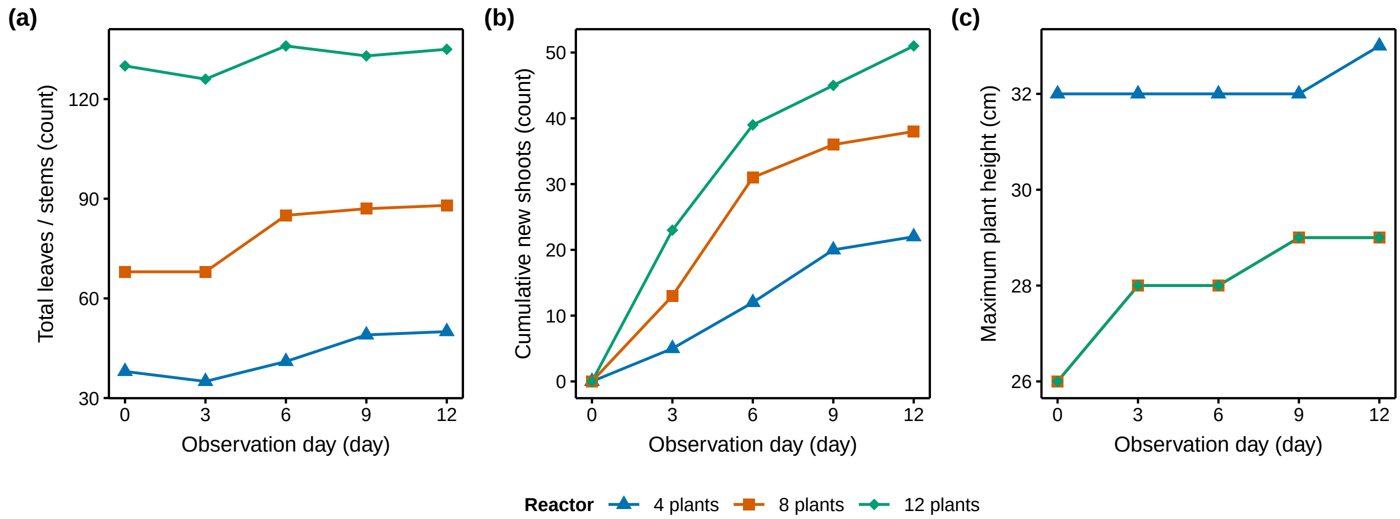

Figure 9. Growth Response of *Echinodorus palaefolius* During the 12-Day Treatment Process Across the Three Planted Reactors (4, 8, and 12 Plants): (a) Total Leaves/Stems, (b) Cumulative New Shoots, and (c) Maximum Plant Height. The Control Reactor is Omitted as it Contained No Plants

Table 5. Normalized Productivity Metrics of *Echinodorus palaefolius* Across the Three Planted Reactors Over the 12-Day Treatment Period

Reactor	Initial leaves (D0)	Leaves Growth (%)	Cumul shoots (D12)	Specific Shoot production[a]	Mortality (%)[b]
4 plants	38	+31.6	22	0.58	13.2
8 plants	68	+29.4	38	0.56	7.4
12 plants	130	+ 3.8	51	0.39	16.9

[a] Cumulative new shoots at Day 12 divided by initial number of leaves/stems at Day 0. [b] Dead stems at Day 12 divided by initial leaves/stems at Day 0.

Table 6. Two-Way ANOVA Results for the Effects of Plant Density and Observation Day on COD and TDS Concentrations in the FWS-CW System

Parameter	Source	df	SS	MS	F	p-value	η_p^2
COD	Plant density	3	2908.46	969.49	4.29	0.021	0.446
	Observation day	3	10336.03	3445.34	15.26	<0.001	0.741
	Density × Day	9	714.44	79.38	0.35	0.942	0.165
	Error (residual)	16	3612.56	225.78	–	–	–
TDS	Plant density	3	862.59	287.53	137.33	<0.001	0.963
	Observation day	3	520.59	173.53	82.88	<0.001	0.939
	Density × Day	9	51.28	5.70	2.72	0.039	0.605
	Error (residual)	16	33.50	2.09	–	–	–

Note: SS = sum of squares (Type II); df = degrees of freedom; MS = mean square; F = F-statistic; η_p^2 = partial eta-squared $(SS_{factor}/(SS_{factor} + SS_{error}))$. By Cohen's convention, $\eta_p^2 \geq 0.14$ denotes a large effect. Significance level set at $p < 0.05$. Analysis performed on raw COD ($n = 32$) and TDS ($n = 32$) measurements (4 reactor configurations × 4 observation days × 2 replicates).

Table 7. Tukey HSD Post-Hoc Pairwise Comparisons for Plant Density and Observation Day, for Both COD and TDS

Parameter	Comparison	Mean diff	p-adj	95% CI	Sig
Plant density (mg/L for COD, ppm for TDS)					
COD	12 plants vs. Control	−25.03	0.151	[−56.21, 6.21]	ns
	12 plants vs. 4 plants	−18.41	0.390	[−49.65, 12.83]	ns
	12 plants vs. 8 plants	− 8.48	0.880	[−39.76, 22.76]	ns
	8 plants vs. Control	−16.56	0.482	[−47.80, 14.68]	ns
	8 plants vs. 4 plants	− 9.94	0.821	[−41.18, 21.31]	ns
	4 plants vs. Control	− 6.62	0.938	[−37.86, 24.62]	ns
TDS	12 plants vs. Control	−14.20	<0.001	[−20.60, −7.90]	***
	8 plants vs. Control	−10.13	0.001	[−16.47, −3.78]	**
	4 plants vs. Control	− 8.75	0.004	[−15.10, −2.40]	**
	12 plants vs. 4 plants	− 5.50	0.107	[−11.85, 0.85]	ns
	12 plants vs. 8 plants	− 4.13	0.307	[−10.47, 2.22]	ns
	8 plants vs. 4 plants	− 1.38	0.934	[− 7.72, 4.97]	ns
Observation day (mg/L for COD, ppm for TDS)					
COD	Day 12 vs. Day 3	−49.27	<0.001	[−71.22, −27.33]	***
	Day 12 vs. Day 6	−30.07	0.004	[−52.01, − 8.12]	**
	Day 9 vs. Day 3	−31.65	0.003	[−53.60, − 9.71]	**
	Day 12 vs. Day 9	−17.62	0.150	[−39.56, 4.33]	ns
	Day 6 vs. Day 3	−19.21	0.103	[−41.15, 2.74]	ns
	Day 9 vs. Day 6	−12.45	0.423	[−34.39, 9.50]	ns
TDS	Day 12 vs. Day 3	−10.88	0.004	[−18.82, − 2.93]	**
	Day 12 vs. Day 6	− 7.88	0.053	[−15.82, 0.07]	ns
	Day 12 vs. Day 9	− 4.63	0.400	[−12.57, 3.32]	ns
	Day 9 vs. Day 3	− 6.25	0.163	[−14.19, 1.69]	ns
	Day 6 vs. Day 3	− 3.00	0.733	[−10.94, 4.94]	ns
	Day 9 vs. Day 6	− 3.25	0.682	[−11.19, 4.69]	ns

Note: Mean differences are reported as (group 1 − group 2). $ns = p > 0.05$; $^{**}\ p < 0.01$; $^{***}\ p < 0.001$. Family-wise error rate set at $\alpha = 0.05$.

had the highest leaf number (up to 135), followed by 8 plants (≈88) and 4 plants (≈50), while the control reactor showed no vegetative growth. New shoots increased significantly up to day 12, with 51 shoots in the 12-plant reactor, 38 in 8 plants, and 22 in 4 plants. Average plant height gradually increased from 5–26 cm to 5–29 cm for 12- and 8-plant reactors, and 5–33 cm for the 4-plant reactor. Despite greater vertical growth at lower densities, total leaf and shoot numbers were higher in dense reactors, resulting in larger photosynthetic surface areas. These growth patterns are consistent with the significant overall effect of plant density on both COD and TDS removal observed in the two-way ANOVA (Table 6), although the Tukey HSD post-hoc test (Table 7) indicates that differences among the 4-, 8-, and 12-plant reactors did not reach pairwise significance. Stem mortality occurred when *Echinodorus palaefolius* reached its pollutant absorption threshold in domestic wastewater (Safira Koesputri and Lanang Dangiran, 2016).

To resolve the apparent paradox between strong overall density effects and non-significant pairwise contrasts, three normalized productivity metrics were calculated from the growth data and are summarized in Table 5. The 4- and 8-plant reactors exhibited similar leaves growth (+32% and +29%, respectively) and similar specific shoot production (0.58 and 0.56 new shoots per initial stem). In sharp contrast, the 12-plant reactor showed only a 3.8% increase in total leaves, the lowest specific shoot production (0.39), and the highest mortality rate (16.9%, compared with 13.2% and 7.4% for the 4- and 8-plant reactors). This pattern is consistent with density-dependent stress, in which intra-clump competition for light, nutrients, and dissolved oxygen suppresses per-capita performance once a carrying-capacity threshold is reached. Importantly, this biological ceiling provides a mechanistic explanation for the statistical similarity of the three planted reactors with respect to COD and TDS removal: as plant density rises, the gain in total root biomass is offset by reduced per-plant vitality, so that pollutant removal efficiency plateaus rather than scaling linearly with the number of plants. From an applied standpoint, these findings suggest that moderate planting densities (around 4–8 plants per ∼0.14 m^2 of surface area) deliver effectively the same removal performance as denser plantings while requiring less plant material and producing a healthier, more sustainable vegetative cover.

3.6 Effect of Plant Density and Hydraulic Retention Time on Removal Efficiency

The effects of *Echinodorus palaefolius* density and hydraulic retention time on the removal efficiency of COD and TDS in domestic wastewater were analyzed using two-way ANOVA performed with IBM SPSS Statistics 26. A summary of the two-way ANOVA results for COD and TDS is presented in Table 6.

Because the two-way ANOVA indicated significant main effects for both plant density and observation day on at least one parameter, Tukey's HSD post-hoc test was performed to identify which pairwise differences contributed to those effects. The pairwise results are summarized in Table 7.

For COD, the two-way ANOVA indicated significant main effects of both plant density ($F_{3,16} = 4.29$, $p = 0.021$) and observation day ($F_{3,16} = 15.26$, $p < 0.001$), with no significant density × day interaction ($F_{9,16} = 0.35$, $p = 0.942$). The non-significant interaction suggests that the effect of plant density on COD removal was consistent across the four sampling time points. Tukey HSD pairwise comparisons for the day factor confirmed a substantial drop in COD between Day 3 and Day 9 ($p = 0.003$) and between Day 3 and Day 12 ($p < 0.001$), as well as between Day 6 and Day 12 ($p = 0.004$). For the density factor, however, none of the pairwise comparisons reached significance individually; the closest contrast was 12 plants versus control ($\Delta = -25.03$ mg/L, $p = 0.151$). This pattern is typical when an omnibus ANOVA is significant but cell-level replication ($n = 2$ per cell) limits the power of pairwise tests. The visual trend in Figure 7(a) nonetheless shows a consistent ranking of 12 plants > 8 plants > 4 plants > control, in agreement with the significant overall density effect.

For TDS, the two-way ANOVA revealed strong main effects of plant density ($F_{3,16} = 137.33$, $p < 0.001$) and observation day ($F_{3,16} = 82.88$, $p < 0.001$), as well as a weak but significant density × day interaction ($F_{9,16} = 2.72$, $p = 0.039$), indicating that the magnitude of the density effect varied slightly across sampling days. Tukey HSD comparisons showed that all three planted reactors differed significantly from the unplanted control (12 plants vs. control: $p < 0.001$; 8 plants vs. control: $p = 0.001$; 4 plants vs. control: $p = 0.004$), while differences among the planted reactors (4 vs. 8, 4 vs. 12, 8 vs. 12 plants) were not statistically significant. This pattern indicates that the presence of *Echinodorus palaefolius* substantially enhanced TDS removal compared with the unplanted control, but that further increasing plant density beyond four plants per reactor did not yield a statistically detectable additional improvement within the tested range. For the day factor, only the Day 12 versus Day 3 contrast reached significance ($p = 0.004$), confirming that longer hydraulic retention time progressively improved dissolved solids removal through filtration, adsorption, and uptake by the *Echinodorus palaefolius* root system.

4. CONCLUSIONS

This study demonstrated that Free Water Surface Constructed Wetlands (FWS-CWs) planted with *Echinodorus palaefolius* effectively reduced COD and TDS in domestic wastewater. Two-way ANOVA confirmed that both observation day and plant density exerted significant main effects on removal efficiency, with the highest performance achieved in the reactor containing 12 plants at Day 12, reaching COD and TDS removal efficiencies of 86.04% and 12.41%, respectively. Tukey HSD post-hoc analysis showed that the presence of *Echinodorus palaefolius* significantly enhanced TDS removal relative to the unplanted control, while differences among the tested planting densities (4, 8, and 12 plants) were not statistically significant. These findings highlight the crucial role of plant–microbe interactions in enhancing organic matter degradation and dissolved solids uptake, and suggest that even moderate plant densities can deliver effective treatment in this configuration.

The present work should be regarded as a laboratory-scale, preliminary investigation, and several directions for follow-up research follow naturally from its scope. First, the parameter set should be expanded to include BOD_5, TSS, dissolved oxygen, pH, and at least one nutrient (NH_3-N, NO_3^-, or PO_4^{3-}) so that the full environmental relevance of the system can be assessed. Second, the operation window should be extended to at least 28 days, and replication increased to $n \geq 4$ reactors per treatment, in order to capture longer-term dynamics and to strengthen the statistical power of post-hoc comparisons — particularly for COD, where pairwise differences were not resolvable in the present design. Third, multi-source and seasonal sampling of domestic wastewater would help generalize the findings beyond the single snapshot used here. Finally, in-depth analyses of rhizosphere microbial dynamics and the removal potential of emerging pollutants such as microplastics and heavy metals would further optimize the design of sustainable tropical constructed wetlands for community-scale wastewater treatment.

5. ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Institut Teknologi Sumatera (Itera) for the financial support provided through the Hibah Penelitian Itera 2025 (Contract No. 1998k/IT9.2.1/PT.01.03/2025). The authors also wish to thank the staff and laboratory technicians of the Environmental Engineering Department, Itera, for their valuable assistance during the experimental setup, data collection, and analysis phases of this study. Their technical expertise and support were instrumental in the successful completion of this research.

REFERENCES

Al Kholif, M. and W. Diah Indah Pratiwi (2021). Penurunan Kadar Chemical Oxygen Demand (COD) dan Fosfat Pada Limbah Laundry Dengan Metode Adsorpsi. *Jurnal Sains & Teknologi Lingkungan*, **13**(2); 155–165 (In Indonesia)

Ali, M., A. Aslam, A. Qadeer, S. Javied, N. Nisar, N. Hassan, A. Hussain, B. Ali, R. Iqbal, T. Chaudhary, M. S. Alwahibi, and M. S. Elshikh (2024). Domestic Wastewater Treatment by *Pistia stratiotes* in Constructed Wetland. *Scientific Reports*, **14**(1); 7553

Ayuningtyas, E., N. Muyasaroh, H. B. Hermawan, I. A. AS, R. Susetyaningsih, and Jumiati (2023). Pengolahan Limbah Domestik Secara Fitoremediasi Sistem Constructed Wetlands dengan Tanaman hHias Iris (*Iris pseuadacorus*) dan Melati Air (*Echinodorus palifolius*). *Jurnal Rekayasa Lingkungan*, **23**(2); 80–87 (In Indonesia)

Badan Pusat Statistik (2020). Statistik Lingkungan Hidup Indonesia (SLHI) 2020. (In Indonesia)

Chu, J. and Z. Liao (2024). Optical and Molecular Characteristics of Urban Wastewater Dissolved Organic Matter: Nnsights Into Their Correlations. *Environmental Science: Water Research & Technology*, **10**(10); 2559–2576

Dissanayaka, D. M. S. H. and S. G. V. D. H. Gunasekara (2022). Use of Constructed Wetland Systems for Greywater Treatment: A Review. *International Journal of Trend in Scientific Research and Development*, **6**(4)

Domínguez-Solís, D., M. C. Martínez-Rodríguez, H. G. Ramírez-Escamilla, L. E. Campos-Villegas, and R. Domínguez-Solís (2025). Constructed Wetlands as a Decentralized Treatment Option for Domestic Wastewater: A Systematic Review (2015–2024). *Water*, **17**(10); 1451

Dwi Putri, A., F. Indah Fajarwati, and J. Rachmadansyah (2021). Analisis Parameter Fisika dan Kimia Outlet IPAL komunal domestik Dusun Sukunan. *Indonesian Journal of Chemical Research*, **6**(2); 98–110 (IN Indonesia)

Gaballah, M. S., H. Yousefyani, and R. W. Lammers (2024). From Literature to Action: Analyzing How Nitrogen and Phosphorus Removal Responds to Different Design Factors in Free Water Surface Constructed Wetlands. *ACS ES&T Engineering*, **4**(12); 2974–2986

Gunes, K., B. Tuncsiper, S. Ayaz, and A. Drizo (2012). The Ability of Free Water Surface Constructed Wetland System to Treat High Strength Domestic Wastewater: A Case Study for the Mediterranean. *Ecological Engineering*, **44**; 278–284

Kamaruzaman, N. A., M. H. Jaafar, M. Mohideen, and S. Fatinathan (2023). Effects of Treated and Untreated Sludge Applications on Human Health, the Environment and Other Ecological Factors. In *Green Energy and Technology*. pages 23–42

Khan, M. E., A. Mohammad, W. Ali, and A. A. Sharwani (2022). Chemically Modified Carbon Nanotubes in Removal of Textiles Effluents. In *Chemically Modified Carbon Nanotubes for Commercial Applications*. pages 151–167

Kim, H. K., T. I. Jang, S. M. Kim, and S. W. Park (2014). Impact of Domestic Wastewater Irrigation on Heavy Metal Contamination in Soil and Vegetables. *Environmental Earth Sciences*, **73**(5); 2377–2383

Koul, B., D. Yadav, S. Singh, M. Kumar, and M. Song (2022). Insights into the Domestic Wastewater Treatment (DWWT) Regimes: A Review. *Water*, **14**(21); 3542

Muoghalu, C. C., P. A. Owusu, S. Lebu, A. Nakagiri, S. Semiyaga, and O. T. Iorhemen (2023). Biochar as a Novel Technology for Treatment of Onsite Domestic Wastewater: A Critical Review. *Frontiers in Environmental Science*, **11**; 1095920

Novita, E., A. Agustin, and H. Andiananta (2021). Pengendalian Potensi Pencemaran Air Limbah Rumah Pemotongan Ayam Menggunakan Metode Fitoremediasi dengan Beberapa Jenis Tanaman Air. *Agroteknika*, **4**(2); 106–119 (In Indonesia)

Panrare, A., T. Tondee, and P. Sohsalam (2016). Effect of Plant Density in Constructed Wetland on Domestic Wastewater Treating Efficiency. *International Journal of Applied and Physical Sciences*, **2**(1); 7–12

Parab, C., A. V. Patel, K. D. Yadav, and V. Prajapati (2025). Evaluating Constructed Wetlands with Water Hyacinth for Greywater Treatment: Media Comparison and ANN-Based Predictive Modelling. *Bioresource Technology Reports*, **30**; 102112

Perdana, M. C., H. B. Sutanto, and G. Prihatmo (2018). Vertical Subsurface Flow (VSSF) Constructed Wetland for Domestic Wastewater Treatment. *IOP Conf. Ser.: Earth Environ. Sci.*, **148**(1); 012025

Qomariyah, S., A. H. Ramelan, P. Setyono, and Sobriyah (2021). Initial Stage in Designing Household Constructed Wetlands: Selection of a Suitable Aquatic Plant. *International Journal on Advanced Science, Engineering and Information Technology*, **11**(3); 1014–1021

Ratnawati, R., I. Nurhayati, I. N. Rohim, and V. Andriani (2024). Phytoremediation of Landfill Leachate Using *Chlorophytum comosum*, *Echinodorus palaefolius*, and *Hippochaetes lymenalis*. *Journal of Ecological Engineering*, **25**(12); 124–135

Safira Koesputri, A. and H. Lanang Dangiran (2016). Pengaruh Variasi Lama Kontak Tanaman Melati Air (*Echinodorus palaefolius*) dengan Sistem Subsurface Flow Wetlands Terhadap Penurunan Kadar BOD, COD dan Fosfat dalam Limbah Cair Laundry. *Jurnal Kesehatan Masyarakat*, **4**(4); 771–778 (In Indonesia)

Saha, S., M. B. Roy, R. Mandal, and P. K. Roy (2025). Hybrid Constructed Wetlands for Multi-Source Wastewater Treatment: Performance Analysis and Design Insights from Urban and Industrial Wastewater Sources. *Next Research*, **2**(3); 100649

Sai Krishna, R. V. M., H. A. Khan, R. Vamsi, and S. K. Khaja Sameer (2023). Utilization of Treated Wastewater in Concrete. *IOP Conf. Ser.: Earth Environ. Sci.*,

1280(1); 012016

Sané, N., M. Mbengue, A. Laffite, S. Stoll, J. Poté, and P. Le Coustumer (2022). Development of a Process for Domestic Wastewater Treatment Using *Moringa oleifera* for Pathogens and Antibiotic-Resistant Bacteria Inhibition under Tropical Conditions. *Water*, **14**(15); 2379

Sangeetha, R., R. Rajamathanghi, G. Sowmiya, G. Jahnaveswari, P. Suresh Babu, and A. Sai Ramesh (2023). Feasibility and Performance Evaluation of *Mentha Aquatica* in Treating Domestic Wastewater. In *Environmental Science and Engineering*. pages 87–98

Shen, Y., J. Li, R. Gu, L. Yue, X. Zhan, and B. Xing (2017). Phenanthrene-Triggered Chlorosis is Caused by Elevated Chlorophyll Degradation and Leaf Moisture. *Environmental Pollution*, **220**; 1311–1321

Sun, H., Y. Zhou, and C. Jiang (2024). Regulating Denitrification in Constructed Wetlands: The Synergistic Role of Radial Oxygen Loss and Root Exudates. *Water*, **16**(24); 3706

Syamlal, C. A., A. George, and D. Sayantan (2024). Phytoremediation: An Eco-Friendly Solution for Environmental Contamination. *International Journal of Advanced Research in Science, Communication and Technology*; 553–577

Thakur, T. K., M. P. Barya, J. Dutta, P. Mukherjee, A. Thakur, and S. L. Swamy (2023). Integrated Phytobial Remediation of Dissolved Pollutants from Domestic Wastewater through Constructed Wetlands. *Water*, **15**(22); 3877

Ur Rahman, S., A. Qin, M. Zain, Z. Mushtaq, F. Mehmood, L. Riaz, et al. (2024). Pb Uptake, Accumulation, and Translocation in Plants: Plant Physiological, Biochemical, and Molecular Response: A Review. *Heliyon*, **10**(6); e27724

Vishwakarma, S. and D. Dharmendra (2024). Evaluating Domestic Wastewater Treatment Efficiency of Field Scale Hybrid Flow Constructed Wetland in Series. *Pollution*, **10**(1); 392–403

Wang, B., L. Wu, R. Wang, J. Huo, Z. Yi, Z. Wang, and H. Zhang (2024). Rhizosphere Microorganisms in Subsurface Flow Garden Constructed Wetland and their Influence on Nitrogen Removal Efficiency. *Water, Air, & Soil Pollution*, **235**(7); 428

Yang, Y., Y. Hu, A. Duan, X. C. Wang, H. H. Ngo, and Y. Y. Li (2021). Characterization of preconcentrated domestic wastewater toward efficient bioenergy recovery. *Bioresource Technology*, **319**; 124144

