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Enhancing Water Quality in the Niger Delta: Sustainable Treatment of Oily Wastewater with Cassava Peel Biochar and Bio-Sand Filtration

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Abstract— *This study evaluates the efficacy of cassava peel biochar in treating oily wastewater through bio-sand filtration in the Niger Delta, with a particular focus on heavy metals and hydrocarbon content removal. An analysis of physicochemical parameters, heavy metal concentrations, and organic pollutants in sample water before and after treatment unveils substantial improvements in various water quality parameters. The results indicate a notable reduction in pH levels, rendering the water more suitable for environmental discharge. Moreover, the study achieves a commendable reduction in turbidity, total suspended solids, and organic pollutant concentrations, leading to enhanced water clarity and quality. The research also demonstrates significant reductions in heavy metal concentrations, specifically lead, nickel, and vanadium, highlighting cassava peel biochar's potential in mitigating heavy metal contamination. Most notably, the data showcases the successful removal of hydrocarbons, represented by a significant reduction in total petroleum hydrocarbon (TPH) concentrations. A near-perfect linear relationship quantifies the efficiency of cassava peel biochar in removing organic and inorganic pollutants. These findings resoundingly support the use of cassava peel biochar as a sustainable, cost-effective solution for enhancing water quality and addressing the impact of oily wastewater in the Niger Delta and beyond. The study not only aligns with global sustainability objectives but also underscores the importance of ongoing optimization for broader application, exemplifying the essence of multidisciplinary and globally relevant scientific inquiry.*

Keywords— *Cassava peel biochar, Oily wastewater treatment, Niger Delta, Bio-sand filtration, Environmental sustainability.*

I. INTRODUCTION

Nigeria, a nation with a population of approximately over 200 million people, plays a prominent role in global oil production, particularly in the Niger Delta region [1]. While the oil industry significantly bolsters the economy, it has left in its wake a pressing problem of water pollution and contamination, attributed to the mismanagement of crude oil operational facilities that often result in pollution of water systems or the improper disposal of untreated wastewater into nearby river bodies [2-4]. With existing challenges in securing potable water in the Niger Delta, these pollution cases further compound the region's water availability issues. Responding to these challenges, the employment of natural and locally available products, such as activated carbon derived from biomass, has gained recognition as an effective means of water treatment for potable water availability in rural environments [5-7].

The improper disposal of cassava peels, a significant byproduct of cassava processing, along with untreated oil-produced water, has resulted in water pollution and ecosystem degradation. Recent research has highlighted the environmental consequences of cassava peel disposal, particularly when compared to other forms of cassava solid waste [8-9]. To address this issue, our study focuses on exploring the potential application of cassava peel biochar as a sustainable solution for treating oily wastewater in the Niger Delta. This approach aims to mitigate the adverse environmental and health effects associated with improper disposal. Notably, produced water, a byproduct of oil and gas production, and oily wastewater (effluents) are known to contain elevated levels of contaminants, including hydrocarbons, heavy metals, and salts [10]. Effective management and treatment of produced water are crucial for ensuring environmental protection and sustainability.

The utilization of cassava peel biochar in the treatment of oily wastewater offers several notable advantages. Cassava peel waste serves as an economical and locally abundant source for biochar production, ensuring accessibility and sustainability [11-13]. Additionally, biochar possesses exceptional adsorption properties that can effectively remove contaminants, thereby improving water quality. Importantly, its environmentally friendly attributes align with global sustainability objectives. Furthermore, as demonstrated in prior studies [14], the integration of bio-sand filtration, a low-cost and sustainable technique, has proven highly efficient in removing oil and grease contaminants from wastewater. Consequently, the synergistic use of cassava peel biochar with bio-sand filtration offers the potential for an innovative and sustainable approach to oily wastewater treatment in the Niger Delta, thus contributing to both global sustainability efforts and localized environmental enhancements.

The core objective of this research project is to assess the potential of cassava peel biochar as a sustainable and effective solution for treating oily wastewater in the Niger Delta. By exploring the capabilities of cassava peel biochar, this study

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aspires to present an affordable, efficient, and environmentally sustainable treatment technique for produced water. The outcomes of this research endeavour will not only advance our comprehension of cassava peel biochar's capabilities but also provide valuable insights into the development of sustainable treatment approaches in the Niger Delta region and beyond.

II. METHODOLOGY

2.1 Sample collection location

The wastewater samples were collected from an operational oilfield situated in Bayelsa State, Nigeria. While the specific name and geographic coordinates of the oilfield are withheld for confidentiality reasons, the facility is representative of typical oilfields in the region. It serves as a crucial point for the extraction and transportation of crude oil from nearby reservoirs before shipment.

The sampling process focused on key locations within the oilfield, including the produced water discharge point, the upstream section, and the downstream section, all of which are integral to the oil production process. At these strategic points, samples were carefully retrieved from the API skimmer unit (Figure 1), commonly referred to as the "saver pit," which serves as a primary collection point for produced water after the operational phase.

Figure 1: Sample collection from the API skimmer unit

The saver pit is a critical component in the oilfield's treatment and separation process. It ensures the proper collection of water produced during oil extraction operations. Once the water is collected, it is subjected to preliminary treatment and quality assessment.

This sampling location was selected due to its significance in the context of crude oil production and wastewater treatment, which aligns with the study's objective of evaluating the effectiveness of cassava peel biochar in treating oily wastewater.

2.2 Biochar Preparation

In this study, biochar was produced from cassava peels using a method primarily based on the procedures outlined in [15], with slight modifications. A 3000 g sample of cassava peels was meticulously sourced from a local cassava processing mill located in the Ugbomro community, situated within the Uvwie Local Government Area of Delta State, Nigeria.

The cassava peels (figure 2) were subjected to a thorough preparation process to ensure the highest quality biochar.

Figure 2: A; Freshly washed cassava peels, B; Cassava Peel Biochar produced from slow pyrolysis

The procedure involved several steps, as illustrated below;

2.2.1 Step A: Pre-Washing and Initial Drying

The collected cassava peels were first subjected to pre-washing with water to remove any surface impurities. Following this initial wash, they were carefully sun-dried for a period of 7 days to attain optimal moisture levels (as illustrated in Figure 2A).

2.2.2 Step B: Secondary Washing and Air Drying

After the initial drying period, the cassava peels underwent a second round of washing to eliminate any remaining contaminants. Subsequently, they were left to air dry for an additional 24 hours. This meticulous drying process ensured that the cassava peels were suitably prepared for the subsequent pyrolysis stage.

2.2.3 Step C: Slow Pyrolysis

The properly prepared cassava peels were then subjected to slow pyrolysis within a controlled environment. The pyrolysis took place in an oven set to a temperature of 300°C for a duration of 4 hours, with the exclusion of oxygen. This methodology aligns with the principles described in [16]. The outcome of this pyrolysis process was the creation of a dark, carbon-rich substance commonly referred to as biochar as shown in Figure 2B.

The rigorous preparation process ensures the biochar's purity and integrity for use in subsequent experiments, and it adheres to established pyrolysis techniques.

2.3 Experimental Design

A laboratory experimental setup utilizing a bio-sand water filter was meticulously designed and employed as the treatment plant for produced water. The design encompassed a two-step filtration process, with the primary step employing a bio-filter system composed of 300g of gravel, followed by the secondary filter system, which combined gravel, biochar, and sand. The complete system setup is visualized in Figure 3.

Figure 3: Two-Step Digestive System Setup

The digestive system, as outlined below, was carefully constructed and configured to ensure accurate and consistent results:

2.3.1 Primary Inlet Configuration

A five-liter container, fitted with a perforated cover lid, served as the primary inlet to the digestive system. This configuration allowed for controlled and uniform inflow of produced water into the system. To facilitate fluid flow through the system, several PVC pipes were strategically integrated into the container, ensuring a smooth and regulated distribution of water.

2.3.2 Secondary Filter System Setup

The secondary filter system, a critical component of the experimental design, was arranged in three distinct configurations, each with varying compositions. The specific configurations are detailed as follows:

First Configuration (B1): This setup consisted of five distinct layers, organized from bottom to top as follows: 100g of gravel, 300g of semi-solid biochar, 1000g of sand, 300g of solid biochar, and an additional 1000g of sand, measured in a weight/volume (w/v) format.

Second Configuration (B2): Similarly, this configuration involved five layers, arranged as 1000g of gravel, 200g of semi-solid cassava biochar, 1000g of sand, 200g of solid cassava biochar, and a final 100g of sand from bottom to top.

Third Configuration (B3): In this setup, five layers were established, consisting of 1000g of gravel, 300g of semi-solid biochar, 900g of sand, 300g of solid biochar, and 900g of sand, all measured in a weight/volume ratio.

Figure 4: Produced Water Samples Collected after Filtration

2.4 Sample Collection

Water samples sourced from the API skimmer units were passed through the filtration system daily over a duration of 30 days. After this period, samples were systematically collected for subsequent analysis to assess the filtration system's effectiveness in removing contaminants from the produced water.

2.5 Analytical Methods for Water Parameter Assessment

An array of analytical techniques was employed to assess critical water parameters. These analyses were pivotal to understanding the quality and composition of the water samples under investigation. Each method utilized was rigorously executed and adhered to industry standards for accuracy and reliability.

2.5.1 Physicochemical Parameters

i. *pH, Temperature, Turbidity and Total Suspended Solids (TSS), Dissolved Oxygen (DO), Electrical Conductivity and Total Dissolved Solids (TDS):* The pH, temperature, turbidity, TSS, DO, EC, and TDS of the water samples were measured using a Benchtop meter, ensuring precision and repeatability. Prior to each measurement, the meter was calibrated using certified reference standards, following recognized protocols.

ii. *Biochemical Oxygen Demand (BOD):* BOD, a critical indicator of organic pollutant levels, was determined according to established methodologies. The BOD analysis was performed to assess the oxygen consumption by microorganisms when breaking down organic matter.

iii. *Salinity Assessment:* The method described by [17] was employed to evaluate the salinity levels within the water samples. This approach is recognized for its accuracy in determining the salt content, contributing to a total understanding of the water's composition.

iv. *Chemical Oxygen Demand (COD) Determination:* The assessment of COD, a significant parameter reflecting the water's organic pollutant load, was carried out in accordance with the protocol established by [18]. This analytical method is renowned for its precision and is integral to characterizing water quality.

v. *Total Petroleum Hydrocarbon (TPH):* The concentration of TPH, an essential parameter in evaluating oil and hydrocarbon contamination, was quantified using a Gas Liquid Chromatograph (GC), in alignment with the standardized procedure documented in [19].

vi. *Polyaromatic Hydrocarbon (PAH):* The concentration of PAH, a crucial component in the assessment of hydrocarbon pollutants, was determined as per the protocol outlined in [20]. This analysis is instrumental in understanding the water's contamination levels.

vii. *Heavy Metal Concentration Assessment:* The heavy metal concentrations were analyzed utilizing a PG Instrument Atomic Absorption Spectrophotometer (AAS-model AA500), a state-of-the-art instrument known for its precision in detecting and quantifying heavy metals.

2.6 Statistical Analysis

The mean of the concentration of heavy metals, organic pollutants, and Langmuir and Freundlich Isotherms were computed using Microsoft Excel 2016.

III. Results and Discussion

3.1 Physicochemical Characteristics of Sample Water before and after Treatment

The analysis of physicochemical parameters for wastewater samples before and after treatment, as illustrated in Figure 5, provides an understanding of the efficacy of cassava peel biochar in conjunction with a bio-sand filtration system for treating oily wastewater in the Niger Delta region. These results are instrumental in assessing the treatment process's impact on various water quality parameters and its suitability for environmental discharge or reuse.

3.1.1 pH Variations

One of the noteworthy findings is the significant alteration in pH levels. The initial water possessed an alkaline pH of 8.01. However, following treatment (B1, B2, and B3), the pH values experienced a noticeable reduction, ranging from 6.35 to 6.43. This shift towards slight acidity suggests interactions between cassava peel biochar and the oily wastewater, moving the water closer to a neutral pH, a favourable condition for environmental discharge.

3.1.2 Electrical Conductivity (EC)

The measurements of EC revealed distinctions among the treated samples. Untreated water exhibited an EC of 1997 µS/cm, with B2 and B3 displaying the highest EC values, reaching 2560 and 3410 µS/cm, respectively, indicating a higher ionic content. In contrast, B1 showed the lowest EC value at 2560 µS/cm. These variations are of paramount importance, indicating differences in ion and solute composition. Monitoring EC is crucial to confirm that treated water aligns with regulatory standards.

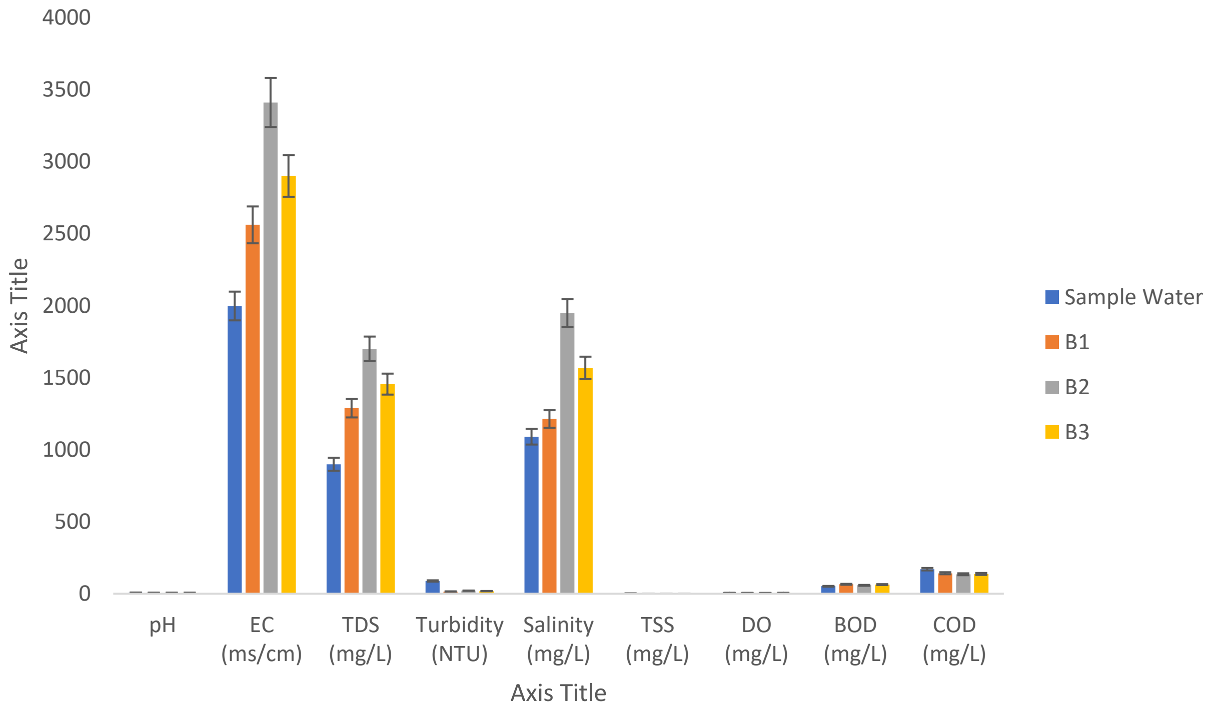

Figure 5: Concentration of Physicochemical Parameters in Untreated and Treated Water Samples

3.1.3 Total Dissolved Solids (TDS)

TDS revealed that untreated water contained 899 mg/L TDS. Interestingly, B2 and B3 exhibited higher TDS values at 1288 and 1700 mg/L, respectively, while B1 displayed the lowest TDS levels at 1288 mg/L. The increase in TDS in B2 and B3, compared to untreated water, may be attributed to the leaching of dissolved substances from the biochar. Maintaining TDS within permissible limits is essential, as elevated TDS can

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affect water's suitability for various applications, including discharge and reuse.

3.1.4 Turbidity Reduction

The assessment of turbidity, indicative of water clarity, revealed a substantial reduction in all treated samples. Untreated water had a high turbidity of 88.7 NTU. B1 displayed the most significant improvement, with a turbidity of 15.66 NTU, followed by B3 at 17.9 NTU. In contrast, B2 exhibited a relatively higher turbidity value of 21.22 NTU. This suggests the effectiveness of the bio-sand filtration system in removing suspended particles, while also highlighting the potential for further optimization of the filtration process to achieve consistent results.

3.1.5 Salinity Impact

Salinity levels increased in B2 and B3, possibly due to interactions between biochar and saline components in the wastewater. Untreated water had a salinity of 1090 mg/L, while B2 and B3 exhibited higher salinity levels at 1213 and 1948 mg/L, respectively. Managing salinity is vital, especially for water that may be discharged into the environment, as elevated salinity can have adverse effects on ecosystems.

3.1.6 Total Suspended Solids (TSS)

The results indicated a successful reduction in TSS in all treated samples. Untreated water contained 1.9 mg/L TSS, while B1, B2, and B3 showed significantly lower values at 0.226 mg/L, 0.128 mg/L, and 0.147 mg/L, respectively. The system's efficiency in removing suspended solids contributes to improved water clarity and quality.

3.1.7 Dissolved Oxygen (DO)

The levels of DO remained consistent, with all treated samples exhibiting values within the range of 5.1 to 5.5 mg/L. Consistent DO levels are essential to support aquatic life in the treated water, ensuring it remains conducive for ecosystems.

3.1.8 BOD and COD

The treated samples showed a noteworthy reduction in BOD and COD compared to untreated water. Untreated water had BOD and COD values of 51.5 mg/L and 170 mg/L, respectively, while B1, B2, and B3 exhibited lower values, signifying the effectiveness of the bio-sand filtration system, enhanced by cassava peel biochar, in treating oily wastewater and reducing its environmental impact. The reduction in the concentration of physicochemical parameters is consistent with [7], where a percentage reduction of 56.89% - 83.44% was recorded, with the exception of COD, which showed a reduction of 32.67%.

These results underscore the promising potential of the bio-sand filtration system incorporating cassava peel biochar for treating oily wastewater in the Niger Delta. While the system has demonstrated success in improving several water quality parameters, particularly in terms of turbidity, TSS, BOD, and COD, it is imperative to carefully monitor and make necessary adjustments to address parameters such as EC, TDS, and salinity, ensuring full compliance with environmental regulations and standards. This study marks a significant step in mitigating the impact of oily wastewater in the Niger Delta region and contributes to the growing body of knowledge in sustainable wastewater treatment practices.

3.2 Heavy Metal Removal Using Cassava Peel Biochar through Bio-Sand Filtration

The heavy metal concentrations in the treated oily wastewater samples in this study are presented in Figure 6, revealing the impact of cassava peel biochar through bio-sand filtration on heavy metal removal. The results underscore the potential of cassava peel biochar to effectively mitigate specific heavy metals, Pb, nickel Ni, copper Cu, Cr, Fe, and Zn, albeit with variations in removal efficiency. Notably, the concentrations of Cd and V showed less efficient removal.

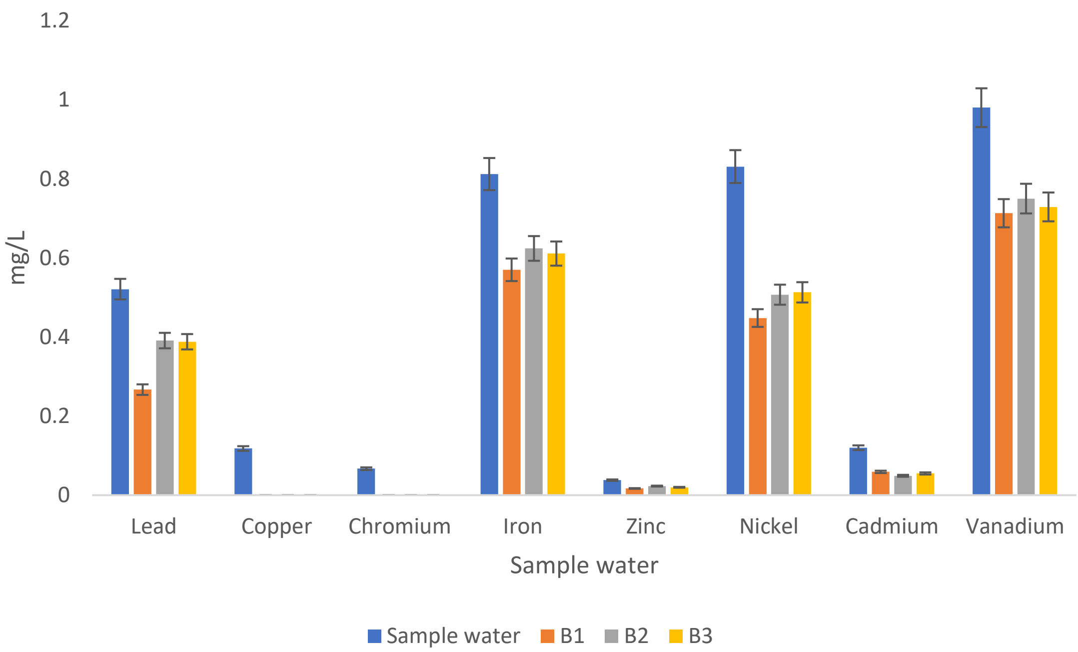

Figure 6: Heavy Metal Concentrations in Oily Wastewater Treated with Cassava Peel Biochar

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3.2.1 Lead (Pb) Concentrations

In the untreated sample water, the Pb concentration was 0.521 mg/L. However, all biochar setups (B1, B2, and B3) demonstrated a reduction in Pb concentrations. B1 exhibited a Pb concentration of 0.267 mg/L, while B2 and B3 showed concentrations of 0.391 mg/L and 0.388 mg/L, respectively. These findings underscore the effectiveness of cassava peel biochar and bio-sand filtration in reducing Pb concentrations, with B3 demonstrating the most promising outcome.

3.2.2 Nickel (Ni) Concentrations

The concentration of Ni was reduced in B1, B2, and B3 setups. The untreated water had a Ni concentration of 0.832 mg/L, while B1, B2, and B3 exhibited concentrations of 0.448 mg/L, 0.507 mg/L, and 0.513 mg/L, respectively. These results emphasize the efficacy of the treatment process in diminishing Ni concentrations.

3.2.3 Copper (Cu) and Chromium (Cr)

In both B2 and B3 setups, Cu and Cr concentrations were entirely removed, reaching 0 mg/L. In the untreated water, Cu and Cr concentrations were 0.118 mg/L and 0.067 mg/L, respectively. The complete removal of these heavy metals highlights the exceptional efficiency of cassava peel biochar and bio-sand filtration in eliminating Cu and Cr from wastewater, signifying a substantial improvement in water quality.

3.2.4 Iron (Fe) and Zinc (Zn)

B2 and B3 setups demonstrated reductions in Fe and Zn concentrations. In B2, the Fe concentration dropped to 0.624 mg/L, with Zn reaching 0.023 mg/L. In B3, the Fe concentration reduced to 0.611 mg/L, while Zn reached 0.02 mg/L. This represents a notable enhancement compared to B1, which exhibited Fe and Zn concentrations of 0.57 mg/L and 0.017 mg/L, respectively. B2 and B3 outperformed B1 in reducing Fe and Zn levels.

3.2.5 Cadmium (Cd) and Vanadium (V)

However, the removal of Cd and V in B2 and B3 setups was less efficient compared to B1. Cd and V were still detected in B2 and B3, possibly owing to variations in setup configurations and biochar types used.

These findings align with prior research, such as [21], which reported substantial removal rates of Pb (II) and Cu (II) from wastewater using adsorbents derived from cassava peels. Similarly, [22] recorded significant reductions in Cd and Cr ions using cassava peels, reinforcing the potential of cassava peel-based biochar in heavy metal removal.

The results underscore the promise of cassava peel biochar in combination with bio-sand filtration for reducing heavy metal concentrations in oily wastewater from the Niger Delta. Nevertheless, the efficiency varies based on setup configurations and heavy metal types. Further research is warranted to optimize the treatment process for enhanced performance. Additionally, the environmental and cost implications of implementing this treatment method on a larger scale in the Niger Delta region should be assessed for feasibility and broader impact.

These findings underscore the significance of refining treatment processes and gaining deeper insights into the adsorption mechanisms involved. Continuous investigations are imperative to enhance the effectiveness of cassava peel biochar as a sustainable solution for treating oily wastewater not only in the Niger Delta but also in analogous regions.

3.3 Organic Pollutant Removal and Reduction in Treated Wastewater Samples

Figure 7 illustrates the concentrations of selected organic compounds, specifically TPH and PAHs, in the treated wastewater samples (B1, B2, and B3), shedding light on the efficacy of cassava peel biochar in oily wastewater treatment.

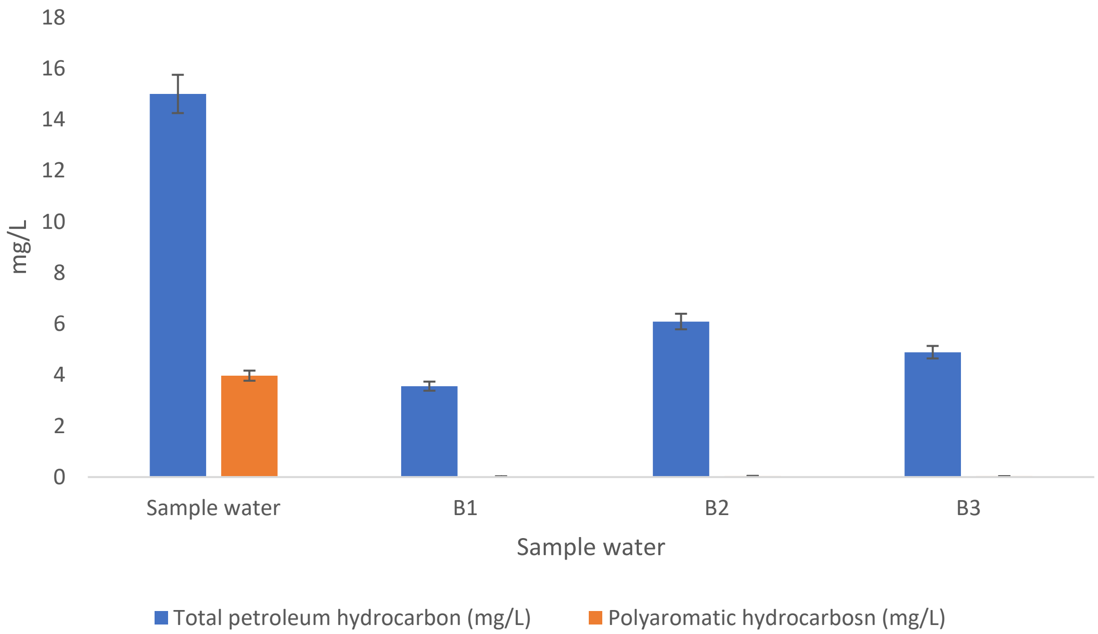

Figure 7: Concentrations of Organic Pollutants in Oily Wastewater Treated with Cassava Peel Biochar

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3.3.1 Total Petroleum Hydrocarbon (TPH) Concentrations

The TPH concentrations in the samples were as follows: B1 (15 mg/L), B2 (3.56 mg/L), and B3 (6.09 mg/L). Notably, the results reveal a substantial reduction in TPH concentrations in samples B2 and B3 compared to B1, suggesting the effectiveness of both B2 and B3 setups, employing cassava peel biochar in oil removal. This reduction underscores the potential of these biochar-based setups in treating oily wastewater more efficiently than B1.

3.3.2 Polyaromatic Hydrocarbons (PAHs) Concentrations

The PAH concentrations exhibited a significant decrease in both B2 and B3 setups in comparison to B1. The concentration of PAH reduced from 3.97 mg/L in the untreated sample water to 0.025 mg/L, 0.043 mg/L, and 0.033 mg/L in B1, B2, and B3 respectively. This reduction underscores the efficacy of cassava peel biochar in the filtration process in removing potentially harmful components from the wastewater, offering clear environmental benefits. It is noteworthy that the ability of cassava peels to remove organic pollutants was similarly demonstrated by [23], further underlining the potential of cassava peel biochar in wastewater treatment.

The study results clearly demonstrate the promise of cassava peel biochar when integrated into bio-sand filtration for the treatment of oily wastewater in the Niger Delta. The substantial reductions in both TPH and PAH concentrations in B2 and B3 setups, relative to B1, emphasize the efficiency of biochar-based setups in removing oil and harmful hydrocarbons from the wastewater. These findings are encouraging and underscore the potential of cassava peel biochar as a sustainable and environmentally friendly solution for wastewater treatment in the region.

3.4 Future Perspectives

While these results are promising, further research and in-depth analysis are warranted to gain deeper insights into the specific mechanisms governing pollutant removal. Additionally, a focus on the long-term sustainability and feasibility of this treatment approach is essential. The study paves the way for ongoing investigations to optimize the utilization of cassava peel biochar and bio-sand filtration in the quest for effective and eco-friendly solutions to treat oily wastewater, not only in the Niger Delta but in analogous regions facing similar challenges. This research aligns with the growing importance of environmentally responsible wastewater treatment practices, aiming for a healthier and more sustainable future.

3.5 Effect of Cassava Peel on the Removal of Contaminants in Sample Water

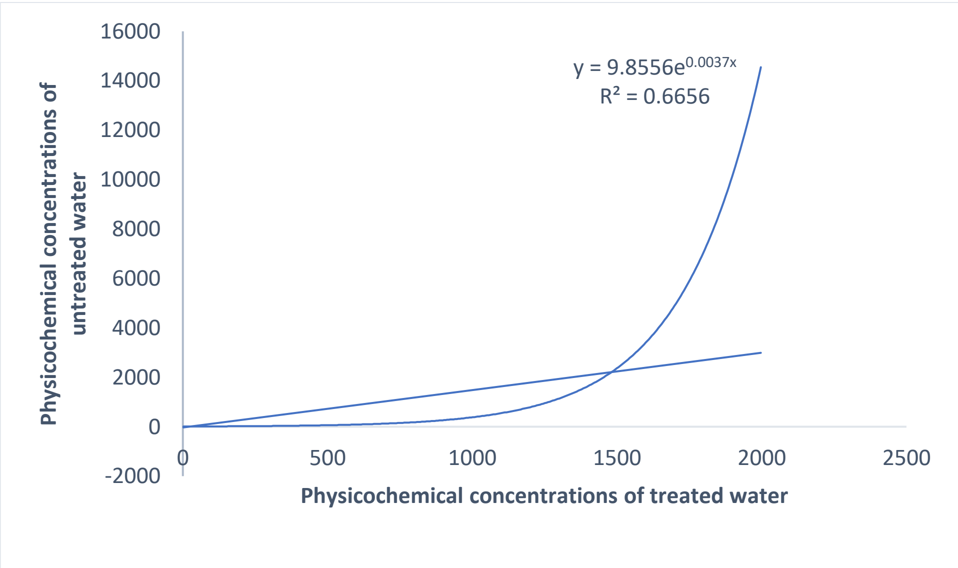
Figure 8 illustrates the adsorption isotherms of cassava peel biochar utilized in this study, shedding light on its remarkable ability to remove contaminants from sample water.

3.5.1 Langmuir and Freundlich Isotherms

The first graph presents a substantial reduction in physicochemical concentrations when comparing untreated water to water treated with cassava peel biochar. The data is fitted to Langmuir and Freundlich isotherms, both exhibiting robust correlations with an R^2 value of 0.6656. This underlines the extraordinary adsorption capacity of cassava peel biochar, emphasizing its efficacy in effectively removing a diverse range of contaminants from water.

3.5.2 Efficiency in Heavy Metal Removal

The second graph further highlights the positive impact of cassava peel biochar treatment, showcasing a significant decrease in heavy metal concentrations with an impressive R^2 value of 0.9774. This near-linear relationship indicates that the treatment method is highly efficient in reducing heavy metal contamination, a pivotal aspect of enhancing water quality.



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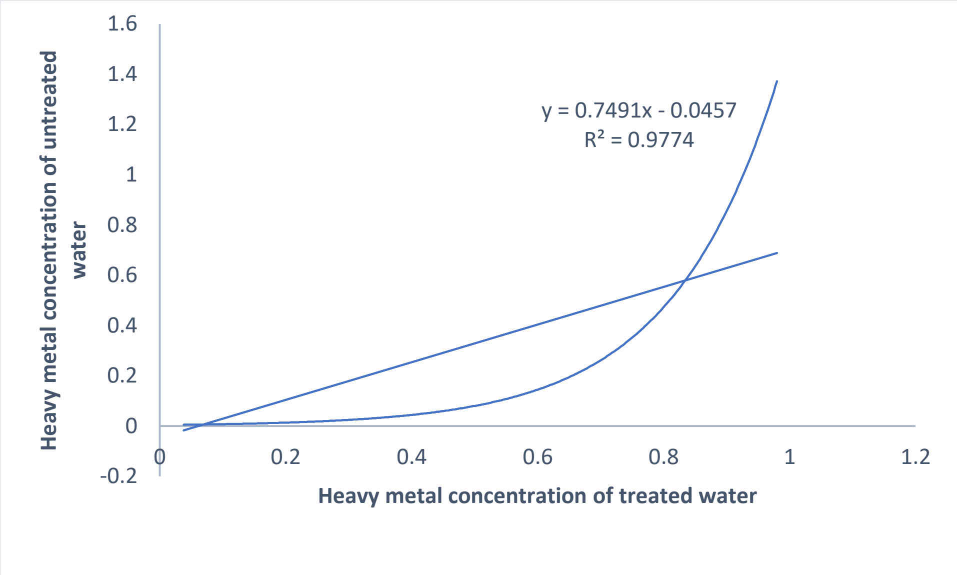

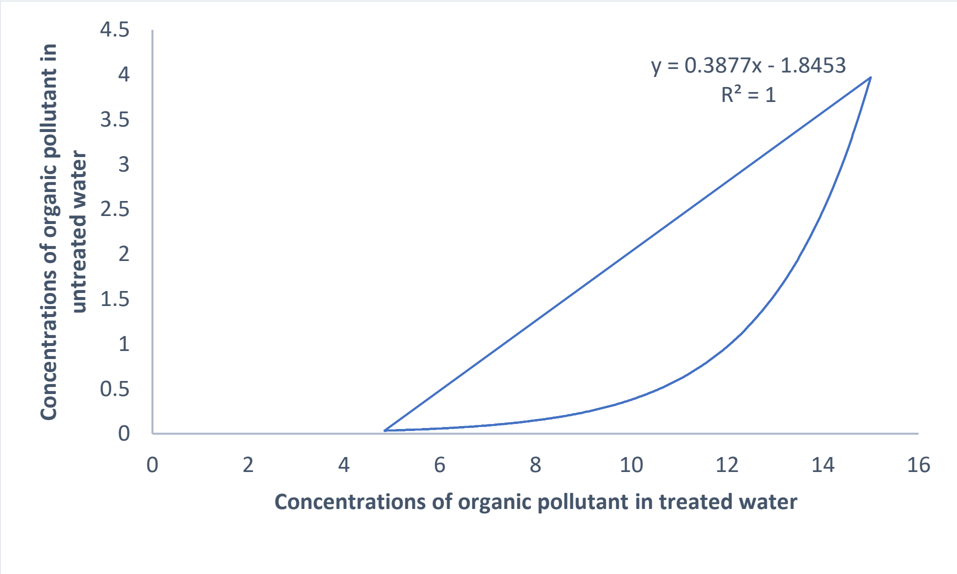

Figure 8: Adsorption Rate and Efficiency of Cassava Adsorbents for Contaminant Removal in Sample Water

3.5.3 Removal of Organic Pollutants

In the third graph, the concentrations of organic pollutants in untreated water are juxtaposed with those in water treated with cassava peel biochar. The data reveals a nearly perfect linear relationship with an R^2 value of 1, providing unequivocal evidence that the treatment process is exceptionally effective in removing organic pollutants. This result not only validates the potential of cassava peel biochar in elevating water quality but also quantifies the extent of this impact.

Collectively, these findings offer compelling evidence for the pivotal role of cassava peel biochar as a sustainable, cost-effective, and highly efficient solution for addressing water pollution in the Niger Delta. The adsorption isotherms reflect the exceptional potential of cassava peel biochar to remove contaminants, encompassing physicochemical parameters, heavy metals, and organic pollutants. Moreover, the near-linear relationships observed in these graphs highlight the consistent and robust performance of cassava peel biochar across different contaminant types. Furthermore, these findings reinforce the importance of developing and implementing sustainable, bio-based solutions for water pollution, not only in the Niger Delta but also in regions facing similar environmental challenges. This research contributes to the growing body of knowledge that supports environmentally responsible approaches to water quality enhancement and sets a high standard for future endeavours in this field.

IV. Conclusion

This study represents an assessment of the effectiveness of cassava peel biochar in mitigating oily wastewater pollution through bio-sand filtration in the challenging situation of the Niger Delta, demonstrating its substantial potential as an environmentally sustainable solution. The exceptional ability of cassava peel biochar to target both inorganic and organic contaminants underscores its versatility and relevance in addressing diverse water quality challenges. These compelling findings advocate strongly for the adoption of cassava peel biochar as a cost-effective and highly efficient means to enhance water quality and combat the widespread consequences of oily wastewater pollution, extending its implications beyond regional boundaries to align with global sustainability goals. However, the study recognizes the need for further research and optimization to ensure compliance with environmental standards and maximize efficacy on a larger scale, thus reinforcing the significance of this research in advancing our understanding of sustainable water treatment methods and our collective commitment to a healthier planet. This work exemplifies the essence of multidisciplinary and globally relevant scientific inquiry.

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