Research Article

Innovative Biosorption of Crystal Violet Dye Using Chemically-Enhanced Pineapple Crown Leaf (CPCL)

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Abstract: *This study presents a sustainable and innovative approach to dye-contaminated wastewater treatment using pineapple crown leaves (PCL) as a low-cost biosorbent for the removal of crystal violet (CV) dye. Synthetic dyes like CV are widely used in the textile industry and pose serious environmental threats due to their toxicity, stability, and resistance to conventional treatment methods. Agricultural waste such as PCL offers an eco-friendly alternative for wastewater remediation, aligning with circular economic principles. In this work, raw PCL (RPCL) and NaOH-treated PCL (CPCL) were evaluated for their adsorption performance. Chemical treatment with sodium hydroxide significantly enhanced the surface properties of PCL by increasing porosity, surface area, and the number of active functional groups, as confirmed by Fourier Transform Infrared Spectroscopy (FTIR) analysis. Batch adsorption studies were conducted with varying adsorbent dosages to compare the dye removal efficiency of RPCL and CPCL. The results revealed that CPCL exhibited better adsorption capacity, achieving a maximum dye removal efficiency of 98.35%, compared to 97.02% for RPCL. The improved performance of CPCL demonstrates the effectiveness of alkali activation in enhancing biosorbent properties. This research emphasizes the potential of transforming agricultural waste into high-performance adsorbents for industrial wastewater treatment. The method is not only cost-effective and environmentally friendly but also scalable, offering practical applications in textile effluent management and rural water purification. The findings contribute to green chemistry initiatives and support sustainable innovation in environmental technology, making it highly relevant for industries seeking efficient, environmentally responsible dye remediation solutions.*

Keywords: adsorption; crystal violet; pineapple crown leaves.

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1. INTRODUCTION

The growing demand for sustainable environmental solutions has led to the search for innovative and cost-effective wastewater treatment methods. Industrial dye pollution, primarily from textile and chemical industries, remains a pressing environmental concern due to its toxic and non-biodegradable nature. Besides, synthetic dyes like crystal violet (CV), pose a significant threat to aquatic ecosystems and human health (Tran et al., 2023). Conventional treatment methods such as coagulation and advanced oxidation are often expensive and yield secondary pollutants (Kato & Kansha, 2024).

As reported by David (2019), Sarawak is known as Malaysia's second-largest pineapple producer. Malaysia's pineapple industry generates large amounts of organic waste including from crown leaves. Utilizing agricultural biomass for environmental applications presents a sustainable solution to both environmental pollution and agricultural waste management. This research proposes an innovative design by transforming agricultural waste into an efficient biosorbent through chemical modification. This study explores the potential of both raw PCL (RPCL) NaOH-treated PCL (CPCL) as a breakthrough in dye remediation, contributing to sustainable waste management and water purification technologies.

2. METHOD & MATERIAL

2.1 Materials

Pineapple crown leaves, Crystal Violet ACS reagent anhydrous dye >= 90.0%, distilled water, and 10% NaOH.

2.2 Method

PCL was sourced from local farms, washed, and oven-dried at 70°C until constant weight. The dried leaves were ground into fine powder and sieved through a U.S.A. Standard Sieve with a mesh size range of 850 µm to ensure a uniform powdered form. This samples are referred as raw PCL (RPCL). 15g of powdered RPCL was treated with 150mL of 10% NaOH at 100°C for 1 hour, followed by washing and drying to yield CPCL (Nieva et al., 2020).

FTIR spectroscopy was utilized to analyse the functional group presence in both RPCL and CPCL which can help in adsorption process. The FTIR spectra were recorded in the wavenumber range of 4,000–600 cm^{-1} with accumulations of 16 scans using the Attenuated Total Reflectance (ATR) method on a Perkin-Elmer Frontier FTIR instrument (Ni et al., 2024).

Batch experiments using 0.1–1g of biosorbents in 100 ppm dye solution were conducted at room temperature. The samples were agitated at 150 rpm for 3 hours. UV-Visible spectrophotometry at 590.5 nm was used to measure the remaining dye concentration (Zamouche et al., 2020). Removal efficiency and adsorption capacity were calculated to determine optimal performance using equations below (Rathi et al., 2025).

$$removal\ efficiency = \frac{(C_i - C_e)}{C_i} \times 100\%$$

Where,
C_i is the initial dye concentration (mg/L),
C_e is the equilibrium dye concentration (mg/L).

$$adsorption\ capacity, q_e = \frac{(C_i - C_e)V}{m}$$

Where,
C_i is the initial dye concentration (mg/L),
C_e is the equilibrium dye concentration (mg/L),
V is the volume of the solution (L),
m is the mass of the biosorbent (g).

3. FINDINGS

FTIR analysis confirmed that NaOH treatment enhanced the intensity of hydroxyl and carboxyl functional groups, increasing the material's adsorption potential. FTIR spectra of RPCL and CPCL are shown in Figure 1 and Figure 2 respectively.

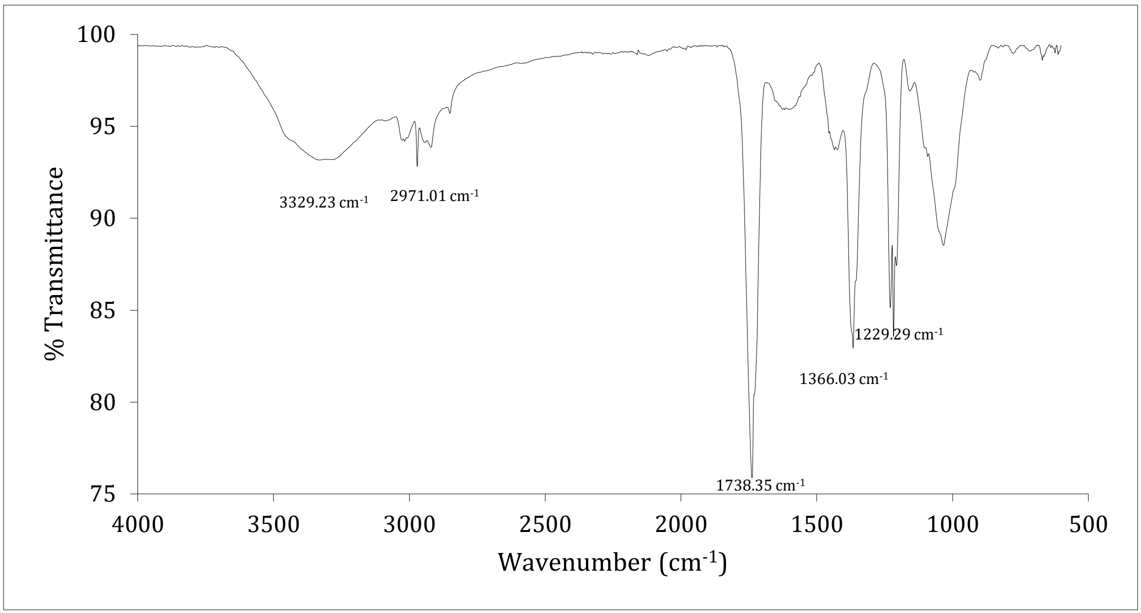

Figure 1. IR spectrum of RPCL

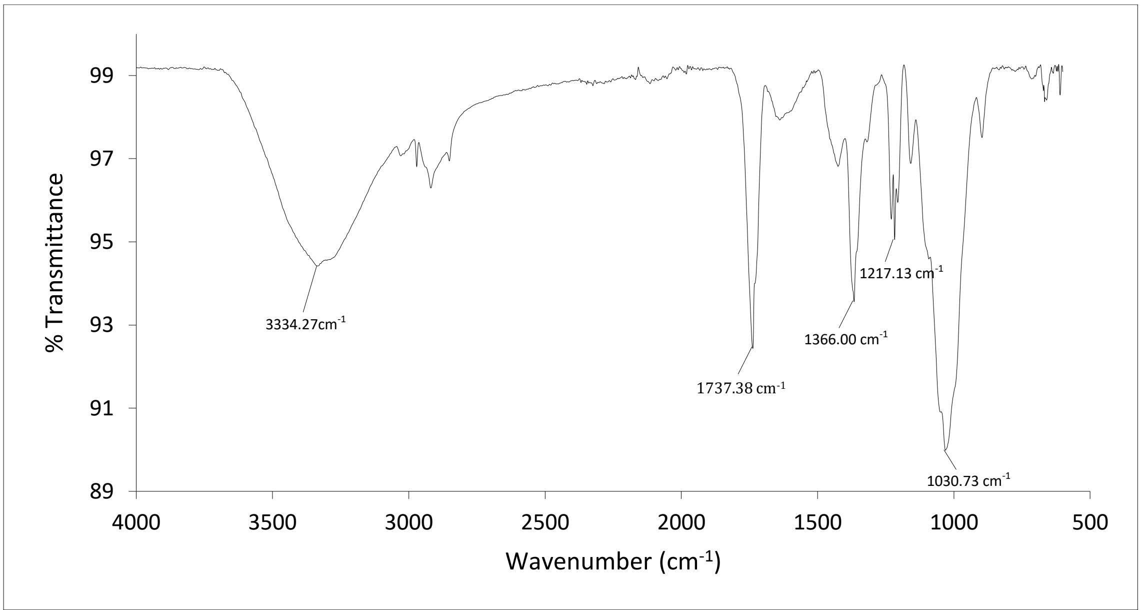

Figure 2. IR spectrum of CPCL

Batch adsorption experiments demonstrated that the removal efficiency of CV dyes increased from 90.83% to 97.02% for RPCL and from 93.29% to 98.35% for CPCL with increasing adsorbent dosage, as depicted in Figures 3 and 4. In contrast, the adsorption capacity exhibited a declining trend, decreasing from 45.42 mg/g to 4.84 mg/g for RPCL and from 46.65 mg/g to 6.14 mg/g for CPCL.

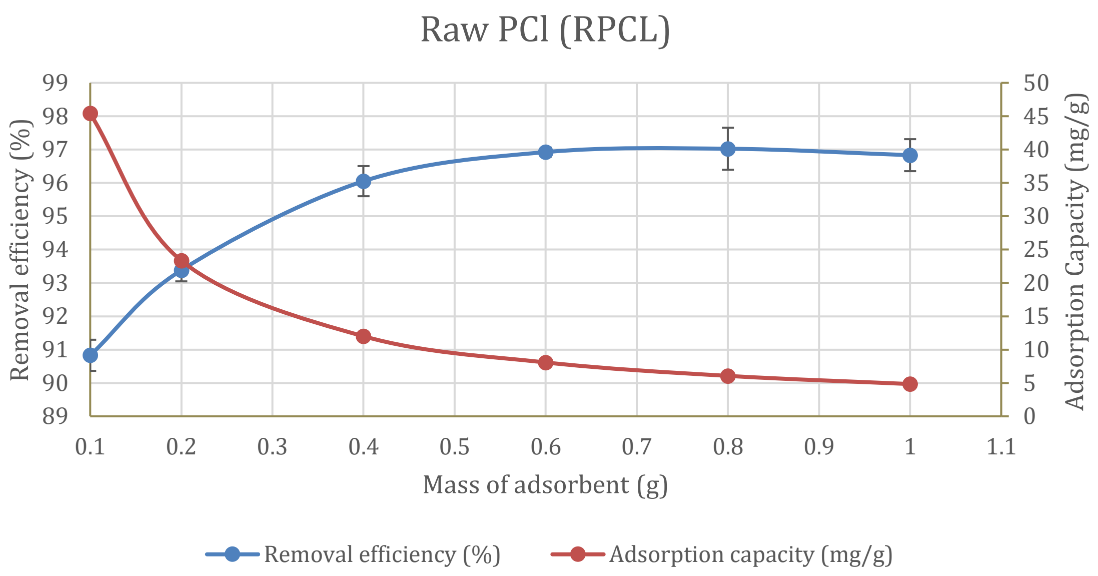

Figure 3. Removal Efficiency (%) and Adsorption Capacity (mg/g) of CV at different mass of adsorbent (g) of RPCL

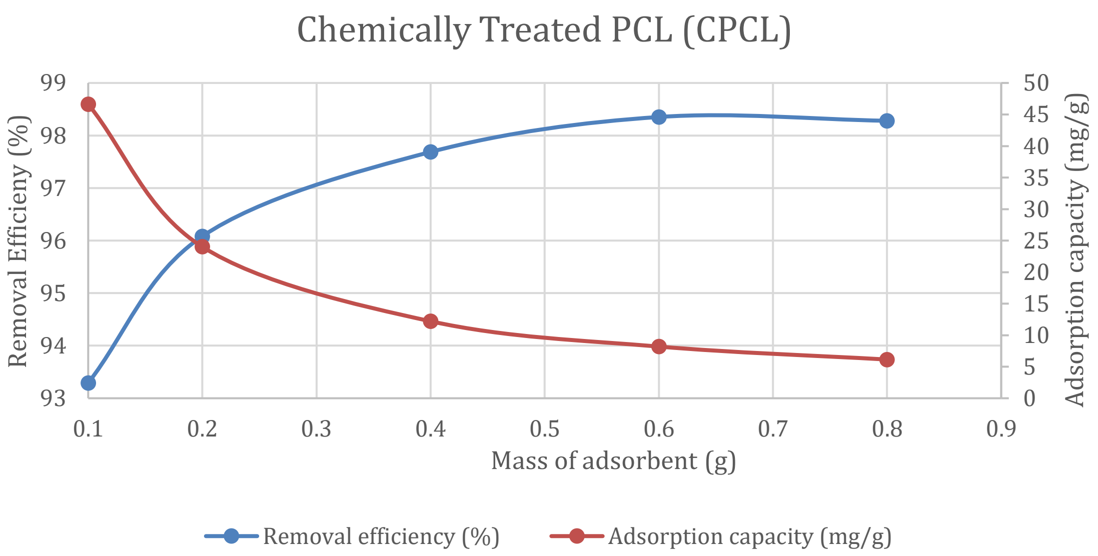

Figure 4. Removal Efficiency (%) and Adsorption Capacity (mg/g) of CV at different mass of adsorbent (g) of CPCL

4. DISCUSSION

4.1 Removal efficiency of RPCL and CPCL

There are two ways to determine the adsorption performance which is removal efficiency and adsorption capacity. Removal efficiency refers to the percentage of a compound's molecules that are removed or degraded in an oxidizing system compared to the total number of molecules initially introduced (von Sperling et al., 2020). In contrast, adsorption capacity represents the amount of a substance that can be adsorbed by an adsorbent at equilibrium in a saturated solution. It provides a roughly idea of the surface area available in the adsorbent, taking into consideration that the size of the adsorbed molecule is proportional to the number of available physical adsorption sites (Gonzales-Garcia, 2018).

The removal efficiency increases as the adsorbent mass increases due to the greater availability of active binding sites on the adsorbent surface. Figure 3 shows the removal efficiency of CV by RPCL increased from 90.83% to 97.02% as the adsorbent dosage rose from 0.1 g to 0.8 g. Similarly, as presented in Figure 4 the CV removal efficiency for CPCL improved from 93.29% to 98.35% with an increase in dosage from 0.1 g to 0.6 g. However, further increases in adsorbent dosage beyond 1.0 g for RPCL and 0.8 g for CPCL resulted in no significant improvement in removal efficiency. This plateau effect suggests that most CV dye molecules had already occupied the available active sites, leaving limited scope for additional adsorption (Homagai et al., 2022).

4.2 Adsorption capacity of RPCL and CPCL

The adsorption capacity of both RPCL and CPCL adsorbents were found to decrease with increasing adsorbent dosage. For example, as the dosage of RPCL increased from 0.1 g to 1.0 g, the adsorption capacity decreased from 45.42 mg/g to 4.84 mg/g. Similarly, for CPCL, the adsorption capacity declined from 46.65 mg/g to 6.14 mg/g over the same dosage range. This decline is primarily due to the excessive amount of adsorbent relative to the available dye molecules, resulting in underutilization of active sites. Consequently, even though the overall removal efficiency remains high, the adsorption capacity per gram of adsorbent is reduced (Neupane et al., 2015).

According to Figure 3, the highest removal efficiency of crystal violet (CV) using RPCL was achieved at a dosage of 0.8 g, reaching 97.02%. However, the optimal adsorbent dosage, based on the balance between removal efficiency and adsorption capacity, is approximately 0.2 g. Similarly, according to Figure 4, the maximum removal efficiency for CPCL was 98.35% at a dosage of 0.6 g, with the optimal dosage occurring around 0.19 g. These optimal values reflect the point at which the adsorbent is most efficient in terms of dye uptake per unit mass.

4.3 Innovation opportunities

The success of CPCL is attributed to improved porosity and the availability of functional groups for dye bonding. Its simple treatment process, minimal equipment requirement, and greater performance make it suitable for decentralized water treatment systems. Moreover, innovation reflects principles of green chemistry and waste valorization, showing scalability potential for industrial and rural applications (Aili Hamzah et al., 2021; Neupane et al., 2015).

The enhanced adsorption properties of PCL open new opportunities for large-scale applications in industrial effluent treatment plants, reducing reliance on expensive synthetic adsorbents. The findings of this study highlight a promising approach to sustainable wastewater treatment through conversion of agricultural waste into a value-added product. Utilizing PCL as a raw material aligns with circular economy principles by repurposing biomass that would otherwise be discarded. The CPCL demonstrates cost-effectiveness when compared to commercial activated carbon, offering a viable low-cost alternative for industrial applications Furthermore, the simplicity and low cost of the adsorbent preparation process suggest that the method is readily scalable, with strong potential for industrial deployment and commercialization. These attributes position CPCL as a practical and sustainable solution for addressing dye pollution in wastewater.

5. CONCLUSION

This study confirms the innovative potential of PCL as an advanced biosorbent for CV dye removal. The innovation addresses both environmental pollution and agricultural waste. The NaOH treatment significantly enhances adsorption capacity, offering a scalable and sustainable solution for industrial wastewater management. By utilizing agricultural waste, this approach promotes eco-friendly practices while addressing global pollution challenges. Future work should explore integration into modular filters and broader community-scale deployment.

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