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Development of a Hybrid System for Greywater Treatment Using Biochar Filter with Integration of Water Hyacinth

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Greywater pollution poses a significant threat to environmental and public health, particularly in rapidly urbanizing regions. In this context, hybrid treatment systems that combine nature-based solutions offer a sustainable and cost-effective approach for decentralized wastewater management. This study investigates the synergistic effectiveness of a two-stage greywater treatment system integrating phytoremediation using *Eichhornia crassipes* (Water Hyacinth) with biochar filtration derived from palm kernel shells. System performance was evaluated based on the removal of ammoniacal nitrogen (AN) and chemical oxygen demand (COD) using standard APHA methods. FTIR-ATR spectroscopy was employed to characterize functional group changes on the biochar surface before and after treatment. Results showed that the phytoremediation unit significantly reduced AN (80.8 %) and COD (75.8 %). Subsequent biochar filtration enhanced these outcomes, achieving final cumulative removals of 85.5 % for AN and 89.3 % for COD. The combined system outperformed either component alone, highlighting the synergistic interaction between plant uptake and biochar adsorption in pollutant removal. Effluent pH approached neutrality, and FTIR analysis indicated organic compound adsorption on the biochar surface. These findings support the application of integrated phytoremediation–biochar systems as effective, low-cost solutions for greywater treatment in developing urban areas.

1. Introduction

Urban water pollution is a growing issue in developing countries like Malaysia, mainly due to the discharge of untreated or poorly treated greywater from domestic activities (Foo and Hameed, 2020). Though greywater lacks sewage, it contains high levels of organic matter, AN, and suspended solids, contributing to eutrophication and water quality decline (Al-Gheethi et al., 2021). Centralized treatment systems are costly and often impractical for small communities, prompting interest in decentralized, low-cost, and sustainable options. Water hyacinth is effective in phytoremediation, especially for nutrient uptake, while biochar, a porous carbon material from biomass pyrolysis is a proven low-cost adsorbent for organic pollutants, improving COD removal (Al-Awadhi et al., 2022). This study proposes a hybrid system using water hyacinth for nutrient removal and biochar for polishing the effluent and the system's performance is assessed based on AN, COD, and pH. Post-treatment FTIR analysis of biochar is used to examine contaminant adsorption. The aim is to evaluate whether combining phytoremediation with biochar enhances greywater treatment efficiency and then compared with Department of Environment (DOE) standards.

2. Materials and Methods

Greywater for this study was collected from a surface drain at 1°33'21.8"N, 110°20'13.9"E, a major pollution source discharging into Tebingan Sungai Bintangor, Kuching, Sarawak. The drain receives runoff from nearby residential and commercial areas. Wastewater was collected in clean polyethylene containers, transported immediately, and refrigerated to minimize degradation. The treatment system operated in two sequential batch-mode stages. As shown in Figure 1, in Stage 1 (Water Hyacinth Unit), 4 L batches were retained for 48 h with

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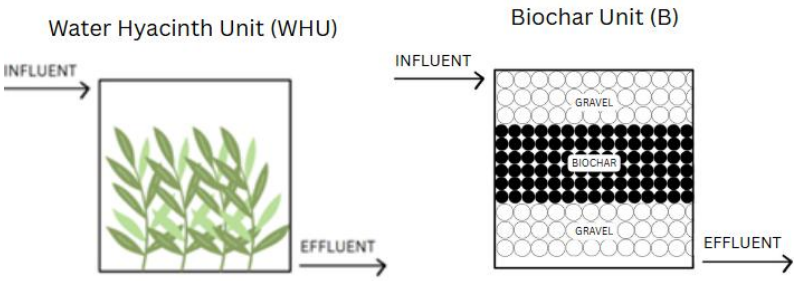
floating Water Hyacinth, aligning with studies showing 48 h as optimal for NH_4^+-N removal (Prasad et al., 2023). In Stage 2 (Biochar Filtration Unit), effluent was polished via a palm kernel biochar–gravel layered filter with 3 h contact time, capitalizing on evidence that biochar achieves near-maximal DOC adsorption within 2 – 3 h (Thompson et al., 2020). A control setup with untreated greywater under the same time conditions (48 h) was included for baseline comparison. To evaluate individual and combined treatment performances, the setup is as follows. WHU only (WHU): Greywater was treated in the WHU alone and then sampled. Biochar only (B): Greywater was treated in the biochar unit only. Hybrid System (WHB): Greywater was first treated in the WHU, then passed through B sequentially. A control setup with untreated greywater under the same retention time was included for baseline comparison. All treatments were run in triplicate (n=3).

(a)



(b)

Figure 1: (a) Schematic diagram of water hyacinth unit (left) (Stage 1) and biochar filtration unit (right) (Stage 2). (b) Actual setup pictures

Influent and effluent were analysed immediately before and after each treatment stage. AN was measured using APHA Method 8155 with a HACH DR900 colorimeter. COD was analysed using APHA USEPA Method 8000 with High or Low Range vials, digested at 150 °C for 2 h in a HACH reactor, and read at 620 nm (HR) or 420 nm (LR) via spectrophotometer. The pollutant removal efficiency (%) was calculated using Eq(1):

$$Removal\ Efficiency(\%) = \left(\frac{C_i - C_e}{C_i}\right) \times 100 \quad (1)$$

Where:
Ci = initial concentration of the pollutant (mg/L)
Ce = final concentration of the pollutant (mg/L)
pH was measured before and after each treatment stage using a calibrated handheld digital pH meter. FTIR analysis in ATR mode was used to characterise biochar pre- and post-treatment, identifying functional groups involved in adsorption. Spectra were recorded using an FTIR spectrometer (4,000–400 cm^{-1} range, 4 cm^{-1} resolution, 32 scans/sample).

3. Results and Discussion

The changes in contaminant concentration and the corresponding removal efficiencies at each treatment stage were examined to evaluate the individual performance of the Water Hyacinth Unit, the biochar filter, and the integrated hybrid system. This evaluation provides insight into how each component contributed to the overall treatment process and helps explain the observed patterns in the reduction of key pollutants, including COD, BOD, ammoniacal nitrogen, and suspended solids.

3.1 Removal of Ammoniacal Nitrogen

As shown in Figure 2a, the initial AN concentration was 103.83 mg/L. WHU achieved significant AN removal of 80.78 %, reducing it to 19.97 mg/L. This high removal is attributed to plant uptake of nutrients where sunlight supports oxygen production, and the oxygen is then utilized by microorganisms to degrade organic matter in the wastewater (Vymazal, 2005). B showed lower AN removal efficiency at 30.78 %, with the effluent AN concentration increasing to 71.83 mg/L. This limited performance is expected because biochar without surface modification has a low affinity for ionic species like NH_4^+ (Kizito et al., 2015). WHB achieved the highest AN removal of 85.54 %, indicating a synergistic effect where the treatment by water hyacinth improved the subsequent biochar filtration efficiency. Compared to activated biochar from agricultural waste done by Mwenge and Seodigeng (2019), which achieved an average ammonia nitrogen removal of 60.21 % across various greywater sources, the WHB system demonstrated superior performance with a consistent removal efficiency of 85 %, highlighting its potential as a more effective treatment approach. In contrast, A control setup using untreated greywater with the same hydraulic retention time was included to serve as a baseline for performance comparison.

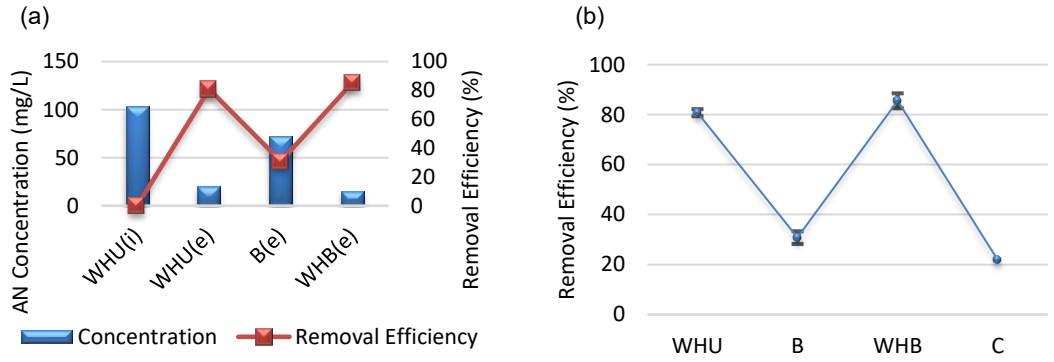


Figure 2: (a) AN concentration (left axis) and removal efficiency (right axis) across treatment stages and (b) overall removal efficiency across treatment stages including control

One-way ANOVA was also applied to test whether ammoniacal nitrogen (AN) removal efficiency significantly varied among WHU, B, and WHB treatment setups. The test returned a p-value of 2.44×10^{-7}, well below the 0.05 threshold, allowing us to reject the null hypothesis (H_0). This confirms that the treatment setup had a statistically significant effect on AN removal efficiency. The results support previous literature which suggests that phytoremediation using water hyacinth is more effective in nutrient (nitrogen) uptake compared to adsorption-based methods like biochar. The hybrid system, which incorporates both, demonstrated enhanced performance due to synergistic mechanisms.

3.2 Removal of Chemical Oxygen Demand (COD)

Figure 4a shows influent COD concentration was 104.67 mg/L. The WHU significantly reduced COD by 75.84 %, down to 25.33 mg/L, demonstrating effective removal of organic load via plant nutrient uptake. Biochar filtration further enhanced COD removal to 81.11 %, with effluent COD at 19.67 mg/L. The observed high removal efficiency of COD in the biochar unit is consistent with other studies that attribute organic matter adsorption to biochar's surface charge, alkalinity, and carbon structure when using spent coffee grounds biochar (Filho et al., 2022).

This is due to biochar's adsorption capabilities linked to its surface functional groups, which interact with organic molecules through hydrogen bonding and van der Waals forces (Kizito et al., 2015). Together, the hybrid system achieved the highest COD removal of 89.28 %, lowering COD to 11.33 mg/L. The WHB system demonstrated superior COD removal efficiency (89.28 %) compared to the 77.05 % achieved by Lim's (2024) constructed wetland system, which is based on phytoremediation alone. This suggests the combined adsorptive capacity of biochar and biological action from water hyacinth can be highly effective even at a shorter total contact time. As shown in Figure 4b, the control treatment had a 41.2 % COD reduction, attributed to passive processes rather than active treatment. A one-way ANOVA was conducted to evaluate the significance of differences in COD removal efficiency across the three treatment configurations: water hyacinth unit (WHU), biochar filtration unit (B), and the combined hybrid unit (WHB). The results yielded a p-value of 0.00106, which is below the significance threshold of 0.05. Therefore, the null hypothesis (H_0) was rejected, indicating that there is a statistically significant difference in COD removal efficiencies between at least two treatment groups.This implies

that the treatment configuration plays a substantial role in enhancing COD removal and supports the effectiveness of system design in optimizing performance.

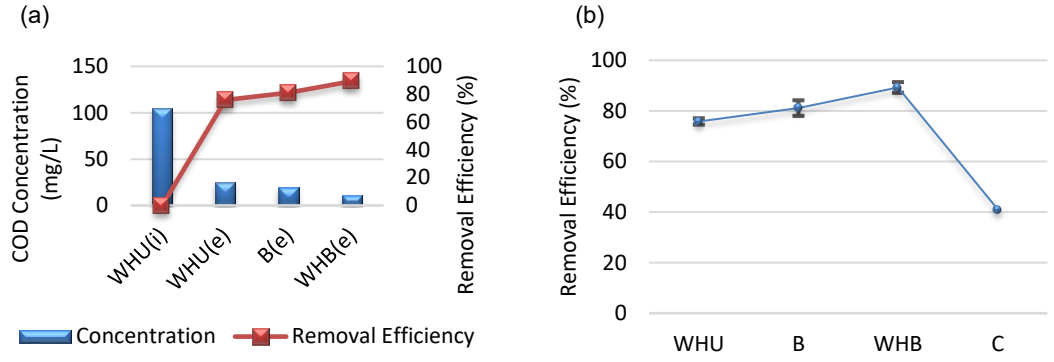


Figure 3: (a) COD concentration (left axis) and removal efficiency (right axis) across treatment stages and (b) overall removal efficiency across treatment stages including control

3.3 pH Levels

As shown in Figure 5, the pH of greywater remained stable during phytoremediation, changing slightly from 6.39 to 6.35, likely due to the absence of buffering media and short retention time (Churko et al., 2023). After biochar filtration, pH rose to 6.81 and the final effluent reached near-neutral pH (6.93), confirming biochar's stabilizing effect, which is consistent with findings by Dai et al. (2014), where biochar additions increased soil pH by 0.5 to 2 units due to its inherent alkalinity and buffering capacity. The control also showed a minor pH increase (6.40 to 6.70), This change is likely the result of natural mechanisms such as particle settling and exposure to air, which can slightly alter microbial conditions and reduce carbon dioxide concentration, thus causing a gradual shift toward a more neutral or alkaline pH. Comparable findings have been documented in non-treated greywater systems (Yusoff et al., 2021).

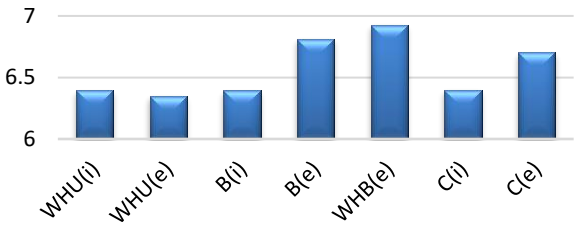


Figure 4: pH levels across treatment stages

3.4 Treatment performance compared to DOE standards

Table 1 presents the discharge limits set by the Malaysian Department of Environment (DOE) under the Environmental Quality (Sewage) Regulations 2009. To assess the treatment system's performance, the final effluent from WHB(e) is evaluated against the criteria for Standard A (sensitive receptors) and Standard B (general inland water discharge).

Table 1: Environmental Quality (Sewage) Regulations 2009 Discharge Limits (Department of Environment Malaysia, 2009)

Parameter	Standard A	Standard B
Chemical Oxygen Demand (COD)	≤ 120 mg/L	≤ 200 mg/L
Ammoniacal Nitrogen (as N)	≤ 10 mg/L	≤ 20 mg/L
pH	6.0–9.0	6.0–9.0

The final effluent meets DOE standards for COD (11.33 mg/L) where it is well within both Standard A (50 mg/L) and B (100 mg/L) limits. Ammoniacal nitrogen (15 mg/L) complies with Standard B (20 mg/L) but exceeds Standard A (10 mg/L). Further optimization is needed to fully meet Standard A, particularly for nutrient removal, where higher retention time could be better for nutrient removal. Both the B effluent (pH 6.81) and the final

effluent from WHB (pH 6.93) fall within the DOE Standard A and B pH range of 6.0 – 9.0, indicating compliance with regulatory discharge limits. The WHU effluent (pH 6.35) also meets the standards, though it lies closer to the lower limit.

3.5 Characterization of Biochar

As shown in Figure 9a, FTIR shows hydroxyl, aromatic, and oxygenated groups, indicating potential for adsorption via hydrogen bonding and π–π interactions. Figure 9b shows FTIR spectra of biochar After treatment (Figure 9b), spectral shifts, especially in C–H and C=O regions which indicates adsorption of organic contaminants. No significant changes in N–H, N–O, or C–N bands suggest minimal adsorption of nitrogenous compounds like ammonium.

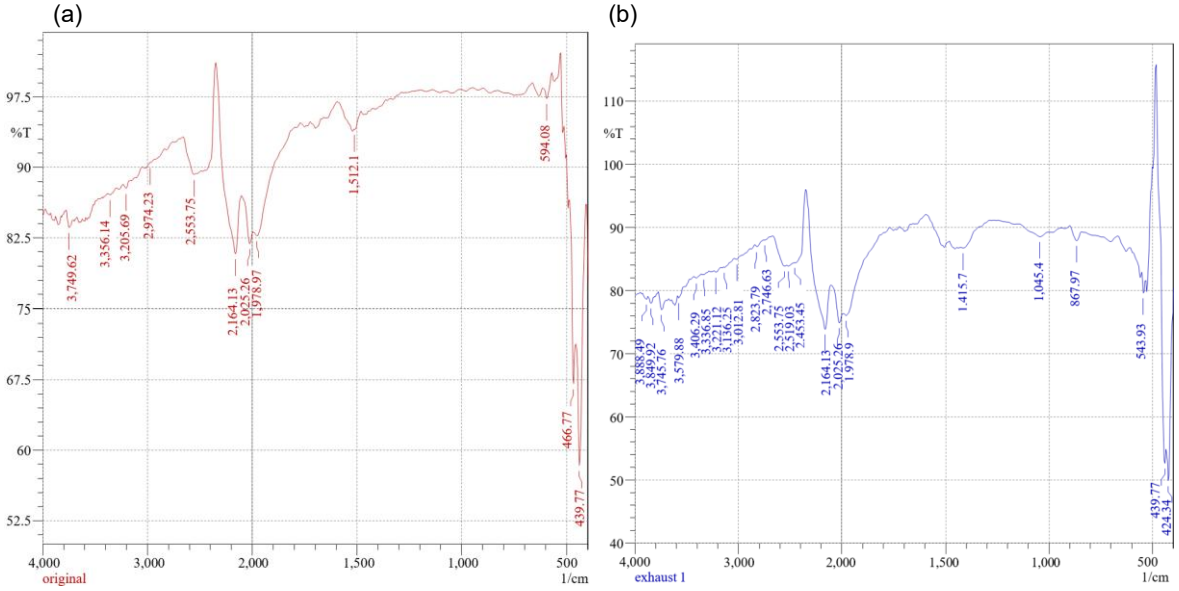


Figure 5: (a) FTIR spectra of biochar before and (b) after treatment

Table 2 describes the functional groups present at the initial stage of biochar. Fresh biochar is chemically active with oxygenated and aromatic functional groups, which are key for interacting with organic pollutants.

Table 2: Functional Groups Present at Initial Stage of Biochar

Wavenumber (cm^{-1})	Likely Bond	Functional Group	Notes
3,594	O–H stretch	Alcohols / Phenols	Hydroxyl groups
2,164	C≡N stretch	Nitriles (trace)	Possibly formed during pyrolysis
1,512	C=C stretch	Aromatic rings	Aromaticity
1,300–1,000	C–O stretch	Alcohols, ethers, acids	Indicates oxygenated organic structures

Table 3 describes the functional groups present after the treatment with biochar, showing how the FTIR peaks changed after biochar was used. The shifts and changes confirm that the biochar actively adsorbed organic contaminants, supporting its role in COD reduction.

Table 3: Functional Groups Present After Treating with Biochar

Changed Region (cm^{-1})	Observation	Interpretation
3,500–3,200 (O–H)	Reduced intensity/shifted	Loss or consumption of hydroxyl groups
2,950–2,850 (C–H)	New or increased peaks	Adsorption of aliphatic organics
1,700–1,750 (C=O)	New peak appeared or intensified	Binding of carboxylic acids, aldehydes, and ketones
1,300–1,000 (C–O)	Decreased intensity	Saturation of oxygenated surface groups
1,512–1,600 (C=C)	Shifted or slightly reduced	Possible π–π interactions with aromatic compounds

4. Conclusion

This study met its objectives by developing a two-stage hybrid system—water hyacinth and biochar unit for treating greywater from Tebingan Sungai Bintangor. Designed to be low-cost, decentralized, and eco-friendly, the system proved effective in reducing key pollutants. The water hyacinth unit removed 80.8 % of ammoniacal nitrogen and COD (75.8 %) reductions through plant uptake. The biochar unit further improved treatment, achieving final removal rates of 89.3 % COD, and 85.5 % AN. A slight increase in pH also brought the effluent closer to neutral. These results highlight the effectiveness of combining biological and physicochemical processes for decentralized treatment. The system's simplicity, affordability, and reliance on locally available materials make it especially suitable for decentralized wastewater management in resource-limited rural communities, such as Tebingan Sungai Bintangor itself. Its application can provide an accessible and sustainable solution to improve water quality and reduce environmental pollution in similar peri-urban and rural settings. In conclusion, this work contributes to the growing body of research promoting nature-based, decentralized wastewater treatment, demonstrating the feasibility of hybrid systems integrating plant-based nutrient uptake and biochar filtration. Future studies should focus on optimization, long-term stability, and field-scale implementation to enhance its real-world viability and adoption in rural communities.

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