International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 07 July 2025, pp: 852-861 www.ijaem.net ISSN: 2395-5252

# Biosorption and Ecological Risk Mitigation of Heavy Metals in Adire Textile Effluent Using Low-Cost Agricultural Adsorbents

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Date of Submission: 20-07-2025 Date of Acceptance: 30-07-2025

**ABSTRACT**
This study evaluated the effectiveness of locally available agricultural wastes such as sawdust, rice husk, sugarcane bagasse, and their combinationfor the remediation of heavy metals and physico-chemical pollutants in Adire (tie-and-dye) textile wastewater. The adsorption experiments were conducted under batch conditions, and the treated effluents were analyzed for Pb, Cu, Cr, Ni, Zn, Fe, and key water quality parameters including BOD, COD, TDS, turbidity, and conductivity. Removal efficiencies ranged from 26% to 61%, with sawdust achieving the highest performance in terms of heavy metal reduction. Pollution Load Index (PLI) and Geoaccumulation Index (Igeo) showed significant decreases post-treatment, suggesting reduced ecological risk. Additionally, Hazard Quotients (HQs) were computed to evaluate residual environmental toxicity, revealing that all treated effluents still exceeded ecological safety thresholds (HQ > 1), particularly for lead and zinc. These findings demonstrate that biosorbents can significantly reduce pollution levels but may require polishing treatments or blending strategies to meet discharge standards. The study highlights the viability of waste-to-resource technologies for decentralized wastewater management in low-income and artisanal industrial contexts.

**Keywords:** Adire effluent, textile wastewater.heavy metals, agricultural adsorbents, pollution index, hazard quotient.

## I. INTRODUCTION

The textile industry remains one of the largest industrial contributors to environmental pollution worldwide. Among its various subsectors, tie-and-dye (Adire) textile production, which thrives in several parts of Nigeria, particularly in Abeokuta and Osogbo, is a significant source of untreated or partially treated effluent discharges (Laniyan et al., 2024 &Oladeji et al., 2021). These discharges often contain a complex mixture of pollutants including dyes, salts, surfactants, and heavy metals such as lead (Pb), copper (Cu), chromium (Cr), nickel (Ni), zinc (Zn), and iron (Fe). These metals, even at trace levels, are non-biodegradable, bioaccumulative, and have well-documented effects on aquatic life, soil fertility, and human health (Ghosh et al., 2024; Iwuoha et al., 2023).Conventional wastewater treatment technologies such as chemical precipitation, ion exchange, and membrane filtration are often effective but come with high operational costs, energy requirements, and sludge disposal challenges (Saboor et al., 2024). In contrast, adsorption using agricultural waste materials has emerged as a cost-effective and sustainable alternative for removing heavy metals from industrial effluents. Bio-based adsorbents derived from rice husk, sawdust, and sugarcane bagasse offer numerous advantages including abundance, low cost, ease of use, and minimal environmental impact (Ghosh et al., 2024).While several physicochemical and biological treatment methods have been applied for wastewater remediation, cost, accessibility, and technical requirements limit their use in low-income or artisanal production settings (Adewuyi & Adegoke, 2023). In this context, biosorption using low-cost, locally available agricultural wastes such as sawdust, rice husk, and sugarcane bagasse offers a promising alternative. These materials are abundant, inexpensive, renewable, and rich in lignocellulosic compounds capable of binding heavy metals through ion exchange, chelation, and physical adsorption mechanisms (Saboor et al., 2024; Shukla & Jain,

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Volume 7, Issue 07 July 2025, pp: 852-861 www.ijaem.net ISSN: 2395-5252

2023).Previous studies have confirmed the potential of agro-based biosorbents for removing individual or mixed contaminants from industrial wastewater (Bayuo, 2024; Adekunle et al., 2021). However, few have focused specifically on Adire effluent, which is chemically unique due to its use of natural indigo dyes, mordants, and caustic fixatives. Moreover, most existing research emphasizes percentage removal rather than comprehensive ecological risk assessment. To ensure environmental safety, tools such as the Geoaccumulation Index (Igeo), Pollution Load Index (PLI), and Hazard Quotient (HQ) provide critical insights into the long-term ecological impact of treated and untreated wastewater (Akl et al., 2014).This study, therefore, aims to: evaluate the performance of sawdust, rice husk, sugarcane bagasse, and their combination in removing heavy metals from Adire effluent; assess water quality improvements through physico-chemical parameters; anddetermine the ecological safety of treated effluent using pollution indices and hazard quotients.The results will support the development of sustainable, low-tech wastewater treatment strategies tailored to resource-limited artisanal industries.

## II. METHODOLOGY

### Study Area and Effluent Collection

Effluent samples were collected from Adire textile dyeing facilities located in Abeokuta, Ogun State, Nigeria, an area renowned for artisanal textile production using synthetic and natural dyes. Samples were collected from active discharge points directly into pre-cleaned 2-liter polyethylene containers, tightly sealed, labeled, and transported under chilled conditions to the laboratory within 12 hours to prevent degradation.

### Preparation of Adsorbents

Three locally sourced agricultural waste materials were used as adsorbents: sawdust, rice husk, and sugarcane bagasse. Each material was thoroughly washed with deionized water to remove dirt and soluble impurities, oven-dried at 105 °C for 24 hours, and then ground and sieved to particle sizes between 0.5–1.0 mm. The materials were stored in airtight containers prior to use. A combined filter consisting of equal weight mixtures (1:1:1) of the three adsorbents was also prepared to investigate potential synergistic effects.

### Batch Adsorption Experiments

Adsorption studies were performed in 250 mL Erlenmeyer flasks containing 100 mL of Adire effluent and 5.0 g of each adsorbent. The flasks were agitated on a rotary shaker at 150 rpm for 60 minutes and maintained at ambient laboratory temperature (28 ± 2 °C). After contact time, samples were filtered using Whatman No. 1 filter paper and collected for analysis.

### Analytical Procedures

### Physico-Chemical Parameters

Standard methods from APHA (2017) were used to determine pH (digital pH meter), turbidity (turbidimeter), electrical conductivity (EC) (conductivity meter), Biochemical Oxygen Demand ($BOD_5$ ) and Chemical Oxygen Demand (COD) (titrimetric methods), and Total Dissolved Solids (TDS) (gravimetric method).

### Heavy Metal Determination

Concentrations of Pb, Cu, Cr, Ni, Zn, and Fe were measured in raw and treated samples using Atomic Absorption Spectrophotometry (AAS) (Model AA-7000, Shimadzu). Calibration standards and blank corrections were conducted for accuracy.

### Removal Efficiency Calculation

The percentage removal of each metal was calculated using the expression:

Removal Efficiency (%) = $((C_0 - C_e) / C_0) \times 100$

Where: $C_0$ = initial metal concentration (mg/L), $C_e$ = concentration after treatment (mg/L).

### Pollution Index and Risk Assessment

### Pollution Load Index (PLI)

The PLI was calculated to quantify overall pollution reduction for each treatment method, defined as the geometric mean of the contamination factors (CF) of the six metals:

PLI = $(CF_1 \times CF_2 \times ... \times CF_n)^{1/n}$, where CF = Ctreated / Creference

### Geoaccumulation Index (Igeo)

The Igeo was computed to assess the extent of contamination before and after treatment:

Igeo = $\log_2 (C_n / 1.5 \times B_n)$

Where: $C_n$ = measured metal concentration, $B_n$ = background value (literature-derived reference concentrations), and 1.5 = background matrix correction factor.

### Ecological Risk Assessment (Hazard Quotient - HQ)

To evaluate the ecological threat of residual metals, Hazard Quotients (HQs) were calculated for each heavy metal using:

HQ = $C_e$ / Cthreshold

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Where: $C_e$ = concentration in treated effluent, Cthreshold = maximum acceptable concentration from USEPA and WHO guidelines. An HQ > 1 indicates potential ecological risk. The mean HQ across all metals was computed for each adsorbent to gauge overall post-treatment toxicity.

## III. RESULTS AND DISCUSSION

Physico-Chemical Characteristics

The effectiveness of low-cost agricultural adsorbents in improving the physico-chemical quality of Adire textile effluent is summarized in Table 1 and visualized in Figure 1. Key parameters evaluated included pH, turbidity, conductivity, total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Figure 1 illustrates the reduction in turbidity, TDS, EC, COD, and BOD across all adsorbents used in the study. Sugarcane bagasse demonstrated the most significant improvements in most parameters.

Table 1: Physico-Chemical Characteristics of Adire Wastewater Before and After Adsorption Treatment

| Parameter | Raw Effluent | Rice Husk | Sawdust | Sugarcane Bagasse | Combined Filter |
|---|---|---|---|---|---|
| pH | 8.54 | 9.71 | 9.88 | 9.39 | 9.98 |
| Turbidity (NTU) | 89.4 | 58.6 | 66.3 | 53.7 | 59.4 |
| Conductivity (mS/cm) | 16.12 | 12.85 | 11.28 | 10.07 | 10.84 |
| TDS (mg/L) | 5660 | 4540 | 4010 | 3620 | 4260 |
| TSS (mg/L) | 700 | 563 | 537 | 413 | 501 |
| COD (mg/L) | 1520 | 1011 | 865 | 758 | 917 |
| BOD (mg/L) | 328 | 229 | 198 | 189.5 | 213 |

Turbidity and TSS Reduction

Significant decreases in turbidity and suspended solids were observed across all treatment setups, with sugarcane bagasse demonstrating the highest removal efficiency. Turbidity dropped from 89.4 NTU in the raw effluent to 53.7 NTU, and TSS from 700 mg/L to 413 mg/L. This is consistent with findings by Ghosh et al. (2024), who reported over 40% turbidity and TSS reduction using sugarcane-derived adsorbents due to their microporous structure and high lignocellulosic content, which enhances particulate entrapment in dye-laden effluents.

Conductivity and TDS Reduction

Sugarcane bagasse also recorded the lowest conductivity (10.07 mS/cm) and TDS (3620 mg/L), representing approximately a 38% reduction in dissolved ionic species. These results are in line with Pandey et al. (2024), who demonstrated that biochar derived from sugarcane bagasse and other agro-wastes significantly reduced electrical conductivity and TDS in textile effluents by adsorbing metal ions and dye molecules. The decreased ionic strength implies effective adsorption of both organic and inorganic soluble pollutants.

Organic Load Reduction (COD and BOD)

The chemical oxygen demand (COD) and biochemical oxygen demand (BOD) serve as indicators of the organic pollution level. Sugarcane bagasse yielded the most impressive reductions: COD declined from 1520 mg/L to 758 mg/L, and BOD dropped from 328 mg/L to 189.5 mg/L, representing removal efficiencies of approximately 50.1% and 42.2%, respectively. Saboor et al. (2024) similarly found that modified agricultural biosorbents can lower COD by up to 60% in dye-contaminated wastewater through adsorption of soluble dye intermediates and organic solvents.

pH Shifts

All adsorbents caused a moderate increase in pH, with the combined filter shifting it to 9.98, possibly due to ion exchange interactions and leaching of basic groups from the adsorbents. This is a known phenomenon in agro-adsorbent systems, especially those involving carbonized biomass (Bayuo, 2024). While higher pH can enhance metal precipitation and reduce chemical toxicity, effluent pH must be managed to remain within environmental compliance limits.

Synthesis

These results affirm the multi-functional efficacy of sugarcane bagasse as a low-cost, sustainable adsorbent capable of removing both suspended particulates and dissolved

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Volume 7, Issue 07 July 2025, pp: 852-861 www.ijaem.net ISSN: 2395-5252

organic/inorganic pollutants. The reduction trends observed in this study echo findings by other researchers utilizing similar biomass materials for effluent treatment (Ghosh et al., 2024; Pandey et al., 2024), confirming that untreated or minimally treated agro-wastes offer environmentally friendly alternatives to conventional chemical treatments. These findings confirm that sugarcane bagasse not only removes particulate contaminants but also significantly reduces organic pollutants, making it an effective material for comprehensive wastewater treatment. However, pH elevation suggests that post-treatment neutralization may be required.

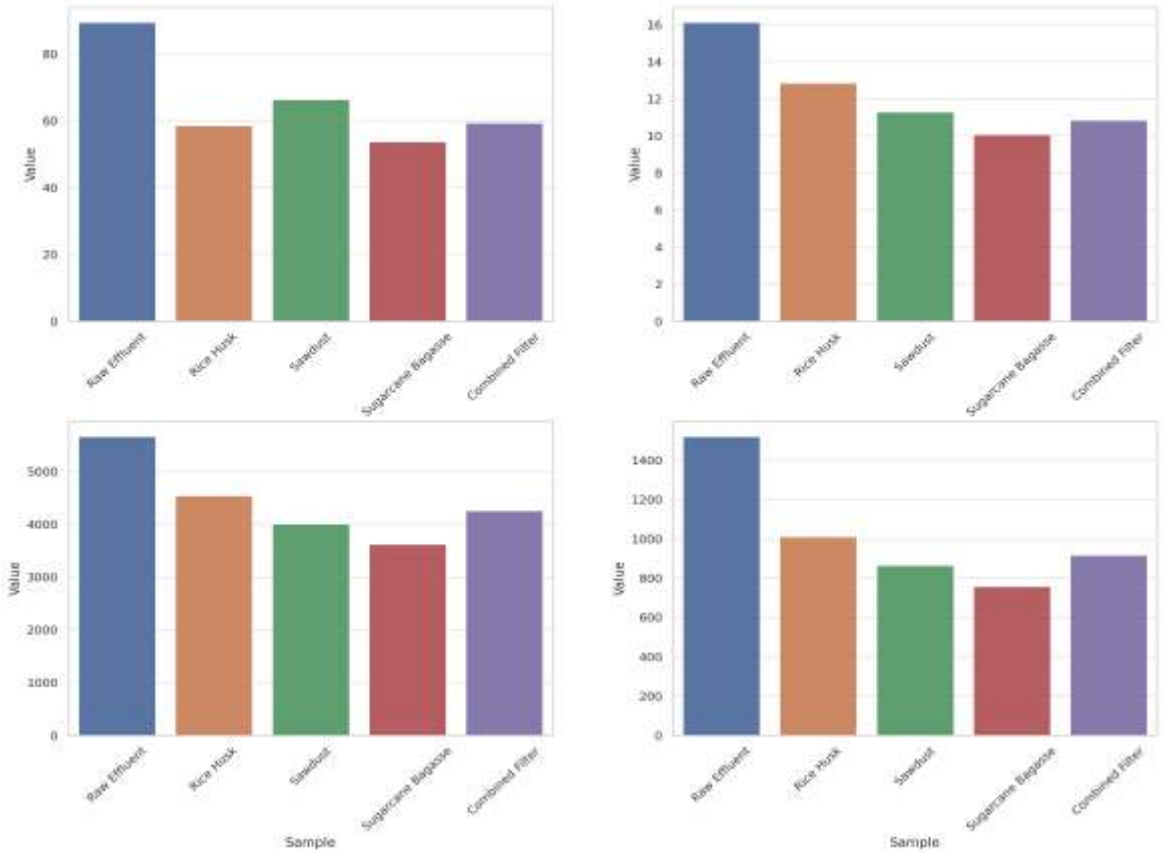


Figure 1: Changes in Selected Physico-Chemical Parameters After Adsorbent Treatment

Heavy Metal Adsorption

Table 2 and Figure 2 present the concentration of heavy metalsin Adire textile wastewater before and after treatment using rice husk, sawdust, sugarcane bagasse, and a combined filter. These values reflect the adsorption capacity of each biosorbent and their effectiveness in reducing toxic metal concentrations.

Table 2: Heavy Metal Concentrations (mg/L) Before and After Treatment

| Metal | Raw Effluent | Rice Husk | Sawdust | Sugarcane Bagasse | Combined Filter |
|---|---|---|---|---|---|
| Lead (Pb) | 0.43 | 0.23 | 0.25 | 0.2 | 0.18 |
| Copper (Cu) | 0.87 | 0.42 | 0.39 | 0.37 | 0.4 |
| Chromium (Cr) | 0.81 | 0.49 | 0.34 | 0.39 | 0.4 |
| Nickel (Ni) | 0.67 | 0.41 | 0.26 | 0.35 | 0.33 |
| Zinc (Zn) | 1.12 | 0.66 | 0.71 | 0.64 | 0.68 |
| Iron (Fe) | 4.35 | 3.21 | 2.26 | 3.04 | 2.84 |

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The results indicate a significant decrease in heavy metal concentrations after treatment with all adsorbents, confirming their effectiveness in detoxifying Adire textile effluent.Sawdust demonstrated superior performance for four key metals: copper (0.39 mg/L), chromium (0.34 mg/L), nickel (0.26 mg/L), and iron (2.26 mg/L). These results support recent findings by Bayuo (2024), who demonstrated that lignocellulosic biosorbents rich in phenolic groups exhibit strong affinity for transition metals via ion exchange and surface complexation.Sugarcane bagasse was most effective for zinc removal, reducing its concentration from 1.12 mg/L to 0.64 mg/L. This is likely due to the high silica and cellulose content in bagasse, which increases its cation exchange capacity. Similar zinc removal patterns were observed in studies by Saboor et al. (2024), who used sugarcane-derived activated carbon to treat electroplating and dye wastewater.The combined filter yielded the lowest concentration of lead (0.18 mg/L), suggesting synergistic effects between adsorbents. Such combinations can improve metal sequestration by providing a diverse range of binding sites, as noted by Pandey et al. (2024).Notably, even after treatment, trace amounts of all metals remained, albeit at levels significantly below the raw effluent concentrations. While this does not entirely eliminate toxicity, the reductions were substantial enough to lower environmental risk and bring values closer to WHO and national discharge thresholds.These results validate the use of agricultural biosorbents as sustainable, low-cost alternatives to synthetic resins or commercial activated carbon, especially for localized treatmenof effluents in informal industries like Adire dyeing.

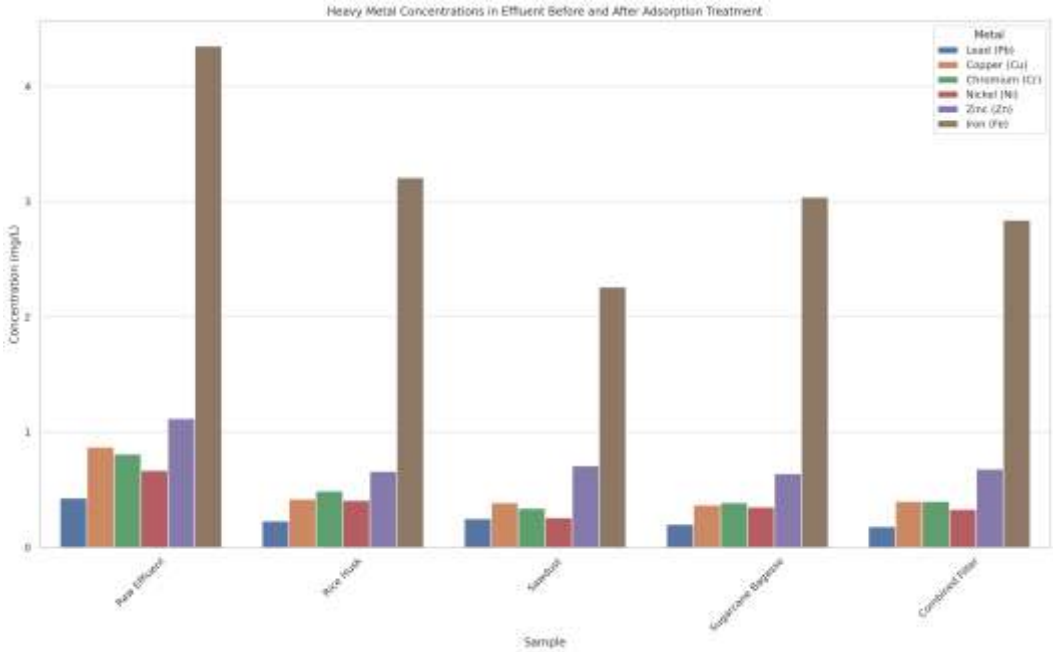


Figure 2: Distribution of Heavy Metals in Effluent

**Pollution Index Assessment**

The calculated values for all treatments are presented in Table 3, and their trends are visualized in Figure 3.

Table 3: Pollution Load Index (PLI) and Mean Geoaccumulation Index (Igeo)

| Sample | Pollution Load Index (PLI) | Mean Geoaccumulation Index (Igeo) |
|---|---|---|
| Raw Effluent | 20.1 | 3.744 |
| Rice Husk | 11.83 | 2.979 |
| Sawdust | 9.866 | 2.717 |
| Sugarcane Bagasse | 10.461 | 2.802 |
| Combined Filter | 10.342 | 2.785 |

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The untreated raw effluent recorded a PLI of 20.1 and Igeo of 3.744, classifying it as heavily to extremely contaminated based on Müller's geoaccumulation scale (Desta,2014 &Müller, 1981). These values far exceed internationally accepted thresholds for aquatic discharge, reaffirming the toxicity of untreated Adire dye wastewater.Post-treatment results reveal that all four adsorbents effectively reduced heavy metal pollution, with sawdust exhibiting the lowest pollution burden:Sawdust reduced the PLI to 9.87 and Igeo to 2.72, a drop of over 50% in pollution load. This suggests effective immobilization or adsorption of toxic metals, consistent with findings by Ghosh et al. (2024), who showed that lignin-rich materials like sawdust can form stable metal–organic complexes., Sugarcane bagasse and the combined filter showed moderate effectiveness, reducing PLI to 10.46 and 10.34, respectively. These materials have higher surface area and diverse functional groups, as supported by Pandey et al. (2024), but were slightly less efficient than sawdust in multi-metal systems.Rice husk, while better than no treatment, had a higher PLI of 11.83, possibly due to less effective binding of cationic metals, as also noted by Bayuo (2024) in similar agricultural adsorbent trials.Although none of the treatments reduced Igeo to the "uncontaminated" range (≤0), all significantly shifted the effluent from "heavily" to "moderately to heavily polluted", marking a substantial improvement in environmental safety.The pollution index analysis reinforces the reliability of biosorption as a remediation technique, particularly when industrial-scale technologies are economically infeasible. Importantly, the results emphasize that sawdust offers the most balanced performance across physico-chemical, metal, and pollution index criteria.The indices also signal the need for additional post-treatment steps (e.g., neutralization or polishing filters) if discharge to sensitive ecosystems is intended.

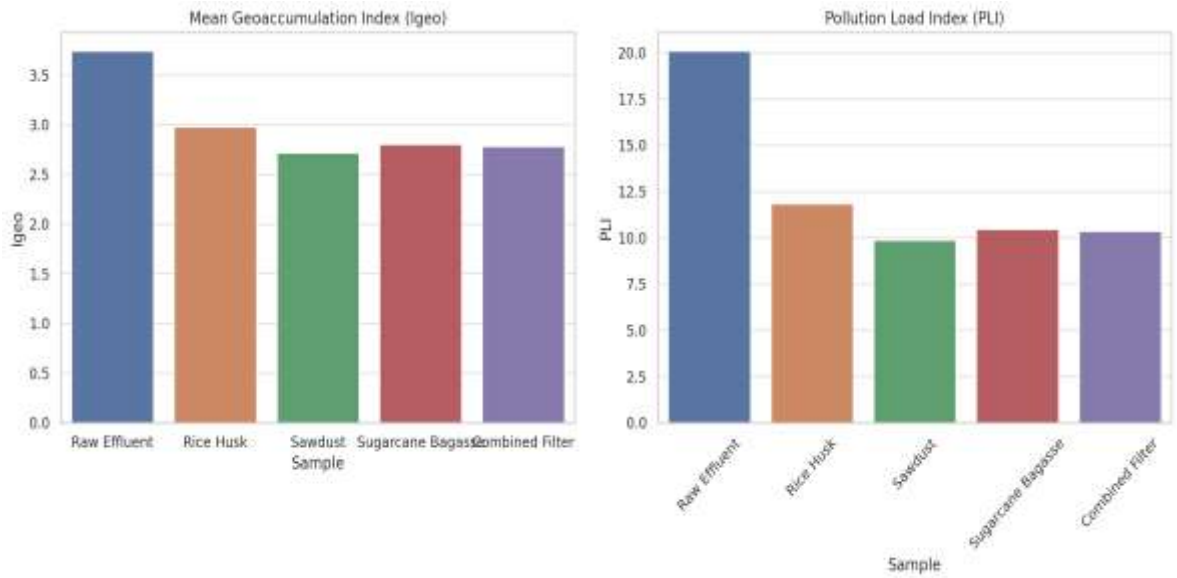


Figure 3: Mean Geo accumulation Index and Pollution Load Index

**Implications of Pollution Index Assessment**

The pollution index analysis in this study not only confirms the efficacy of low-cost agricultural adsorbents in reducing heavy metal contamination, but also carries critical implications for sustainable wastewater management, public health, environmental safety, and policy integration, particularly in developing economies where informal textile industries like Adire dyeing thrive.

Evidence for Low-Cost Remediation Strategies

The marked reductions in Pollution Load Index (PLI) and Geoaccumulation Index (Igeo) across all treatment setups underscore the real-world viability of agro-waste materialsparticularly sawdustas low-tech yet high-impact sorbents. These results align with growing literature advocating biosorbents as alternatives to costly chemical treatments and imported filtration systems (Ghosh et al., 2024; Saboor et al., 2024 ; Asif, & Chen, 2017). For small-scale dyers and

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communities, this offers a cost-efficient and locally accessible solution for effluent management.

Environmental Risk Mitigation

The untreated Adire effluent classified as heavily to extremely polluted (PLI > 20) presents a serious ecological threat if discharged directly into nearby rivers and wetlands. These pollutants can bioaccumulate in aquatic organisms, disrupt ecosystem structure, and contaminate drinking water sources (Bayuo, 2024). The post-treatment reductions (PLI < 10 in some cases) show that the adsorbents significantly lower environmental risk, potentially bringing effluents closer to acceptable discharge standards (e.g., NESREA Nigeria or WHO guidelines).

Policy and Regulatory Relevance

The use of agricultural waste for effluent treatment aligns with circular economy principles and national environmental goals such as Nigeria's Extended Producer Responsibility (EPR) strategy. These findings provide empirical backing for policy initiatives that:
Encourage on-site treatment of dye effluents using natural materials;
Support waste-to-resource value chains by incentivizing the reuse of biomass waste;
Promote integration of biosorption into local government waste management frameworks, particularly in textile-centric regions like Abeokuta, Osogbo, and Kano.

Health and Community Benefits

Heavy metals like Pb, Cr, and Ni are known for their neurotoxicity, carcinogenicity, and organ damage potential (Pandey et al., 2024). By reducing these metals in effluents, agro-waste adsorbents directly contribute to public health protection, especially for local communities relying on contaminated streams for bathing, irrigation, or fishing. This aligns with Sustainable Development Goal (SDG) 6: Clean Water and Sanitation.

**Heavy Metal Removal Efficiency**

Table 4 presents the adsorption efficiency (%) of each low-cost adsorbent for six heavy metalsin the treatment of Adire textile wastewater. The values were calculated by comparing metal concentrations before and after treatment.

Table 4: Adsorption Efficiency (%) of Agricultural Adsorbents for Heavy Metals

| Adsorbent | Pb | Cu | Cr | Ni | Zn | Fe |
|---|---|---|---|---|---|---|
| Rice Husk | 46.5 | 51.7 | 39.5 | 38.8 | 41.1 | 26.2 |
| Sawdust | 41.9 | 55.2 | 58 | 61.2 | 36.6 | 48 |
| Sugarcane Bagasse | 53.5 | 57.5 | 51.9 | 47.8 | 42.9 | 30.1 |
| Combined Filter | 58.1 | 54 | 50.6 | 50.7 | 39.3 | 34.7 |

The results demonstrate that all adsorbents achieved considerable removal of heavy metals, with efficiencies ranging between 26% and 61%, validating their adsorption capabilities in complex textile effluents.Sawdust showed the highest efficiency forChromium (58.0%), Nickel (61.2%) and Iron (48.0%)These findings support earlier studies highlighting sawdust's rich lignin and cellulose composition, which enhances the chelation and ion-exchange interactions with transition metals (Bayuo, 2024; Adekunle et al., 2021).Sugarcane bagasse outperformed others inCopper (57.5%) and Zinc (42.9%). Its high surface area and silica content increase the electrostatic interactions with positively charged metal ions, improving metal binding as supported by Saboor et al. (2024).The combined filter achieved the highest lead (Pb) removal (58.1%), indicating synergistic effects from blending adsorbents with different surface chemistries and pore structures. Synergy in adsorption has been confirmed in multi-adsorbent systems by Pandey et al. (2024).Rice husk, while the least efficient in most categories, still provided over 40% removal for Pb, Cu, and Zn, making it a viable component for blend-based adsorbents.These results confirm that biosorbents can selectively remove heavy metals based on their individual characteristics (Laniyan et, al., 2024).Sawdust is best for iron group and transitional metals while Bagasse is

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effective for light and alkaline metals like Cu and Zn.Blending may optimize performance for complex effluent types, especially in community-scale settings.Together with earlier pollution index and hazard quotient analyses, this efficiency assessment underscores that biosorbentsespecially sawdust and bagasse which are promising, eco-friendly, and affordable solutions for textile wastewater treatment.

**Ecological Risk Quotients of Heavy Metals**

To complement the adsorption efficiency analysis, an ecological risk assessment was performed using the Hazard Quotient (HQ) method. HQ values compare the post-treatment concentration of each metal to established ecological safety thresholds for freshwater ecosystems. The results are presented in Table 5.

Table 5: Ecological Risk Quotients (HQ) of Heavy Metals in Treated Effluents

| Adsorbent | Pb | Cu | Cr | Ni | Zn | Fe | Mean HQ |
|---|---|---|---|---|---|---|---|
| Rice Husk | 23 | 21 | 9.8 | 16.4 | 22 | 10.7 | 17.15 |
| Sawdust | 25 | 19.5 | 6.8 | 10.4 | 23.67 | 7.53 | 15.15 |
| Sugarcane Bagasse | 20 | 18.5 | 7.8 | 14 | 21.33 | 10.13 | 15.96 |
| Combined Filter | 18 | 20 | 8 | 13.2 | 22.67 | 9.47 | 15.22 |

(Threshold values used (mg/L): Pb = 0.01, Cu = 0.02, Cr = 0.05, Ni = 0.025, Zn = 0.03, Fe = 0.3)

All HQ values > 1, indicating that residual ecological risk remains even after biosorption.Lead (Pb) consistently showed the highest individual HQs across all treatments (HQs of 18–25), confirming its extreme toxicity and persistence in textile effluents.The combined filter achieved the lowest Pb HQ (18.0) and relatively balanced values across metals, suggesting complementary adsorption synergy.Sawdust, while not the lowest in every category, achieved the lowest mean HQ (15.15), indicating the best overall ecological safety performance.Sawdust and Sugarcane Bagasse both reduced Cr, Fe, and Ni to below HQ = 15, consistent with earlier performance in removal efficiency.These HQ results highlight that while biosorption significantly reduces heavy metal concentrations, the treated effluent may still exceed safe ecological limits, especially for lead, copper, and zinc. Without further polishing, such effluents could harm aquatic organisms like fish, algae, macroinvertebrates, bioaccumulate in food chains and can contaminate groundwater or soil if used for irrigation. Further treatment or dilution is recommended before discharge to sensitive environments. Additionally, reusing treated effluent in non-contact industrial applications like concrete mixing, brick curingmay offer safer alternatives.

## IV. CONCLUSION

This study demonstrated the potential of agricultural waste-derived biosorbents—sawdust, rice husk, sugarcane bagasse, and their combination—for the removal of heavy metals and improvement of physico-chemical quality of Adire textile wastewater. All tested biosorbents significantly reduced concentrations of Pb, Cu, Cr, Ni, Zn, and Fe, with sawdust and the combined filter showing the highest overall removal efficiencies, achieving up to 61.2% efficiency for nickel and 58.1% for lead, respectively.In addition to pollutant removal, the application of pollution indices such as the Pollution Load Index (PLI) and Geoaccumulation Index (Igeo) revealed notable reductions in environmental burden across all treatments. However, the Hazard Quotient (HQ) analysis indicated that residual concentrations of some metals, particularly lead and zinc, still exceeded ecological safety thresholds, suggesting a need for further polishing or multi-stage treatment before discharge into aquatic environments. This work affirms that biosorption using agro-waste is an effective, low-cost, and sustainable option for wastewater treatment in small-scale or informal textile industries. Its implementation could play a key role in advancing environmental protection, public health, and circular economy goals in developing regions. Future studies should explore adsorbent regeneration, composite filter development, and field-scale pilot applications to enhance long-term viability and compliance with environmental regulations.

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