

# Optimization of Substrate Variations in Free Water Surface Constructed Wetlands for Pollutant Removal in The Penjemuran River, Sukarami District

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## Article history

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**Abstract:** Penjemuran River is polluted by leachate from the Sukawinatan Landfill, causing a decline in water quality that affects local communities. The river is an important water source for daily activities, especially fisheries, but contamination threatens aquatic life and disrupts livelihoods that rely on it. This study investigated the effect of substrate variations on the efficiency of the Free Water Surface (FWS) constructed wetland for pollutant removal. A laboratory scale experiment was conducted using a 60 cm × 30 cm × 50 cm reactor filled with pre-filtered water from the Penjemuran River. The system was tested with three substrates: sand and gravel, biochar, and zeolite, with *Wrightia religiosa* (water jasmine) as the vegetation. The hydraulic residence time (HRT) was set at 24 hours. The results showed that the biochar was the most effective in removing ammonia (83.2%), while zeolite had the highest removal efficiency for COD by 81.9% and TSS by 75%. Meanwhile, sand and gravel performed best in reducing BOD by 89.4%. The pH remained stable between 6 and 8, meeting Class II water quality standards under Government Regulation 22 of 2021. Based on these findings, a field-scale system was designed using a combination of biochar and zeolite to optimize treatment performance. A cost estimate was also calculated to support implementation in the field. This research provides an innovative and sustainable approach to improving water quality, helping to restore aquatic ecosystems and support fisheries.

**Keywords:** Constructed Wetland, Free Water Surface (FWS), substrate variation, water quality

## 1. Introduction

The Penjemuran River in Palembang has long supported local fisheries, but water quality has declined in recent years. Rapid urbanization and inadequate waste management have allowed leachate from the Sukawinatan Landfill to enter the river, resulting in pollution that contains high concentrations of organic matter, suspended solids, nutrients, and toxic substances. These contaminants deteriorate aquatic ecosystems [1], [2]. In the Penjemuran River, dissolved oxygen levels have decreased as ammonia, organic matter, and heavy metals have increased [1], [2], [3]. Changes in water quality now inhibit fish growth, increase the risk of mass fish mortality, and reduce overall fish productivity [1], [2].

Ecological impacts are not the only concern; surface water pollution also affects public health. Kenny et al. [2] reported that contaminated surface water causes waterborne diseases and chronic health disorders in affected communities. Furthermore, water degradation in the landfill-impacted river is not only an environmental issue but also a socio-economic concern for urban communities that depend on aquatic resources for their livelihoods.

To mitigate these impacts, there is a need for low-cost and sustainable water treatment approaches. Constructed wetlands (CWs) are widely used for water

and wastewater treatment due to their simple operation and low energy demand [4], [5]. CWs remove pollutants through physical, biological, and chemical processes, including sedimentation, filtration, adsorption, microbial degradation, and plant uptake [4]. Previous studies report effective removal of organic matter, suspended solids, and nutrients (nitrogen and phosphorus) using CW systems [4], [5].

CWs are classified into subsurface flow and free water surface (FWS) systems [4], [5]. The FWS configuration allows direct interaction with atmospheric oxygen, aquatic plants, and microbial communities [4]. FWS systems are suitable for treating polluted rivers with high organic and suspended solid loads [4], [5], [6], [7]. Despite their effectiveness, the practical implementation of CW in river rehabilitation remains limited [5]. Constraints include land availability, maintenance needs, insufficient technical knowledge, and public misconception (such as concerns over mosquito breeding) [4], [5]. These limitations highlight the need for optimized wetland designs that improve treatment efficiency while remaining practical [5].

Substrate properties influence the performance of CWs. In addition to supporting vegetation, the substrate regulates hydraulic conductivity, oxygen transfer, microbial growth, and pollutant adsorption

within the system [4], [5], [8]. Suitable substrates provide adequate pore space, promote uniform water flow, and offer sufficient surface area for microbial attachment [9], [10]. Conventional media such as sand and gravel are effective at removing suspended solids but have limited capacity to adsorb dissolved contaminants, particularly nitrogen compounds [8], [11]. Therefore, alternative materials such as zeolite and biochar have been investigated for their high adsorption capacity and cation-exchange properties [12], [13], [14], [15], [16].

Most existing studies of CWs focus on municipal or industrial wastewater treatment, while fewer address polluted river water impacted by landfill leachate, particularly in tropical regions [7], [8], [10]. In addition, many studies evaluate single substrate materials without directly comparing their performance under similar operational conditions [8], [10]. The application of such findings to field-scale design and cost considerations has also received limited attention.

This study evaluates the performance of three substrate types – aggregate (sand and gravel), zeolite, and biochar – in a laboratory-scale FWS constructed wetland treating water from the polluted Penjemuran River. Initial water quality characteristics were analyzed, and pollutant removal efficiency was assessed based on Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), ammonia, and pH. In addition to laboratory evaluation, a full-scale wetland design was developed, including an estimation of construction costs to assess field applicability. By combining substrate comparison under controlled laboratory conditions with preliminary field-scale design considerations, this study provides practical insight for the rehabilitation of landfill-impacted rivers.

## 2. Material and Methods

The research was conducted in a laboratory-scale constructed wetland system (60 cm x 30 cm x 50 cm), designed based on the discharge characteristics of the Penjemuran River and a length-width aspect ratio of 2:1 for a FWS configuration [17]. River water was collected from the Penjemuran River following SNI 6989.59:2008 standards [18] using the grab sampling method, pre-filtered with cotton, and used as the influent. Three substrates – aggregate, biochar, and zeolite – were evaluated using water jasmine (*Echinodorus palaefolius*) as the wetland vegetation, with a hydraulic retention time of 24 hours [4]. Each substrate treatment was conducted in separate experimental runs using river water collected at different times. Therefore, variations in influent characteristics reflect temporal fluctuations in river water quality.

Water quality parameters, including pH, ammonia, TSS, BOD, and COD were measured to assess treatment performance according to Class II Water Quality under Government Regulation 22 of

2021 [19]. Laboratory analyses were conducted according to standard methods based on the Indonesian National Standards (SNI). BOD was analyzed using the 5-day incubation method (SNI 6989.72:2009) [20], COD using the closed reflux method with potassium dichromate (SNI 6989.02:2019) [21], total ammonia by spectrophotometry with Nessler reagent (SNI 06-6989.30:2005) [22], and TSS using the gravimetric method (SNI 6989.3:2019) [23].

### 2.1 Materials

A laboratory-scale constructed wetland was built using several materials, including a wetland unit measuring 60 cm × 30 cm × 50 cm, a filter bucket for filtration, and water bottles to collect samples before and after treatment. A water faucet controlled the inlet and outlet flow of the system. Various auxiliary tools supported the construction of the treatment tank and laboratory testing. Each CW reactor contained a single uniform layer of either biochar, zeolite, or an aggregate substrate consisting of a sand and gravel mixture. The selected aquatic plant for the treatment system was *Echinodorus palaefolius* (water jasmine), and water from the Penjemuran River was used for testing purposes.

After 24 hours of treatment, water samples were collected from the outlet faucet of the constructed wetland system. A total of 2 liters of water was sampled and stored in appropriate containers to maintain its quality. The samples were transported to the Environment and Defense Agency Laboratory, Palembang City, South Sumatra for quality analysis.

### 2.2 Experimental Variable and Analytical Procedures

In this study, the variables used are to test the influence of variations in the substrate used as planting media in the constructed wetland system with the aim of reducing the level of pollutants contained in the polluted water of the Penjemuran River. The plant used is water jasmine (*Echinodorus palaefolius*). This is because the main purpose of this study is to determine the influence of the substrate as a planting medium so that plants that can physically interact with the substrate are selected.

The research procedure started with setting up the constructed wetland system, which included a water tap to regulate the water flow. The predetermined substrates were placed in the wetland tank at a designated height of 20 cm based on UN-HABITAT (2008) [24]. River water is put into a filter tank to remove large solid particles in the water. After that, the water slowly flowed into the constructed wetland tank until it reached a predetermined height. At the same time, water jasmine is prepared and planted with a density of 4 plants per square meter.

This experimental setup was intended as a comparative screening study. Therefore, the results are interpreted to indicate relative substrate performance rather than statistically definitive outcomes.

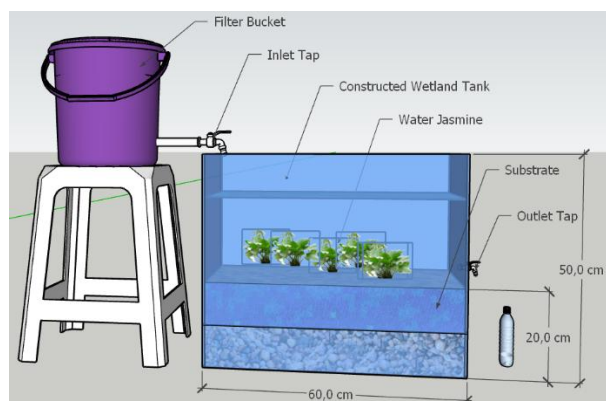


Figure 1 Schematic diagram of the laboratory-scale FWS CW system, showing the water column (30 cm) and the substrate zone (20 cm). Each reactor contains a single type of substrate (sand-gravel, zeolite, or biochar), arranged as a uniform layer at the bottom of the wetland tank.

### 2.3 Field-Scale Design and Upscaling Method

The field-scale CW was designed by scaling up laboratory results using a hydraulic similarity and volume-based approach. The hydraulic retention time (HRT) is a key operational parameter, with effective pollutant removal at an HRT of 24 hours. This value was therefore maintained as the primary hydraulic criterion in field-scale design.

The field-scale system was designed through proportional and volume-based calculations for the intake, equalization tank, sedimentation tank, CW, and reservoir units. In particular, the required wetland volume was determined using the following relationship:

$$V = Q \times HRT$$

Where  $V$  is the wetland volume ( $m^3$ ),  $Q$  is the design flow rate ( $m^3/day$ ), and HRT is the hydraulic retention time (days).

Based on the target treatment capacity, the calculated wetland volume was subsequently translated into wetland dimensions following standard FWS CW design guidelines to ensure appropriate flow distribution and hydraulic performance. The laboratory findings were further used as a performance reference for substrate selection in the field-scale design. The field-scale CW utilized the substrate that exhibited the optimal pollutant removal performance during laboratory-scale testing. However, this study is limited to technical analysis and system design. Field implementation aspects such as regional topography, site selection, and hydrological variables, including rainfall, were not considered.

### 2.4 Data Analysis

This study compares water quality characteristics before and after treatment in artificial wetlands. The focus includes observations on several main parameters: Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended

Solid (TSS), and Total Ammonia. In addition, the analysis also includes a comparison of the efficiency of pollutant removal from each type of substrate to determine the most effective of substrate.

## 3. Results and Discussion

### 3.1 Initial Water Quality Conditions of the Penjemuran River

The Penjemuran River's water quality varied between experimental runs due to temporal changes and specific substrate treatments. These variations mirror natural environmental dynamics and enhances the reliability of substrate assessments under real field conditions. However, all measured parameters exceeded Class II water quality standards set by Government Regulation No. 22 of 2021 [19].

Table 1. Initial Parameter Values of River Water

Parameter	Initial Value			Class II Standards
	Sand-Gravel	Zeolite	Biochar	
BOD (mg/L)	26.3	23	14.2	3
COD (mg/L)	90.2	88.8	89.5	25
TSS (mg/L)	54.9	77.3	121	50
Ammonia (mg/L)	0.21	0.858	0.591	0.2
pH	6.37	6.18	6.52	6-9

As presented in Table 1, the concentrations of BOD, COD, TSS, and ammonia substantially exceeded the Class II standards specified in Government Regulation No. 22 of 2021, while pH remained within the permissible range. The high levels of BOD and COD indicate significant organic loading due to domestic wastewater and landfill leachate. In addition, high levels of TSS and ammonia further suggest contributions from surface runoff and agricultural activities. These results confirm that the river water does not comply with the designated fisheries standard and therefore requires treatment before use.

### 3.2 Pollutant Removal Performance of Different Substrates

To guide substrate selection for landfill-impacted rivers, the pollutant removal performance of sand-gravel, zeolite, and biochar was evaluated using BOD, COD, TSS, ammonia, and pH as indicators. The hydraulic retention time was 24 hours. Given the variability of influent concentration across experimental runs due to changing river conditions, removal efficiency (%) was adopted as the primary performance metric to ensure a fair and meaningful comparison among substrates.

As summarized in Table 2, biochar achieved the highest ammonia removal (83.2 %), while sand-gravel resulted in the lowest ammonia and TSS removal among the three media. Detailed influent and effluent concentrations for each experimental run are provided in Supplementary Table S1.

Table 2. Removal Efficiency of Different Substrates under 24-h HRT

Parameter	Sand-Gravel (%)	Zeolite (%)	Biochar (%)
BOD	89.4	88.8	75.1
COD	73.9	81.9	68.9
TSS	63.2	75.0	72.8
Ammonia	-	29.3	83.2

Sand and gravel are commonly used filtering media. They effectively remove pollutants through physical filtration and sedimentation that can remove suspended solids and bind organic matter in water [4]. In this study, sand-gravel demonstrated strong BOD reduction, confirming its suitability for biodegradable organic removal. TSS concentrations were reduced to within the permissible limit, reflecting efficient particle retention. However, ammonia removal remained limited, indicating that inert mineral media possess low adsorption capacity for dissolved nitrogen. These findings are consistent with Li et al. [25], who reported that sand effectively removes suspended solids but has minimal affinity for dissolved ammonium. The limited nitrogen removal performance suggests that sand-gravel alone is insufficient for nutrient control and requires integration with more adsorptive substrates to achieve comprehensive treatment.

Zeolite is a natural aluminosilicate mineral with a high cation-exchange capacity and porous crystalline structure, enabling ion exchange and molecular adsorption [12]. In this study, zeolite removed COD and TSS effectively by adsorbing dissolved organics and retaining suspended particles. However, it removes ammonia less effectively (Table 3.2). The untreated natural zeolites ion exchange capacity may not be sufficient for significant ammonium reduction under these conditions. Chemical modification, such as sodium activation, improves ammonia adsorption [13][14]. The moderate nitrogen removal here suggests that natural zeolite alone may not provide sufficient nutrient control and should be combined with more active substrates in constructed wetland systems.

Although a slight increase in pH was observed following treatment, values remained within the acceptable Class II range, indicating that the ion exchange process did not adversely affect overall water quality. Biochar is a carbon-rich material derived from biomass pyrolysis and is characterized by a high surface area and abundant functional groups that enhance adsorption capacity [15][16]. In this study, biochar demonstrated substantial removal of organic matter and suspended solids, reflecting the combined

effects of adsorption and particle retention within its porous structure. Although BOD and COD concentrations remained slightly above the Class II limits, biochar contributed significantly to TSS reduction while maintaining stable hydraulic conditions. The most notable performance was observed in ammonia removal, where biochar achieved the highest efficiency among all substrates (Table 2), successfully reducing ammonia to below the regulatory threshold.

Nitrogen removal can be attributed to multiple mechanisms, including ion exchange between  $\text{NH}_4^+$  and alkali metal ions in biochar ash, as well as surface complexation with oxygen-containing functional groups such as  $-\text{OH}$  and  $-\text{COOH}$  [26] [27]. In addition to physicochemical adsorption, the porous structures of biochar may facilitate microbial colonization, thereby enhancing biological degradation. These combined mechanisms explain its high nutrient removal performance compared to sand-gravel, and natural zeolite.

However, although ammonia concentrations under biochar treatment complied with Class II standards, further optimization, such as extended HRT or post-treatment polishing, may be necessary to ensure consistent compliance for BOD and COD under fluctuating river conditions.

Across all treatments, pH remained within the acceptable Class II range (6-9), indicating that the use of different substrates did not disrupt the system's chemical stability. This stability is essential for sustaining microbial activity and ensuring regulatory compliance.

Overall, the findings demonstrate that substrate performance in the constructed wetland system is parameter-specific and governed by distinct removal mechanisms. Sand-gravel primarily facilitates physical filtration and sedimentation, making it effective for particulate and biodegradable organic removal but limited for dissolved nutrients. Zeolite enhances adsorption through cation exchange, contributing to reductions of organic and suspended solids, yet shows only moderate nitrogen removal under natural conditions. In contrast, biochar provides multi-functional removal pathways, including ion exchange, surface complexation, and biofilm support, resulting in high ammonia removal. These results highlight that no single substrate is optimal, instead, integrating complementary media is necessary to achieve balanced pollutant removal and regulatory compliance in the landfill-impacted river system.

### 3.3 Comparative Analysis of Substrate Performance

The evaluation of sand-gravel, zeolite, and biochar demonstrates that substrate performance is governed by distinct dominant removal mechanisms rather than uniform treatment capacity. Sand-gravel primarily facilitates physical filtration and sedimentation, effectively reducing suspended solids and

biodegradable organic matter [4]. Zeolite contributes through cation exchange and adsorption processes, enhancing the removal of dissolved pollutants [14]. Meanwhile, biochar provides multifunctional removal pathways, including ion exchange, surface complexation, and microbial support, which enhance nutrient removal performance [25][26]. These differences indicate that substrate selection should be aligned with the dominant pollutant fraction to achieve optimal treatment efficiency.

Among the evaluated parameters, ammonia emerged as the most discriminating indicator of substrate effectiveness. Considering that ammonia concentrations exceeded the Class II regulatory threshold in the initial river condition and pose ecological risks to fisheries, their removal represents a critical design parameter. Biochar achieved the highest ammonia removal efficiency, confirming its strong affinity for ammonium through ion exchange and functional group interactions [26]. Zeolite exhibited moderate nitrogen removal, consistent with previous findings that natural zeolites require modification to maximize ammonium adsorption capacity [14]. In contrast, sand-gravel showed minimal ammonia removal, indicating that physical filtration alone is insufficient for controlling dissolved nutrients [4].

For BOD and TSS, the differences among substrates were less pronounced, suggesting that hydraulic retention time and particle retention mechanisms contributed substantially across all treatments. However, effective nutrient control requires substrates with active adsorption properties capable of targeting dissolved nitrogen.

These findings indicate that no single substrate can simultaneously optimize organic, particulate, and nutrient removal. Therefore, integrating complementary media within a constructed wetland system is recommended. The combined use of biochar and zeolite has been reported to enhance the simultaneous removal of organic pollutants and nitrogen compounds [15][4]. A stratified configuration, where sand-gravel functions as a primary filtration layer followed by zeolite and biochar as adsorption-enhancing media, may optimize sequential removal processes while maintaining hydraulic stability. Such integration can compensate for the limitations of individual substrates and improve overall treatment performance under variable river water conditions [25][26][14].

For landfill-impacted rivers, where pollutant composition fluctuates and nutrient loading remains a primary concern, a multi-substrate configuration offers greater operational resilience and improves the likelihood of meeting Class II water quality standards for fisheries use.

Table 3 Comparison of Substrate Performance Based on Pollutant Removal Efficiency

Substrate	Dominant Removal Mechanism	Strengths	Limitations
Sand-gravel	Physical filtration and sedimentation.	High BOD and TSS removal; good hydraulic stability.	Very limited ammonia removal; low adsorption for dissolved pollutants.
Zeolite	Cation exchange and adsorption.	Moderate COD and TSS removal; partial ammonium adsorption.	Ammonia removal is limited without chemical modification.
Biochar	Ion exchange, surface complexation, and biofilm support.	Highest ammonia removal; multifunctional adsorption capacity.	Slight limitation in achieving full COD compliance as single medium.

Based on the comparative characteristics summarized in Table 3, sand-gravel is more suitable as a primary filtration layer, zeolite as an intermediate adsorption medium, and biochar as a nutrient polishing substrate in a stratified constructed wetland configuration.

### 3.4 Water Treatment Plant

The Penjemuran River water undergoes a multi-stage treatment process designed to meet quality standards for community-based fisheries. This system was developed based on experimental findings on Sections 3.2 and 3.3, which identified ammonia as the primary water quality concern and biochar as the most effective substrate for nitrogen removal. Accordingly, the treatment consists of five main components: an intake pump, a filtration tank, a sedimentation tank, a constructed wetland tank, and a reservoir (Figure 1). Each unit serves a specific function within a sequential removal framework, targeting particulate matter, organic load, and dissolved nutrients to ensure comprehensive water quality improvement.

#### 3.4.1 Pump Intake

The intake system consists of a submersible water pump equipped with an integrated pre-filter to prevent sediment and coarse particles from entering the treatment units. The pump has a capacity of 3,000 L h<sup>-1</sup>, which exceeds the designed treatment flow rate (1 m<sup>3</sup> day<sup>-1</sup>), ensuring a stable water supply and operational flexibility.

Given the river's relatively low discharge, mechanical pumping was selected as the most practical solution to maintain consistent inflow and support the designed hydraulic retention time in the downstream

treatment units [28]. The use of a pre-filter also minimizes clogging risk and helps maintain hydraulic stability throughout the treatment system.

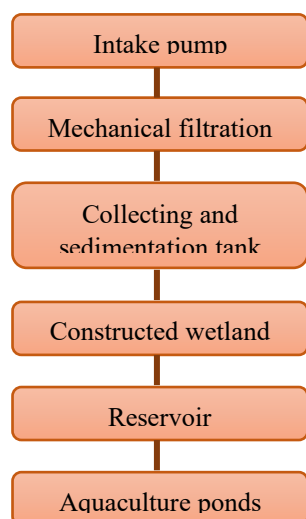


Figure 1. Water Treatment Unit for Penjemuran River

### 3.4.2 Filtration Tank

The filtration tank functions as a preliminary treatment unit primarily targeting suspended solids and coarse particulate matter before water enters the sedimentation and constructed wetland. The unit consists of a container filled with a cotton-based filtering medium designed to retain solid particles and reduce particulate loading.

Positioned above the collection tank, the system operates under gravity flow, minimizing additional energy requirements and enhancing operational efficiency [29][30][31]. By reducing suspended solids at the initial stage, this unit helps prevent clogging in downstream treatment components and supports hydraulic stability within the constructed wetland system.

### 3.4.3 Sedimentation Tank

The sedimentation tank serves as a gravity-based clarification unit that removes fine particles, silt, and heavier suspended solids prior to wetland treatment. Integrated with the collection tank, it forms a solid-liquid separation stage that further reduces particulate loading before water enters the constructed wetland system [29][32].

The rectangular tank configuration supports uniform flow distribution and settling efficiency under the designed discharge capacity of  $1 \text{ m}^3 \text{ day}^{-1}$ . A sludge drainage outlet is provided to allow periodic removal of accumulated sediments, preventing excessive buildup and maintaining operational efficiency [33].

### 3.4.4 Constructed Wetland

The constructed wetland was designed as a rectangular Free Water Surface (FWS) system to promote uniform flow distribution and effective hydraulic retention. The configuration was developed

based on experimental findings that identified ammonia removal as the most critical treatment objective and biochar as the most effective substrate for nitrogen removal.

Pollutant removal within wetland occurs through a combination of physical, chemical, and biological processes, including sedimentation, filtration, adsorption, microbial degradation, and plant uptake [5][34][29]. The selected hydraulic retention time of 24 hours corresponds to the operational condition that achieved optimal pollutant removal during laboratory-scale experiments and aligns with commonly reported values for FWS constructed wetlands [35]. This retention time ensures sufficient interaction between the water column, substrate media, and plant root zone to enhance treatment efficiency.

The wetland was designed with dimensions of  $5 \text{ m} \times 1.5 \text{ m} \times 0.5 \text{ m}$ , providing a total water depth of 50 cm, consisting of a 20 cm substrate layer and a 30 cm water column. The substrate layer comprises sand-gravel as supporting media, integrated with biochar and zeolite to enhance nutrient adsorption capacity. This multimedia configuration reflects the comparative performance analysis presented in Section 3.3 and aims to optimize sequential removal of particulate matter, organic load, and dissolved nitrogen.

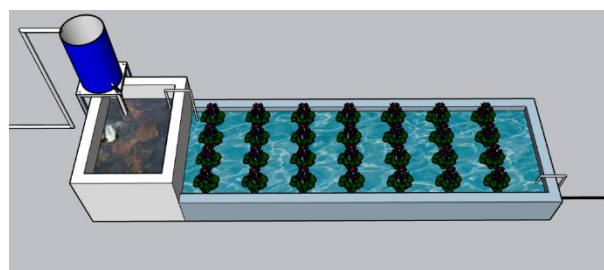


Figure 2. Constructed Wetland Tank

Water jasmine (*Echinodorus palaefolius*) was planted at approximately 4 plants  $\text{m}^2$  to facilitate nutrient uptake and support microbial activity in the rhizosphere. The inlet and outlet structures were positioned to promote uniform flow distribution and minimize short-circuiting, thereby maintaining hydraulic efficiency throughout the wetland cell.

### 3.4.5 Reservoir

The final stage of the treatment system is a reservoir for storing and distributing treated water. The system consists of six independent 1,000-L polyethylene tanks selected for their chemical resistance, durability, and ability to preserve water quality. Each tank operates independently to reduce the risk of leakage, system failure, and cross-contamination. This segmented storage configuration enhances operational flexibility, water security, and post-treatment water quality protection (Figure 3).

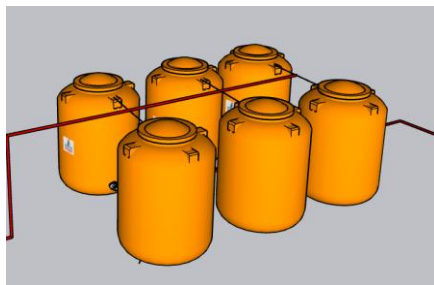


Figure 3. Reservoir

### 3.5 Cost Budget Plan

Based on the 2022 AHSP guidelines[36] for Palembang City, the estimated construction cost of the proposed water treatment system includes an intake pump, a filtration tank, a sedimentation tank, a constructed wetland unit incorporating zeolite and biochar substrates, and a reservoir tank. The total estimated investment cost is IDR 45,414,703 (Table 4). The constructed wetland unit represents the largest cost component, reflecting the structural and substrate requirements associated with multi-media integration.

Table 4. Recapitulation of the Budget Plan for the Construction of the Water Treatment Unit

No.	Units	Total (Rp)
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

Considering the system's designed capacity of 1 m<sup>3</sup> day<sup>-1</sup> and its targeted application for community-based fisheries, the estimated cost indicates that the proposed multi-stage treatment system is financially feasible for small-scale implementation. The integration of natural and locally available substrates further supports cost-effectiveness and long-term sustainability.

## 4. Conclusion

This study demonstrates that substrate selection is a critical determinant of pollutant removal performance in constructed wetlands. Among the evaluated media, biochar exhibited the highest ammonia removal efficiency, confirming its strong adsorption capacity for dissolved nitrogen. Sand-gravel effectively reduced suspended solids through physical filtration, while zeolite contributed additional removal of dissolved pollutants through cation-exchange mechanisms. The findings indicate that no single substrate can simultaneously optimize organic, particulate, and nutrient removal. Therefore, integrating complementary media within a multi-layer configuration is essential to achieve balanced treatment

performance. The proposed Free Water Surface constructed wetland system, designed with a 24-hour hydraulic retention time and combined sand-gravel, zeolite, and biochar substrates, provides a technically feasible approach for improving water quality in rivers affected by landfill leachate.

From a practical perspective, the field-scale design and cost estimation demonstrate that the system is suitable for small-scale, community-based fisheries applications. By targeting ammonia as the primary limiting factor and using locally available materials, the proposed system offers a sustainable, decentralized solution for river water quality management in urban areas.

Future research should evaluate long-term substrate performance, potential adsorption saturation, and seasonal variations to further optimize system stability and nutrient removal efficiency under continuous operation.

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