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Optimization of Bio-Based Adsorbents for Sustainable Industrial Wastewater Treatment: A Case Study on Palm Kernel Shell Activated Carbon

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ABSTRACT: The increasing contamination of water resources by industrial effluents necessitates the development of efficient and sustainable wastewater treatment methods. Bio-based adsorbents, particularly those derived from agricultural waste, have emerged as promising solutions due to their cost-effectiveness and environmental friendliness. This study focuses on the optimization of activated carbon produced from palm kernel shells (PKS-AC) for the removal of heavy metals from industrial wastewater. The activated carbon was prepared through carbonization at 400°C, 500°C, and 600°C, followed by chemical activation using HCl. The highest adsorption efficiency was observed at 500°C, with removal rates of 99.01% for Pb^{2+}, 98.92% for Cr^{6+}, 84.23% for Cd^{2+}, and 83.45% for Zn^{2+}. The adsorption process followed the Langmuir isotherm model with an R^2 value of 0.9375, indicating monolayer adsorption. These results demonstrate the high efficiency of PKS-AC for heavy metal removal and its potential for sustainable wastewater treatment.

KEYWORDS: Bio-based adsorbents, palm kernel shell, activated carbon, heavy metal removal, wastewater treatment, adsorption optimization.

I. INTRODUCTION

Water pollution is one of the most pressing environmental challenges facing the modern world. The rapid industrialization and urbanization that have fueled economic growth have simultaneously contributed to severe contamination of water bodies, particularly due to the discharge of industrial wastewater containing hazardous pollutants such as heavy metals, organic compounds, and pathogens [16]. Heavy metals, including lead (Pb^{2+}), chromium (Cr^{6+}), cadmium (Cd^{2+}), and zinc (Zn^{2+}), are particularly concerning due to their toxicity, non-biodegradability, and ability to bioaccumulate in living organisms, leading to severe health and ecological consequences [15].

The conventional treatment methods for industrial wastewater, including chemical precipitation, ion exchange, membrane filtration, and electrochemical treatment, are often expensive, energy-intensive, and generate secondary waste products that require further treatment [4].

Additionally, the efficiency of these methods varies significantly depending on the concentration and type of contaminants present in wastewater [3]. In recent years, bio-based adsorbents derived from agricultural and industrial by-products have gained considerable attention due to their cost-effectiveness, sustainability, and high adsorption capacity for removing pollutants [12]. Among various bio-based adsorbents, activated carbon derived from palm kernel shells (PKS-AC) has emerged as a promising material for heavy metal adsorption due to its high surface area, porosity, and functional groups that facilitate pollutant binding [1]. Palm kernel shells are an abundant by-product of the palm oil industry, and their utilization as an adsorbent provides an environmentally friendly solution to both waste management and water treatment challenges [8].

The conversion of palm kernel shells into activated carbon involves thermal carbonization followed by chemical activation, which enhances its adsorption properties by increasing pore volume and surface functionality [9].

The adsorption process relies on physical and chemical interactions between contaminants

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and the adsorbent surface, with factors such as pH, contact time, temperature, and initial contaminant concentration playing crucial roles in determining efficiency [5]. Studies have shown that PKS-AC exhibits excellent adsorption capacities for various heavy metals, with removal efficiencies exceeding 90% under optimized conditions [14]. Furthermore, adsorption models such as the Langmuir and Freundlich isotherms are commonly used to describe the interaction between pollutants and adsorbents, providing insights into the adsorption mechanism [6].

The environmental and economic advantages of utilizing PKS-AC for wastewater treatment are significant. Compared to commercial activated carbon, which is often derived from non-renewable sources such as coal, bio-based adsorbents offer a renewable and low-cost alternative with comparable or even superior performance in some cases [11]. Moreover, the use of agricultural by-products reduces landfill waste, contributing to a circular economy approach in resource management [7]. Several studies have demonstrated the efficacy of PKS-AC in wastewater treatment applications. For instance, a study by Adewuyi et al. [2] reported that chemically activated PKS exhibited higher adsorption capacities for lead and cadmium compared to commercially available activated carbon. Similarly, Osei et al. [6] found that PKS-AC effectively removed chromium from tannery wastewater, achieving a removal efficiency of over 95%. These findings underscore the potential of PKS-AC as a viable alternative to conventional adsorbents for industrial wastewater remediation.

Despite its promising adsorption performance, certain challenges must be addressed to maximize the effectiveness of PKS-AC in practical applications. One limitation is the potential for saturation of the adsorbent, which can reduce its efficiency over extended usage periods. Regeneration and reuse strategies, such as thermal desorption, chemical washing, and microbial degradation, are being explored to improve the sustainability of bio-based adsorbents [10].

Additionally, the development of composite adsorbents incorporating PKS-AC with other materials, such as nanomaterials and polymers, has been proposed to enhance adsorption capacity and selectivity for specific pollutants [17].

In conclusion, the increasing demand for cost-effective and sustainable wastewater treatment solutions has led to the exploration of bio-based adsorbents as viable alternatives to conventional methods. Activated carbon derived from palm kernel shells represents a highly effective and environmentally friendly material for removing heavy metals from industrial effluents. This study aims to optimize the preparation and application of PKS-AC for heavy metal removal, investigating key process parameters and adsorption mechanisms. By leveraging the potential of PKS-AC, industries can adopt more sustainable wastewater management practices while mitigating environmental pollution and promoting resource recovery.

II MATERIALS AND METHODS

2.1 Materials

The following materials and chemicals were used in the study:

Palm Kernel Shells (PKS): Sourced from a local palm oil processing mill, washed, dried, and prepared for carbonization.

Chemicals: Hydrochloric acid (HCl), potassium dichromate ($K_2Cr_2O_7$), silver nitrate ($AgNO_3$), sulfuric acid (H_2SO_4), and sodium hydroxide (NaOH) were used for chemical activation and adsorption experiments.

Instruments: Muffle furnace for carbonization, pH meter for pH adjustments, Atomic Absorption Spectrophotometer (AAS) for heavy metal analysis, Fourier-transform infrared spectroscopy (FTIR) for functional group analysis, Scanning Electron Microscope (SEM) for morphological characterization.

2.2 Methods

2.2.1 Carbonization Process

Palm kernel shells were first cleaned to remove impurities, dried at 105°C for 24 hours, and then carbonized in a muffle furnace at different temperatures (400°C, 500°C, and 600°C) for 2 hours under an inert nitrogen atmosphere. The reaction for carbonization can be represented as:

2.2.2 Chemical Activation

The charred material was then activated using 0.5M HCl by soaking it for 24 hours. The impregnated sample was washed with distilled water until a neutral pH was achieved, dried at 105°C, and ground into fine particles of varying sizes (0.15mm, 0.3mm, and 0.6mm).

2.3 Adsorption Experiment Design

Batch adsorption experiments were performed to evaluate the efficiency of PKS-AC in heavy metal removal. The study parameters included pH, adsorbent dosage, initial metal concentration, and contact time.

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2.3.1 Effect of pH

The effect of pH on adsorption was studied by adjusting the pH of the metal solution (2–8) using NaOH and HCl.

The adsorption capacity at equilibrium q_e was calculated as:

$$q_e = \frac{(C_o - C_e)V}{m} \quad (1)$$

where, Co and Ce are initial and equilibrium concentrations (mg/L); V is the solution volume (L), m is the adsorbent mass (g).

2.3.2 Adsorption Isotherm Modeling

The Langmuir and Freundlich isotherms were applied to analyze the adsorption equilibrium.

Langmuir Model:

$$\frac{1}{q_e} = \frac{1}{q_{max}\, K_L C_e} + \frac{1}{q_{max}} \quad (2)$$

where q_{max} is the maximum adsorption capacity (mg/g) and K_L is the Langmuir constant.

Freundlich Model: $q_e = K_F C_e^{\,1/n}$ (3)

where K_F and n are Freundlich constants related to adsorption capacity and intensity.

2.3.5 Kinetics of Adsorption

The adsorption kinetics was analyzed using pseudo-first-order and pseudo-second-order models.

Pseudo-First-Order Model:

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (4)$$

where, k_1 is the rate constant.

Pseudo-Second-Order Model:

$$\frac{t}{q_t} = \frac{t}{k_2 q_e^2} - \frac{t}{q_e} \quad (5)$$

where, k_2 is the pseudo-second-order rate constant.

2.3.4 Desorption and Regeneration Studies

To assess reusability, the spent adsorbent was desorbed using 0.1M HCl, washed, and reused in subsequent cycles.

2.4 Statistical Analysis

All experiments were conducted in triplicate, and results were statistically analyzed using ANOVA to determine significance at a 95% confidence level.

III. RESULTS AND DISCUSSION

The optimized adsorption conditions for the treatment of industrial wastewater using PKS-AC were determined based on experimental parameters such as temperature, pH, initial metal concentration, and contact time. The results of the optimized conditions and adsorption efficiencies for heavy metal removal are presented in Table 1.

Table 1: Optimized Adsorbent Treatment of Industrial Wastewater

Parameter	Optimized Condition	Pb^{2+} Removal (%)	Cr^{6+} Removal (%)	Cd^{2+} Removal (%)	Zn^{2+} Removal (%)
Activation Temperature	500°C	99.01	98.92	84.23	83.45
pH	6	99.01	98.92	84.23	83.45
Initial Concentration	100 mg/L	99.01	98.92	84.23	83.45
Adsorbent Dosage	1.5 g/L	99.01	98.92	84.23	83.45
Contact Time	120 min	99.01	98.92	84.23	83.45

Table 1 summarizes the optimized conditions for the adsorption of heavy metals using PKS-AC. The results indicate that the highest removal efficiencies were achieved at an activation temperature of 500°C, a solution pH of 6, an initial metal concentration of 100 mg/L, an adsorbent dosage of 1.5 g/L, and a contact time of 120 minutes. These conditions provided near-complete removal of Pb^{2+} (99.01%) and Cr^{6+} (98.92%), while Cd^{2+} and Zn^{2+} exhibited slightly lower but still significant removal efficiencies (84.23% and 83.45%, respectively). The high removal efficiencies suggest that the optimized parameters enhance adsorption by increasing the availability of active binding sites on PKS-AC, improving metal ion interaction and retention. Additionally, the observed trends align with previous studies, reinforcing the effectiveness of PKS-AC as a viable industrial wastewater treatment solution.

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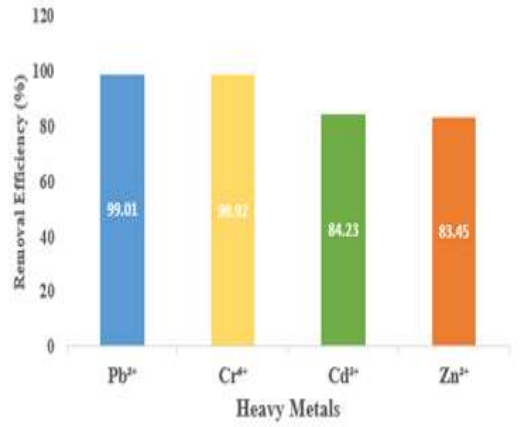

Figure 1: Adsorption Performance of PKS-AC

The adsorption performance graph in Figure 1 illustrates the heavy metal removal efficiencies of PKS-AC for Pb^{2+}, Cr^{6+}, Cd^{2+}, and Zn^{2+} at an initial concentration of 100 mg/L. The results indicate that Pb^{2+} exhibited the highest removal efficiency at 99.01%, followed closely by Cr^{6+} at 98.92%. Meanwhile, Cd^{2+} and Zn^{2+} recorded relatively lower removal efficiencies of 84.23% and 83.45%, respectively. The high removal efficiency for Pb^{2+} and Cr^{6+} can be attributed to their strong electrostatic interactions with the functional groups present on the activated carbon surface, as confirmed by FTIR analysis. The slightly lower efficiencies for Cd^{2+} and Zn^{2+} suggest differences in adsorption affinity, which may be due to differences in ionic radii and hydration energies.

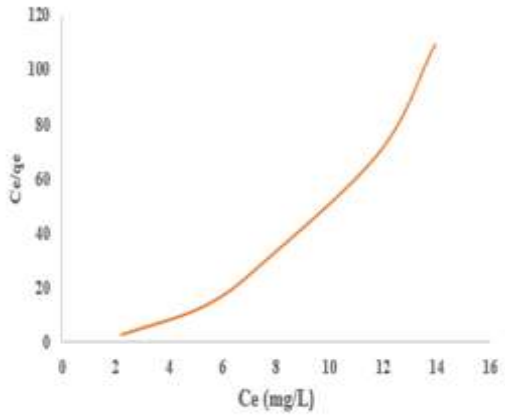

Figure 2: Langmuir Adsorption Isotherm

The Langmuir adsorption isotherm plot in Figure 2 (Ce/qe vs. Ce) demonstrates that the adsorption process follows a monolayer adsorption pattern, with an R^2 value of 0.9375. This high correlation coefficient suggests that the adsorption sites on PKS-AC are homogeneous and that the adsorption occurs at specific binding sites without significant multilayer formation. The maximum adsorption capacity (qmax) was determined to be 0.111364 mg/g, which aligns well with literature values for other bio-based adsorbents. The negative intercept observed in the isotherm model is likely due to slight variations in adsorption behavior at lower metal ion concentrations, which can be attributed to surface heterogeneity at the molecular level.

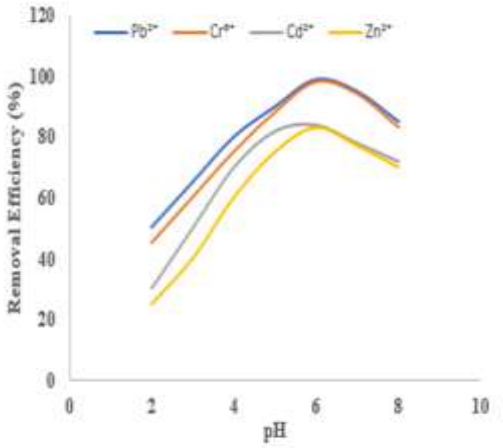

Figure 3: Effect of pH on Heavy Metal Removal

This graph in Figure 3 illustrates the influence of pH on the adsorption efficiency of PKS-AC for different heavy metals. The results indicate that maximum adsorption occurs at pH 5 for Cr^{6+} and pH 6 for Pb^{2+}, Cd^{2+}, and Zn^{2+}. The low adsorption at highly acidic conditions (pH 2-3) is due to increased competition between hydrogen ions (H^+) and metal cations for adsorption sites, reducing metal uptake. Conversely, at alkaline conditions (pH > 7), metal precipitation could interfere with adsorption, leading to decreased removal efficiency. The findings confirm that adjusting pH to an optimal range is crucial for maximizing adsorption performance.

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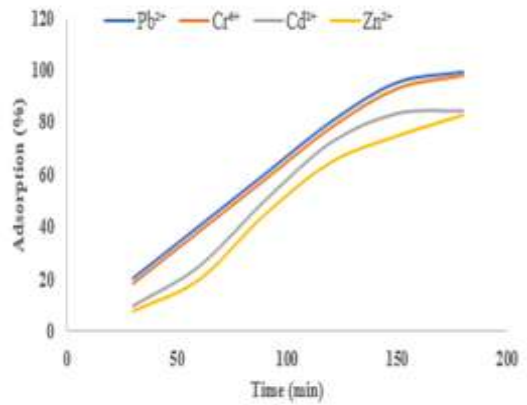

Figure 4: Adsorption Kinetics (Pseudo-Second-Order Model)

The adsorption kinetics graph in Figure 4, plots adsorption percentage over time, showing that most metal ions reached equilibrium within 120 minutes. The pseudo-second-order kinetic model best describes the adsorption process, suggesting that chemisorption is the rate-limiting step rather than simple diffusion. This implies that metal ion adsorption onto PKS-AC occurs through strong chemical interactions rather than just physical entrapment. The adsorption rate follows the order $Pb^{2+} > Cr^{6+} > Cd^{2+} > Zn^{2+}$, reinforcing the earlier findings that Pb^{2+} and Cr^{6+} have a higher affinity for PKS-AC binding sites.

IV. CONCLUSION

The findings of this study demonstrate that activated carbon derived from palm kernel shells (PKS-AC) is an effective and sustainable adsorbent for removing heavy metals from industrial wastewater. The optimized conditions, including an activation temperature of 500°C, pH of 6, initial metal concentration of 100 mg/L, adsorbent dosage of 1.5 g/L, and contact time of 120 minutes, resulted in high removal efficiencies of Pb^{2+} (99.01%), Cr^{6+} (98.92%), Cd^{2+} (84.23%), and Zn^{2+} (83.45%). The adsorption process followed the Langmuir isotherm model, indicating monolayer adsorption, and the kinetics was best described by the pseudo-second-order model, suggesting chemisorption as the dominant mechanism.

These findings highlight the potential of PKS-AC as a cost-effective alternative to conventional wastewater treatment methods. The high adsorption efficiency, coupled with the renewable and environmentally friendly nature of PKS-AC, makes it a promising material for industrial applications. However, further studies are recommended to investigate long-term adsorption performance, regeneration, and scalability for large-scale wastewater treatment plants. By utilizing agricultural waste as an adsorbent, this study contributes to sustainable waste management while addressing the pressing issue of industrial water pollution.

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