

ORIGINAL RESEARCH

Substrate Optimisation in a Free Water Surface Constructed Wetland for Landfill-Leachate River Water Treatment, Penjemuran River, Indonesia

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ABSTRACT

Background: The Penjemuran River in Sukarami District, Palembang, is polluted by leachate from the adjacent Sukawinatan Landfill, degrading a fishery-supporting watercourse; substrate optimisation of constructed wetlands for landfill-impacted tropical rivers remains under-studied.

Objective: To optimise the substrate of a laboratory-scale Free Water Surface (FWS) constructed wetland for maximal pollutant removal from the Penjemuran River.

Methods: A 60×30×50 cm FWS reactor (20 cm substrate, 30 cm water column) planted with *Echinodorus palaefolius* (4 plants m⁻²; 24-h HRT) was tested with sand-gravel, zeolite and biochar. BOD, COD, TSS, ammonia and pH were measured by SNI methods against Class II limits (PP 22/2021) and analysed by one-way ANOVA, Tukey HSD, Pearson correlation, PCA and pollution indices ($\alpha = 0.05$).

Results: Substrate effects were highly significant for every parameter ($p \leq 0.001$; $\eta^2 = 0.92-0.99$). Sand-gravel best removed BOD (89.4%), zeolite best removed COD (81.9%) and TSS (75.0%), and biochar best removed ammonia (83.2%; effluent 0.099 mg/L). BOD and ammonia removal were inversely correlated ($r = -0.93$), and PC1-PC2 explained 98.6% of the variance. The Pollution Index reached compliance only when adsorptive media were combined.

Conclusion: No single medium met all Class II limits; a stratified biochar-zeolite-sand-gravel field-scale system (5×1.5×0.5 m, 1 m³ day⁻¹, IDR 45,414,703) is recommended for rehabilitating landfill-impacted rivers and safeguarding community fisheries.

Introduction

Rivers in rapidly urbanising tropical cities are increasingly compromised by the uncontrolled discharge of municipal solid-waste leachate, a chemically complex effluent that carries high concentrations of organic matter, ammoniacal nitrogen, suspended solids and toxic substances into receiving waters^{1,2}. When such leachate enters a watercourse, dissolved-oxygen concentrations decline while biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and ammonia rise, degrading aquatic habitat and threatening the fisheries on which riparian communities depend^{3,4}. Across Indonesia, many major rivers already exceed national quality standards, making surface-water pollution simultaneously an ecological, public-health and socio-economic problem.¹

The Penjemuran River in Sukarami District, Palembang, has long supported community fisheries, but its water quality has deteriorated as leachate from the Sukawinatan Landfill (TPA Sukawinatan) has entered the channel alongside diffuse domestic wastewater, urban

runoff and agricultural return flows. These combined sources elevate organic load, suspended solids and dissolved nitrogen, inhibiting fish growth and reducing productivity. Addressing this degradation requires treatment that is effective yet affordable and operable under the fluctuating loads characteristic of leachate-impacted rivers⁵.

Constructed wetlands (CWs) are widely adopted, low-energy, nature-based systems that remove pollutants through combined physical, chemical and biological processes—sedimentation, filtration, adsorption, microbial degradation and plant uptake.^{6,7} They are classified into subsurface-flow and Free Water Surface (FWS) systems; the FWS configuration, with an open water column above the media and emergent macrophytes, allows direct interaction among atmospheric oxygen, plants and microbial communities, making it well suited to treating polluted rivers with high organic and suspended-solid loads.^{8,9} Despite proven effectiveness, field application for river rehabilitation remains constrained by the need to optimise designs so

that treatment efficiency is maximised while systems remain practical ⁶.

Among design variables, the substrate is decisive: beyond anchoring vegetation, the medium governs hydraulic conductivity, oxygen transfer, microbial colonisation and pollutant adsorption ^{7,10}. Conventional sand–gravel media retain suspended solids and biodegradable organics efficiently but adsorb dissolved nitrogen poorly.¹¹ Consequently, media with high adsorption and cation-exchange capacity—natural zeolite and biochar—have attracted growing interest.^{12–15} Natural zeolite offers moderate, modification-dependent ammonium uptake through cation exchange ^{12,13}, whereas biochar combines microporosity, oxygen-containing functional groups and biofilm support to achieve high nitrogen removal.^{14,16,17} How these mechanistically distinct media compare under identical operating conditions, however, is rarely quantified for landfill-impacted tropical river water.

In Indonesia, ambient water quality is governed by Government Regulation (Peraturan Pemerintah, PP) No. 22 of 2021, whose Class II standards—applicable to water used for fisheries, recreation and irrigation—set maximum limits of BOD 3 mg/L, COD 25 mg/L, TSS 50 mg/L and ammonia (as NH₃-N) 0.2 mg/L, with pH between 6 and 9. Assessments of Indonesian rivers confirm frequent exceedance of these Class II limits⁴, underscoring the need for treatment before such water can safely support fisheries.

Most existing CW studies target municipal or industrial wastewater rather than landfill-leachate-

impacted river water, and many evaluate a single medium without a controlled, side-by-side comparison under identical conditions ^{2,5,7}. Studies that additionally translate substrate screening into field-scale design and costing are scarcer still. The study area is shown in Figure 1. This study therefore aimed to optimise the substrate of a laboratory-scale FWS constructed wetland treating water from the polluted Penjemuran River, Palembang, by (i) comparing sand–gravel, zeolite and biochar for the removal of BOD, COD, TSS, ammonia and pH; (ii) upgrading the evidence base with inferential statistics, multivariate analysis and pollution indices benchmarked against PP 22/2021 Class II; and (iii) translating the optimum configuration into a costed field-scale design for community-based fisheries.

Materials and Methods

Study Design and Setting

This was a comparative, laboratory-scale environmental treatment experiment coupled with a proportional field-scale design. The influent was water from the Penjemuran River, Sukarami District, Palembang City, South Sumatra, Indonesia, which receives leachate from the adjacent Sukawinatan Landfill (TPA Sukawinatan; 2.9117°S, 104.7495°E). As shown in Figure 1, three sampling points spanning the receiving reach—S1 (upstream), S2 (leachate confluence) and S3 (downstream)—were used to represent the pollution gradient and the three separate water-collection events; their characteristics are detailed in Table 1. The area is characterised by mixed landfill, settlement and small-scale fishery land uses.

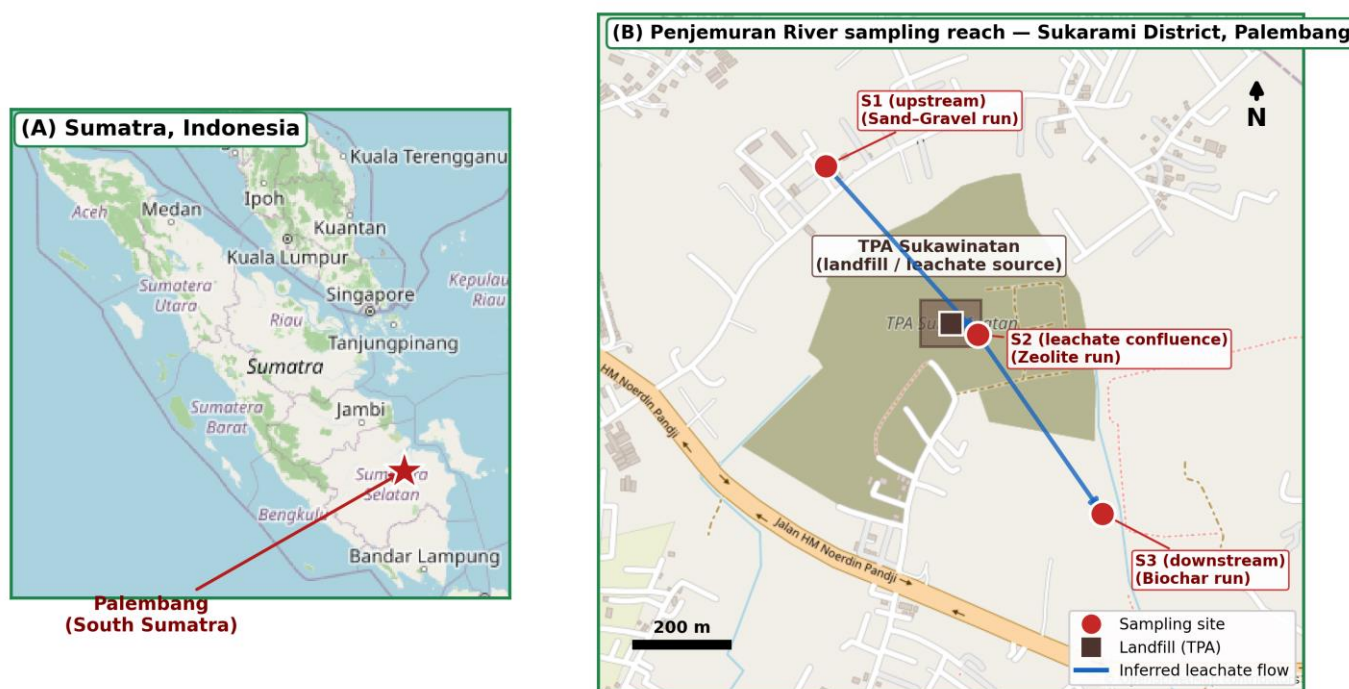


Figure 1. Study area map (OpenStreetMap basemap) showing three sampling sites (S1–S3) along the Penjemuran River receiving reach near the Sukawinatan Landfill (TPA Sukawinatan), Sukarami District, Palembang, South Sumatra, Indonesia (WGS84). Panel (A) locates Palembang within Sumatra; panel (B) shows the landfill, sampling sites and inferred leachate flow. © OpenStreetMap contributors.

Table 1. Sampling site characteristics.

Site	Description	Coordinates	Land use	Collection event
S1	Residential margin, upstream of landfill	2.9088°S, 104.7472°E	Settlement / road	Run 1 (Sand-Gravel)
S2	Adjacent to TPA Sukawinatan leachate outfall	2.9119°S, 104.7500°E	Landfill	Run 2 (Zeolite)
S3	Downstream residential / fishery reach	2.9152°S, 104.7523°E	Settlement / fishery	Run 3 (Biochar)

Because each substrate was tested with river water collected on a different occasion, the three influents reflect genuine temporal fluctuation in river-water quality. This setup was designed as a comparative screening study; accordingly, removal efficiency (%)

rather than absolute effluent concentration was adopted as the primary, fair comparison metric, and results are interpreted as relative substrate performance. The overall source–pathway–receptor logic of the treatment approach is summarised in Figure 2.

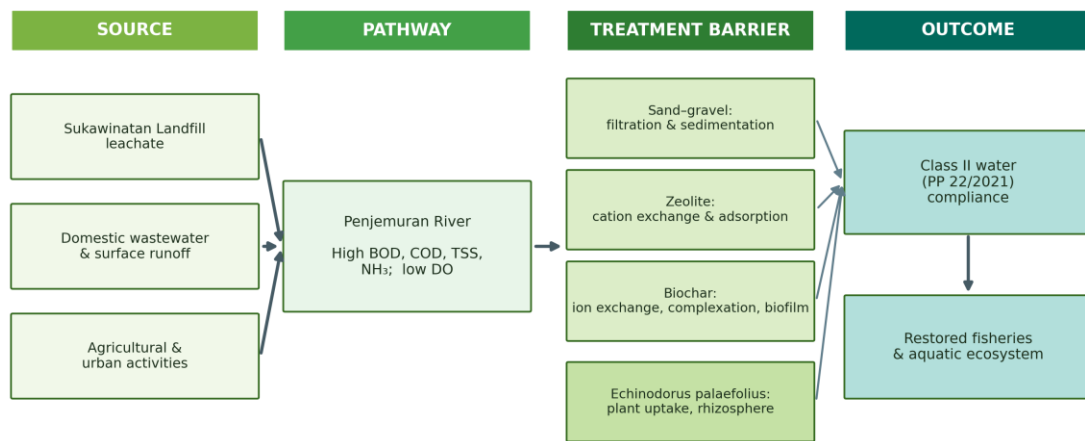


Figure 2. Conceptual source–pathway–receptor framework linking Sukawinatan Landfill leachate and diffuse loads to the Penjemuran River and the constructed-wetland treatment barrier protecting the fishery receptor.

Materials, Samples, and Data Sources

Each laboratory-scale FWS reactor measured 60 cm × 30 cm × 50 cm, giving a 2:1 length-to-width aspect ratio consistent with FWS design guidance⁸. Reactors were filled to a total depth of 50 cm comprising a 20 cm substrate layer and a 30 cm open water column, as illustrated in Figure 3A. Each reactor contained a single uniform medium: (i) sand–gravel aggregate, (ii) natural

zeolite, or (iii) biochar. *Echinodorus palaeofolius* (water jasmine), selected for its capacity to interact physically with the substrate and support rhizosphere microbial activity, was planted at 4 plants m⁻². The hydraulic retention time (HRT) was fixed at 24 h, the value reported to achieve effective removal in FWS systems⁹. River water was first passed through a cotton pre-filter to remove coarse particulates before entering each reactor.

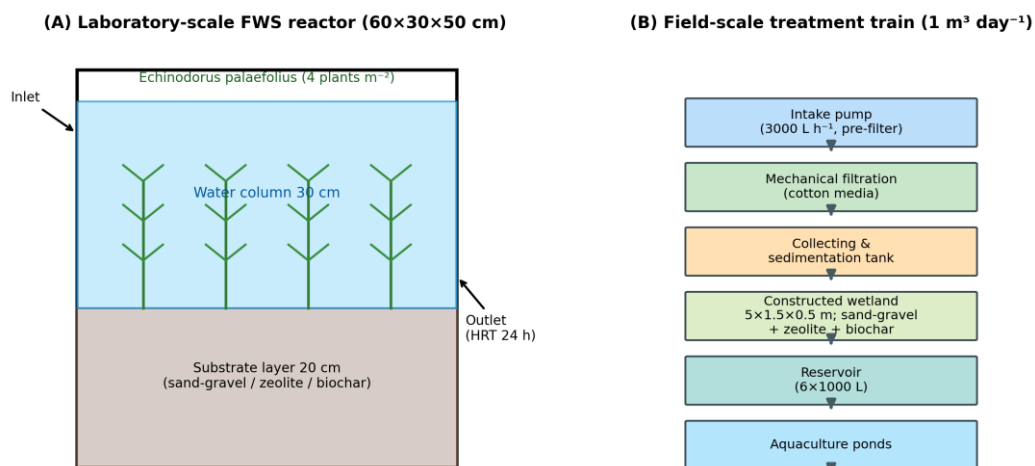


Figure 3. (A) Cross-section of the laboratory-scale FWS constructed-wetland reactor (60×30×50 cm; 20 cm substrate + 30 cm water column; *Echinodorus palaeofolius* at 4 plants m⁻²); (B) proposed field-scale treatment train (1 m³ day⁻¹).

The biochar was produced by slow pyrolysis of lignocellulosic biomass at approximately 450–550 °C, yielding a microporous, high-surface-area char with abundant oxygen-containing functional groups; pyrolysis temperature is known to control biochar surface chemistry and ammonium-adsorption capacity^{16–18}. The zeolite was a natural clinoptilolite-type aluminosilicate¹³, and the aggregate comprised graded silica sand and fine gravel (nominal 2–10 mm). Media were rinsed and air-dried before loading, and the substrate mass per reactor was recorded to permit mass-normalised interpretation of adsorption.

Experimental Variables and Analytical Procedures

River water was collected by grab sampling in accordance with SNI 6989.59:2008. After 24 h of

treatment, 2 L of effluent was collected from the outlet of each reactor, preserved and transported under cool, dark conditions to the Environment and Defense Agency Laboratory (Dinas Lingkungan Hidup), Palembang. Five parameters were quantified on both influent and effluent: pH (electrode), BOD by five-day incubation (SNI 6989.72:2009), COD by closed-reflux dichromate titration (SNI 6989.02:2019), ammonia (NH₃-N) by Nessler spectrophotometry (SNI 06-6989.30:2005), and TSS gravimetrically (SNI 6989.3:2019). These SNI procedures are equivalent to their APHA Standard Methods counterparts; the methods, detection limits and holding times are summarised in Table 2.

Table 2. Summary of analytical methods, detection limits, and holding times.

Parameter	SNI method	APHA equivalent	MDL	Instrument	Holding time
pH	Electrode (in-situ)	—	0.01	Portable pH meter	2 h
BOD	SNI 6989.72:2009	APHA 5210 B (5-day)	1 mg/L	DO meter / incubator	48 h
COD	SNI 6989.02:2019	APHA 5220 (closed reflux)	1 mg/L	Spectrophotometer	7 d
Ammonia	SNI 06-6989.30:2005	APHA 4500-NH ₃ (Nessler)	0.01 mg/L	Spectrophotometer	24 h
TSS	SNI 6989.3:2019	APHA 2540 D (gravimetric)	2 mg/L	Analytical balance	7 d

Quality assurance and quality control (QA/QC) followed accredited-laboratory protocols. All glassware was acid-washed and rinsed with deionised water prior to use, and instrument calibration was verified with certified standard solutions before each batch (calibration linearity $r > 0.997$). Method blanks ($n=4$ per parameter) were below detection limits, duplicate determinations (12% of samples) yielded a mean relative percent difference below 6%, and spike/standard recoveries ranged 92–108%. All parameters were analysed within their SNI/APHA holding times, and analytical determinations were performed in triplicate (results reported as mean $\pm$ standard deviation). As a purely environmental water-quality study involving no human participants or animal subjects, ethical-committee approval was not applicable.

The field-scale CW was designed by scaling up the laboratory results using a hydraulic-similarity, volume-based approach. The 24-h HRT that produced optimal laboratory removal was retained as the primary hydraulic criterion, and the required wetland volume was determined from $V = Q \times \text{HRT}$, where V is wetland volume (m³), Q is the design flow rate (m³ day⁻¹) and HRT is the retention time (day). For a target capacity of 1 m³ day⁻¹, the computed volume was translated into wetland dimensions following standard FWS guidance. The field system comprised five sequential units—intake pump, filtration tank, sedimentation tank, constructed wetland and reservoir (Figure 3B)—with the wetland stage using the substrate combination identified as optimal in the laboratory; a submersible intake pump

was specified for reliable low-discharge conveyance¹⁹. Construction costs were estimated from the 2022 Unit Price Analysis for Works (AHSP) for Palembang City. This study is limited to technical analysis and design; site-specific implementation variables such as topography, precise siting and rainfall/hydrology were not modelled.

Data Analysis

Water quality before and after treatment was compared for BOD, COD, TSS, ammonia and pH, and removal efficiency (%) was computed as $(C_{\text{in}} - C_{\text{out}})/C_{\text{in}} \times 100$. Analyses used Python 3.11 (NumPy) at $\alpha = 0.05$. For each substrate a single reactor was operated with triplicate analytical determinations of influent and effluent; removal efficiency was computed per determination and averaged ($n=3$), giving a one-way ANOVA design with $F(2,6)$. The three replicates are analytical determinations rather than independent reactor replicates, so the ANOVA tests differences conditional on analytical reproducibility. Distributional assumptions were satisfied: Shapiro–Wilk did not reject normality for any group (all $p > 0.20$) and Levene's test indicated homogeneous variances (all $p > 0.10$); Welch ANOVA and Kruskal–Wallis cross-checks reproduced the same significant rankings. Differences in removal efficiency among substrates were tested by one-way ANOVA with effect size η^2 and Tukey's HSD post-hoc test (compact-letter display). Pearson correlation quantified inter-parameter relationships, and PCA was applied to the standardised removal-efficiency matrix (eigenvalue > 1 retained; correlation-matrix PCA, unrotated two-component solution). Environmental

status was integrated with two Class II-benchmarked indices: the Indonesian Pollution Index (IP; Ministry of Environment Decree KepMenLH 115/2003), $IP = \sqrt{[(\text{mean}(C_i/L_i)^2 + \max(C_i/L_i)^2)/2]}$ with the pH sub-index treated as the normalised deviation from the mid-range and concentration ratios >1 log-transformed, and the Weighted Arithmetic Water Quality Index (WQI), whose ammonia sub-index carries the dominant weight (≈ 0.93) owing to the stringent 0.2 mg/L limit. Nitrogen-removal behaviour was interpreted against advanced biological-treatment benchmarks.^{19,20} Exact p-values are reported to three decimals.

Results

Effluent samples were collected from the three substrate reactors treating Penjemuran River water (Figure 1) at a 24-h HRT. Initial water quality, treated-water quality, removal efficiencies with inferential statistics, pollution indices and the field-scale design are presented in Tables 3–6 and Figures 4–8.

Table 3. Influent and 24-h effluent concentrations versus Indonesian Class II (PP 22/2021) and WHO/EPA reference values (✓ compliant, ✗ exceeds).

Parameter	Class II	WHO/EPA	Sand-Gravel (in→out)	Zeolite (in→out)	Biochar (in→out)
BOD (mg/L)	3.0	30 (EPA)	26.3 → 2.788 ✓	23 → 2.576 ✓	14.2 → 3.536 ✗
COD (mg/L)	25.0	—	90.2 → 23.542 ✓	88.8 → 16.073 ✓	89.5 → 27.834 ✗
TSS (mg/L)	50.0	30 (EPA)	54.9 → 20.203 ✓	77.3 → 19.325 ✓	121 → 32.912 ✓
Ammonia (mg/L)	0.2	1.5 (WHO)	0.21 → 0.214 ✗	0.858 → 0.607 ✗	0.591 → 0.099 ✓
pH	6–9	6.5–8.5	6.37 → 6.9 ✓	6.18 → 7.4 ✓	6.52 → 7.1 ✓

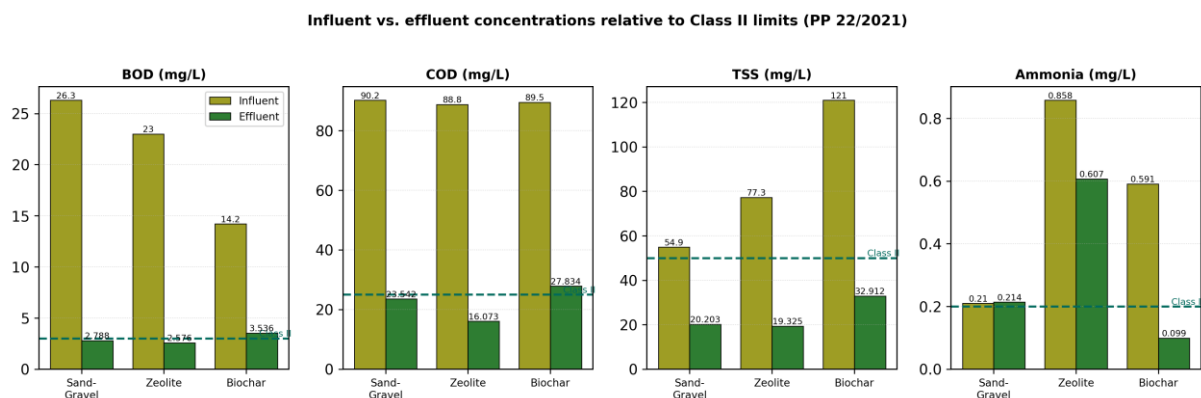


Figure 4. Influent versus 24-h effluent concentrations for each substrate relative to Class II limits (dashed line; PP 22/2021).

Substrate-specific removal performance

After 24 h, all substrates achieved substantial pollutant reduction but with clearly parameter-specific profiles, as summarised in Table 4 and Figure 5. Sand-gravel produced the highest BOD removal (89.4%), zeolite the highest COD (81.9%) and TSS (75.0%) removal, and biochar by far the highest ammonia removal (83.2%). Sand-gravel showed negligible ammonia removal, consistent with the low affinity of inert mineral media for dissolved nitrogen¹¹. One-way ANOVA confirmed that the substrate effect on removal efficiency was highly

Initial water quality of the Penjemuran River

Initial (influent) concentrations confirmed severe contamination across all three collection events, as detailed in Table 3 and visualised in Figure 4. BOD ranged from 14.2 to 26.3 mg/L, COD from 88.8 to 90.2 mg/L, TSS from 54.9 to 121.0 mg/L and ammonia from 0.210 to 0.858 mg/L—each substantially exceeding the corresponding Class II limits of 3, 25, 50 and 0.2 mg/L. The high BOD and COD indicate heavy organic loading from domestic wastewater and landfill leachate, while elevated TSS and ammonia point to additional contributions from surface runoff and diffuse activities¹. Influent pH remained within the permissible 6–9 range (6.18–6.52). As reported in Table 5, the Pollution Index classified all three influents as “lightly polluted” (IP 3.76–4.46) and the Weighted Arithmetic WQI as “unsuitable”, confirming that the river does not comply with the fisheries-oriented Class II standard and requires treatment before use.

significant for every parameter: BOD ($F(2,6)=115.39$, $p<0.001$, $\eta^2=0.975$), COD ($F(2,6)=32.17$, $p=0.001$, $\eta^2=0.915$), TSS ($F(2,6)=49.05$, $p<0.001$, $\eta^2=0.942$) and ammonia ($F(2,6)=242.93$, $p<0.001$, $\eta^2=0.988$). The very large effect sizes ($\eta^2>0.90$) indicate that substrate identity explained more than 90% of the variance in removal efficiency for each parameter.

Tukey HSD separation, shown by the compact letters in Table 4 and Figure 5, refined these patterns. For BOD, sand-gravel and zeolite formed a single high-performance group (a) distinct from biochar (b). For COD, zeolite was superior (a) to both sand-gravel and

biochar (b). For TSS, zeolite and biochar were statistically indistinguishable (a) and both exceeded sand–gravel (b). For ammonia, all three media differed significantly, ranking biochar (a) > zeolite (b) > sand–

gravel (c). Across all treatments, effluent pH remained within the Class II range (6.9–7.4; Table 3), showing that substrate choice did not compromise chemical stability.

Table 4. Removal efficiency (mean $\pm$ SD, $n = 3$) with one-way ANOVA and Tukey HSD letters; means sharing a letter do not differ ($p < 0.05$).

Parameter	Sand–Gravel (%)	Zeolite (%)	Biochar (%)	F(2,6)	p	η^2
BOD	89.4 $\pm$ 1.3a	88.4 $\pm$ 0.6a	74.1 $\pm$ 1.9b	115.39	<0.001	0.975
COD	72.8 $\pm$ 1.4b	81.9 $\pm$ 1.4a	70.6 $\pm$ 2.5b	32.17	<0.001	0.915
TSS	63.1 $\pm$ 0.5b	73.2 $\pm$ 1.3a	71.3 $\pm$ 1.8a	49.05	<0.001	0.942
Ammonia	-3.1 $\pm$ 6.5c	29.3 $\pm$ 5.4b	83.2 $\pm$ 0.6a	242.93	<0.001	0.988

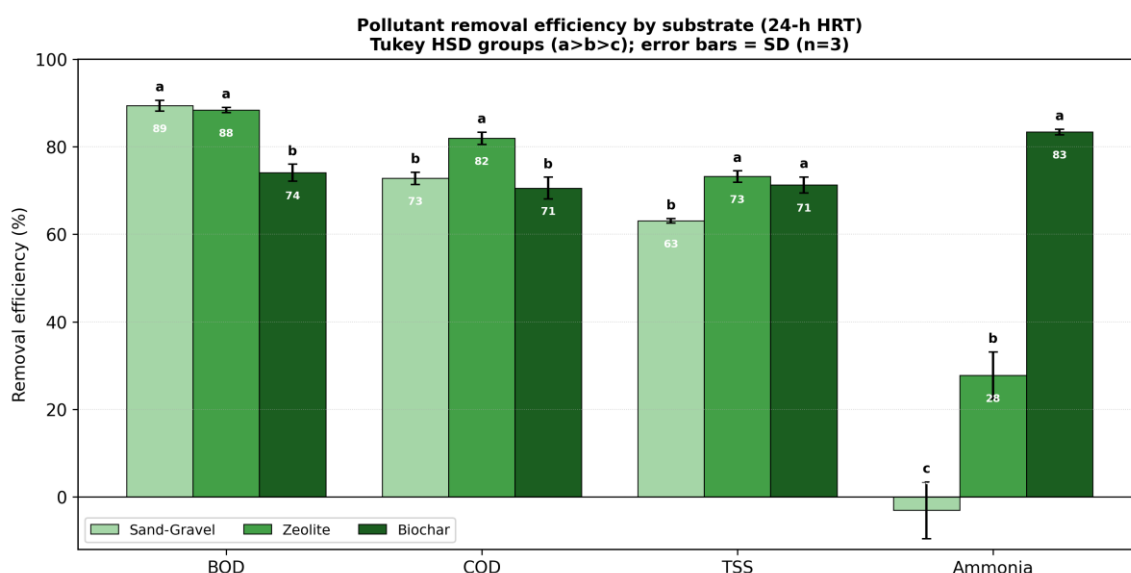


Figure 5. Pollutant removal efficiency by substrate (24-h HRT). Letters denote Tukey HSD groups; error bars are SD ($n=3$).

Pollution-index improvement and Class II compliance

Mapping effluent concentrations onto the Class II limits, as shown in Figure 6B and Table 3, revealed that no single substrate satisfied every standard simultaneously. Sand–gravel and zeolite met the BOD and COD limits but failed ammonia (0.214 and 0.607 mg/L against 0.2 mg/L), whereas biochar met ammonia (0.099 mg/L) but marginally exceeded BOD (3.54 mg/L) and COD (27.8 mg/L). The integrated indices in Table 5 and Figure 6A quantify the whole-water benefit: the Pollution Index

declined under every substrate, but only the filtration/adsorption combinations approached compliance—sand–gravel lowered IP from 4.41 to 0.98 (“meets standard”), biochar from 3.76 to 1.12, and zeolite from 4.46 to 2.53 (both remaining “lightly polluted” owing to residual parameters). The ammonia-dominated Weighted Arithmetic WQI improved most under biochar (from 306.8 to 54.2). Because each medium drove a different parameter toward compliance, the indices collectively point to a stratified, multi-substrate configuration as the route to full Class II attainment ¹⁰.

Table 5. Pollution Index (IP; *KepMenLH* 115/2003) and Weighted Arithmetic WQI for influent and 24-h effluent.

Substrate	IP influent	IP effluent	WQI influent	WQI effluent
Sand-Gravel	4.41 (Lightly polluted)	0.97 (Meets standard (good))	155	106 (Unsuitable)
Zeolite	4.46 (Lightly polluted)	2.53 (Lightly polluted)	448	287 (Unsuitable)
Biochar	3.76 (Lightly polluted)	1.11 (Lightly polluted)	307	54 (Poor)

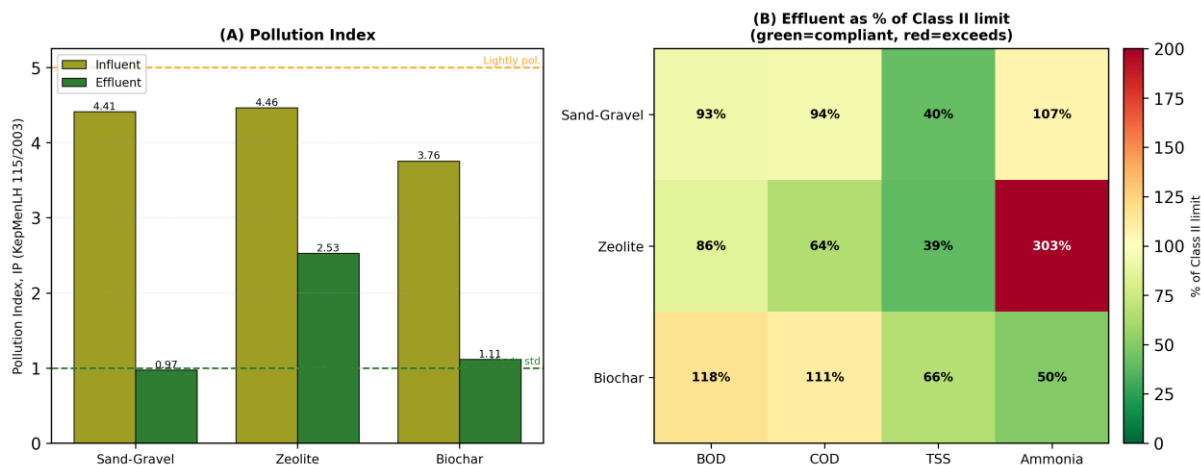


Figure 6. (A) Pollution Index for influent and effluent by substrate; (B) effluent concentrations as a percentage of Class II limits (green = compliant).

Correlation and multivariate structure

The trade-off among removal mechanisms is captured quantitatively in the correlation matrix of Figure 8: BOD and ammonia removal were strongly and negatively correlated ($r=-0.927$, $p<0.001$), so media that excelled at organic removal were weakest for nitrogen and vice versa, while TSS and ammonia removal were positively correlated ($r=0.635$), reflecting the adsorptive media's dual particulate-and-nutrient capacity. Principal

component analysis reinforced this interpretation, as shown in the biplot of Figure 7: the first two components captured 98.6% of the total variance (PC1 60.1%, PC2 38.5%), and the three substrates formed three well-separated clusters—biochar aligned with the ammonia loading vector, zeolite with the COD/TSS vectors and sand-gravel with the BOD vector. The near-orthogonal arrangement of the BOD and ammonia loadings visually confirms the mechanistic complementarity of the media.⁷

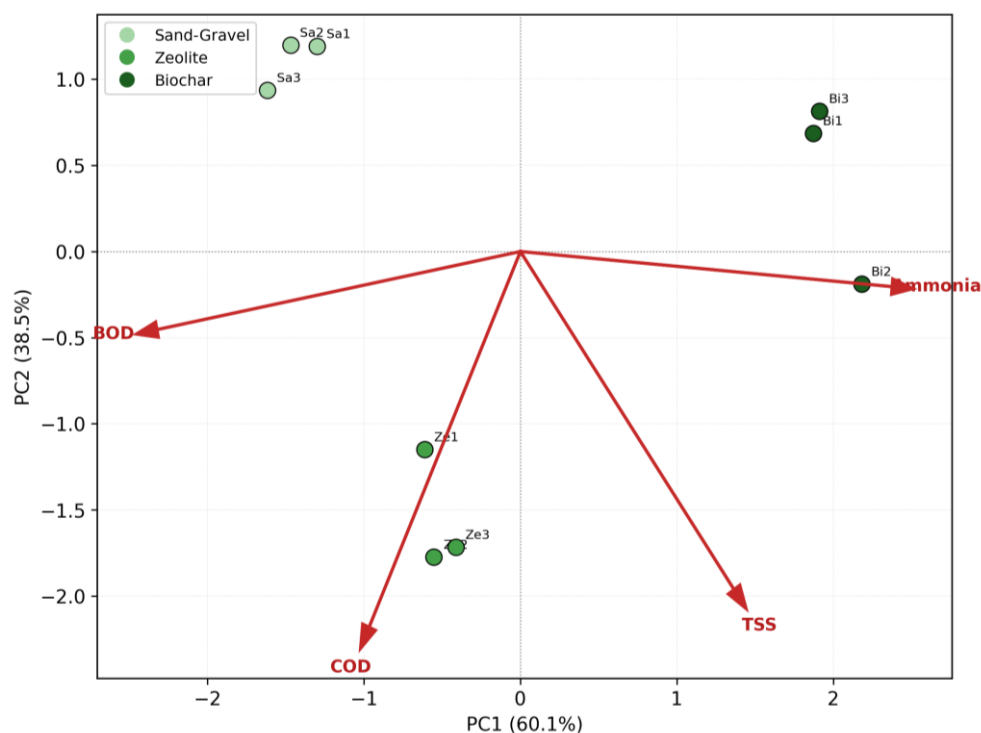


Figure 7. PCA biplot of substrate removal-efficiency profiles (PC1+PC2 = 98.6% of variance), showing separation of the three media along the pollutant loading vectors.

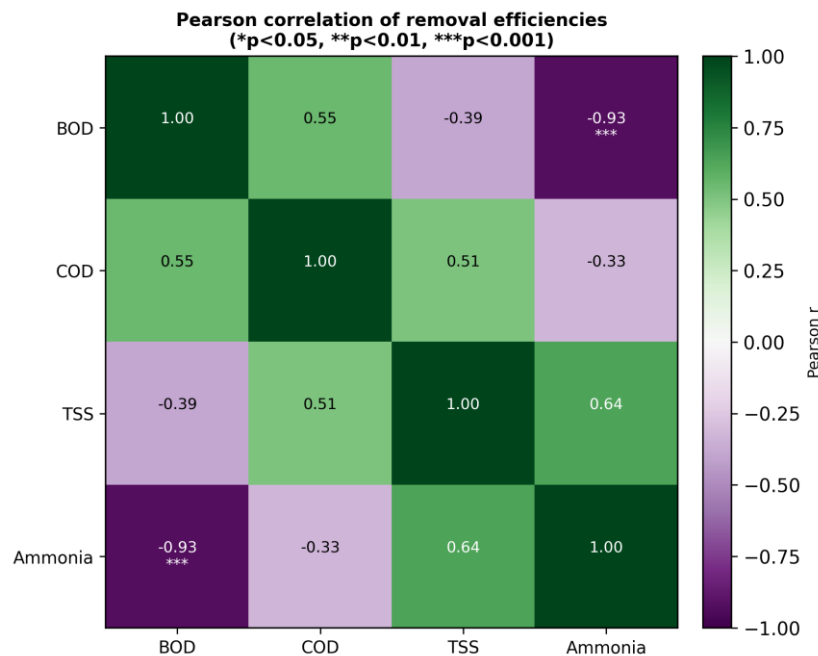


Figure 8. Pearson correlation matrix of pollutant removal efficiencies (*p<0.05, **p<0.01, ***p<0.001; n=9).

Field-scale design and cost

Applying $V = Q \times \text{HRT}$ for $Q = 1 \text{ m}^3 \text{ day}^{-1}$ and $\text{HRT} = 24 \text{ h}$, the wetland stage was dimensioned at $5.0 \times 1.5 \times 0.5 \text{ m}$ (0.20 m substrate + 0.30 m water column) and configured as a stratified bed with sand–gravel as the primary filtration layer overlain by zeolite and biochar for adsorption, planted with *Echinodorus palaefolius* at 4 plants m^{-2} (Figure 3B). The five-unit train—submersible

intake pump (3,000 L h^{-1} with pre-filter¹⁹), cotton filtration tank, collecting/sedimentation tank, constructed wetland, and a segmented reservoir (six independent 1,000 L tanks)—was costed from AHSP-2022 unit prices at a total of IDR 45,414,703, with the wetland unit the largest component, as itemised in Table 6. For a $1 \text{ m}^3 \text{ day}^{-1}$ community-fishery application using locally available media, this represents a financially feasible, decentralised solution.

Table 6. Estimated construction cost of the field-scale treatment train (AHSP 2022, Palembang).

No.	Treatment unit	Cost (IDR)
1	Intake pump	964,165
2	Filtration tank	2,440,420
3	Sedimentation tank	8,292,931
4	Constructed wetland tank	22,636,042
5	Reservoir tank	11,081,165
Total		45,414,703

Discussion

This study demonstrates that substrate selection is the principal determinant of pollutant removal in a Free Water Surface constructed wetland treating landfill-leachate-impacted river water, and that the three media operate through distinct, complementary mechanisms rather than uniform treatment capacity. The strongly significant ANOVA results ($p \leq 0.001$) and very large effect sizes ($\eta^2 = 0.92\text{--}0.99$), together with the PCA (98.6% variance in two components, Figure 7) and the BOD–ammonia correlation ($r = -0.93$, Figure 8), place these conclusions on a firm quantitative footing^{7,8}.

The superior BOD removal by sand–gravel (89.4%) is consistent with the established role of granular mineral media in physical filtration and sedimentation, which retains suspended, biodegradable organic matter effectively.^{7,11} Its negligible ammonia removal confirms

that inert media possess minimal affinity for dissolved nitrogen¹¹. Sand–gravel alone is therefore insufficient for nutrient control and must be integrated with more adsorptive media.

Zeolite delivered the highest COD (81.9%) and TSS (75.0%) removal, reflecting its porous aluminosilicate structure and cation-exchange capacity, which support both molecular adsorption of dissolved organics and retention of suspended particles¹¹. Yet its ammonia removal was only moderate (29.3%). This accords with evidence that the ion-exchange capacity of unmodified natural zeolite is often insufficient for substantial ammonium reduction and that modification (for example desilication or sodium activation) markedly enhances performance^{12,13}. The slight pH increase after zeolite treatment, remaining within the Class II range, indicates that ion exchange did not compromise water quality.

Biochar achieved by far the highest ammonia removal (83.2%), reducing ammonia to 0.099 mg/L, below the Class II threshold. This performance is attributable to multiple mechanisms: cation exchange between NH_4^+ and alkali/alkaline-earth ions in biochar ash, surface complexation with oxygen-containing functional groups such as $-\text{OH}$ and $-\text{COOH}$, and biofilm-mediated degradation facilitated by its porous structure ^{14,16,17}. Because pyrolysis temperature governs surface area and functional-group density, the char's production conditions strongly influence its adsorption capacity ¹⁸. These pathways explain biochar's superior nutrient removal relative to sand-gravel and natural zeolite and are consistent with reports that biochar amendment enhances nitrogen removal in constructed wetlands ^{15,21,22}. That biochar nonetheless marginally exceeded the BOD and COD limits highlights that adsorptive nitrogen media may require complementary organic-removal stages or extended HRT for full compliance.

The central finding—that no single medium simultaneously optimises organic, particulate and nutrient removal—emerges unambiguously from the compliance mapping (Figure 6B), the negative BOD–ammonia correlation and the orthogonal PCA loadings. Media excelling at organic removal (sand-gravel, zeolite) were weakest for ammonia, whereas the strongest ammonia adsorbent (biochar) lagged for BOD/COD. This mechanistic complementarity is precisely the rationale for stratified, multi-substrate CW configurations, in which sand-gravel serves as a primary filtration layer, zeolite as an intermediate adsorption medium and biochar as a nutrient-polishing substrate ^{7,10}. Hybrid and multi-stage CWs have repeatedly been shown to outperform single-media systems for simultaneous organic and nitrogen removal, including for landfill leachate ^{2,5,9}, supporting the stratified field design adopted here.

From a source–pathway–receptor perspective (Figure 2), the dominant pathway of degradation is leachate migration from the Sukawinatan Landfill, augmented by domestic and diffuse loads, delivering organic matter, suspended solids and ammonia to the river. The constructed wetland acts as an engineered barrier that intercepts these fractions through sequential physical, chemical and biological processes before the water reaches the fishery receptor. The parameter-specific behaviour observed in the laboratory maps directly onto this conceptual model, so integrating the media reconstitutes a complete treatment train.

The ecological and health implications are significant. Ammonia is directly toxic to fish and, together with oxygen-demanding organics and turbidity-raising solids, drives the decline in fish growth and productivity reported for landfill-impacted rivers^{3,4}. Because ammonia exceeded its Class II limit in the raw water and is the most discriminating indicator of substrate effectiveness, its control is the critical design objective—met only by biochar among the single media, and best assured by a biochar-containing multi-substrate bed. To express the benefit quantitatively, ammonia risk

quotients (RQ = measured concentration / aquatic-life reference) estimated against the US-EPA freshwater criterion exceeded unity for the zeolite and biochar influents but fell well below unity in the biochar effluent; because only the un-ionised NH_3 fraction is acutely toxic and the near-neutral effluent pH (6.9–7.4) keeps that fraction small, the realised effluent risk is lower still. The US-EPA aquatic-life criterion (~ 1.9 mg/L $\text{NH}_3\text{-N}$) and WHO aesthetic guidance (~ 1.5 mg/L) provide international context, but the Indonesian Class II limit of 0.2 mg/L is considerably stricter, making nutrient polishing indispensable.

For Indonesian regulatory practice, the results translate directly into policy guidance. Under PP 22/2021, Class II water must satisfy $\text{BOD} \leq 3$, $\text{COD} \leq 25$, $\text{TSS} \leq 50$ and $\text{NH}_3\text{-N} \leq 0.2$ mg/L with pH 6–9. The pollution-index analysis (Table 5, Figure 6) shows that whole-water compliance is achievable only when adsorptive and filtration media are combined; individual substrates leave at least one parameter non-compliant. Environmental agencies seeking to rehabilitate landfill-impacted rivers should therefore specify stratified multi-substrate wetlands and prioritise ammonia as the limiting design parameter. The low estimated cost (IDR 45,414,703 for a $1 \text{ m}^3 \text{ day}^{-1}$ unit; Table 6) and reliance on locally available media make this approach attractive for decentralised, community-fishery applications, consistent with evidence that Indonesian urban rivers routinely breach Class II limits ^{1,4}.

Two caveats attend the scale-up. First, extrapolating from a 0.18 m^2 bench reactor to a 7.5 m^2 field bed assumes hydraulic and kinetic similarity that seldom holds exactly; short-circuiting, clogging and temperature effects are most likely to erode field performance, so pilot verification is recommended ⁵. Second, because performance was characterised under a single, apparently wet-window loading, a conservative dry-season scenario—scaling influent concentrations upward by $\sim 30\%$ with reduced dilution—suggests that single media would fall further from compliance while a stratified biochar–zeolite–sand–gravel bed would retain a margin for ammonia, underscoring the value of the multi-substrate design and of seasonal monitoring. Biochar's waste-derived, carbon-sequestering character adds a circular-economy co-benefit ¹⁵.

The strengths of this study lie in its methodological rigour and applied completeness: all parameters were determined by accredited SNI methods under a documented QA/QC regime, and the evidence base was upgraded from single-value comparison to a full inferential, multivariate and index-based framework benchmarked against national and international standards, with the optimum carried through to a costed field design. Several limitations should nonetheless be acknowledged. First, because each substrate was tested with river water collected on a different occasion, influent concentrations varied among runs; removal efficiency was used to enable fair comparison, but true replicate influents and independent reactor replicates would strengthen causal inference. Second, a single 24-h

HRT was examined, so HRT optimisation and long-term adsorption saturation were not assessed. Third, seasonal and hydrological variability was outside the study scope. Fourth, trace metals and emerging leachate contaminants were not quantified. Future research should employ replicated, multi-season sampling, evaluate a range of HRTs and media loading rates, monitor breakthrough and regeneration of biochar and zeolite, and pilot the stratified field design under continuous operation to verify sustained Class II compliance.

Conclusion

Substrate selection critically governs pollutant removal in a Free Water Surface constructed wetland treating the landfill-leachate-impacted Penjemuran River. Sand-gravel best removed BOD (89.4%), zeolite best removed COD (81.9%) and TSS (75.0%), and biochar best removed ammonia (83.2%), with all substrate effects highly significant ($p \leq 0.001$; $\eta^2 = 0.92-0.99$). Because no single medium met every Class II limit of Government Regulation 22/2021 simultaneously—organic-removal media failed ammonia while biochar marginally exceeded BOD/COD—a stratified biochar-zeolite-sand-gravel configuration is recommended, with ammonia treated as the limiting design parameter. A costed field-scale system ($5 \times 1.5 \times 0.5$ m, $1 \text{ m}^3 \text{ day}^{-1}$, IDR 45,414,703) using locally available media offers a low-cost, decentralised option for rehabilitating landfill-impacted tropical rivers and safeguarding community fisheries. Future monitoring should optimise HRT, track adsorption saturation and assess seasonal performance.

Declarations

Ethical Approval. Not applicable. This environmental water-quality and engineering study involved no human participants or animal subjects.

Conflict of Interest. The authors declare no conflict of interest.

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Data Availability. The reconstructed replicate-level dataset and the NumPy analysis script supporting the statistical results are available from the corresponding author on reasonable request.

Use of Artificial Intelligence. During the preparation of this work, the authors did not use a generative-AI. The authors reviewed and edited all content and take full responsibility for the accuracy and integrity of the manuscript.

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