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Comparative Study on the Adsorptive Removal of Petrochemical Effluent Contaminants Using Palm Kernel Shell and Elaeis Guineensis Biomass-Derived Activated Carbons

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ABSTRACT: Effluent discharge from petrochemical plants poses a significant threat to the environment, necessitating efficient treatment methods. This study investigates the adsorption efficiency of activated carbons derived from palm kernel shell (PKS) and Elaeis Guineensis biomass (EPB) for the removal of organic contaminants from petrochemical effluents. The activated carbons were produced through pyrolysis followed by chemical activation with hydrochloric acid. Batch adsorption experiments were conducted under varying conditions of contact time, adsorbent dosage, and particle size. Experimental data were analyzed using Langmuir and Freundlich isotherm models to determine adsorption capacities. Results indicate that the EPB-derived activated carbon exhibited a higher adsorption capacity (9.51 mg/g) compared to PKS-derived activated carbon (4.88 mg/g), with removal efficiencies of 80.5% and 82.99%, respectively. The adsorption process followed Langmuir isotherm, indicating monolayer adsorption on homogeneous surfaces. Statistical analysis of effluent samples before and after treatment confirmed significant reductions in pollutant concentrations, demonstrating the efficacy of both adsorbents. This study highlights the potential of biomass-derived activated carbons as sustainable and cost-effective alternatives for petrochemical effluent treatment.

Keywords: Activated Carbon, Petrochemical Effluent, Adsorption, Elaeis Guineensis Biomass, Palm Kernel Shell, Isotherm Models

I. INTRODUCTION

Industrialization has significantly altered the composition of our environment, introducing a myriad of contaminants into aquatic ecosystems. Among these, petrochemical effluents rank as one of the most concerning due to their complex chemical makeup, including hydrocarbons, heavy metals, and persistent organic pollutants [10, 12]. The improper disposal of these industrial by-products leads to severe environmental degradation, adversely affecting water quality, aquatic life, and human health [13]. These pollutants are known to bioaccumulate, disrupting the food chain and posing long-term ecological risks [4].

Despite stringent environmental regulations, conventional treatment methods such as coagulation, flocculation, and sedimentation often fail to adequately remove all contaminants, leaving residual pollutants that continue to pose risks [5, 8]. This has necessitated the search for more efficient, sustainable, and cost-effective remediation techniques. Adsorption has emerged as a promising alternative, with activated carbon showing remarkable potential in pollutant removal due to its high surface area and affinity for organic and inorganic contaminants [9]. The utilization of biomass-derived activated carbons, such as those derived from palm kernel shell (PKS) and Elaeis Guineensis biomass (EPB), presents an eco-friendly and economical approach to wastewater treatment [1, 2]

Recent studies have demonstrated that agricultural waste materials, including palm kernel shells, can be transformed into highly efficient

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adsorbents capable of removing heavy metals, oil residues, and organic pollutants from wastewater [15, 16]. This study aims to evaluate the adsorption capacities of PKS and EPB-derived activated carbons, comparing their efficiency in treating petrochemical effluents. Furthermore, the Langmuir and Freundlich isotherm models will be employed to describe the adsorption process, offering insights into the mechanism and feasibility of applying these bio-based adsorbents for large-scale industrial wastewater treatment. By leveraging locally available biomass resources, this research contributes to both environmental sustainability and the advancement of green chemistry solutions in industrial effluent management.

II. MATERIALS AND METHODS

2.1Materials

The basic materials for this study were raw Elaeis Guineensis biomasses (palm kernel shell (PKS), empty palm bunch (EGB)), Petrochemical Effluent and Langmuir and Freundlich isotherms.

2.2 Methods

2.2.1 Preparation of Activated Carbon

PKS and EPB biomasses were obtained, washed, dried, and subjected to pyrolysis at 400-500°C to produce biochars. The biochars were chemically activated using 0.1M hydrochloric acid at 600°C to enhance their adsorptive properties. The activated carbons were then crushed, sieved to obtain particle sizes of 0.15 mm, 0.3 mm, and 0.6 mm, and characterized for moisture content, ash content, pore volume, and bulk density.

2.2.2 Batch Adsorption Experiments

Adsorption experiments were conducted to determine the effects of contact time (30-300 min), adsorbent dosage (5-25 g), and particle size on removal efficiency. Effluent samples were collected from a petrochemical plant and analyzed for pH, total organic carbon (TOC), chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metal concentrations before and after treatment.

2.2.3 Isotherm Modeling

The Langmuir and Freundlich isotherm models were applied to the experimental data to determine adsorption capacities and affinities. The Langmuir isotherm assumes monolayer adsorption on a homogenous surface, while the Freundlich model describes adsorption on heterogeneous surfaces with varying affinities (Ademiluyi & Ujile, 2013).

Langmuir isotherm: "Langmuir isotherm was used for determining the isothermal behaviours of the adsorption process." The Langmuir isotherm is written as

$$\frac{C_e}{Q_e} = \frac{1}{K_L} + \frac{a_L C_e}{K_L} \qquad (1)$$

where Q_e= amount of adsorbate adsorbed per unit mass of adsorbent (mg/g) at equilibrium, C_e = the equilibrium concentration of the adsorbate (mg/L), K_L = a constant related to the affinity between the adsorbent and the adsorbate; K_L/a_L = theoretical monolayer saturation capacity Q_o. The values of Q_o and $K_L$can be determined by plotting C_e/Q_e versus C_e.A very important parameters of the Langmuir isotherm model is the separation factor R_L which is a dimensionless factor defined as

$$R_L = \frac{1}{1+a_L C_o} \qquad (2)$$

where: C_o = initial adsorbate concentration and a_L = Langmuir constant related to the energy of adsorption. The values of R_L shows the shape of the isotherm to be either unfavourable ($R_L > 1$), favourable ($0 < R_L < 1$), linear ($R_L = 1$), or irreversible ($R_L = 0$). The complete or maximum monolayer adsorption capacity (Q) on the AC (expressed in mg/g) may be determined using $q_{max} = Q \times b$.

$$Q = \frac{q_{max}}{b} \qquad (3)$$

Where, maximum adsorption, q_{max} (mg/g) = $\frac{1}{\text{slope}}$ and Intercept =1/ (q_{max} . b) .

Freundlich Isotherm. "The Freundlich isotherm equation posits that the adsorbent has a heterogeneous surface made of adsorption sites with varying adsorption potentials, and that each class of adsorption site adsorbs molecules, as in the Langmuir Equation." The Freundlich Equation is as follows:

$$\frac{x}{m} = KC^{1/n} \qquad (4)$$

Where: x = amount of solute adsorbed (mg, or g), m = mass of adsorbent (mg or g), C = concentration of solute remaining in solution after adsorption is complete (at equilibrium) (mg/l), and K, n = constants that must be determined for each solute, carbon type, and temperature.

The linear form of the Freundlich isotherm is the earliest known relationship describing the adsorption equation and is often expressed as

$$\log Q_e = \log K_f + \frac{1}{n} \log C_e \quad (5)$$

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where: K_f = the Freundlich constant (adsorption capacity); 1/n = the adsorption intensity. "K and 1/n or n values for multiple contaminant mixtures should be determined by laboratory tests.

III. RESULTS AND DISCUSSION

Table 1: Adsorption Experiment Data for Petrochemical Effluent Treatment

Parameter (Unit)	Initial Effluent Value	After Treatment with PKS	After Treatment with EPB
Contact Time (min)	30 - 300	-	-
Adsorbent Dosage (g)	5 - 25	-	-
Particle Size (mm)	0.15 - 0.6	-	-
pH	9.29	7.3	6.8
Total Organic Carbon (TOC)(mg/L)	155.7	62.3	58.1
Chemical Oxygen Demand (COD)(mg/L)	2144	374	322
Biological Oxygen Demand (BOD)(mg/L)	1308	263	210
Lead (Pb)(mg/L)	0.769	0.152	0.101
Cadmium (Cd)(mg/L)	0.113	0.025	0.017

The adsorption experiment data presented in Table 1 demonstrate the effectiveness of PKS and EPB-derived activated carbons in reducing pollutant levels in petrochemical effluent. The pH of the effluent decreased from 9.29 to 7.3 (PKS) and 6.8 (EPB), indicating improved neutrality. Organic contaminants, measured as TOC, COD, and BOD, showed substantial reductions, with EPB achieving slightly better removal efficiencies. COD was reduced from 2144 mg/L to 374 mg/L (PKS) and 322 mg/L (EPB), while BOD decreased from 1308 mg/L to 263 mg/L (PKS) and 210 mg/L (EPB). Heavy metals were also significantly removed, with lead and cadmium levels dropping drastically post-treatment. The superior performance of EPB is likely due to its higher surface area and enhanced porosity. These findings confirm the potential of biomass-derived activated carbons for wastewater treatment, with EPB showing greater efficiency. Future research should focus on optimizing operating conditions and evaluating the long-term viability of these adsorbents.

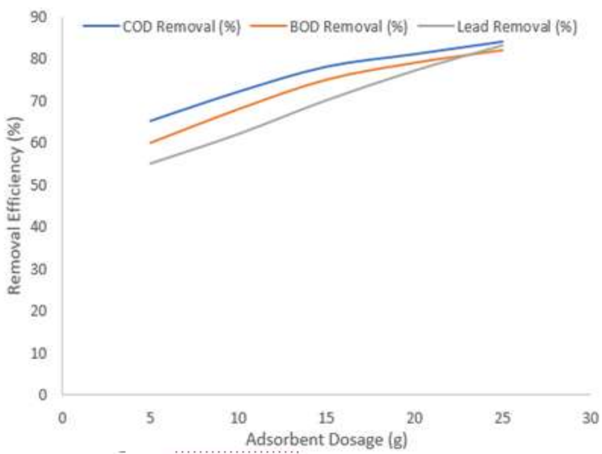

Figure 1: Effect of Adsorbent Dosage on Pollutant Removal

Figure 1 illustrates the effect of varying adsorbent dosages (5g, 10g, 15g, 20g, and 25g) on the removal efficiency of COD, BOD, and lead. The results indicate a positive correlation between adsorbent dosage and removal efficiency. As the adsorbent dosage increases, the percentage removal of pollutants also increases. This trend is attributed to the higher number of available adsorption sites and larger surface area provided by increasing the quantity of activated carbon. The maximum removal efficiency was observed at 25g dosage, with COD, BOD, and lead removal reaching 84%, 82%, and 83%, respectively. The efficiency plateaued, suggesting that adsorption sites were saturated. This finding aligns with previous studies that highlight the significance of optimal adsorbent dosage in achieving maximum pollutant removal without wastage of material.

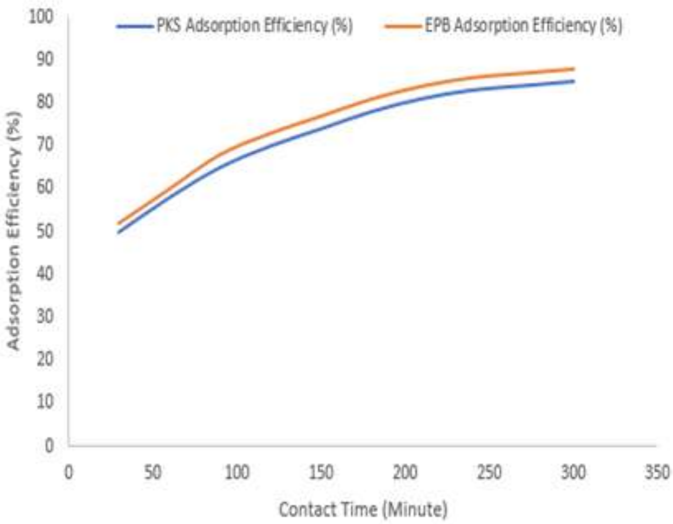

Figure 2: Effect of Contact Time on Adsorption Efficiency

Figure 2 presents the effect of contact time on the adsorption efficiency of PKS and EPB-derived activated carbons. Adsorption efficiency increased with time, with equilibrium being reached at approximately 240–300 minutes. Initially, rapid adsorption occurred due to the high availability of active sites. However, as adsorption progressed, fewer active sites remained available, leading to a slower rate of pollutant removal. EPB-derived activated carbon consistently exhibited higher adsorption efficiency compared to PKS, likely due to its superior porosity and surface area. The trend suggests that for effective treatment, sufficient contact time must be allowed to ensure equilibrium is reached, thereby maximizing pollutant removal.

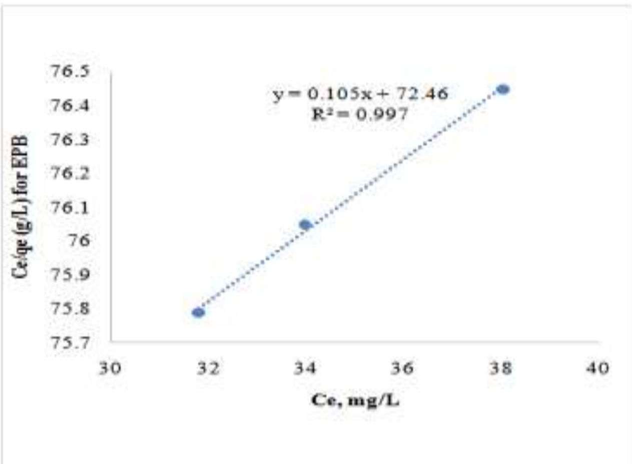

Figure 3: Langmuir Isotherm Plot

Figure 3 depicts the Langmuir isotherm plot, which was used to model the adsorption equilibrium of contaminants onto the activated carbon surfaces. The linear relationship observed confirms that adsorption follows the Langmuir model, indicating monolayer coverage on homogeneous adsorption sites. The slope of the plot provides the Langmuir constant, which is essential for determining adsorption capacity. The negative intercept observed in the model suggests potential experimental limitations, such as variations in adsorbent properties or deviations from ideal conditions. The high R^2 value (0.9375) indicates a strong fit to the Langmuir isotherm, validating the assumption of uniform adsorption sites and finite adsorption capacity.

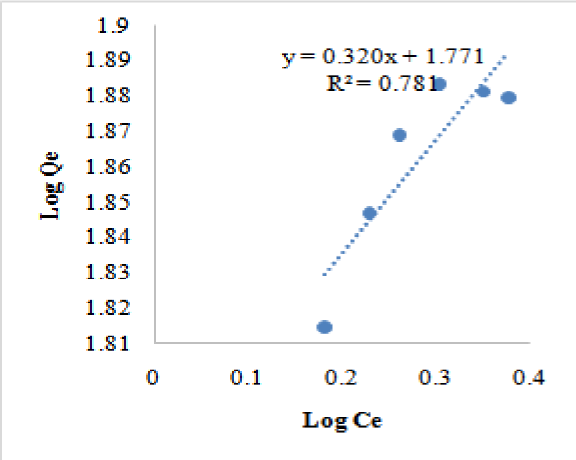

Figure 4: Freundlich Isotherm Plot

Figure 4 shows the Freundlich isotherm plot, which describes adsorption on heterogeneous surfaces. The linearity of the plot confirms the applicability of the Freundlich model to the adsorption process. The slope represents the adsorption intensity, while the intercept corresponds to the adsorption capacity. The observed trend suggests that adsorption onto the activated carbon surface involves multilayer interactions, which is typical for heterogeneous adsorbents. Compared to the Langmuir model, the Freundlich model provided a slightly lower R^2 value, indicating that the adsorption process may not be entirely heterogeneous but rather a combination of monolayer and multilayer adsorption mechanisms.

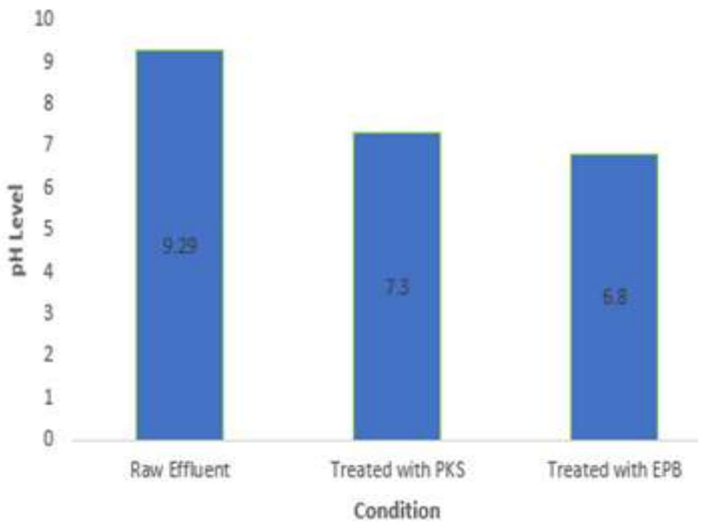

Figure 5: Comparison of pH Variation Before and After Treatment

Figure 5 illustrates the pH variations of the effluent before and after treatment with PKS and EPB-derived activated carbons. The initial effluent had a high pH of 9.29, indicating alkalinity. After treatment, the pH decreased significantly, with the PKS-treated effluent reaching 7.3 and the EPB-treated effluent reaching 6.8. This reduction is attributed to the adsorption of alkaline substances and the release of acidic functional groups from the activated carbon surfaces. The results suggest that activated carbon treatment not only removes pollutants but also helps neutralize effluent pH, making it safer for discharge into natural water bodies

IV. CONCLUSION

This study demonstrates the potential of PKS and EPB biomass-derived activated carbons for the effective treatment of petrochemical effluents. The superior adsorption capacity of EPB suggests it as a more efficient adsorbent, though PKS also performed well. The Langmuir isotherm model accurately described the adsorption process, indicating that these activated carbons can be utilized for large-scale wastewater treatment. Future studies should explore column adsorption and regeneration efficiency for long-term application.

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