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Original Research Article

Enhancing Stabilized Leachate Treatment with *C. comosum*, *E. palaefolius*, and *E. hyemale* in Constructed Wetlands

Imam Nur Rohim[1, 2*], Bimo Tri Goutomo[3]

[1] Program Study of Environmental Engineering, Faculty of Engineering and Science, Universitas PGRI Adi Buana Surabaya, Jalan Dukuh Menanggal XII, Dukuh Menanggal, Gayungan, Surabaya, Indonesia 60234

[2] Program Study of Law, Faculty of Law, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Jalan Rungkut Madya, Gn. Anyar, Surabaya, Indonesia 60294

[3] Department of Environmental Engineering, Pukyong National University, Busan, South Korea 48513

* Corresponding Author, email: imamnrohim1@gmail.com

Abstract

Stabilized landfill leachate is challenging to treat because of its high content of refractory organic matter and low biodegradability (BOD/COD ratio <0.16). This study investigated the performance of three ornamental plants, *C. comosum*, *E. palaefolius*, and *E. hyemale*, in laboratory-scale subsurface-flow constructed wetlands for treating stabilized leachate from the Ngipik Landfill, Gresik, Indonesia. The experiments were conducted under batch conditions with a hydraulic retention time (HRT) of 9 days. The treatment efficiency was evaluated based on the removal of BOD, COD, TSS, and TN. *E. palaefolius* achieved the highest COD and TSS removal efficiencies of 46.92% and 99.36%, respectively. The greatest COD reduction was observed in *E. hyemale* (63.30%), whereas *C. comosum* showed the highest TN removal efficiency (93.01%). Despite significant reductions in pollutants, only the TSS concentration in the treated effluents (2-12 mg/L) met the 100 mg/L discharge standard. BOD, COD, and TN levels remained above the regulatory limits. The results indicate that these ornamental plants are suitable for leachate pre-treatment, although longer retention times or additional treatment processes are required to achieve full compliance with environmental standards.

Keywords: *C. comosum*; constructed wetlands; *e. hyemale*; *e. palaefolius*; landfill.

1. Introduction

Landfill leachate poses a persistent environmental concern because of its complex composition and potential to contaminate groundwater (Igwegbe et al., 2024; Mukherjee et al., 2015). As landfills age, leachate gradually shifts to a stabilized stage characterized by high concentrations of refractory organic compounds, elevated ammonium levels, and low biodegradability (Wu et al., 2022; Zhao et al., 2017). The BOD/COD ratio of stabilized leachate is typically below 0.1, rendering conventional biological treatment processes less effective (Naveen et al., 2016; Wu et al., 2022). Therefore, sustainable and cost-effective treatment technologies are needed to improve pollutant removal (Abdel-Shafy et al., 2024; Torretta et al., 2016).

Constructed wetlands (CWs) have been widely applied as nature-based wastewater treatment systems because of their low operating costs, simple maintenance requirements, and environmental benefits (Chen et al., 2023; Riyanti et al., 2024). Pollutant removal in CWs occurs through a combination of physical filtration, adsorption, microbial activity, and plant uptake. In tropical countries such as Indonesia, favorable climatic conditions support continuous biological processes, enhancing CWs performance throughout the year (Arliyani et al., 2021).

The use of ornamental plants in CWs has attracted increasing interest because it combines wastewater treatment with landscape value (Sandoval et al., 2019). Aquatic species, such as Equisetum hyemale and *E. palaefolius*, have demonstrated the ability to reduce organic pollutants through root-associated oxygen transfer and microbial interactions (Lai et al., 2012; Singh et al., 2024). In contrast, the use of terrestrial ornamental species, such as *C. comosum*, is relatively unexplored (Mutar et al., 2022; Pan et al., 2021). Its rapid growth and extensive root system suggest potential benefits for nutrient uptake and pollutant removal (Simek et al., 2021; Simek et al., 2018).

This study evaluated the performance of *C. comosum*, *E. palaefolius*, and *E. hyemale* in treating stabilized landfill leachate using batch subsurface-flow constructed wetlands. Particular attention was given to pollutant removal under carbon-limited conditions and to the mechanisms responsible for the reduction of organic matter and nitrogen during a 9-day hydraulic retention period.

2. Methods

2.1 Initial and Source of Leachate

The leachate samples used in this study were obtained from the Ngipik Landfill located in Gresik, East Java, Indonesia. Sampling was performed directly at the inlet of the Ngipik Landfill Leachate Treatment Unit. Based on the preliminary analysis results in **Table 1**, the leachate characteristics showed BOD and COD concentrations of 439 mg/L and 2,695 mg/L, respectively. The initial concentrations of TSS and TN were 375 and 2,788 mg/L, respectively. The initial concentrations of mercury and Cd were 1.39 mg/L and 0.02 mg/L, respectively. The concentrations of BOD, COD, TSS, TN, and Mercury exceeded the established quality standards (Minister of Environment and Forestry of the Republic of Indonesia, 2016). Meanwhile, the concentration of Cd was far below the established quality standards. The BOD/COD ratio of 0.16 suggests that the leachate was in the stabilization phase.

Table 1. Quality of leachate in Ngipik Landfill, Gresik, East Java, Indonesia.

Parameter	Unit	Result	Standard
pH value	-	8	6-9
Temperature	°C	39	-
BOD	mg/L	439	150
COD	mg/L	2695	300
TSS	mg/L	375	100
TN	mg/L	2788	60
Mercury	mg/L	1.39	0.005
Cadmium	mg/L	0.02	0.1
BOD/COD Ratio	-	0.16	-

2.2 Acclimatization

The plants tested for their phytoremediation capabilities in this process included *C. comosum*, *E. palaefolius*, and *E. hyemale*. Before treatment began, an acclimatization process was carried out for seven days to ensure that the plants could adapt to their new environment. During this adaptation period, the plants were maintained using clean water without any leachate to ensure that the plants used were healthy and did not die. Plant acclimatization was carried out in a high-density polyethylene (HDPE) tank measuring 30 cm × 18 cm × 24 cm.

2.3 Range Finding Test (RFT)

Before entering the main remediation stage, a range finding test (RFT) was conducted for nine days. The purpose of this stage was to identify the tolerance level of plants to pollutants and determine the safe leachate concentration that would not damage plant morphology. The RFT was conducted in a reactor with a volume capacity of 5 L and dimensions of 26 cm × 23 cm × 24 cm. The RFT growing medium consisted of soil measuring 0.053–0.075 mm at the top and gravel measuring 10–20 mm at the bottom, each 7 cm in height. One RFT reactor contained 1 L of leachate diluted according to the specified variations. The concentration ratios of leachate to tap water were 25%:75%, 50%:50%, 75%:25%, and 100%:0% (v/v). All three plant species survived and adapted to variations in leachate and tap water concentrations of 100%:0% (v/v). Thus, this variation in leachate and tap water was used in the main stage of the experimental study.

2.4 Research Set-Up

In this experimental study, four laboratory-scale reactors were operated in static batch mode. All reactors were designed from an HDPE tank with measurements of 51 cm × 32 cm × 31 cm. The substrate media in the reactor were composed of fertile soil (0.053–0.075) on the upper layer and gravel (0.085-1.18 mm) on the bottom. This substrate medium was intended to optimize hydraulic conductivity and prevent clogging. The reactors were equipped with an inlet pipe placed in the upper center of the side wall to introduce inflow and an outlet tap at the lower center of the opposite side wall to facilitate drainage and sampling. The outlet tap was placed 3 cm above the base of the reactor. The outlet tap was constructed using ½-inch PVC, whereas the inlet used a ¾-inch 90° PVC elbow. The substrate media size was conditioned by screening in accordance with the ISO 565/3310-1 and ASTM E11 standards to ensure a uniform particle-size distribution. The overall experimental procedure is illustrated in **Figure 1**.

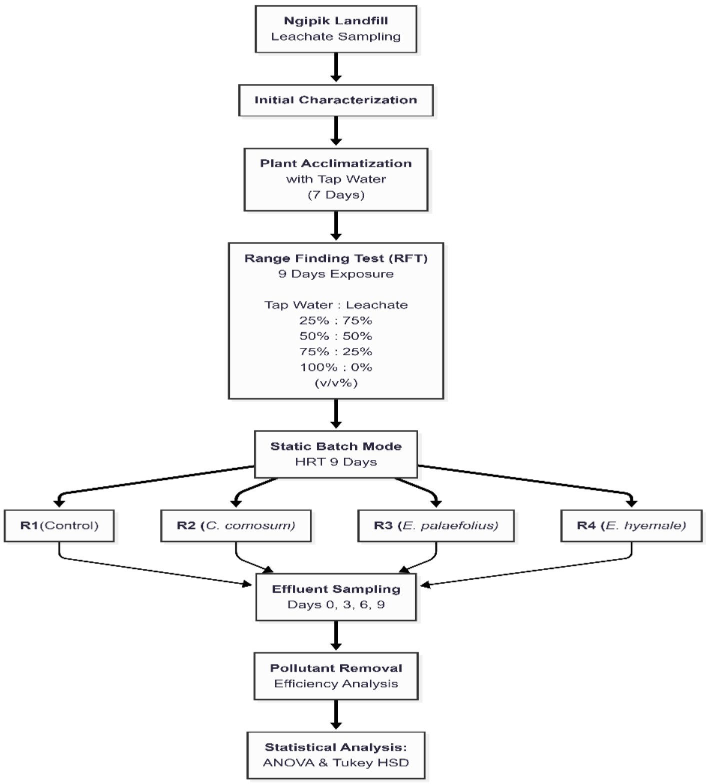

Figure 1. Experimental framework of this study.

The effective pore water volume for each reactor was calibrated to 15 L, and the planted reactors contained 1 kg of initial fresh biomass. The experiments were conducted with a hydraulic retention time (HRT) of 9 days. On day-0, 15 L of influent water was introduced into each reactor. Effluent samples were collected from the sampling valve on days 0, 3, 6, and 9 of the experiment. The reactors were divided into four groups: unplanted control (R1), *C. comosum* (R2), *E. palaefolius* (R3), and *E. hyemale* (R4). The design of leachate treatment using constructed wetlands is shown in **Figure 2**.

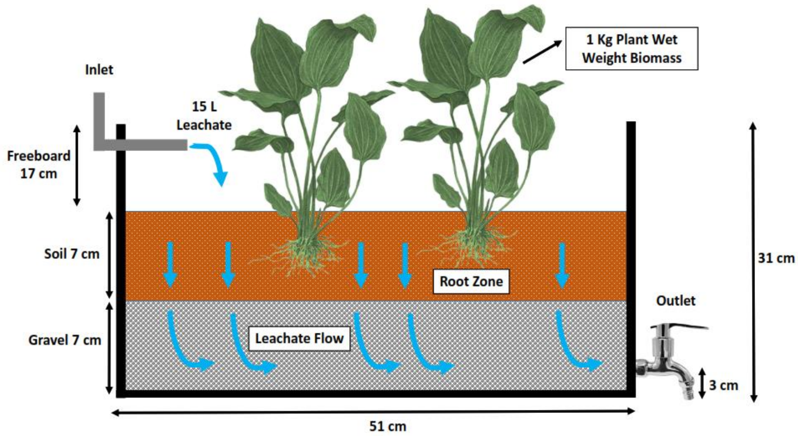

Figure 2. Reactor configuration with constructed wetlands

The reactor was housed in a semi-indoor facility with 12 h of sunlight exposure, an ambient temperature between 28°C and 32°C, and a relative humidity of 65% to 80%. This aims to condition the reactor as it would in an actual biological process. The initial environmental condition of the stabilized leachate within the reactor was characterized by a slightly alkaline pH of 8.0, which remained relatively stable between 7.8 and 8.2 throughout the 9-day observation period. This specific pH condition is considered highly optimal for supporting the rhizodegradation process and maintaining the activity of heterotrophic denitrifying bacteria in CWs media, while remaining within the tolerance limit of the selected plant species (Gutierrez et al., 2025).

2.5 Data Analysis

TN and COD concentration analyses were performed using a DR 900 colorimeter (HACH, USA). BOD concentration measurements were performed using a DO-5510 DO meter (MRC) after incubation for five days at 20°C. The TSS concentration was determined using the gravimetric method. The removal efficiency (RE%) of the pollutant concentrations was calculated according to Equation (1) (Ratnawati et al., 2024b):

$$RE(\%) = \frac{C_{in} - C_{out}}{C_{in}} \qquad \text{Eq (1)}$$

where RE% is the removal efficiency of pollutants (%), and C_{in} and C_{out} (mg/L) are the pollutant concentrations in the inlet and outlet, respectively.

2.6 Statistical Analysis

All data obtained from the removal efficiencies of BOD, COD, TSS, and Total Nitrogen (TN) were statistically analyzed using IBM SPSS Statistics software (Version 29.0, IBM Corp., Armonk, NY, USA). To determine the significance of the differences in pollutant removal among the three ornamental plant species (*C. comosum*, *E. palaefolius*, and *E. hyemale*), a One-Way Analysis of Variance (ANOVA) was conducted. Before ANOVA, the data were tested for normality and homogeneity of the variance. A post-hoc Tukey's Honest Significant Difference (HSD) test was performed at a significance level of $\alpha = 0.05$. Statistical significance was set at $p < 0.05$.

3. Result and Discussion

3.1 BOD Removal Efficiency on Leachate

The BOD concentration in the leachate decreased throughout the reactors, as illustrated in **Figure 3a**. The initial BOD concentration in each reactor was 439 mg/L. The most significant decrease in concentration was observed in reactor *E. hyemale* (R4) on day 3, where the BOD level dropped dramatically to 252 mg/L. This significant decrease at the beginning of the study was a result of the phytostabilization process, in which the gravel and soil media acted as physical filters to trap organic particles, while the root system began to immobilize pollutants in the rhizosphere (Tangahu et al., 2011; Torretta et al., 2016). *E. hyemale* plants have the advantage of a hollow stem structure that facilitates the transfer of atmospheric oxygen to the root system through a radial oxygen loss mechanism (Amalludin et al., 2025; Wang et al., 2018). This oxygen availability provides energy for microorganisms to oxidize organic compounds more intensively through rhizodegradation (Shelef et al., 2013).

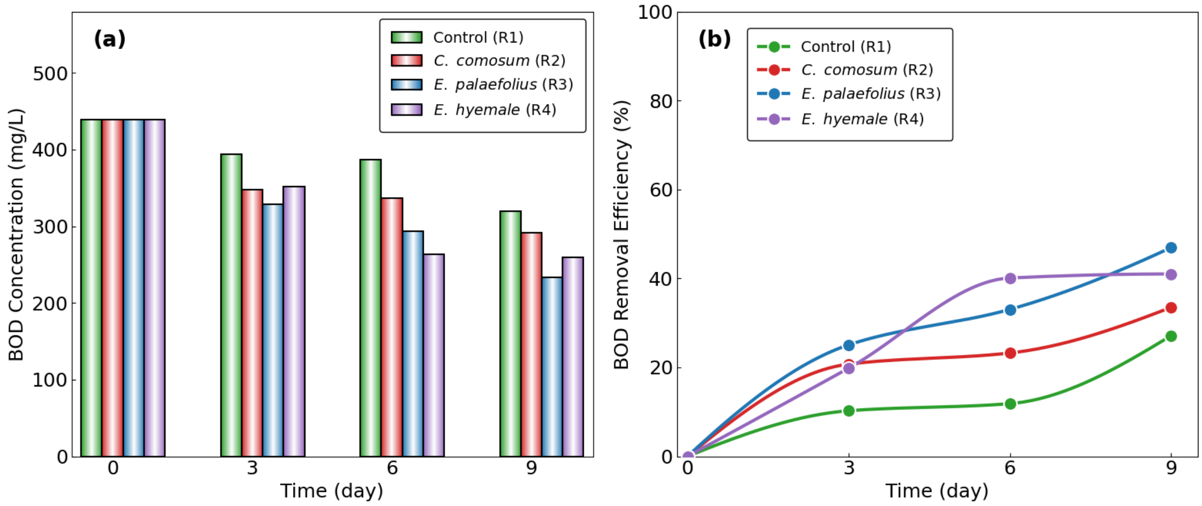

Figure 3. BOD removal (a) removal efficiency (b) during the 9-day stabilization leachate treatment.

A different decline was observed in *E. palaefolius* (R3). On day-6 of HRT, the decline was slower than that of *E. hyemale* (R4), reaching 323 mg/L. This indicates that *E. palaefolius* (R3) requires a longer adaptation time to tolerate leachate toxicity. However, this reactor showed a very sharp decline on day 9, reaching the lowest concentration of 233 mg/L. The success of *E. palaefolius* (R3) at day-9 of HRT stemmed from a mature phytodegradation process, in which the symbiotic relationship between plant roots and rhizosphere microorganisms was optimal (Sánchez et al., 2022). Microorganisms break down organic matter into simple molecules with the stimulation of enzymes released by the roots, which are then absorbed by plants as nutrients through the phytoextraction mechanism (Ratnawati et al., 2024a).

In *C. comosum* (R2), the decrease was gradual and consistent until it reached 292 mg/L on the 9th day. Meanwhile, the control (R1) showed the slightest decrease, with a final concentration of 320 mg/L. The decrease in the control (R1) depended purely on the methods of gravity sedimentation and physical filtration of the substrate without the support of rhizosphere oxygenation and biological absorption from the plant root system (Khalifa et al., 2020).

Figure 3b shows that BOD removal progressively increased in all reactors throughout the 9-day treatment period. Among the tested macrophytes, *E. palaefolius* (R3) exhibited the highest removal efficiency, reaching 46.92% by day 9. This was followed by *E. hyemale* (R4) and *C. comosum* (R2), with removal efficiencies of 41.00% and 33.49%, respectively. All planted reactors outperformed the unplanted control (R1), which achieved aBODreductionoff 27.11%.

The enhanced performance of *E. palaefolius* is likely associated with its well-developed root system, which provides a larger surface area for microbial colonization and promotes oxygen transfer within the rhizosphere. These conditions can enhance microbial activity and accelerate the breakdown of biodegradable organic matter (Ratnawati et al., 2024a; Sari et al., 2018). Although the planted system demonstrated improved BOD removal, the efficiencies obtained in this study were lower than those reported in previous investigations, where removal rates exceeded 77% for similar species (Harmayani et al., 2025). This difference may be related to the characteristics of the stabilized leachate used in the present study, which contained a limited fraction of readily biodegradable compounds. In addition, a 9-day HRT may not be sufficient for the complete degradation of refractory organic matter (Ningrum et al., 2022). Statistical analysis using Two-Way ANOVA revealed significant differences in BOD removal among the treatments ($p = 0.026$; $p < 0.05$), indicating that the presence and type of macrophyte significantly influenced the degradation of organic pollutants compared with the unplanted control (R1).

3.2 COD Removal Efficiency on Leachate

The initial COD concentration in all reactors was 2,695 mg/L. **Figure 4a** shows that on day 9, the control (R1), *C. comosum* (R2), *E. palaefolius* (R3), and *E. hyemale* (R4) removed the COD concentration by 1251 mg/L, 1114 mg/L, 1013 mg/L, and 989 mg/L, respectively. The decrease in COD concentration in **Figure 4b** indicates a significant removal, with the final COD removal efficiency across all reactors ranging from 54% to 63%.

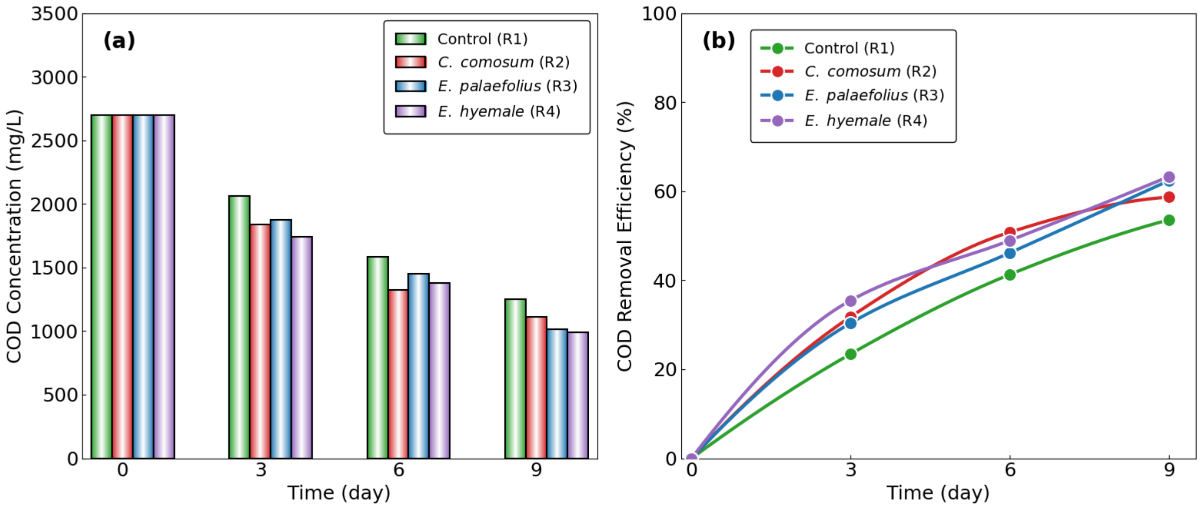

Figure 4. COD removal (a) removal efficiency (b) during the 9-day stabilization leachate treatment.

A substantial reduction in COD concentration was observed in all planted reactors throughout the treatment period. Among the tested species, *E. hyemale* (R4) showed the most pronounced decrease, with COD declining to 1,739 mg/L on day 3 and then to 989 mg/L by day 9. This enhanced COD removal efficiency may be due to the plant's hollow stem structure (Zajączkowska et al., 2017). The hollow stem structure facilitates the radial oxygen loss (ROL) mechanism, allowing atmospheric oxygen to diffuse into the plant rhizosphere (Wang et al., 2018). This condition increases oxygen availability to support aerobic microbial activity (Wang et al., 2018). Therefore, the degradation of organic pollutants in stabilized landfill leachate is accelerated.

A similar trend in COD concentration was also observed in *E. palaefolius* (R3), which reduced COD to 1,013 mg/L by the end of the experiment. In comparison, *C. comosum* (R2) achieved a final COD concentration of 1,114 mg/L. The better performance of *E. hyemale* and *E. palaefolius* suggests that aquatic macrophytes are more effective at transferring oxygen under saturatedconditions thannterrestrial species, suchh as *C. comosum*, resulting in more efficient oxidation of organic matter (Lai et al., 2012).

As shown in **Figure 4b**, the COD removal efficiency increased steadily in all reactors over the 9-day period. The highest removal efficiency was recorded for *E. hyemale* (R4) at 63.30%, followed closely by *E. palaefolius* (62.41%) and *C. comosum* (58.66%). The control reactor (R1) exhibited the lowest removal efficiency (53.58 %). Although these results demonstrate the positive contribution of vegetation to COD reduction, the removal efficiencies remained lower than those reported in studies treating young leachate, where 85%–99% removal has been achieved (Ratnawati et al., 2024b). This difference is likely due to the stabilized nature of the leachate used in the present study, which contained a high proportion of refractory organic compounds and a low BOD/COD ratio (0.16) (Wang et al., 2022). Two-way ANOVA revealed significant differences in COD removal among the treatments ($p = 0.019$; $p < 0.05$), indicating that plant species played an important role in oxygen-transfer mechanisms in promoting the breakdown of recalcitrant organic matter in CWs systems (Wang et al., 2018; Zajączkowska et al., 2017).

3.3 TSS Removal Efficiency on Leachate

The initial TSS concentration was 375 mg/L in all the reactors. As shown in **Figure 5a**, the TSS levels decreased markedly throughout the 9-day treatment period, regardless of the reactor configuration. A substantial reduction was already observed on day 3, although the rate of removal varied among the treatments. *E. hyemale* (R4) exhibited a superior response, lowering the TSS concentration to 44 mg/L, followed by *C. comosum* (R2) with a concentration of 80 mg/L. Sedimentation and filtration processes occurring within wetland media can be largely attributed to this rapid initial decrease (Ratnawati et al., 2024b). The fibrous roots of *E. hyemale* and tuberous roots of *C. comosum* form very dense natural plant tissues, enabling them to trap suspended particles immediately after the leachate passes through the media (Bakhshoodeh et al., 2020). In contrast, *E. palaefolius* (R3) showed a slightly slower decrease on day 3, amounting to 216 mg/L, owing to the larger morphology of its rhizome roots, which required more time to form a stable filter density in the soil (Bakhshoodeh et al., 2020; Ratnawati et al., 2024b).

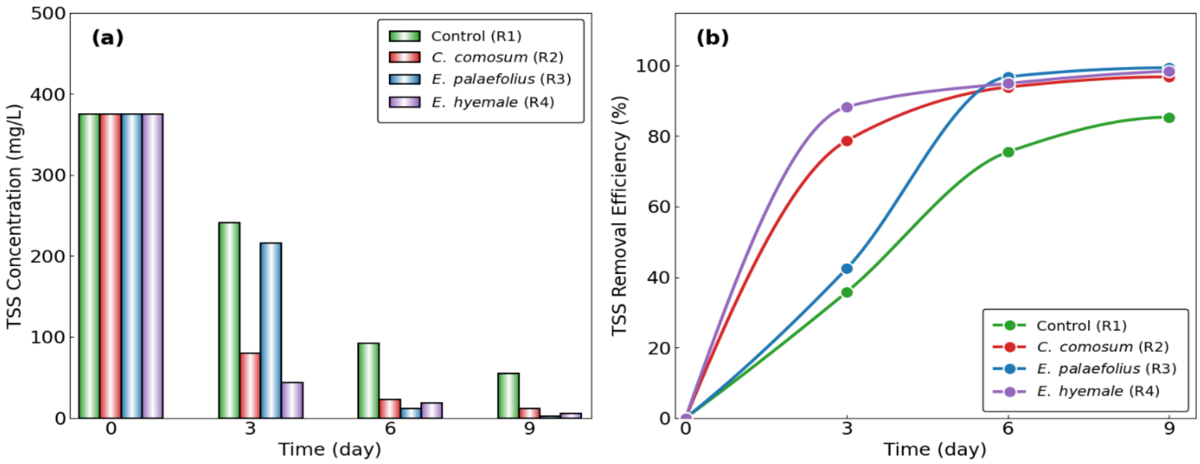

Figure 5. TSS removal (a) removal efficiency (b) during the 9-day stabilization leachate treatment.

On day 9, *E. palaefolius* (R3) showed the greatest decrease at a TSS concentration of 2 mg/L. *E. hyemale* (R4) and *C. comosum* (R2) were followed by concentrations of 6 mg/L and 12 mg/L, respectively, whereas the control (R1) remained at 55 mg/L. The superiority of *E. palaefolius* (R3) on day 9 indicates that the maturity of the ecosystem in the rhizosphere zone of *E. palaefolius* plants is highly effective for stabilizing solid particles (Bakhshoodeh et al., 2020; Ratnawati et al., 2024a). Plant roots function as physical filters and as a place for microorganisms to attach, which helps in the biodecomposition of trapped organic solids (Bakhshoodeh et al., 2020; Saeed et al., 2020).

Figure 5b. illustrates the corresponding increase in the TSS removal efficiency over time. By the end of the experiment, *E. palaefolius* (R3) achieved the highest efficiency at 99.36%, followed by *E. hyemale* (R4) at 98.40%, and *C. comosum* (R2) at 96.80%. In contrast, the unplanted control was 85.33%. These findings are comparable to those of a previous study that reported TSS removal efficiencies ranging from 98.80% to 99.68% (Ratnawati et al., 2024a).

As a result, all planted reactors successfully reduced the TSS concentration below the Indonesian discharge standard of 100 mg/L (Minister of Environment and Forestry of the Republic of Indonesia, 2016).

Although Two-Way ANOVA indicated no significant difference among treatments over the overall experimental period ($p = 0.142$; $p > 0.05$), the lower final effluent concentration observed in planted reactors suggests that vegetation helped maintain filtration performance. The extensive root system likely enhanced particle retention and helped prevent media clogging, thereby supporting the stable long-term operation of the constructed wetland system (Bakhshoodeh et al., 2020; Ratnawati et al., 2024a).

3.4 TN Removal Efficiency on Leachate

The initial TN concentration in all the reactors was 2,788 mg/L. A significant decrease in the TN concentration is shown in **Figure 6a**. On day 3, a simultaneous drastic decrease was observed in all reactors. *E. hyemale* (R4) showed the sharpest decline in this phase to 512 mg/L, followed by *E. palaefolius* (R3) to 574 mg/L, *C. comosum* (R2) to 750 mg/L, and the control (R1) to 757 mg/l. The drastic decrease on day 3 indicates the dominance of physical adsorption and cation exchange mechanisms (Ratnawati et al., 2024a). Ammonium ions (NH_4^+), which are the dominant form of nitrogen in leachate, bind to the negative charges of soil particles and gravel through ion exchange before biological processes take effect (Bakhshoodeh et al., 2020; Saeed et al., 2020). In addition, the volatilization of ammonia (NH_3) into the atmosphere also contributes to the removal in nitrogen mass at the beginning of the process (Bakhshoodeh et al., 2020).

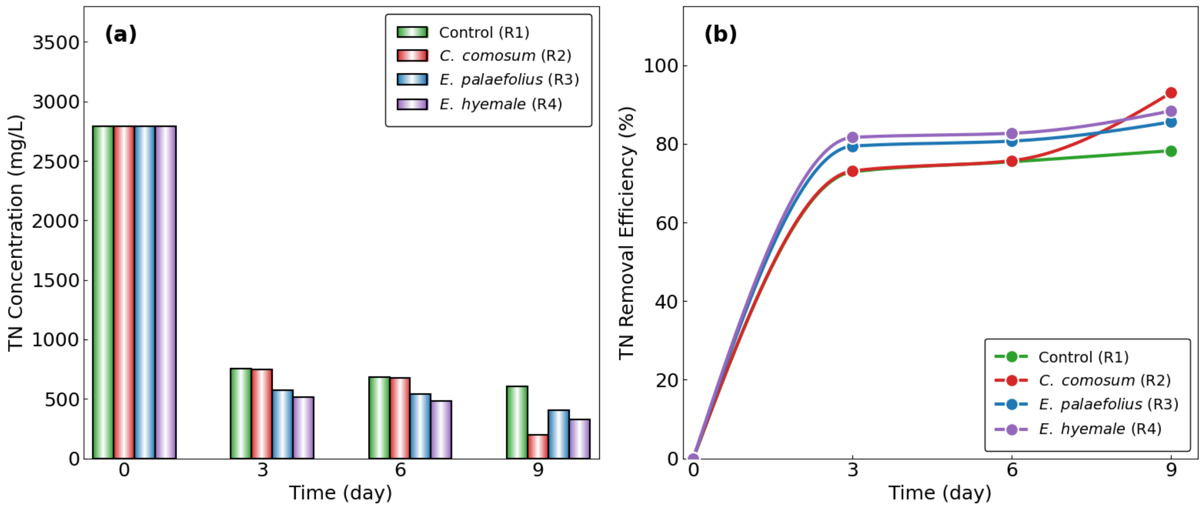

Figure 6. TN removal (a) removal efficiency (b) during the 9-day stabilization leachate treatment.

In *C. comosum* (R2), phytoremediation mechanisms were notably dominant. *C. comosum* (R2) showed a sharp decline, reaching a final concentration of 195 mg/L. In contrast, the concentrations of *E. palaefolius* (R3) and *E. hyemale* (R4) were 402 mg/L and 324 mg/L, respectively. The final TN concentration in the control (R1) was 606 mg/L. The superiority of *C. comosum* on day 9 was closely related to the symbiosis between plant roots and microorganisms in the nitrogen cycle. The nitrogen removal process involves ammonification, nitrification, and denitrification (Bakhshoodeh et al., 2020; Kulshreshtha et al., 2022). Nitrosomonas and Nitrobacter bacteria in the root zone oxidize ammonium into nitrate (NO_3^-) with the aid of oxygen released through the radial oxygen loss mechanism (Bakhshoodeh et al., 2020; Saeed et al., 2020). Subsequently, nitrate is removed to nitrogen (N_2) by denitrifying bacteria or absorbed directly by plants as an essential nutrient for the formation of leaf and root biomass (Bakhshoodeh et al., 2020; Kulshreshtha et al., 2022). *C. comosum* has a fast vegetative growth rate, enabling it to perform more intensive rhizofiltration and plant uptake than other species to support its growth (Simek et al., 2018; Tangahu et al., 2011).

As shown in **Figure 6b**, TN removal increased throughout the-9 day treatment period in all reactors. Among the tested species, *C. comosum* (R2) achieved the highest removal efficiency, reaching 93.01% by day 9. This was followed by *E. hyemale* and *E. palaefolius*, with removal efficiencies of 88.38%

and 85.58%, respectively, whereas the control reactor (R1) achieved 78.26%. The strong performance of *C. comosum* is consistent with previous studies reporting TN removal efficiencies approaching 95% and highlights the potential of this species for nitrogen uptake via rhizofiltration and plant assimilation (Ratnawati et al., 2024b; Tangahu et al., 2011).

Despite the high removal efficiencies observed, the final TN concentration in the treated effluent remained at 195 mg/L, which exceeded the applicable discharge standard (Minister of Environment and Forestry of the Republic of Indonesia, 2016). This result suggests that a longer hydraulic retention time or integration of additional treatment processes may be required to achieve regulatory compliance. Two-way ANOVA indicated that the difference in TN removal among the treatments was not statistically significant over the experimental period ($p = 0.158$; $p > 0.05$). This may be attributed to non-biological removal mechanisms, such as ammonium volatilization and ion exchange, which occurred across all reactors during the early stages of treatment (Bakhshoodeh et al., 2020; Saeed et al., 2020). Nevertheless, the higher TN removal observed in *C. comosum* at the end of the experiment suggests that plant-mediated uptake became increasingly important over time and contributed to the overall reduction of nitrogen in the system (Simek et al., 2018; Tangahu et al., 2011).

3.5 Visual Assessment of Plant

Water quality parameters and changes in plant morphology were monitored throughout the experiment to assess each species' ability to tolerate the harsh conditions of stabilized leachate. Plant health and visual appearance are important indicators of phytoremediation performance and adaptation to environmental stress (Nurhayati et al., 2026). Following the 9-day treatment period, all plant species remained alive, indicating that the 7-day acclimatization period was sufficient to support their establishment in the constructed wetland system. The visual assessment of the three plants is shown in **Figure 7**.

Figure 7. Visual assessment of the plant: (a) day 0; (b) day 9.

C. comosum (R2) showed mild chlorosis, particularly at the margins of older leaves. Chlorosis occurred at all stages of leaves and plant stems of E. palaefolius (R3) and E. hyemale (R4). This symptom may be correlated with physiological stress resulting from high pollutant loads and elevated nutrient concentrations in the stabilized landfill leachate. This condition can affect chlorophyll production and overall plant vigor (Pan et al., 2021; Simek et al., 2018).

3.6 Comparative Performance and Future Directions

The results of a previous study showed that *C. comosum*, *E. palaefolius*, *and E. hyemale* were highly efficient in removing suspended solids and nitrogen from stabilized landfill leachate. The highest removal efficiencies in this study were 99.36% for TSS and 93.01% for TN. Thus, they are comparable to or higher than those reported for other commonly used macrophyte plants, including *P. australis* and *C. indica* (Angmo et al., 2024; Sial et al., 2023). A comparison of the abilities of plant-based landfill leachate treatment systems reported in the literature is presented in **Table 2**.

Table 2. Comparison of constructed wetland system for landfill leachate treatment

Plant Species	CWs Type	Media	HRT (day)	Hybrid Technology	Efficiency (%)	Reference
C. comosum	SSF-CW	Soil, gravel	9	-	BOD: 33.49%, COD: 58.66%, TSS: 96.80%, TN: 93.01%.	This study
E. palaefolius	SSF-CW	Soil, gravel	9	-	BOD: 46.92%, COD: 62.41%, TSS: 99.36%, TN: 85.58%.	This study
E. hyemale	SSF-CW	Soil, gravel	9	-	BOD: 41%, COD: 63.30%, TSS: 98.40%, TN: 88.38%.	This study
C. Indica + C. papyrus	SSF-CW	Soil, gravel	9	Bio-augmentation	COD: 80.47%; BOD: 84.05%; TSS: 80.05%; TN: 75.58%	(Arliyani et al., 2023)
T. angustifolia	SSF-CW	Fe-Zeolite, gravel	8	AOP	COD: 97.76%; BOD: 69.84%; TSS: 91.16%	(Ikhlaq et al., 2021)
T. latifolia	HSSF-CW	Gravel	8	AOP	COD: 77%; Nitrat: 98.4%; Sulfat: 58.6%	(Torres Gil et al., 2020)
R. mangle	HSSF-CW	Gravel	21	AOP	COD: 73%; Nitrat: 90.5%; Nitrit: 67%	(Torres Gil et al., 2020)
C. indica	Vertical Flow	Gravel	21	-	COD: 77.7%; BOD: 78.7%; NH_4-N: 63.6%	(Angmo et al., 2024)
E. crassipes	Vertical Flow	Gravel	7	-	TSS: 92.75%; Cr: 89.9%; Cd: 100%	(Angmo et al., 2024)
C. alternifolius	Vertical SSF	Sand	21	-	BOD: 99.26%; COD: 99.61%; TN: 98.78%	(Meetiyagoda et al., 2017)
H. lymenalis	SSF-CW	Soil, gravel	21	-	BOD: 74%; COD: 95%	(Ratnawati et al., 2024b)
C. papyrus	CW	Soil	9	-	BOD & COD: 40–60%	(Mangkoedihardjo and Arliyani, 2023)
A. calamus	SSF	Gravel	4	-	BOD: 26.45%, COD: 26.31%, TSS: 34.91%, TDS: 18.31%.	(Bhagwat et al., 2018)
P. australis	HSSF-CW	Gravel	28	-	BOD: 82%, COD: 46%, TSS: 75%, NH_3-N: 92%, NO_3-N: 87%.	(Sial et al., 2023)

Although TSS and TN removal showed strong efficiency, this study achieved only moderate COD reduction. This highlights the inherent challenge of processing stabilized leachate, given its high concentration of refractory organic compounds. To address this, relying on mixed plant communities can be highly beneficial, as diverse setups encourage complementary nutrient uptake and promote microbial interactions. For instance, pairing *C. indica* with *C. papyrus* in a constructed wetland system has proven effective in boosting the overall efficiency of pollutant removal (Mangkoedihardjo and Arliyani, 2023). Other species, such as *R. mangle* and *A. calamus*, have also shown significant promise has additionally been exhibited under conditions characterized by elevated salinity and pollutant stress (Bhagwat et al., 2018; Torres Gil et al., 2020).

To address the limited biodegradability of stabilized leachate, integrating constructed wetlands with other complementary treatment technologies can significantly improve treatment performance. In previous studies, bacterial bioaugmentation was used to stimulate microbial activity around the rhizosphere, ultimately driving higher COD removal rates (Arliyani et al., 2023). Previous studies have highlighted that advanced oxidation processes, such as catalytic ozonation and photo-Fenton treatment, effectively accelerate the degradation of refractory organic matter, ultimately leading to a much better biodegradability profile for the leachate (Ikhlaq et al., 2021). Simultaneous pollutant removal and energy recovery could become more achievable through novel systems, particularly microbial fuel cells. Therefore, future studies should explore integrated treatment strategies that combine biological and physicochemical processes. This approach is crucial for treating stabilized landfill leachate more effectively and easily combining environmental discharge standards.

4. Conclusions

The performance of three plant species, *C. comosum*, *E. palaefolius*, and *E. hyemale*, was evaluated in this study within subsurface flow constructed wetlands for the treatment of stabilized landfill leachate. Compared to the unplanted control, pollutant removal improved across all planted systems. This outcome demonstrates the potential of constructed wetlands as a sustainable treatment option for stabilizing leachate. The highest removal efficiencies for BOD (46.92%) and TSS (99.36%) were achieved by *E. palaefolius* among all the tested species. Furthermore, the highest COD removal of 63.30% was observed for *E. hyemale*. *C. comosum* recorded the highest TN removal efficiency of 93.01%. However, the concentrations of BOD, COD, TSS, and TN remained above the regulatory limits. This indicates that to achieve full compliance, longer hydraulic retention times or additional treatments may be required. *The overall results suggest that E. palaefolius and E. hyemale are* promising candidates for the treatment of stabilized landfill leachate. To enhance performance and removal efficiency, longer retention times, mixed plant systems, and integrated treatment approaches should be investigated in future studies.

CRediT Author Statement

Imam Nur Rohim: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing - Origional Draft. **Bimo Tri Goutomo**: Concentualization, Methodology, Formal Analysis, Resource, Funding Acquisition, Writing - Review & Editing.

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