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Crystal Violet Removal Using Biomass-Derived Activated Carbons: Influence of Precursor Characteristics, Adsorption Behaviour and Comparison with Commercial Activated Carbon

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ABSTRACT

Biomass-derived activated carbons prepared from taro (*Colocasia esculenta*), crofton weed (*Ageratina adenophora*), and chayote (*Sechium edule*) were activated using phosphoric acid and evaluated for crystal violet removal from aqueous solution. BET, FTIR, SEM, XPS, and pH_{ZPC} analyses were used to characterise the prepared activated carbons. Batch adsorption experiments were carried out by optimising pH, adsorbent dosage, contact time, initial dye concentration, and temperature. The prepared activated carbons achieved crystal violet removal efficiencies of $98.65 \pm 0.30\%$ (YPAC), $96.91 \pm 0.68\%$ (CWAC), and $93.46 \pm 0.45\%$ (SPAC) under the optimized adsorption conditions. The equilibrium data were generally well described by the Langmuir isotherm model, while the pseudo-second-order model showed the best fit for the adsorption kinetics. Langmuir maximum adsorption capacities were 38.853 mg g^{-1} for YPAC, 37.184 mg g^{-1} for CWAC, and 33.220 mg g^{-1} for SPAC, with YPAC showing the highest adsorption affinity based on the Langmuir constant. Thermodynamic analysis showed that adsorption was spontaneous and endothermic for all three activated carbons. The prepared activated carbons also maintained high crystal violet removal in crystal violet-spiked groundwater under laboratory conditions and showed higher removal than commercial activated carbon under the respective optimized conditions. Statistical analysis showed significant differences in crystal violet removal among YPAC, CWAC, and SPAC ($p < 0.001$). These findings show that the choice of biomass precursor can influence the adsorption and regeneration performance of phosphoric acid-activated carbons prepared under identical activation conditions.

Keywords: Adsorption mechanism, Biomass-derived activated carbon, Crystal violet, Phosphoric acid activation, Reusability.

1. INTRODUCTION

Synthetic dye contamination from textile and related industries remains a serious environmental problem because many dyes are chemically stable, visually persistent, and toxic to aquatic systems (Ali 2010, Crini 2006). Even at low concentrations, these pollutants can reduce light penetration and adversely affect water quality, making their removal an important treatment objective. Among the available treatment methods, adsorption is widely used for dye removal because of its simplicity, relatively low cost, and low sludge production (Alharbi et al. 2022, Yakout & Ali 2015). Activated carbon is widely regarded as an effective adsorbent because of its high surface area, porous structure, and adaptable surface chemistry (Neme et al. 2022). However, the high production cost of commercial activated carbon and its dependence on non-renewable precursors have encouraged the development of alternative adsorbents derived from biomass and other low-cost materials (Mohan et al. 2002, Mane et al. 2007, Gupta et al. 2006, Foroutan et al. 2021, Bhatnagar et al. 2011, Kausar et al. 2018). Chemical activation is commonly used to improve pore development and surface functionality in biomass-derived carbons.

Crystal violet (CV) is a cationic triphenylmethane dye widely used in textile dyeing, printing, and microbiological applications. Due to its stability and resistance to degradation, CV can persist in aquatic environments and exhibit toxic effects. Biomass-derived activated carbons prepared from rice husk (Homagai et al. 2022), palm shells (Tan et al. 2008), coconut residues (Aljeboree et al. 2015), and other agricultural by-products (Loulidi et al. 2020), have shown effective CV removal, demonstrating the potential of lignocellulosic biomass as a precursor for low-cost adsorbents. However, most studies focus on single biomass precursors, and comparative investigations using different plant-based materials prepared under identical conditions remain limited. In this study, activated carbons were prepared from three locally abundant and underutilized plant biomasses: taro (*Colocasia esculenta*), crofton weed (*Ageratina adenophora*), and chayote (*Sechium edule*), using phosphoric acid activation under identical preparation conditions. The prepared carbons were comparatively evaluated for crystal violet adsorption through surface characterization using FTIR and XPS analyses, batch adsorption experiments, isotherm and kinetic modelling, thermodynamic analysis, regeneration studies, and comparison with commercial activated carbon.

2. EXPERIMENTAL PROCEDURE

2.1 Adsorbate

Crystal violet (CV) dye obtained from Merck (India) Ltd. was used as the adsorbate. A 1000 mg L⁻¹ stock solution was prepared in distilled water and diluted as required. Dye concentration was measured using a UV–Vis spectrophotometer at 580 nm.

2.2 Preparation of Adsorbent AC

Biomass residues of *Sechium edule* (Chayote), *Ageratina Adenophora* (crofton weed), and *Colocasia esculenta* (taro) were collected from Jotsoma Village, Nagaland, India. The collected biomasses were washed thoroughly with distilled water to remove adhering impurities and dried at 60 °C. The dried biomass was carbonized at 450 °C for 3 h, and the resulting char was ground and sieved to obtain a particle size of 106 µm. The carbonized char was then treated with 0.1 M H₃PO₄ at a biomass-to-acid ratio of 1:3 (w/v) for 24 h. This post-carbonization activation method has been reported for the preparation of biomass-derived activated carbon, where phosphoric acid is applied to the carbonized material to modify its surface properties and improve its adsorption characteristics (Pongener et al. 2018). Phosphoric acid was selected as the activating agent because it promotes pore development and introduces oxygen-containing surface functional groups that contribute to the adsorption behaviour of biomass-derived activated carbons (Neme et al. 2022). The same activation conditions were maintained for all three biomass precursors to allow a direct comparison of the influence of precursor characteristics on the surface properties and adsorption performance of the prepared carbons. After acid treatment, the samples were washed repeatedly with distilled water until near-neutral pH, oven-dried at 110 °C, and labelled as YPAC for *Colocasia esculenta*, CWAC for *Ageratina adenophora* and SPAC for *Sechium edule*. No second thermal activation step was performed after phosphoric acid treatment. Product yield was calculated based on the ratio of activated carbon obtained to the initial biomass weight:

$$Yield \% = \frac{W_{AC}}{W_{BM}} \times 100$$

Where; W_{AC} = weight of activated carbon obtained (g), and W_{BM} = weight of the biomass (g).

2.3 Characterization of surface properties

SPAC, CWAC and YPAC were examined through several commonly used characterization methods to understand their physicochemical behaviour. The specific surface area and pore characteristics were measured by nitrogen adsorption-desorption using the BET method with a Quantachrome surface analyser (ASiQ0000-4, USA). The samples were degassed under vacuum before analysis. The external structure and morphological patterns of the carbons were observed through SEM imaging (JSM 6390LV, JEOL, Japan). FTIR spectroscopy (Spectrum 100 and Frontier IR, Perkin Elmer) was used to identify surface functional groups, while surface chemical composition was further examined using XPS (Thermo Scientific ESCALAB Xi+). The pH_{ZPC} of each activated carbon was identified by monitoring changes in solution pH after equilibration with the adsorbent, following the general method reported in the literature (Babic et al. 1999).

2.4 Batch Adsorption Experiments

Batch adsorption experiments were carried out to determine the optimum conditions for crystal violet removal. An initial adsorbent dosage of 0.5 g was used as the starting point for the experiments. Unless otherwise stated, all adsorption experiments were carried out in 250 mL of crystal violet solution in Erlenmeyer flasks agitated at 165 rpm.

The effect of initial crystal violet concentration was investigated over the range of 10-100 mg L⁻¹ using an adsorbent dosage of 0.5 g for a contact time of 24 h under the natural pH of the dye solution. The optimum concentration obtained from this study was then used to evaluate the effect of adsorbent dosage (0.1-1.0 g), while keeping the initial concentration, and contact time constant. Contact time studies were carried out over 5 min–24 h using the optimum concentration and an adsorbent dosage of 1.0 g. The effect of solution pH was then evaluated over the range of pH 2-10 under the optimized concentration, dosage, and contact time, with pH adjusted using 0.1 M HCl or 0.1 M NaOH. All adsorption experiments were conducted in triplicate, and the results are reported as mean ± standard deviation (SD). The percentage removal of crystal violet and the equilibrium adsorption capacity (q_e) were calculated using the equations below:

$$\text{Removal (\%)} = \frac{C_i - C_f}{C_i} \times 100 \quad q_e = \frac{(C_i - C_f)V}{m}$$

where C_i and C_f represent the initial and final dye concentrations (mg L⁻¹), q_e is the uptake at equilibrium (mg g⁻¹), V is the volume of solution (L), and m is the adsorbent mass (g).

2.5 Error Analysis

To evaluate how well the isotherm and kinetic models described the experimental results, the Root Mean Square Error (RMSE) (Vijayaraghavan et al. 2006) and Chi-square statistic (χ^2) (Jumasiah et al. 2005) were used. They were calculated as:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (q_{e,\text{exp}} - q_{e,\text{cal}})^2} \quad \chi^2 = \sum \frac{(q_{e,\text{exp}} - q_{e,\text{cal}})^2}{q_{e,\text{cal}}}$$

Here, $q_{e,\text{exp}}$ and $q_{e,\text{cal}}$ represent the experimental and predicted equilibrium capacities (mg g⁻¹), and n is the number of observations.

2.6 Thermodynamic Studies

Thermodynamic studies were performed at 298, 308, and 318 K under the optimized adsorption conditions for each activated carbon. The standard thermodynamic parameters, namely enthalpy change (ΔH°) and entropy change (ΔS°), were determined from the linear form of the Van't Hoff equation (Ogunlusi et al. 2023).

$$\ln K_c = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}$$

The equilibrium distribution coefficient (K_d) was calculated as q_e/C_e , where q_e is the equilibrium adsorption capacity (mg g^{-1}) and C_e is the equilibrium dye concentration (mg L^{-1}). Because K_d has units of L g^{-1} , it was converted to a dimensionless equilibrium constant (K_c) using $K_c = K_d \times 1000$ before thermodynamic analysis. The dimensionless K_c values were then used in the Van't Hoff equation to determine ΔH° and ΔS° , while ΔG° was calculated at each temperature using the corresponding K_c value.

$$K_d = \frac{q_e}{C_e} \quad \Delta G^\circ = -RT \ln K_c$$

where q_e denotes the amount of crystal violet adsorbed at equilibrium (mg g^{-1}), C_e corresponds to the residual dye concentration in solution (mg L^{-1}), K_c = dimensionless equilibrium constant, (R) is the universal gas constant, and (T) represents the absolute temperature in Kelvin.

2.7 Regeneration Studies

Regeneration experiments were performed to evaluate the reusability of SPAC, CWAC, and YPAC for crystal violet adsorption. After each adsorption cycle, the spent adsorbent was separated by filtration and washed with distilled water to remove weakly bound dye. Desorption was carried out using 0.1 M NaOH at a solid-to-liquid ratio of 1 g per 250 ml, with agitation at room temperature for 2 h. The adsorbent was then filtered, rinsed repeatedly with distilled water until near-neutral pH, oven-dried at 80 °C, and reused in subsequent cycles. Regeneration performance was assessed over five consecutive adsorption-desorption cycles under identical experimental conditions.

2.8 Groundwater Adsorption Study

The applicability of the prepared activated carbons was evaluated using groundwater samples collected from Jotsoma, Nagaland, India. The groundwater was filtered through Whatman No. 1 filter paper to remove suspended particles, and its physicochemical characteristics were determined prior to the adsorption experiments. The groundwater was subsequently spiked with crystal violet at the optimized initial concentration for each activated carbon and treated under the respective optimized adsorption conditions.

2.9 Statistical Analysis

All adsorption experiments were performed in triplicate, and the results are expressed as mean $\pm$ standard deviation (SD). One-way analysis of variance (ANOVA) was performed using the triplicate crystal violet removal efficiencies obtained under the optimized adsorption conditions to evaluate differences among the prepared activated carbons. Tukey's post hoc test was used for pairwise comparisons, and statistical significance was considered at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Characterization

The physicochemical and textural properties of the prepared activated carbons are summarized in Table 1. YPAC showed the highest BET surface area ($884.44\text{ m}^2\text{ g}^{-1}$) and pore volume ($0.561\text{ cm}^3\text{ g}^{-1}$), followed by CWAC ($803.21\text{ m}^2\text{ g}^{-1}$ and $0.502\text{ cm}^3\text{ g}^{-1}$) and SPAC ($731.46\text{ m}^2\text{ g}^{-1}$ and $0.391\text{ cm}^3\text{ g}^{-1}$). The BET surface areas obtained in this study are comparable with those reported for biomass-derived activated carbons prepared by post-carbonization phosphoric acid treatment, including activation with $0.1\text{ N H}_3\text{PO}_4$ (Pongener et al. 2018), showing that this activation approach can produce highly porous activated carbons. Since the carbonization temperature, phosphoric acid concentration, biomass-to-acid ratio, and activation time were kept constant for all three adsorbents, the observed differences in surface area and pore volume are attributed to the characteristics of the biomass precursors. The higher surface area and pore volume of YPAC provided a larger surface available for crystal violet adsorption, which is reflected in its higher removal efficiency.

Table 1:
Physicochemical and textural properties of the prepared activated

AC	BET	
	SBET ($\text{m}^2\text{ g}^{-1}$)	VTot ($\text{cm}^3\text{ g}^{-1}$)
YPAC	884.440	0.561
CWAC	803.210	0.502
SPAC	731.460	0.391

carbons.

SEM micrographs Fig.1 revealed distinct differences in surface morphology and pore accessibility among the three activated carbons. YPAC displayed a rough and fragmented surface with well-developed interconnected pores. CWAC showed moderate pore development with less uniform pore distribution. In contrast, SPAC exhibited a comparatively compact surface with fewer accessible pores and partially blocked regions.

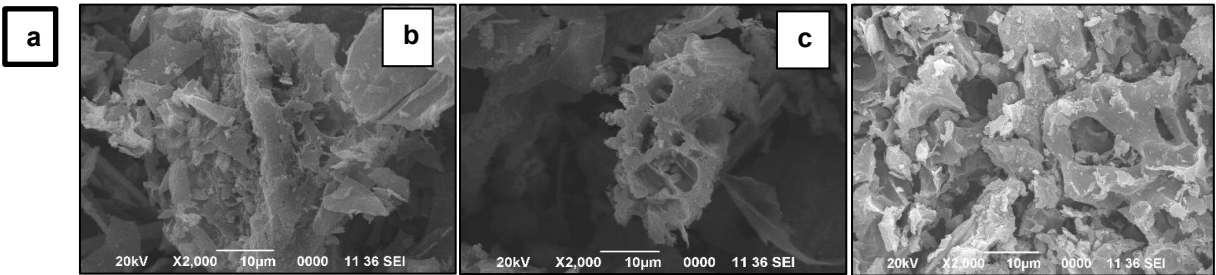


Fig.1: SEM micrographs of phosphoric acid-activated carbons derived from (a) taro, (b) crofton weed and (c) chayote.

FTIR spectra of the three activated carbons Fig. 2 (a), (b), (c) indicated the presence of surface functional groups associated with dye interaction, including O-H, C-H, and C=C vibrations. Variations in the intensity of C-O stretching bands suggest differences in surface oxygen-containing groups among the prepared carbons (Foroutan et al. 2021, Kamboj et al. 2025)

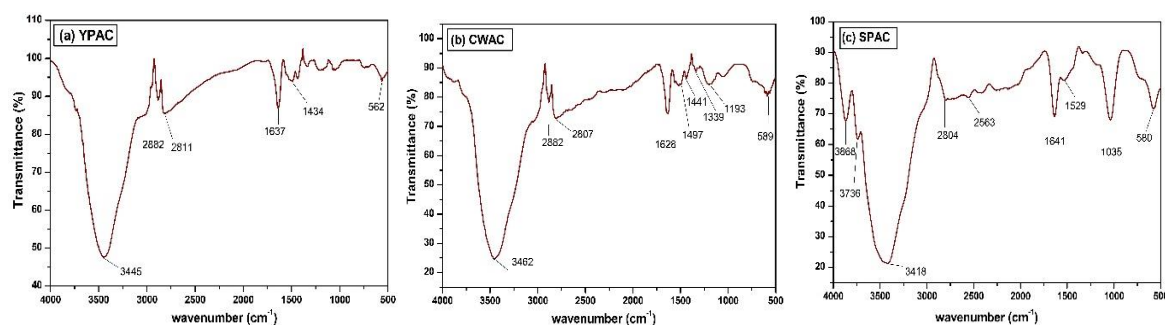


Fig. 2: FTIR spectra of (a) YPAC, (b) CWAC, (c) SPAC.

XPS analysis was performed on YPAC to examine its surface chemical composition. The survey spectrum confirmed carbon and oxygen as the major surface elements. The high-resolution C 1s spectrum was deconvoluted into C–C/C=C, C–O, and C=O components, indicating the presence of aromatic carbon structures together with oxygen-containing functional groups. Similarly, the O 1s spectrum revealed contributions from C–O and C=O species. The presence of these oxygen-containing surface functionalities is consistent with the FTIR results and may contribute to crystal violet adsorption through electrostatic interaction and π - π interaction between the aromatic dye molecules and the carbon surface.

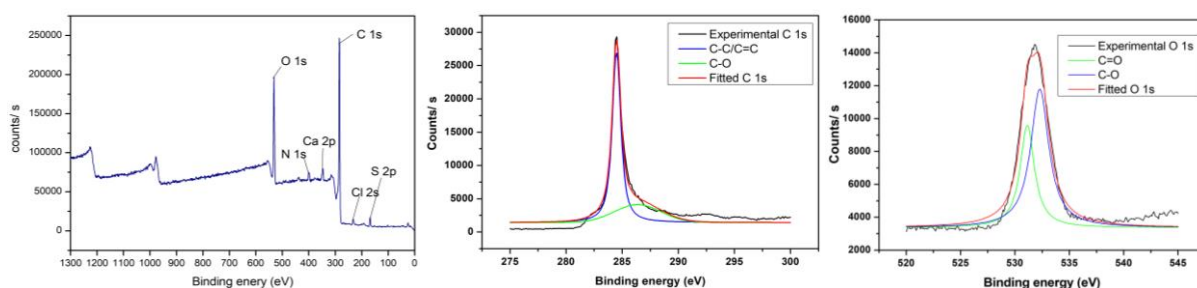


Fig. 3: XPS spectra of YPAC: (a) survey spectrum, (b) C 1s spectrum, and (c) O 1s spectrum.

The pH_{ZPC} values of the activated carbons were 6.3 for YPAC, 6.0 for CWAC, and 5.8 for SPAC, indicating surface charge behaviour among the materials Fig 4. At pH the pH_{ZPC} , the adsorbent surfaces become positively limiting electrostatic attraction toward the cationic crystal violet molecules. When the solution pH exceeds the pH_{ZPC} , deprotonation results in a negatively charged surface, electrostatic attraction and enhancing dye adsorption. The slightly higher pH_{ZPC} of YPAC may contribute to its more stable adsorption behaviour over the studied pH range.

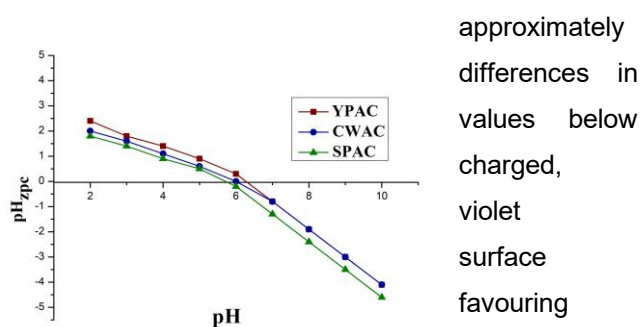


Fig. 4: Determination of the pH_{ZPC} of YPAC, CWAC, and SPAC.

3.2 Batch Adsorption Studies

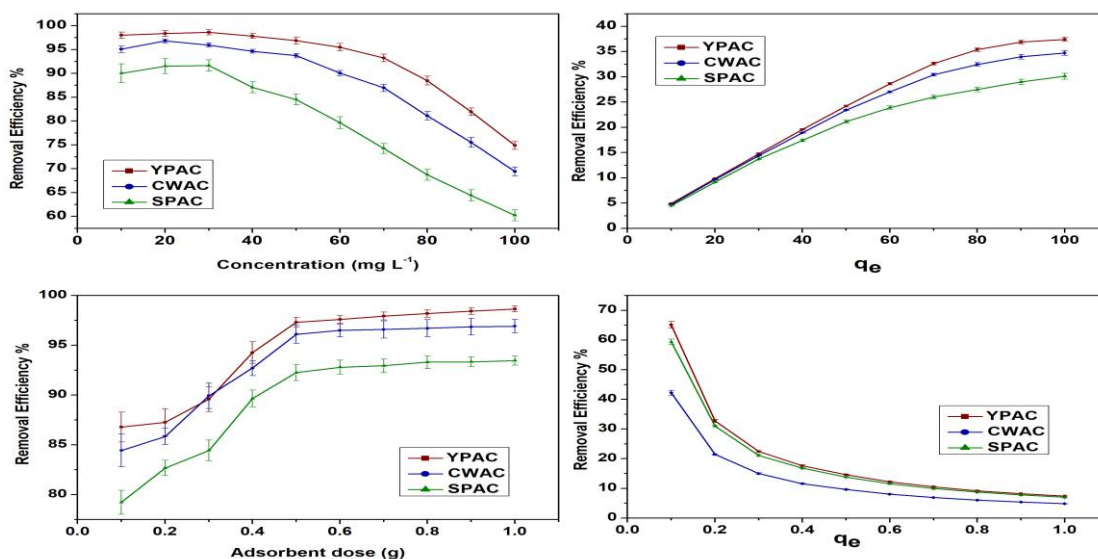


Fig. 5:

Effect of initial dye concentration and adsorbent dosage on crystal violet adsorption by YPAC, CWAC, and SPAC.

Data are presented as mean $\pm$ SD (n = 3).

The optimum adsorption conditions selected for the subsequent studies were 30 mg L⁻¹, pH 9, 1.0 g adsorbent dosage, and 24 h contact time for YPAC, which achieved a crystal violet removal efficiency of $98.65 \pm 0.30\%$; 20 mg L⁻¹, pH 10, 1.0 g dosage, and 24 h contact time for CWAC, which achieved $96.91 \pm 0.68\%$ removal; and 30 mg L⁻¹, pH 10, 1.0 g dosage, and 24 h contact time for SPAC, which achieved $93.46 \pm 0.45\%$ removal. The batch adsorption results showed distinct adsorption behaviour for the three activated carbons under the optimized conditions. With increasing initial dye concentration, the removal efficiency generally increased up to the optimum concentration and then decreased as the available adsorption sites became progressively occupied. Removal decreased from approximately 98 to 74% for YPAC, 97 to 69% for CWAC, and 92 to 60% for SPAC at higher initial concentrations. At the same time, q_e increased due to the higher concentration gradient, which enhanced mass transfer of dye molecules toward the adsorbent surface. YPAC exhibited the highest removal across the studied dosage range, achieving approximately 98% removal at 1.0 g and more than 86% removal at 0.1 g. In comparison, CWAC removed about 97% and 84%, while SPAC achieved about 93% and 79% removal at the same dosages. These differences indicate that YPAC provides a greater number of accessible adsorption sites and more effective surface interactions. Although increasing adsorbent dosage improved overall removal efficiency, the corresponding decrease in equilibrium adsorption capacity (q_e) reflects the distribution of a fixed dye amount over a larger adsorbent mass Fig. 5.

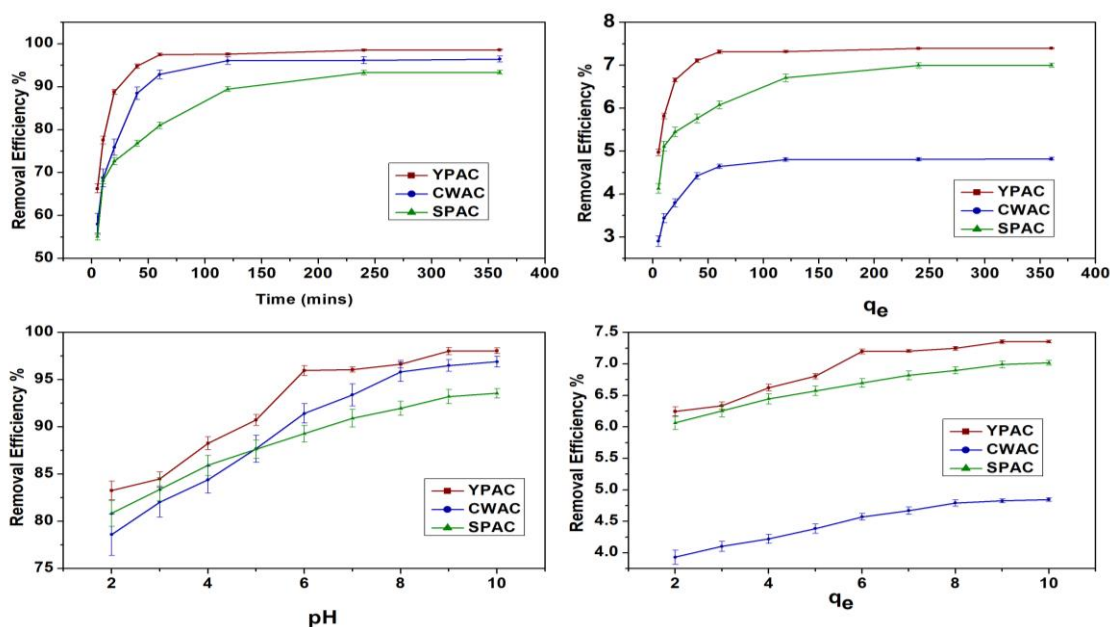


Fig. 6: Effect of contact time and solution pH on crystal violet adsorption by YPAC, CWAC, and SPAC. Data are presented as mean $\pm$ SD ($n = 3$).

Time-dependent adsorption showed rapid initial dye uptake for all adsorbents within the first 30-60 min, followed by a slower adsorption stage associated with pore diffusion. After the initial rapid uptake, the increase in removal became gradual as the available adsorption sites were progressively occupied (Foo & Hamed 2010). Adsorption remained favourable across the studied pH range (2-10), with YPAC maintaining consistently higher removal efficiencies than CWAC and SPAC Fig. 6. Adsorption increased as the solution pH approached and exceeded the pH_{ZPC} values, which may be related to increased electrostatic attraction between the negatively charged adsorbent surface and the cationic dye molecules.

3.3 Adsorption Isotherm

Adsorption equilibrium behaviour for crystal violet was evaluated using non-linear Langmuir, Freundlich, and Temkin isotherm models, while the calculated isotherm parameters are summarized in Table 2 and the corresponding model fits are shown in Fig. 7. The Langmuir model gave the highest R^2 values for all three adsorbents and showed the lowest χ^2 and RMSE values for CWAC and SPAC. For YPAC, the Freundlich model showed lower χ^2 and RMSE values, although its R^2 value was lower than that of the Langmuir model. Overall, the Langmuir model provided a good description of the equilibrium adsorption behaviour of the prepared activated carbons. The calculated Langmuir maximum adsorption capacities were 38.85 mg g^{-1} for YPAC, 37.18 mg g^{-1} for CWAC, and 33.22 mg g^{-1} for SPAC. The Langmuir maximum adsorption capacities followed the order YPAC (38.853 mg g^{-1}) > CWAC (37.184 mg g^{-1}) > SPAC (33.220 mg g^{-1}), which is consistent with the BET surface area and pore volume of the prepared activated carbons. The higher Langmuir affinity constant ($K_L = 1.107 \text{ L mg}^{-1}$) and lower separation factor ($R_L = 0.0292$) obtained for YPAC indicate greater affinity and more favourable adsorption of crystal violet compared with CWAC and SPAC.

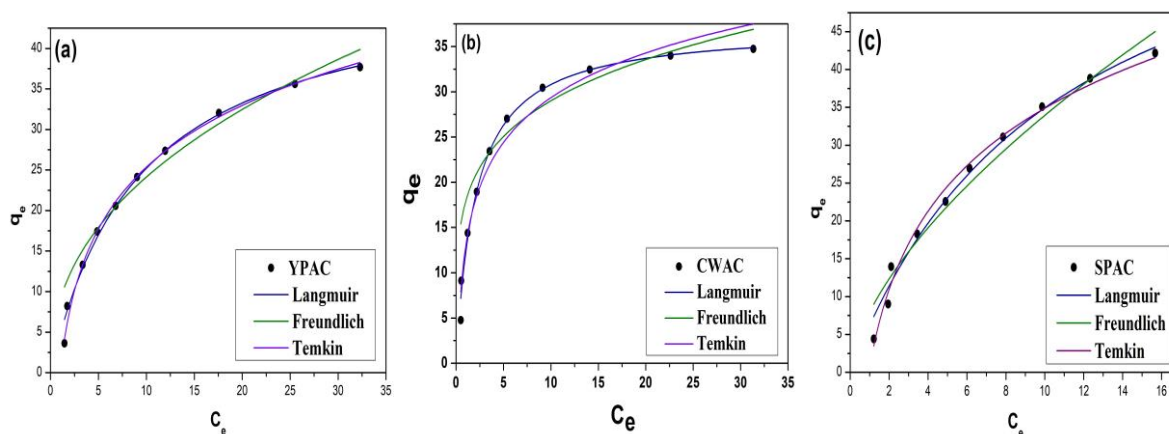


Fig. 7: Langmuir, Freundlich, and Temkin isotherm fits for crystal violet adsorption onto (a) YPAC, (b) CWAC, and (c) SPAC.

Isotherm	Equation	AC	Parameters	R^2	χ^2	RMSE
Langmuir	$q_e = \frac{q_m K_L C_e}{1 + K_L C_e}$	YPAC	$q_m(\text{mg g}^{-1}) = 38.853$ $K_L(\text{L mg}^{-1}) = 1.107$ $R_L = 0.0292$	0.996	1.028	1.014
		CWAC	$q_m(\text{mg g}^{-1}) = 37.184$ $K_L(\text{L mg}^{-1}) = 0.482$ $R_L = 0.0939$	0.995	1.038	1.019
		SPAC	$q_m(\text{mg g}^{-1}) = 33.22$ $K_L(\text{L mg}^{-1}) = 0.226$ $R_L = 0.128$	0.990	0.772	0.879
Freundlich	$q_e = K_F(C_e)^{\frac{1}{n}}$	YPAC	$1/n = 0.222$ $K_F(\text{mg g}^{-1}) = 20.641$	0.989	0.880	0.938
		CWAC	$1/n = 0.2109$ $K_F(\text{mg g}^{-1}) = 17.843$	0.946	3.258	1.805
		SPAC	$1/n = 0.338$ $K_F(\text{mg g}^{-1}) = 9.314$	0.921	6.186	2.487
Temkin	$q_e = B \ln(A_T C_e)$	YPAC	$B = 6.839$ $A_T(\text{L g}^{-1}) = 16.780$	0.950	6.830	2.613
		CWAC	$B(\text{J mol}^{-1}) = 7.132$ $A_T(\text{L g}^{-1}) = 6.117$	0.980	3.703	1.924
		SPAC	$B(\text{J mol}^{-1}) = 6.842$ $A_T(\text{L g}^{-1}) = 2.412$	0.986	1.056	1.027

Table 2:
Isotherm
parameters
for
adsorption
onto
YPAC,
CWAC and
SPAC

3.4 Adsorption Kinetics

Adsorption

kinetics for crystal violet uptake onto YPAC, CWAC, and SPAC were evaluated using non-linear pseudo-first-order, pseudo-second-order, and intraparticle diffusion models. The calculated kinetic parameters are summarized in Table 3, while the corresponding kinetic fits are shown in Fig. 8. For all adsorbents, the PSO model showed better agreement with the experimental data, as reflected by higher correlation coefficients and lower error values.

For YPAC, the PSO model showed close agreement between the experimental and calculated adsorption capacities ($q_e(\text{exp}) = 7.397 \text{ mg g}^{-1}$; $q_e(\text{cal}) = 7.488 \text{ mg g}^{-1}$), together with a high correlation coefficient ($R^2 = 0.995$) and low χ^2 (0.007) and RMSE (0.084) values. Similar behaviour was observed for CWAC ($R^2 = 0.985$) and SPAC ($R^2 = 0.956$). In contrast, the PFO model showed lower R^2 values (0.839-0.942) and higher error values than the PSO model. The intraparticle diffusion model showed moderate correlation ($R^2 = 0.703$ -0.851) with non-zero intercepts for all adsorbents, indicating that diffusion within pores contributes to the adsorption process but does not solely control the overall rate (Foo & Hamed 2010).

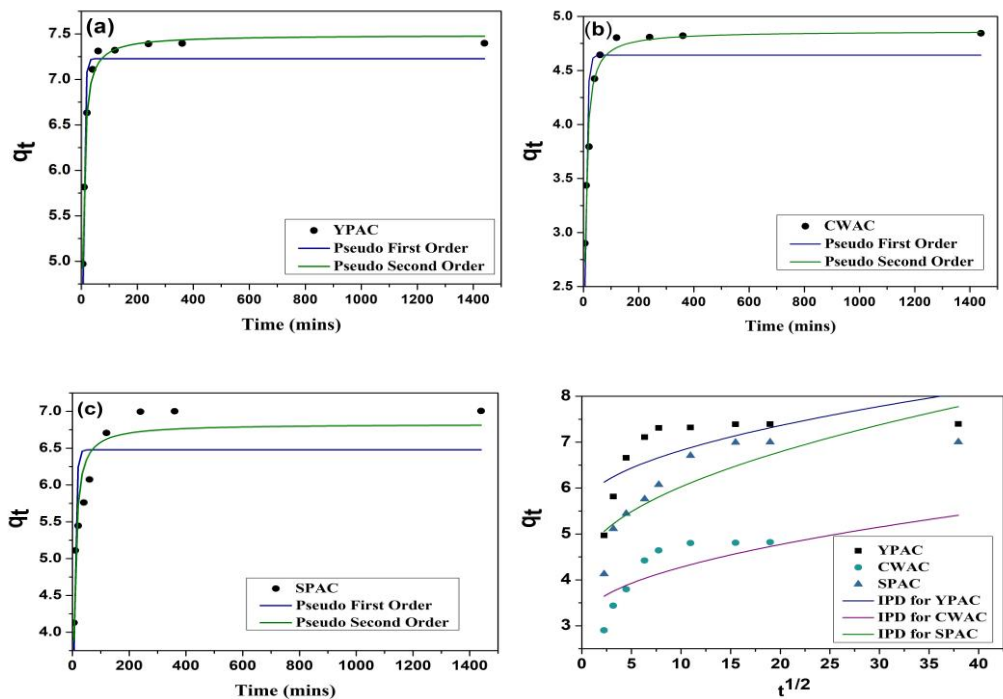


Fig. 8: Pseudo-first-order, pseudo-second-order, and intraparticle diffusion kinetic models for crystal violet adsorption onto YPAC, CWAC, and SPAC.

Table 3: Kinetic parameters for adsorption onto YPAC, CWAC and SPAC

Model	Equation	AC	Parameters	R ²	χ ²	RMSE
Pseudo first order	$q_t = [1 - \exp^{-K_1 t}]$	YPAC	$q_e(\text{exp}) = 7.397$ $q_e(\text{cal}) = 7.227$ $K_1 = 0.199$	0.942	0.096	0.310
		CWAC	$q_e(\text{exp}) = 4.844$ $q_e(\text{cal}) = 4.641$ $K_1 = 0.151$	0.901	0.111	0.334
		SPAC	$q_e(\text{exp}) = 7.005$ $q_e(\text{cal}) = 6.477$ $K_1 = 0.169$	0.839	0.344	0.587
Pseudo second order	$q_t = \frac{K_2 q_e^2 t}{1 + K_2 q_e t}$	YPAC	$q_e(\text{exp}) = 7.397$ $q_e(\text{cal}) = 7.488$ $K_2 = 0.051$	0.995	0.007	0.084
		CWAC	$q_e(\text{exp}) = 4.844$ $q_e(\text{cal}) = 4.865$ $K_2 = 0.052$	0.985	0.017	0.132
		SPAC	$q_e(\text{exp}) = 7.005$ $q_e(\text{cal}) = 6.830$ $K_2 = 0.038$	0.956	0.100	0.316
Intraparticle diffusion	$q_t = K t^{\frac{1}{2}} + C$	YPAC	$K_{\text{diff}} = 0.414$ $C = 5.509$	0.703	0.434	0.658
		CWAC	$K_{\text{diff}} = 0.377$ $C = 3.080$	0.771	0.240	0.490
		SPAC	$K_{\text{diff}} = 0.583$ $C = 4.183$	0.851	0.320	0.566

3.5
Adsorption
Thermodynamics
The thermodynamic parameters presented in Table 4 indicate

favourable crystal violet adsorption by all three activated carbons over the investigated temperature range. The

negative ΔG° values at all temperatures confirm the spontaneous nature of the adsorption process, while the increasingly negative ΔG° values with increasing temperature indicate that adsorption becomes more favourable at higher temperatures. The positive ΔH° values show that crystal violet adsorption is an endothermic process, consistent with the improved dye removal observed at elevated temperatures. The positive ΔS° values suggest an increase in disorder at the adsorbent-solution interface during adsorption. Among the three adsorbents, YPAC exhibited the most negative ΔG° values across the studied temperatures, indicating greater thermodynamic favourability for crystal violet adsorption than CWAC and SPAC.

Table 4: Thermodynamic parameters for crystal violet adsorption onto YPAC, CWAC and SPAC at different temperatures

Adsorbent	Co	ΔH° (KJ mol ⁻¹)	ΔS° (JK ⁻¹ mol ⁻¹)	ΔG° (KJ mol ⁻¹)		
				298K	308K	318K
YPAC	30	26.861	156.220	-19.736	-21.234	-22.863
CWAC	20	15.273	113.494	-18.616	-19.588	-20.94
SPAC	30	1.302	100.592	-17.457	-18.4856	-19.468

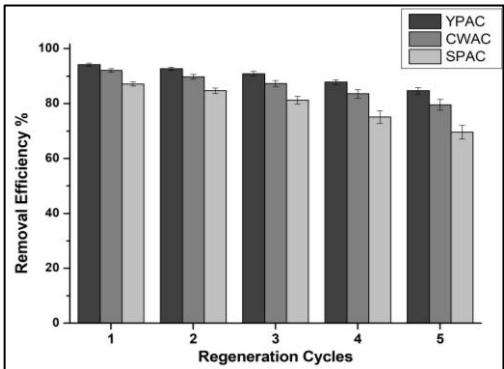
3.6
Adsorption
Mechanism

The
adsorption

behaviour of crystal violet on YPAC, CWAC, and SPAC can be related to their pore structure, surface chemistry, and solution pH. YPAC exhibited higher and more consistent adsorption, which may be related to its more open and interconnected pore structure. The influence of pH can be interpreted based on the pH_{ZPC} values of the adsorbents. Below the pH_{ZPC} , the surface carries a net positive charge, which can limit electrostatic attraction toward the cationic crystal violet molecules. As the pH increases above the pH_{ZPC} , surface deprotonation produces a negatively charged surface, which can enhance electrostatic attraction with the cationic dye. The consistently high removal efficiencies observed across the studied pH range suggest that electrostatic attraction, π - π interactions between the aromatic dye molecules and the carbon surface, and adsorption within the pore network may all contribute to dye uptake (Dąbrowski 2001). FTIR analysis indicated the presence of oxygen-containing surface groups that may contribute to interactions with the dye molecules. Kinetic analysis showed rapid initial uptake followed by a slower stage influenced by diffusion within the pore structure. The non-zero intercepts observed in the intraparticle diffusion plots indicate that diffusion contributes to mass transfer but does not solely control the overall adsorption rate (Weber & Morris 1963).

3.7 Regeneration Studies

The regeneration performance of the prepared activated carbons was evaluated over five consecutive adsorption-desorption cycles using 0.1 M NaOH under the optimized regeneration conditions. YPAC maintained the highest adsorption efficiency throughout the regeneration cycles, decreasing from $94.25 \pm 0.54\%$ in the first cycle to $84.72 \pm 1.17\%$ after the fifth cycle. CWAC showed moderate regeneration stability, with the removal efficiency decreasing from $92.09 \pm 0.63\%$ in the first cycle to $79.58 \pm 1.97\%$ after five cycles, whereas SPAC exhibited the largest decline, decreasing from $87.12 \pm 0.72\%$ to $69.61 \pm 2.54\%$ over the same period (Fig. 9).



The limited decline observed during the initial cycles suggests predominantly reversible adsorption, while the greater loss at later stages is associated with incomplete desorption of strongly bound CV molecules through π - π interactions and adsorption within narrow pores, leading to partial pore blockage and reduced availability of active sites (Hayeeye & Sattar 2020). Despite the gradual decrease

Fig. 9: Regeneration performance of YPAC, CWAC, and SPAC over five adsorption-desorption cycles. Data are presented as mean $\pm$ SD (n = 3).

in removal efficiency, all three activated carbons retained appreciable adsorption performance after repeated adsorption-desorption cycles, indicating that they can be reused under the experimental conditions employed in this study.

3.8 Comparative performance with Commercial Activated Carbon

Fig. 10 compares the crystal violet removal efficiencies of YPAC, CWAC, and SPAC with commercial activated carbon under identical adsorbent dosage (1 g) and contact time (24 h), using the respective optimum pH and initial dye concentration for each adsorbent. All three biomass-derived activated carbons performed better than commercial activated carbon under the optimized conditions.

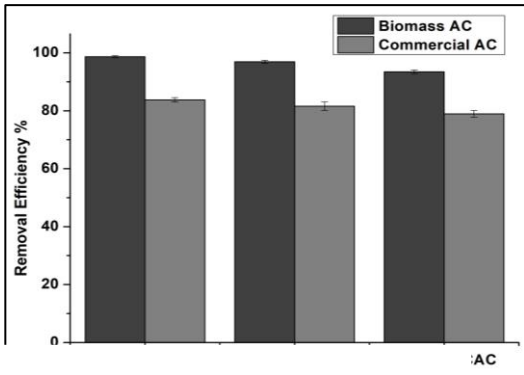


Fig. 10: Comparison of crystal violet removal by the prepared activated carbons and commercial activated carbon under the respective optimized adsorption conditions.

with 93.46 ± 0.45% removal at 30 mg L⁻¹ and pH 10, while commercial activated carbon removed 78.96 ± 1.16%. The consistently higher removal efficiencies obtained with the biomass-derived activated carbons indicate that the prepared adsorbents were more effective than commercial activated carbon under the experimental conditions used in this study. Among the three adsorbents, YPAC showed the greatest improvement over commercial activated carbon, followed by CWAC and SPAC (Sh et al. 2024)

3.9 Statistical Analysis of Adsorption Data

All adsorption experiments were performed in triplicate, and the results are expressed as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed using the triplicate crystal violet removal efficiencies obtained under the optimized adsorption conditions to compare YPAC, CWAC, and SPAC. Tukey's post hoc test was used for pairwise comparisons, and statistical significance was considered at p < 0.05

Table 5: One-way ANOVA for crystal violet removal by YPAC, CWAC and SPAC under optimized adsorption conditions.

Source	df	SS	MS	F	p
Between groups	2	41.756	20.878	65.63	<0.001
Within groups	6	1.909	0.318	–	–
Total	8	43.665	–	–	–

SS= sum of squares; MS= mean square

Table 6: Tukey post hoc comparison of crystal violet removal by the activated carbons

Comparison	Mean difference (%)	p
YPAC vs CWAC	1.65	0.0255

YPAC vs SPAC	5.10	<0.001
CWAC vs SPAC	3.45	<0.001

Tukey's post hoc test was performed following one-way ANOVA (n = 3 for each adsorbent)

One-way ANOVA showed a significant difference in crystal violet removal among YPAC, CWAC, and SPAC ($F_{2,6} = 65.63$, $p < 0.001$). Tukey's post hoc test confirmed significant differences between each pair of adsorbents (Table 6), with the mean removal efficiency following the order YPAC > CWAC > SPAC.

3.10 Comparative Performance with Reported Adsorbent

Table 7 compares the adsorption performance of the prepared activated carbons with selected reported adsorbents based on equilibrium contact time, removal efficiency, and reusability. The biomass-derived activated carbons developed in this study exhibited removal efficiencies exceeding 93% under a fixed contact time of 24 h. Among them, YPAC achieved the highest removal efficiency (98.65%) and showed the greatest regeneration stability, retaining 84.71% efficiency after five adsorption-desorption cycles.

Several reported adsorbents, including bamboo activated carbon (Sun et al. 2023) and activated carbon fabric (Mulla 2024), reached adsorption equilibrium within minutes to one hour. However, reusability data for these materials were not consistently reported, limiting assessment of their long-term applicability. Other adsorbents, including royal palm leaf sheath powder (Sen et al. 2024), calcium alginate-based adsorbents (Dalal 2025), and orange- peel biochar-alginate microspheres (Adeniyi et al. 2023), showed moderate removal efficiencies and a more noticeable decline in adsorption performance after repeated cycles. In contrast, the activated carbons prepared in this study maintained relatively high removal efficiencies over multiple regeneration cycles despite longer equilibrium contact times. The comparison suggests that while some reported adsorbents exhibit faster adsorption kinetics, the prepared carbons provide a more balanced performance in terms of adsorption efficiency and regeneration stability. Among the prepared adsorbents, YPAC showed the most stable regeneration behaviour, supporting its potential for repeated batch adsorption applications.

Table 7: Comparison of adsorption performance of the prepared carbons with reported adsorbents

Adsorbent	Equilibrium contact time	Removal efficiency	Reusability (cycles)	Reference
YPAC	24h	98.65%	5 (declines to 84.71%)	This work
CWAC	24h	96.92%	5 (declines to 79.58%)	This work
SPAC	24h	93.46%	5 (declines to 69.60%)	This work
Bamboo activated carbon (BAC)	10min	99.6%	Not reported	(Sun et al. 2023)
Activated carbon fabric (AC-NWO oxidized)	1h	~90%	Not reported	(Mulla et al. 2024)
Royal palm leaf sheath powder (BMRPLS)	60min	87.2%	3(declines to 75.12%)	(Sen et al. 2024)
Calcium alginate beads (Padina pavonica)	5h	~80%	Not reported	(Dalal 2025)
Orange peel biochar/sodium alginate microspheres (BS800)	12h	Not specified	5 (declines to 60.88%)	(Adeniyi et al. 2023)

Vermiculite-based geopolymer	15min	Not specified	5 (declines to 71%)	(Marubini et al. 2025)
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3.11 Natural water applicability of activated

The adsorption performance of the prepared carbons was evaluated using the groundwater under the optimized adsorption conditions. The physicochemical characteristics of the groundwater presented in Table 8. The groundwater had a near-(7.3) with low total dissolved solids, electrical conductivity, salinity, and hardness. Crystal violet groundwater was slightly lower than that obtained in for all three activated carbons. YPAC achieved the removal efficiency ($91.28 \pm 1.02\%$), followed by CWAC 0.99%) and SPAC ($88.61 \pm 1.28\%$) under the groundwater conditions (Fig. 11). The presence of calcium and magnesium ions in the groundwater may have reduced the availability of adsorption sites through competitive adsorption, resulting in a small decrease in removal efficiency. Even under these conditions, the overall adsorption trend remained unchanged, with YPAC showing the highest removal efficiency, followed by CWAC and SPAC.

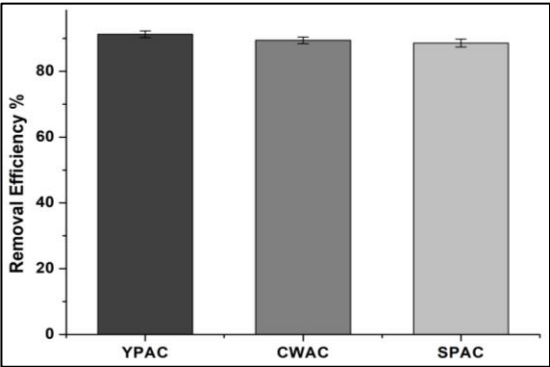


Fig. 11: Crystal violet removal from crystal violet-spiked groundwater using YPAC, CWAC, and SPAC. Data are presented as mean + SD (n = 3)

carbons
activated
sample

are
neutral pH

removal in
distilled water
highest
(89.41 ±

The groundwater study was carried out using crystal violet-spiked groundwater under laboratory conditions. Therefore, the results indicate the performance of the prepared activated carbons in a groundwater matrix and should not be considered a field-scale evaluation.

Table 8: Physicochemical parameters of the natural water

Parameter	Value	Unit
pH	7.3	–
TDS	3.82	ppm
EC	5.81	µS/cm
Salinity	1.61	ppm
Total hardness	54	mg L ⁻¹
Calcium (Ca ²⁺)	12.02	mg L ⁻¹
Magnesium (Mg ²⁺)	5.84	mg L ⁻¹

4. CONCLUSION

Activated carbons prepared from taro (*Colocasia esculenta*), crofton weed (*Ageratina adenophora*), and chayote (*Sechium edule*) showed different crystal violet adsorption performances even though they were produced under the same activation conditions. YPAC gave the highest removal efficiency, followed by CWAC and SPAC, which is consistent with its higher BET surface area and pore volume. The adsorption data were best described by the Langmuir isotherm and the pseudo-second-order kinetic model. The maximum Langmuir adsorption capacities were 38.853 mg g⁻¹ for YPAC, 37.184 mg g⁻¹ for CWAC, and 33.220 mg g⁻¹ for SPAC. The pH study, FTIR, XPS, and intraparticle diffusion analyses showed that adsorption was influenced by surface charge, oxygen-containing functional groups, pore structure, and diffusion during the adsorption process. Thermodynamic analysis indicated that crystal violet adsorption was spontaneous and endothermic for all three activated carbons, with YPAC showing the most favourable ΔG° values. The regeneration study showed a gradual decrease in adsorption efficiency over

five adsorption-desorption cycles, but all three activated carbons remained reusable under the experimental conditions, with YPAC retaining the highest adsorption performance. The prepared activated carbons also performed better than commercial activated carbon under their respective optimized conditions and remained effective in crystal violet-spiked groundwater. The results show that the biomass precursor influenced the adsorption capacity and regeneration behaviour of the activated carbons, with taro producing the most effective adsorbent among the materials investigated in this study.

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COMPETING INTEREST

The authors declare that no competing interests exist.

DATA AVAILABILITY

The data supporting the findings of this study are included within the article.

AUTHORS CONTRIBUTION

Neilanuo Huozha carried out the experimental work, analysed the data, and drafted the manuscript. Nikili K Zhimo contributed to the experimental studies and assisted in data collection. Daniel Kibami supervised the research work and reviewed the manuscript. All authors approved the final version of the manuscript.