

Reactive Yellow 145 Dye Adsorption from Aqueous Solution Using KOH-Activated Banana Peel Carbon: Isotherm, Kinetics, and Thermodynamic Studies

Ghaferah H. Al-Hazmi,^a Abdul-Sabur Ayosubomi Oluwo,^b Moamen S. Refat,^c Ali El-Rayyes,^d Edwin A. Ofudje,^{b,*} Amnah Mohammed Alsuhaibani,^e and Reham. F. Hassan^f

Activated banana peel carbon (BPAC) was prepared and evaluated as an adsorbent for Reactive Yellow 145 (RY 145) dye from aqueous solution. BPAC was prepared from *Musa x paradisiaca* peels via carbonization at 400 °C followed by KOH activation at 650 °C. Structural analysis affirmed the formation of a highly porous, predominantly amorphous carbon having abundant oxygen-containing functional groups suitable for dye adsorption. Batch adsorption studies established that the efficiency was strongly influenced by solution pH (pH 2), adsorbent dosage (25 mg), contact time (90 min.), and initial dye concentration (200 mg L⁻¹). The Langmuir isotherm showed better representation of the equilibrium data with R² = 0.976, which was higher than the Freundlich model (R² = 0.923), suggesting monolayer adsorption on a relatively homogeneous surface with a maximum adsorption capacity of 159.0 mg g⁻¹. Thermodynamic data revealed that the uptake process was spontaneous ($\Delta G^\circ = -1.187$ kJ mol⁻¹ at 323 K), endothermic ($\Delta H^\circ = 7.211$ kJ mol⁻¹), and accompanied by a slight increase in interfacial randomness ($\Delta S^\circ = 26$ J mol⁻¹ K⁻¹). Generally, the BPAC displayed good adsorption performance and represents a promising biomass-derived adsorbent for the treatment of dye-contaminated wastewater.

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Contact information: a: Department of Chemistry, College of Science, Princess Nourah bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia; b: Department of Chemical Sciences, Mountain Top University, Ogun State, Nigeria; c: Department of Chemistry, College of Science, Taif University, P.O. Box, 11099, Taif 21944, Saudi Arabia; d: Center for Scientific Research and Entrepreneurship, Northern Border University, 73213, Arar, Saudi Arabia; e: Department of Sports Health, College of Sport Sciences & Physical Activity, Princess Nourah bint Abdulrahman University P.O. Box 84428, Riyadh 11671, Saudi Arabia; f: Chemistry Department, Faculty of Science, Helwan University, Cairo, Egypt;

* Corresponding author: eaofudje@mtu.edu.ng

INTRODUCTION

Pollution of water bodies from discharges of synthetic dyes from leather processing, textile, paper production, and printing industries is a major global environmental concern. Effluents from these industries mostly carry intense colors, high chemical oxygen demand, and dangerous organic compounds that pose great risks to human health and aquatic ecosystems (Lellis *et al.* 2019; Yaseen and Scholz 2019; Dutta *et al.* 2024). The target dye used in this study, Reactive Yellow 145 (RY 145), is an anionic azo-reactive dye that is extensively used in the textile industry and is resistant to

conventional treatment because of its stable aromatic ring structure and sulfonate functional groups (Ofudje *et al.* 2021; Lam *et al.* 2022).

Synthetic dyes are known to impart intense coloration to receiving water bodies, drastically reducing light penetration and inhibiting photosynthetic activity in aquatic ecosystems (Lellis *et al.* 2019; Dutta *et al.* 2024). Many of these dyes and their by-products have been reported to display mutagenic, carcinogenic, and other toxic effects, thus posing potential risks to human and animal health when dye-contaminated water enters drinking water sources (Lellis *et al.* 2019; Sudarshan *et al.* 2023). In addition, their effluents often contain high chemical oxygen demand (COD) and biochemical oxygen demand (BOD), which can decrease dissolved oxygen levels in water bodies, disrupt aquatic ecosystems, and contribute to biodiversity loss (Yaseen and Scholz 2019; Dutta *et al.* 2024).

Traditional treatment techniques such as advanced oxidation processes, coagulation, membrane filtration, and biological degradation are costly, generate secondary waste, and perform inadequately at low dye concentrations which have limited their applications especially in developing countries (Crini and Lichtfouse 2019; Satyam and Patra 2024). Adsorption onto activated carbon has emerged as one of the most effective and widely applied alternatives because of its operational simplicity, ability to target trace pollutants, and broad applicability (Thitame and Shukla 2016; Nizam *et al.* 2021).

Nevertheless, the high production cost of commercial activated carbon has driven extensive research into low-cost agricultural waste precursors such as coconut shells, rice husks, sugarcane bagasse, and banana peels because they abound in supply, renew naturally, and contain high carbon content suitable for activation (Bhatnagar *et al.* 2015; Jjagwe *et al.* 2021; Lestari *et al.* 2022; Menya *et al.* 2023). But raw biochar typically exhibits limited surface area and poorly developed pore structure, which restricts its adsorptive capacity.

Banana (*Musa x paradisiaca*) peels are an abundant and freely available agricultural residue with high lignocellulosic content that makes them suitable for conversion into activated carbon (Gujar *et al.* 2023; Jagadale *et al.* 2026). Their chemical activation with KOH facilitates intercalation in the carbon lattice, creating an extensive microporous network with high surface area and active surface functional groups (Molina-Sabio and Rodríguez-Reinoso 2004; Bhatnagar *et al.* 2015; Srénscek-Nazzal *et al.* 2024). Though there is growing interest in banana peel-derived carbons, the contribution of this present study lies in addressing the comparatively limited information available on the adsorption of Reactive Yellow 145 (RY 145) specifically by KOH-activated banana-peel carbon (BPAC). This work focuses mainly on RY 145 and integrates physicochemical characterization with a systematic evaluation of adsorption behaviour. The work investigates the impacts of adsorbent dosage, solution pH, contact time, initial dye concentration, and temperature, followed by equilibrium and kinetic modelling, thermodynamic analysis, and regeneration studies.

Therefore, the primary focus of the present study is an application-specific and integrated dataset describing the development, physicochemical characteristics, adsorption behaviour, thermodynamic response, and regeneration performance of KOH-activated *Musa x paradisiaca* peel carbon toward RY 145 under the investigated batch conditions. The work thus extends the existing literature on biomass-derived adsorbents by providing information on the behaviour of BPAC toward RY 145.

EXPERIMENTAL

Adsorbent Preparation

Musa x paradisiaca peel waste was collected from a cafeteria at Mountain Top University, Nigeria. The peels were washed with distilled water, cut into pieces, then sun-dried for seven days to remove surface moisture. The moisture content of the precursor at the individual intermediate processing stages was not quantitatively determined by method. The samples were thereafter oven-dried at 100 °C for 3 h, after which 200 g of the dried banana peel material was weighed and ground using a mechanical grinder before carbonization. After carbonization at 400 °C for 2 h, the carbonized banana-peel material was ground and impregnated with 50 g of carbonized char using 200 mL of 1 M KOH solution, corresponding to a biochar-to-KOH ratio of 1:4 (w/v) using a muffle furnace (Carbolite, ELF 117148, Germany). Thereafter, the solution mixture was maintained for 12 h to allow adequate impregnation and then, the KOH-impregnated biochar was subsequently oven-dried at 110 °C for 2 h and then thermally activated at 650 °C for 1 h with a heating rate of 5 °C min⁻¹ under nitrogen. The obtained product was neutralized with 0.1 M HCl, washed with distilled water to pH 7.5, and dried at 100 °C for 2 h to obtain the final product which was sieved using a mesh size of 150 µm and referred to as banana peel activated carbon (BPAC).

Characterizations

The prepared BPAC adsorbent was characterized using the analytical techniques described below. The instruments were operated according to the manufacturers' instructions and established laboratory protocols. The crystallinity and phase composition of the prepared adsorbent were determined using an X-ray diffractometer (XRD, Rigaku D/Max-III C X-ray diffractometer, Japan) and the diffraction patterns were obtained over a 2θ range of 10 to 80°. A Perkin Elmer (3000 MX, USA) Fourier transform infrared (FT-IR) spectrometer was employed to identify the surface functional groups available on the BPAC before and after adsorption over the range of 400 to 4000 cm⁻¹. A scanning electron microscope (SEM, A Zeiss EVO 18 instrument, Carl Zeiss, Germany) was used to examine the surface morphology of BPAC. Elemental composition of the prepared BPAC was investigated with energy-dispersive X-ray spectroscopy (EDX) attached to the SEM system. Thermogravimetric analysis (TGA) was performed using TGA 4000 (Perkin Elmer, Haarlem, Netherlands) analyzer to determine decomposition and thermal stability features of BPAC. The specific pore volume, surface area, and pore-size distribution of the prepared BPAC material was measured from N₂ adsorption-desorption measurements using the Brunauer-Emmett-Teller (BET) method using a NOVA 2200e surface area and pore size analyzer (Quantachrome Instruments, USA).

Preparation of RY 145 Dye Solution

About 1.0 g of RY 145 powder was measured using an analytical balance, then diluted with 100 mL of distilled water using a beaker. The solution was then transferred into a volumetric flask and was made up to volume with distilled water to obtain the desired stock concentration. Working solutions of the required concentrations were afterward prepared by appropriate dilution of the stock solution by adopting a routine laboratory solution-preparation procedure. This analysis was carried out using a UK Lab Science 752 UV-Vis spectrophotometer. The spectrophotometer was used to obtain the wavelength (λ_{max}).

UV–Vis Spectral Scan and Calibration Curve

The maximum absorption wavelength ($\lambda_{\max}$) of RY 145 was measured using a UV–Visible spectrophotometer (UK Lab Science 752). Different concentrations (40 to 200 mg/L) of RY 145 solution were scanned over the wavelength range of 350 to 600 nm using distilled water as the blank. At the selected wavelength intervals, the absorbance spectrum was recorded, and the wavelength corresponding to the maximum absorbance was identified.

Batch Adsorption

Batch sorption processes were conducted to evaluate the effect of different operational parameters on the elimination of RY 145 dye by the BPAC and to find the most optimal condition for the BPAC's adsorption capacity. BPAC (25 mg) was introduced to a 25 mL of dye solution in conical flasks, and the mixtures were agitated under controlled conditions. Preceding the introduction of the adsorbent, the pH of the RY 145 was altered using 0.1 M NaOH or 0.1M HCl. Thereafter, the content was placed on an orbital shaker and equilibrated at 150 rpm. The adsorption experiments were conducted at a temperature of 50 °C. At different reaction intervals, an aliquot of the RY 145 solution was withdrawn, the suspension was centrifuged, and the residual of RY 145 in the supernatant was determined using a UV–Visible spectrophotometer at the maximum absorption wavelength of the dye ($\lambda_{\max} = 425$ nm). The amount of RY 145 adsorbed at equilibrium and the percentage removal were computed from the concentration difference before and after adsorption as illustrated in Eqs. 1 and 2 below:

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

$$\%Removal = \left[\frac{C_o - C_e}{C_o} \right] \times 100 \quad (2)$$

where C_o is the initial dye concentration (mg/L), C_e is the equilibrium concentration (mg/L), V is the volume of solution (L), and m is the mass of BPAC (g). All adsorption experiments were performed in triplicate.

Effect of Adsorbent Dosage

The impact of BPAC dosage was examined by varying the mass of BPAC while maintaining the RY 145 concentration at 200 mg/L and the solution volume at 25 mL. The selected BPAC masses were 5 to 25 mg. Samples were withdrawn at predetermined contact times between 10 and 120 min and the mixtures were agitated at 150 rpm, after which the samples were separated and analysed at 425 nm using a UV–Visible spectrophotometer at the maximum wavelength of the dye ($\lambda_{\max} = 425$ nm.). Other experimental parameters, including pH, agitation speed, temperature, and contact time were kept constant.

Effect of Solution pH

The impact of solution pH was studied over the pH range of 2 to 8. The initial pH adjustment of the RY 145 solution was achieved using 0.1 M HCl or 0.1 M NaOH before addition of BPAC. Samples were withdrawn at predetermined contact times between 10 and 120 min. The mixtures were agitated at 150 rpm, after which the samples were separated and analysed at 425 nm using a UV–Visible spectrophotometer at the maximum

wavelength of the dye ($\lambda_{\max} = 425$ nm.). The RY 145 concentration, solution volume, BPAC dosage, agitation speed, temperature, and contact time were kept constant.

Kinetic Experiment

Adsorption kinetics were studied by contacting BPAC with RY 145 solutions at initial concentrations ranging from 40 to 200 mg/L. Samples were withdrawn at predetermined contact times between 10 and 120 min and the mixtures were agitated at 150 rpm, after which the samples were separated and analysed at 425 nm using a UV–Visible spectrophotometer at the maximum wavelength of the dye ($\lambda_{\max} = 425$ nm.). The experimental results showed that equilibrium was attained at 90 min; thus, 90 min was chosen as the equilibrium contact time for subsequent equilibrium experiments.

Adsorption Isotherm Models

The equilibrium adsorption data were analyzed using the Langmuir and Freundlich isotherm models. Their linear forms are given below (Thitame and Shukla 2016; Ofudje *et al.* 2023),

$$\frac{C_e}{q_e} = \frac{1}{q_{\max}K_L} + \frac{C_e}{q_m} \quad (3)$$

$$\log(q_e) = \log(K_f) + \left(\frac{1}{n}\right) \times \log(C_e) \quad (4)$$

where $q_{\max}$ represents the maximum monolayer adsorption capacity (mg/g), K_L denotes the Langmuir constant related to the energy of adsorption (L/mg), K_f stands for the Freundlich adsorption capacity constant (mg/g)(L/mg)^(1/n), and n indicates the adsorption intensity parameter. The dimensionless separation factor R_L is calculated as (Ofudje *et al.* 2023; Bakry and Elmesallamy 2025):

$$R_L = \frac{1}{(1 + K_L \times C_o)} \quad (5)$$

Adsorption Kinetics Models

The linearized forms of the pseudo-first order (PFO), pseudo-second order (PSO), and intraparticle diffusion (IPD) models are given as (Abouzieed *et al.* 2025; Kuyucu *et al.* 2025):

$$\log(q_e - q_t) = \log(q_e) - \left(\frac{k_1}{2.303}\right) \times t \quad (6)$$

$$\frac{t}{q_t} = \frac{1}{(k_2 \times q_e^2)} + \frac{t}{q_e} \quad (7)$$

$$q_t = k_{id}t^{1/2} + C \quad (8)$$

where q_t is the amount of RY 145 adsorbed at time t (mg g⁻¹), k_1 and k_2 are the rate constants for PFO (min⁻¹) and PSO {g/(mg·min)} respectively, and K_{id} and C indicate the rate constant and boundary layer for the IPD. The best fit determination was done using the sum of error squares (%SSE):

$$SSE = \sum_{i=1}^n (q_{t,exp,i} - q_{t,cal,i})^2 \times 100 \quad (9)$$

Thermodynamic Analysis

Thermodynamic experiments were performed using 25 mg of BPAC and 25 mL of RY 145 solution with an initial concentration of 200 mg L⁻¹. The suspensions were agitated at 150 rpm for 90 min at 298, 303, 313, 323, 333 and 353 K. Thermodynamic parameters (free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°)) were evaluated from the Van't Hoff equation (Ofudje *et al.* 2023; Bakry and Elmesallamy 2025):

$$\ln(K_d) = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{(RT)} \quad (10)$$

The Gibbs free energy was calculated as (Ofudje *et al.* 2023; Bakry and Elmesallamy 2025),

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \quad (11)$$

where $K_d = q_e/C_e$, $R = 8.314 \text{ J/mol}\cdot\text{K}$, and T is absolute temperature (K). The corresponding dimensionless equilibrium constant was estimated by applying the conversion factor of 1000 (Milonjic 2007),

$$K^\circ = 1000K_d \quad (12)$$

where K_d is the distribution coefficient. Therefore, the standard Gibbs free-energy change was computed the relation below (Milonjic 2007):

$$\Delta G^\circ = -RT \ln(1000K_d) \quad (13)$$

Regeneration and Desorption Study

The regeneration investigation of the prepared BPAC was assessed through five consecutive adsorption–desorption cycles. Following each adsorption experiment, the RY 145-loaded BPAC was separated from the solution by centrifugation at 4000 rpm for 10 min and subjected to desorption using 0.1 M ethanol. Then 20 mg of dye-loaded BPAC was contacted with 25 mL of the desorbing solution and agitated at 150 rpm for 100 min at 25 °C. After desorption was achieved, the adsorbent was separated from the desorbing solution and washed thoroughly with deionized water to remove residual dye and desorbing agent. The regenerated BPAC was thereafter dried at 90 °C for 3 h and used in the next adsorption cycle under the same adsorption conditions. The experiment was repeated for five successive adsorption–desorption cycles.

The amount of RY 145 released during each desorption step was determined from the concentration of RY 145 in the desorption solution using UV–Vis spectrophotometry at 425 nm, and the desorption percentage (DP) was estimated using,

$$DP(\%) = \frac{M_{des}}{M_{ads}} \times 100 \quad (14)$$

where M_{ds} denotes RY 145 amount desorbed during the regeneration step, while M_{ads} stands for RY 145 amount adsorbed during the corresponding adsorption cycle.

Statistical Analysis

All adsorption experiments were conducted in triplicate ($n = 3$), and the results were expressed as mean $\pm$ standard deviation (SD). The mean value was computed from the three independent measurements obtained under each experimental condition, while the SD was used to quantify the experimental variability. Error bars corresponding to $\pm$ SD

were included in the relevant figures, and tables containing experimental adsorption capacities and removal efficiencies were reported as mean $\pm$ SD.

In the case of the kinetic and equilibrium modelling, the mean adsorption capacity obtained from the three replicate experiments at each experimental condition was used as the experimental response for model fitting. The corresponding SD was retained as an indicator of experimental variability and was reported in the tables and/or figures. Replicate measurements were therefore not treated as separate independent observations during model fitting. Model parameters were obtained from the mean experimental data, and model adequacy was evaluated using the reported statistical criteria.

RESULTS AND DISCUSSION

Characterization of BPAC

FTIR analysis

Figure 1 illustrates the FTIR spectra of banana-peel-derived activated carbon (BPAC) before and after the uptake of RY 145. The figure reveals clear changes in surface functional groups following dye uptake. Prior to adsorption, the spectrum profile was relatively smooth with only a few weak absorption bands, which is characteristic feature of KOH-activated carbon materials where carbonization and chemical activation remove much of the original lignocellulosic structure while still retaining a limited number of oxygen-containing functionalities. After the sorption of RY 145, however, the spectrum became more structured, suggesting that RY 145 molecules were successfully interacted with the BPAC surface. A broad absorption observed in the region of 3650 to 3240 cm^{-1} was visible in the after-adsorption spectrum and was assigned to O–H stretching vibrations of hydroxyl groups (Al-Sareji *et al.* 2024; Rahmawati *et al.* 2025). The broadness of this band may indicate extensive hydrogen bonding, which is common in activated carbons containing oxygenated surface groups. The presence of weak peaks around 2920 to 2850 cm^{-1} is attributed to aliphatic C–H stretching vibrations of $-\text{CH}_2$ and $-\text{CH}_3$ groups which may be associated with residual aliphatic fragments inherited from cellulose, hemicellulose, or lignin-derived moieties that were not completely eliminated during thermal conversion and activation (Rahmawati *et al.* 2025).

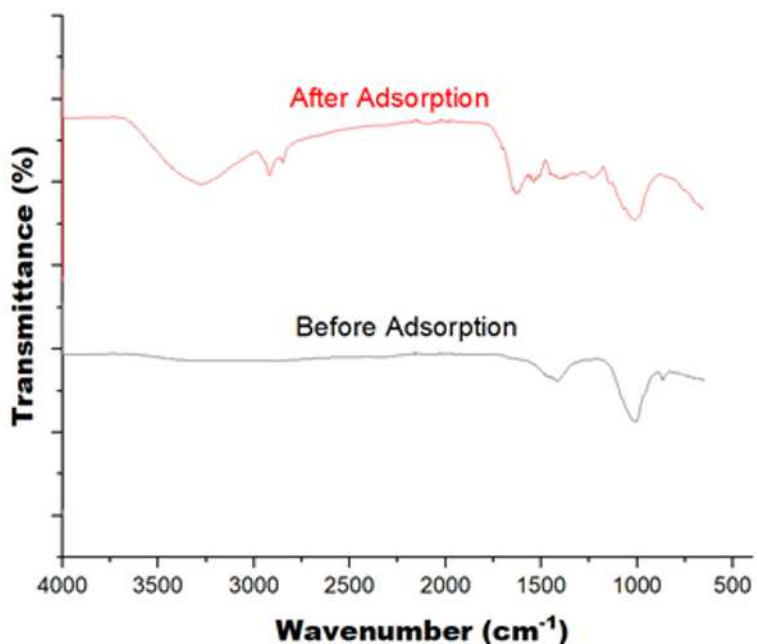


Fig. 1. FTIR spectra of BPAC before and after adsorption of RY 145

The region between 1750 and 1450 cm^{-1} is important for describing the carbon framework of BPAC. The peaks in this region are assigned to overlapping contributions from C=O stretching of carbonyl/carboxyl groups and C=C skeletal stretching of aromatic domains (Al-Sareji *et al.* 2024; Rahmawati *et al.* 2025). For BPAC, these bands are associated with a surface that contains both oxygenated acidic/basic groups and condensed aromatic sheets formed during carbonization. The occurrence of these peaks thus aligns with the view that BPAC possesses a partially graphitized aromatic backbone decorated with residual oxygen-containing functionalities, which is a feature of activated carbons produced from lignocellulosic waste (Jjagwe *et al.* 2021; Jagadale *et al.* 2026). After the uptake process, this region becomes more pronounced and somewhat broader, signifying possible overlap between the intrinsic aromatic vibrations of BPAC and the aromatic ring vibrations of the adsorbed reactive dye. The peak seen at 1050 cm^{-1} is associated with C-O assignment, while the most important prominent change in Fig. 1 is the appearance of a distinct band in the 1170 cm^{-1} region only after RY 145 uptake. This peak is assigned to S=O vibrations of sulfonate groups ($-\text{SO}_3^-$), which is a feature of RY 145 structure. Since this peak is not present in the pristine BPAC spectrum but clearly visible after interaction with the dye solution, it gave strong spectroscopic evidence that RY 145 molecules were deposited onto the adsorbent surface rather than merely causing nonspecific changes in the carbon matrix, thereby confirming that the sulfur-containing sulfonate functionalities of RY 145 remained associated with the carbon after adsorption (Ofudje *et al.* 2021; Lam *et al.* 2022).

Table 1. FTIR Absorption Bands of BPAC before and after Adsorption of RY 145

Wavenumber (cm ⁻¹)	Functional Group / Bond
3650–3240	O–H stretching (broad)
2920–2850	C–H stretching (aliphatic)
1750 and 1450	C=O and C=C stretching
1170	S=O stretching (sulfonate)
1050	C–O stretching
907–710	C–H out-of-plane bending

XRD Analysis

The X-ray diffraction (XRD) patterns of BPAC before and after adsorption of RY 145 is presented in Fig. 2. In both samples, the dominant characteristic was the presence of broad, low-intensity diffraction bands rather than sharp and well-defined Bragg reflections, signifying that BPAC is largely amorphous and structurally disordered. This kind of XRD pattern is a feature of activated carbons obtained from lignocellulosic biomass, particularly after strong alkaline activation with KOH, where the original crystalline organization of cellulose and other biopolymers is largely damaged or removed during carbonization and pore development (Al-Sareji *et al.* 2024). The absence of narrow crystalline peaks in the spectrum confirms that the carbon framework of BPAC is composed mainly of poorly ordered aromatic carbon layers and randomly oriented microcrystallites, rather than a highly crystalline graphite-like structure, in agreement with previous reports for KOH-activated banana peel carbons. The most prominent peaks before the adsorption were centered within the range of $2\theta = 20^\circ$ to 25° which is usually assigned to the reflection of (002) plane of turbostratic graphitic carbon (Molina-Sabio and Rodríguez-Reinoso 2004).

Furthermore, the broad carbon-related reflection assigned to the (002) plane was examined more quantitatively, and the corresponding interlayer spacing, d_{002} , was calculated using first-order Bragg diffraction,

$$n\lambda = 2d \sin \theta \quad (15)$$

where λ is the wavelength of the Cu K α radiation (0.15406 nm) and θ is half of the measured 2θ value. Using Bragg's law, and assuming first-order diffraction ($n = 1$), the interlayer spacing was found to be 0.395 nm which is consistent with a poorly ordered, turbostratic carbon structure containing randomly oriented or imperfectly stacked aromatic carbon layers rather than a highly crystalline graphite-like lattice. In addition, much weaker and broader diffraction features were observed around $2\theta = 43^\circ$, which is assigned to the (100) plane of graphitic carbon (Rahmawati *et al.* 2025).

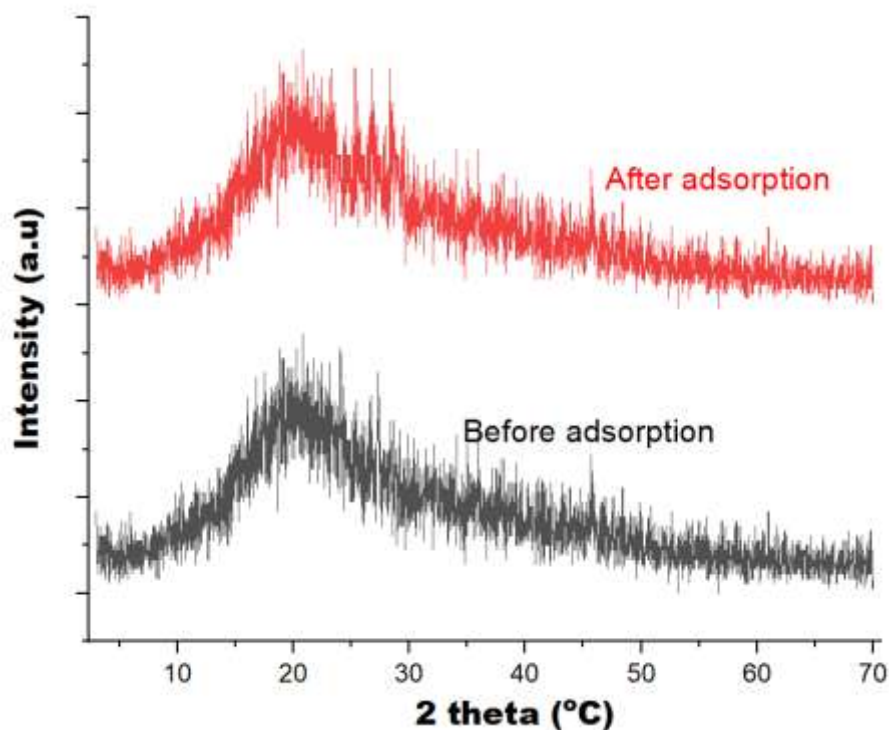


Fig. 2. XRD diffraction patterns of BPAC before and after adsorption of RY 145

This implies that, although the BPAC contained aromatic carbon layers formed during thermal conversion, these layers were not arranged into a highly crystalline lattice but existed as turbostratic microdomains, which are often reported for activated carbons derived from agricultural wastes and other biomass precursors (Jagadale *et al.* 2026). Comparison of the XRD patterns before and after adsorption revealed that the overall profile remained essentially unchanged after dye uptake. This indicates that adsorption of RY 145 did not alter the bulk carbon structure of BPAC and that the adsorbent maintained its structural integrity under the adsorption conditions, with no evidence of phase transformation, carbon framework collapse, or crystallization induced by contact with the dye solution.

EDX Analysis

Figures 3a and 3b indicate that the EDX assessment provided direct evidence for the uptake of RY 145 by BPAC *via* changes in surface elemental composition before and after uptake. The findings show that BPAC prior to adsorption contained C (46.30 wt%), O (34.32 wt%), K (11.44 wt%), Ca (6.80 wt%), P (0.90 wt%), and Na (0.25 wt%), indicating a carbon-rich adsorbent bearing oxygenated functional groups and residual mineral species from biomass precursor and KOH activation (Al-Sareji *et al.* 2024; Rahmawati *et al.* 2025). With the uptake of RY 145, two new signals corresponding to S (4.53 wt%) and N (3.60 wt%), were detected on the BPAC surface, whereas the relative percentages of the original matrix elements were reduced. The presence of sulfur is likely due to the sulfonate groups of RY 145 (Ofudje *et al.* 2021), while nitrogen arises from the dye's functional units, including triazine/amino moieties (Lam *et al.* 2022). The appearance of detectable S and N after adsorption is consistent with the presence of RY 145-associated species on the BPAC surface, since sulfur is associated with the sulfonate groups and

nitrogen occurs in nitrogen-containing functionalities of the dye. Additionally, the reduction in the relative abundance of C, O, K and Ca suggests partial coverage of the BPAC surface by adsorbed dye molecules. The finding shows good alignment with the FTIR results, especially the appearance of the S=O band after adsorption. The occurrence of S and N following the dye uptake is consistent with the retention of RY 145-associated species on the BPAC surface and, together with the FTIR observations, supports the occurrence of dye uptake; nevertheless, these data do not independently establish the specific molecular interactions responsible for adsorption.

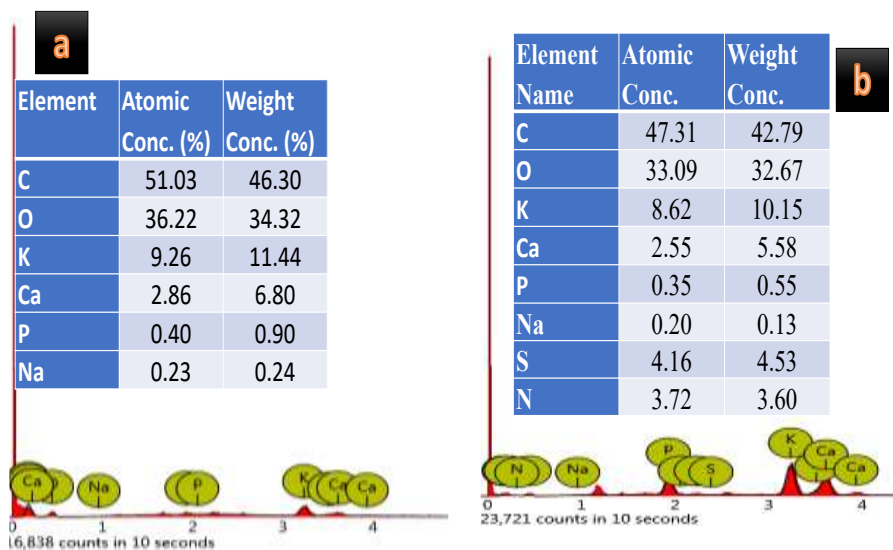


Fig. 3. EDX of BPAC (a) before and (b) after adsorption of RY 145 dye

SEM Analysis

The morphological changes most likely induced by adsorption process are represented by the SEM micrographs in Fig. 4. The structure of BPAC before the uptake process (Fig. 4a) shows a heterogeneous, granular surface with visible pores, cavities, and void spaces, indicating porous structure development from the KOH activation through the mechanism of carbon lattice etching and gasification (Molina-Sabio and Rodríguez-Reinoso 2004). After the uptake of RY 145 (Fig. 4b), the BPAC surface became visibly smoother and more uniform, with previously open pores appearing partially occluded. This surface smoothening may be because of the deposition of RY 145 molecules within and on the BPAC surface, consistent with similar observations reported for banana peel-derived and KOH-activated carbons used for dye removal (Al-Sareji *et al.* 2024).

The TEM image of BPAC before adsorption (Fig. 4c) shows heterogeneous dark-contrast carbonaceous domains at the nanoscale with round shapes, while the post-adsorption image (Fig. 4d) reveals increased aggregation and modified contrast of these domains. These alterations indicate the likely interaction of RY 145 with the carbonaceous surface and partial coverage of accessible regions. Nevertheless, the TEM images alone cannot establish the chemical nature of the observed contrast variations; thus, the morphological observations are considered complementary evidence and interpreted alongside the BET and spectroscopic results.

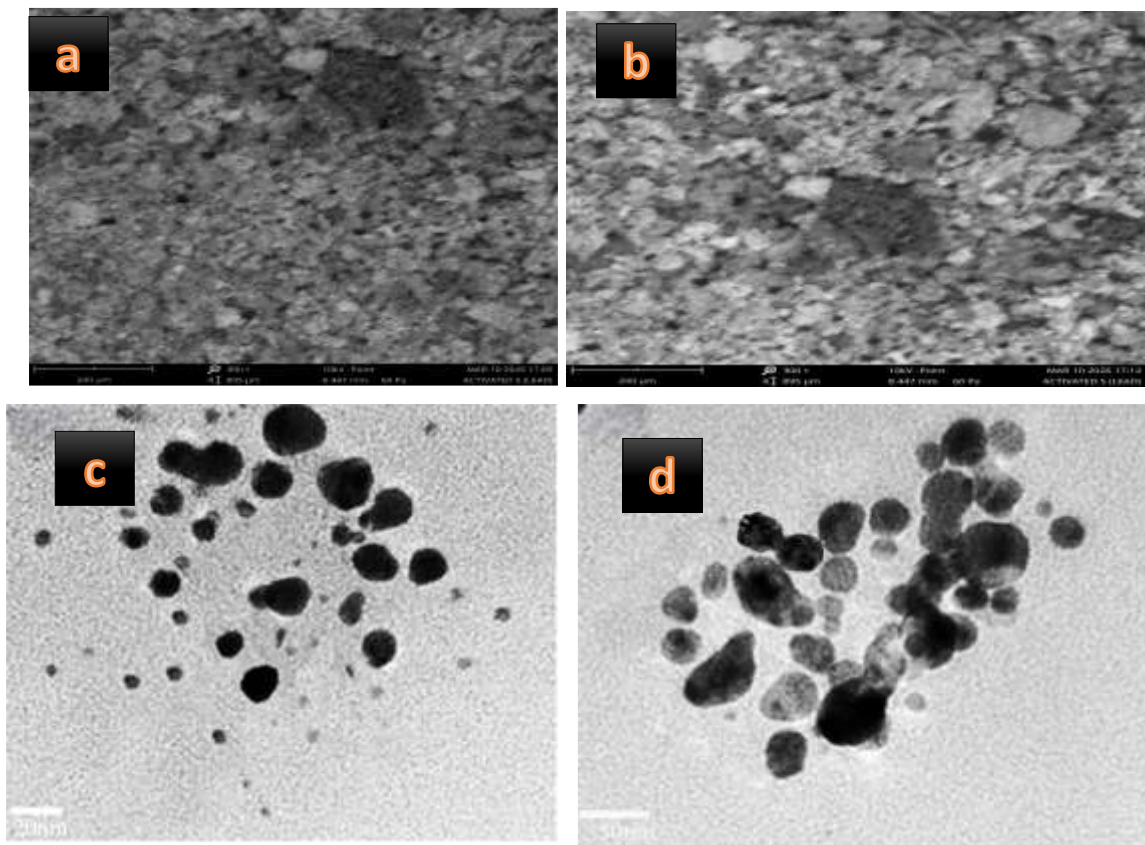


Fig. 4. SEM of BPAC (a) before, (b) after adsorption, (c) TEM image of BPAC before adsorption and (d) TEM image of BPAC after adsorption of RY 145 dye

Thermogravimetric Analysis

The TGA curve for BPAC is illustrated in Fig. 5 and was obtained from 25 to 884 °C at 10°C/min, with a total residual mass of approximately 19.63%. This analysis gave three decomposition stages with the first stage identified within the ambient temperature of 150 °C which corresponds to the evaporation of physically adsorbed water. The decomposition of thermally labile oxygenated surface functional groups (220 to 280 °C), including carboxylic acids and anhydrides is denoted as the second stage (Cain *et al.* 2024). The most distinct weight loss (280 to 420 °C; 95% to 27%) which was assigned to the oxidative combustion of the disordered graphitic carbon framework (Panizio *et al.* 2024). Above a temperature of 420 °C, the curve flattened; a minor event at ~580 to 600 °C may correspond to decomposition of thermally stable potassium salts or carbonates retained from KOH activation (Cain *et al.* 2024). The stable ash plateau (~25%; 450 to 884 °C) reflects the mineral-rich nature of banana peel biomass, confirmed by EDX.

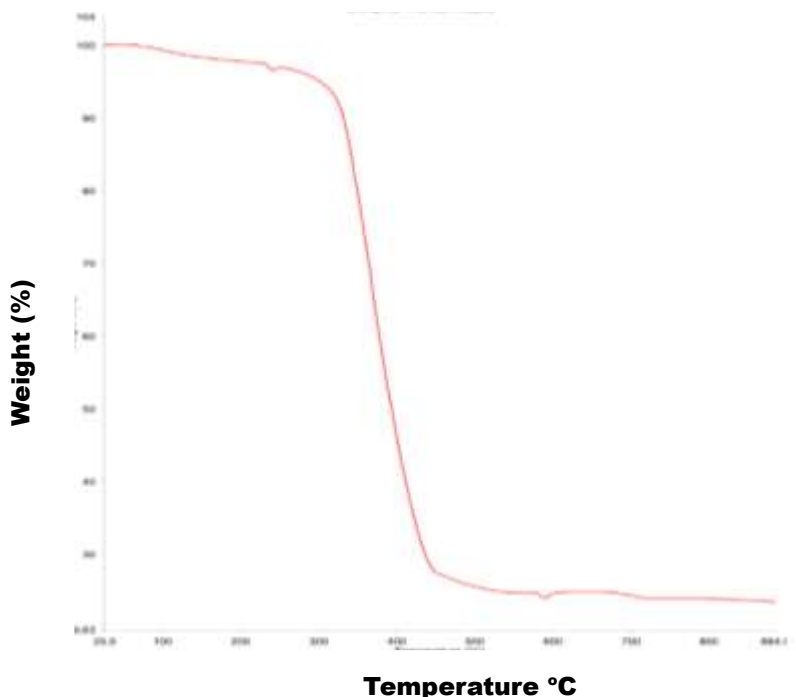


Fig. 5. Thermogravimetric analysis curve of BPAC

Analysis of Textural Properties and Pore Structure

The textural property of the prepared BPAC was investigated as illustrated in Fig. 6. Figure 6a presents the pore-volume distribution as a function of pore diameter, whereas Fig. 6b represents the cumulative and differential pore-volume distributions as the pore-volume profile rose sharply within 1.72 to 2.0 nm and reached a maximum at around 2.82 to 3.1 nm before progressively reducing with increasing pore diameter indicating pore structure dominated by small mesopores. Figure 6b further shows that the largest contribution to pore volume occurs around 2.63 to 2.75 nm, thus confirming the microporosity of the prepared BPAC (Cuong *et al.* 2023; Kwoczynski *et al.* 2025), while the cumulative pore volume approaches $0.055 \text{ cm}^3 \text{ g}^{-1}$ at the upper end of the studied pore-size range. The prevalence of pores within the range of 2 to 3 nm is potentially beneficial for adsorption since these pores can provide accessible diffusion pathways for aqueous adsorbates and facilitate contact between the solute molecules and the internal surface of the carbon matrix. A recent study on biochar adsorbents was reported to have developed a mesoporous and hierarchical pore structure which was reported to improve molecular transport and increase the accessibility of adsorption domains (Cuong *et al.* 2023). Figure 6c represents the BET linear plot which exhibits an approximately linear relationship between the BET-transformed adsorption quantity and relative pressure within the selected pressure interval. This relationship was employed to compute the specific surface area of the biochar, which was found to be $135 \text{ m}^2/\text{g}$.

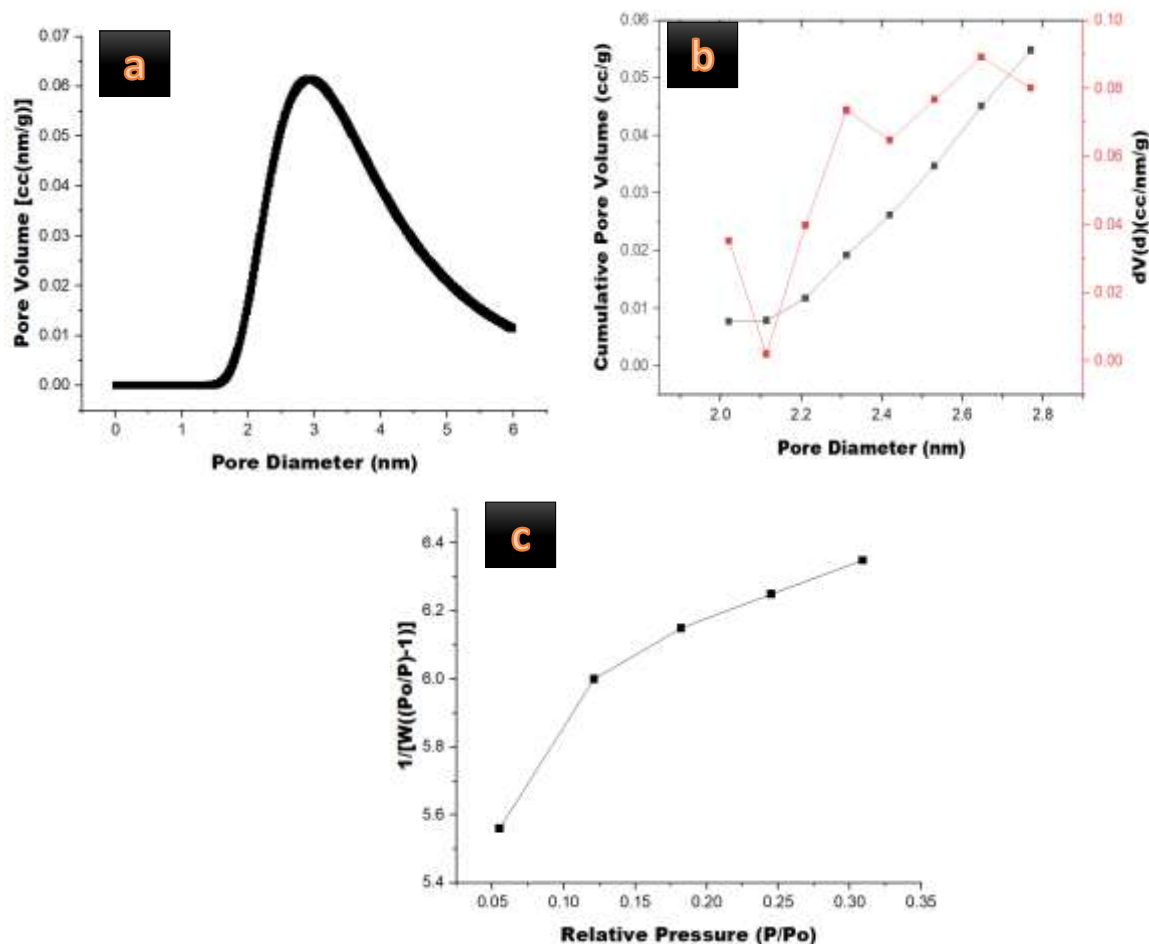


Fig. 6. (a) Pore-volume distribution against pore diameter, (b): cumulative pore volume and differential pore-volume distribution and (c) BET linear plot for determination of the specific surface area of the BPAC

Studies on Batch Adsorption

UV-Vis spectral scan and calibration curve

The UV-Vis absorption spectra of RY 145 at various concentrations (40 to 200 mg/L) in the wavelength range of 350 to 600 nm are shown in Fig. 7a. A distinct maximum of absorption was noticed at 425 nm (λ_{max}) for all investigated concentrations. The absorbance intensity rose progressively with increasing dye concentration, while the position of λ_{max} remained essentially unchanged. The absorbance at 425 nm rose from 0.32 at 40 mg/L to 1.60 at 200 mg/L, signifying the concentration-dependent optical response of RY 145. The absence of a considerable shift in λ_{max} indicates that increasing concentration did not meaningfully modify the principal absorbing species under the measurement conditions. As such, a λ_{max} of 425 nm was chosen as the analytical wavelength for successive quantitative determination of RY 145. The findings obtained from the calibration curve by plotting the absorbance of RY 145 at 425 nm against its corresponding concentration is presented in Fig. 7b. It was observed that a strong linear relationship was seen over the assessed concentration range, confirming the suitability of UV-Vis spectrophotometry for quantitative determination of RY 145 within this range. The coefficient of determination ($R^2 = 0.998$) was used to compute the linearity of the calibration relationship, while the calibration equation was afterward used to estimate the

residual RY 145 concentration in the adsorption experiments. The obtained value of 425 nm as the analytical wavelength is in alignment with recent reports in which RY 145 concentrations were monitored spectrophotometrically at wavelengths close to this region 422 nm and 417 nm as reported by Kuvuran *et al.* (2026) and Bakry and Elmesallamy (2025) respectively.

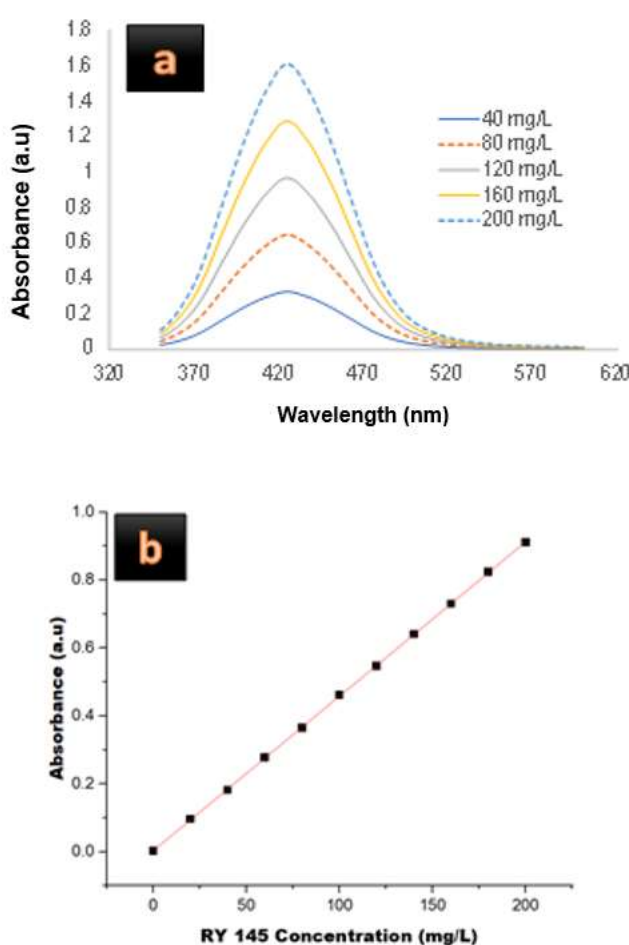


Fig. 7(a). UV–Vis absorption spectrum of RY 145 showing the maximum absorption wavelength (λ_{max}) at 425 nm and (b) UV–Vis calibration curve for RY 145 at 425 nm

BPAC dosage impact on the uptake of RY 145 dye

As displayed in Fig. 8, the percentage removal rose from 21.0% at 5 mg to 74.2% at 25 mg and beyond this point, the rate of improvement became less pronounced. This tendency shows that increasing the BPAC dosage enhances the accessibility of active adsorption sites and total surface area, thus improving the sorption of the dye molecules from solution (Thitame and Shukla 2016). At greater dosages, more adsorption sites are accessible, allowing a larger fraction of RY 145 molecules to be removed from the aqueous phase. On the other hand, the adsorption capacity per unit mass of BPAC decreased from 148 mg g⁻¹ at 5 mg to 42.0 mg g⁻¹ at 25 mg. The uppermost adsorption capacity was recorded at the lowest dosage, after which the adsorption capacity declined steadily as the dosage increased. This inverse relationship between adsorption capacity and adsorbent dosage is often reported in batch adsorption studies and can be as a result of the unsaturation of adsorption sites at higher adsorbent dosages (Ofudje *et al.* 2021; Lam *et al.*

2022). The amount of dye available per unit mass became lower when a fixed initial dye concentration was distributed over a larger mass of adsorbent resulting in reduced loading of dye on each gram of adsorbent. Also, the aggregation of particles at greater dosages may lessen the effective surface area available for adsorption by causing overlap or shielding of active sites. This pattern as observed indicates that although increasing dosage improves overall dye removal efficiency, it does not proportionally increase the adsorption capacity of the adsorbent.

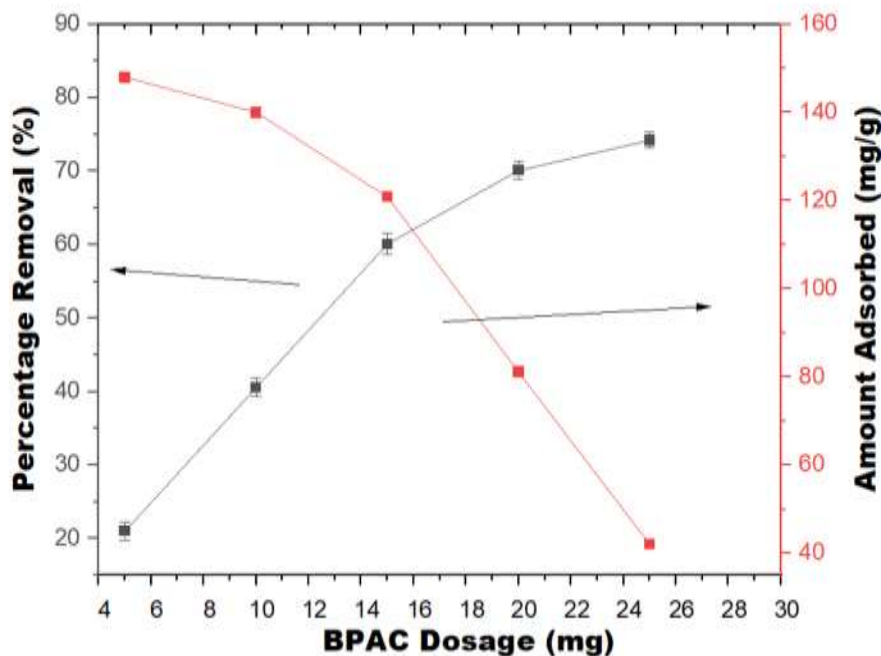


Fig. 8. BPAC dosage impact on the uptake of RY 145 dye

Impact of Reaction Time and RY 145 Concentration on the Uptake of the Dye

The roles played by reaction time and RY 145 concentration on dye uptake by BPAC were studied within the range of 40 to 200 mg L⁻¹ over a contact time of 10 to 120 min as shown in Fig. 9. The adsorption capacity surged swiftly during the initial stages of the adsorption process and then gradually approached equilibrium with increasing contact time at all initial RY 145 dye concentrations tested. It was noticed that the adsorption capacity rose from 5.70 to 35.6 mg g⁻¹ at 10 min when the dye concentration was raised from 40 to 200 mg/L. When the contact time was adjusted to 90 min, the adsorption capacity also rose from 25.2 to 148.4 mg g⁻¹ under the same initial dye concentration (40 to 200 mg L⁻¹). No appreciable rise in adsorption capacity was seen after 90 min, signifying that adsorption equilibrium had been attained and as such, an equilibrium contact time of 90 min was chosen to be sufficient for subsequent adsorption studies.

The fast uptake noticed during the first 60 to 90 min may be due to the abundance of vacant sorption sites on the external surface of the KOH-activated carbon (Din *et al.* 2025). Within this period, RY 145 molecules were readily transferred from the bulk solution to the adsorbent surface, leading to high adsorption rate. With rise in contact time, the available active sites progressively decreased due to continual occupation by dye molecules, and as such, the adsorption rate reduced as equilibrium was approached (Lam *et al.* 2022; Ofudje *et al.* 2023). This reduced adsorption phase can also be associated with intraparticle diffusion of dye molecules into the microporous structure of the activated

carbon and the establishment of equilibrium between adsorption and desorption processes. The observed increasing trend with the dye concentration indicates that increase in the concentration gradient between the adsorbent surface and the bulk solution provides a greater driving force for mass transfer and increasing the probability of effective collisions between available adsorption sites and dye molecules until surface saturation is approached (Lu *et al.* 2023). The larger concentration gradient between the adsorbent and the bulk solution facilitates the diffusion of dye molecules to the active sites, resulting in greater RY 145 uptake. Though the rate of increase became less pronounced as equilibrium was approached and this behavior indicates that the finite number of active sites on the KOH-activated carbon slowly became saturated at higher dye concentrations.

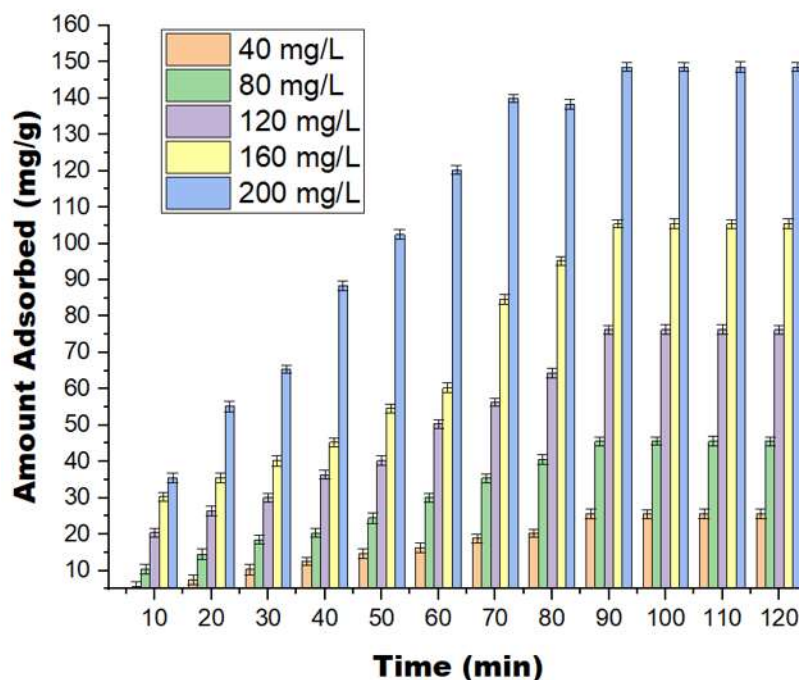


Fig. 9. Initial RY 145 concentration and reaction time on sorption capacity of BPAC

The Role of Solution pH on the Uptake of RY 145 onto KOH-Activated Carbon

The role of solution pH on the uptake of RY 145 by KOH-activated carbon was examined over the pH range of 2 to 8, as presented in Fig. 10. It was observed that the adsorption efficiency was reduced gradually from 78.4% at pH 2 to 54.7% at pH 8, revealing that solution pH exerted a significant influence on the removal process. The uppermost uptake was obtained at pH 2, indicating that acidic conditions favored the elimination of RY 145. This tendency can be explained by the anionic nature of RY 145, which possess sulfonate ($-\text{SO}_3^-$) groups that remain negatively charged in aqueous solution. The improved uptake at low pH may be associated with the protonation of oxygen-containing functional groups on the BPAC surface, which can enhance the availability of positively charged surface sites. These sites may facilitate electrostatic attraction towards the negatively charged sulfonate groups ($-\text{SO}_3^-$) present in RY 145.

With the solution pH increasing, progressive deprotonation of surface functional groups occurs, which may reduce the abundance of positively charged sites, thus weakening the electrostatic attraction between the adsorbent and the anionic dye (Nizam

et al. 2021). Furthermore, hydroxide ions may compete with the dye for certain adsorption sites, possibly contributing to the observed decline in removal efficiency.

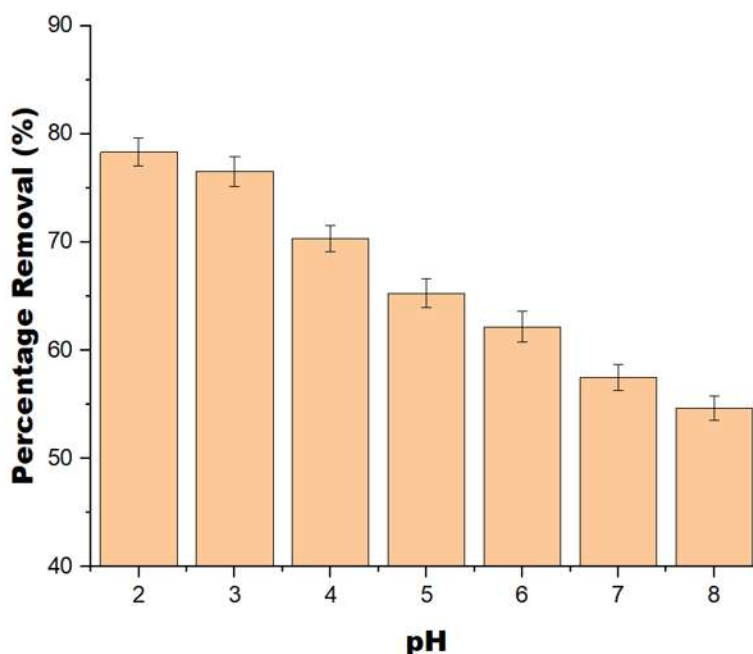


Fig. 10. pH Impact on the percentage removal of RY 145 by BPAC

Kinetic Investigation of the Uptake of RY 145 onto BPAC

The kinetics data for the uptake of RY 145 by KOH-activated banana peel carbon was assessed with PFO, PSO, and IPD kinetic models, as illustrated in Fig. 11, and the values obtained are indicated in Table 2. The PFO model produced calculated adsorption capacity value of 147 mg g^{-1} which is in close agreement with experimental equilibrium adsorption capacity (Q_e) of 148 mg g^{-1} indicating that the PFO model accurately predicted the adsorption of RY 145 by BPAC. Additionally, the model displayed a relatively high coefficient of determination ($R^2 = 0.968$) with a low sum of squared errors ($\%SSE = 0.005$), suggesting a better fit. The rate constant (k_1) was 0.037 min^{-1} , suggesting a relatively rapid adsorption process during the initial stages. For the PSO model, it predicted an equilibrium adsorption capacity of 120 mg g^{-1} , which was far greater than the experimentally observed value of 148 mg g^{-1} . This deviation is corroborated with a lower coefficient of determination ($R^2 = 0.929$) and a much higher error value ($\%SSE = 0.054$) relative to the PFO model, suggesting a poorer representation of the experimental kinetic data.

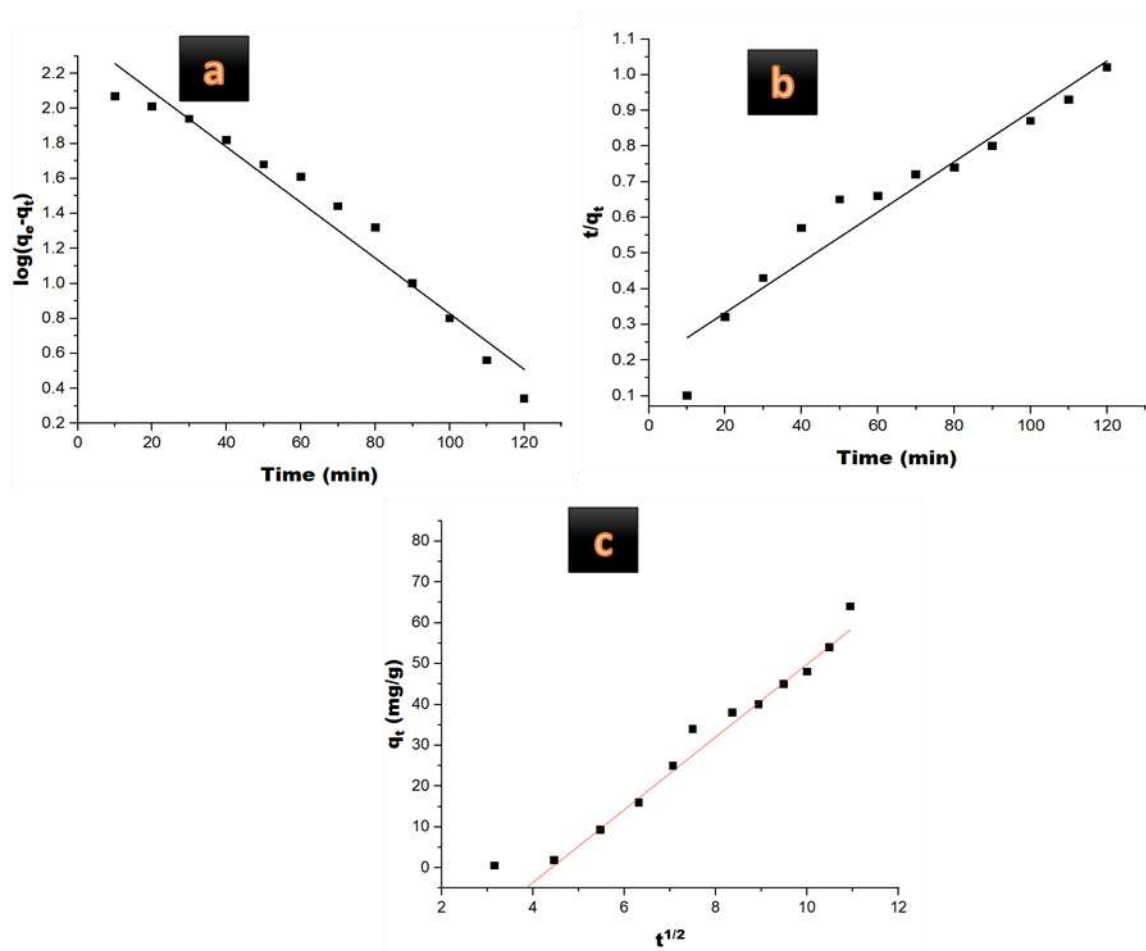


Fig. 11. Adsorption kinetics plots of: (a) PFO, (b) PSO, and (c) IPD models for the sorption of RY 145 by BPAC

Table 2. Values of Kinetics Data for the Removal of RY 145 Dye by BPAC

Models	Parameters	Values
PFO	$Q_e(\text{exp})(\text{mg g}^{-1})$	148.36
	$Q_e(\text{cal})(\text{mg g}^{-1})$	147.30
	$k_1(\text{min}^{-1})$	0.037
	R^2	0.968
	% SSE	0.005
PSO	$Q_e(\text{cal})(\text{mg g}^{-1})$	120.34
	$K_2(\text{mg g}^{-1} \text{min}^{-1})$	2.6×10^{-3}
	R^2	0.929
	% SSE	0.054
IPD	$k_{\text{id}}(\text{mg g}^{-1} \text{min}^{-1/2})$	10.330
	$C(\text{mg g}^{-1})$	1.462
	R^2	0.988

Further evaluation with intraparticle diffusion (IPD) model revealed high coefficient of determination ($R^2 = 0.988$), indicating that intraparticle diffusion contributed to the adsorption process. The relatively high intraparticle diffusion rate constant ($k_{id} = 10.3 \text{ mg} \cdot \text{g}^{-1} \text{ min}^{-1/2}$) indicates swift diffusion of RY 145 molecules into the porous structure of the adsorbent, which could be attributed to the enhanced porosity created by KOH activation. Nevertheless, the non-zero intercept ($C = 1.462 \text{ mg g}^{-1}$) suggests that the plot did not pass through the origin, implying that intraparticle diffusion was not the sole rate-limiting step. Thus, both film diffusion and intraparticle diffusion contributed to the adsorption process of RY 145 onto the activated banana peel carbon.

Adsorption Isotherm Analysis

The data obtained from the equilibrium adsorption for the sorption of RY 145 by KOH-activated BPAC were investigated using the Langmuir and Freundlich isotherm models, and the corresponding fitting results are provided in Fig. 12 and Table 3. Both models demonstrated reasonable descriptions of the experimental equilibrium data; nevertheless, the Langmuir model gave a higher coefficient of determination ($R^2 = 0.976$) compared to the Freundlich model ($R^2 = 0.923$). Therefore, within the concentration range and experimental conditions examined, the equilibrium data were better explained by the Langmuir equation.

The Langmuir model produced an estimated maximum adsorption capacity ($q_{\max}$) of 159 mg g^{-1} . This value signifies the model-derived adsorption capacity associated with the Langmuir equation under the experimental conditions employed. The separation factor (R_L) was 0.161, signifying favorable adsorption according to the conventional interpretation of R_L values between 0 and 1 (Din *et al.* 2025). The Freundlich model produced $K_F = 93.22 (\text{mg g}^{-1})(\text{L mg}^{-1})^{1/n}$ and $1/n = 0.641$, with the latter being below unity and therefore consistent with favorable adsorption behavior (Lu *et al.* 2023).

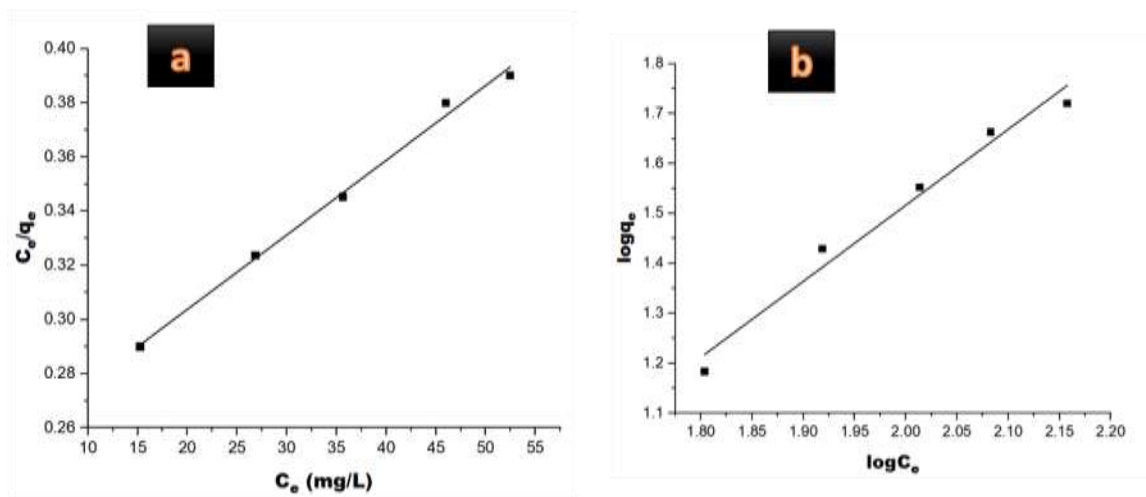


Fig. 12. Adsorption isotherm plots: (a) Langmuir model, and (b) Freundlich model for the sorption of RY 145 by BPAC

Table 3. Determined Parameters for Langmuir and Freundlich Isotherm Models Obtained at 50 °C

Parameter	Langmuir Model	Freundlich Model
R ²	0.976	0.923
$q_{\max}$ (mg g ⁻¹)	159.0	—
R _l	0.161	—
K^f (mg/g)(L/mg) ^{1/n}	—	93.22
1/n	—	0.641

Comparison of the Maximum Adsorption Capacity with Other Adsorbents

The comparative adsorption performance of BPAC with selected adsorbents previously reported for the removal of RY 145 and related dye systems is shown in Table 4.

Table 4. Comparison of Adsorption Capacities of RY 145 for Various Adsorbents

Adsorbent	$q_{\max}$ (mg/g)	Dosage	pH/Temp.	Initial Conc.	Reference
Groundnut shell biochar	7.33	1 g L ⁻¹	2, 35 °C	-	Krishnasamy <i>et al.</i> (2022)
Polypropylene/nickel hydroxide hybrid (Ni/PP)	39.62	1.0 g L ⁻¹	7, 25 °C		Bakry and Elmesallamy (2025)
Eggshell waste powder	88.45	0.1 g	2, 30 °C	100 mg L ⁻¹	Ofudje <i>et al.</i> (2021)
Chitosan-coated magnetite nanoparticles (Fe ₃ O ₄ -CS)	47.62	1.0 g L ⁻¹	4, 30 °C	-	Kalkan <i>et al.</i> (2012)
Chitosan/talc/Cloisite 30B composite (CsTC1)	76.9	0.57 g L ⁻¹	4, 25 °C	-	Kandil and Ali (2023)
CTAB-modified coffee husk biochar (MCH)	68.5	1.0 g L ⁻¹	7, 25 °C	700 mg L ⁻¹	Kosaiyakanon and Kungsanant (2020)
Banana peel activated carbon	159.0	25 mg	2, 50 °C	200 mg L ⁻¹	Present study

The obtained Langmuir maximum adsorption capacity for BPAC in this current study was 159 mg g⁻¹. This value shows that BPAC has measurable adsorption capacity for RY 145; however, this was not interpreted as evidence of superior or exceptional performance in relation to all previously reported adsorbents, since $q_{\max}$ is influenced by several experimental and methodological factors, including initial dye concentration, adsorbent dosage, solution volume, pH, temperature, contact time, adsorbent characteristics, and the equilibrium and fitting procedure used to derive the adsorption parameter. Hence, differences in reported $q_{\max}$ values do not necessarily reflect differences in the intrinsic adsorption capacity of the adsorbents. Therefore, Table 4 is intended to provide contextual comparison rather than a direct ranking of adsorbent performance.

Within this context, the adsorption capacity observed for BPAC suggests its potential for RY 145 removal under the conditions assessed in this current study.

The differences in adsorption capacities could be because of variations in surface chemistry, adsorbent composition, surface area, pore structure, and experimental conditions. The findings also reveal that most previous studies reported optimum adsorption capacity fall within acidic conditions (pH 2 to 4), where electrostatic attraction between the anionic RY 145 molecules and the adsorbent surface is enhanced. On the other hand, some modified adsorbents, including the CTAB-modified coffee husk biochar and Ni/PP hybrid, achieved appreciable adsorption at neutral pH due to their positively charged surface functional groups. The high adsorption capacity of BPAC, together with the low adsorbent dosage (25 mg) required to achieve effective dye removal, demonstrates its potential as a biomass-derived adsorbent for the treatment of dye-contaminated wastewater.

Thermodynamic Investigation of the Uptake of Reactive Yellow 145 onto BPAC

Figure 13 shows the Van't Hoff plot for RY 145 adsorption onto BPAC. The ΔG° at 323 K was found to be $-1.19 \text{ kJ mol}^{-1}$, while the ΔH° and ΔS° were 7.21 kJ mol^{-1} and $26 \text{ J mol}^{-1} \text{ K}^{-1}$, respectively. The plot also gave a coefficient of determination (R^2) of 0.923, suggesting a reasonably good linear relationship.

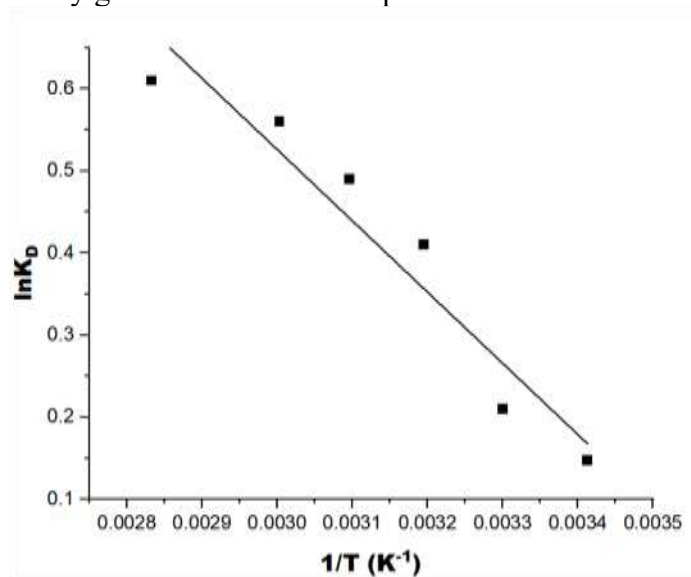


Fig. 13. Van't Hoff plot for adsorption of RY 145 onto BPAC

The negative value of ΔG° is an indication that the removal of RY 145 by BPAC was spontaneous (Abouzied *et al.* 2025; Din *et al.* 2025). Values of ΔG° in the range of 0 and -20 kJ mol^{-1} are usually associated with physisorption, suggesting that adsorption is governed by weak intermolecular interactions including Van der Waals forces, hydrogen bonding, and electrostatic attractions (Lu *et al.* 2023). The observed positive ΔH° value of $7.211 \text{ kJ mol}^{-1}$ suggests that the uptake process is endothermic (Abouzied *et al.* 2025; Din *et al.* 2025). The low value of ΔH° also supports the possibly involvement of physisorption, as physical adsorption processes generally exhibit enthalpy changes below 40 kJ mol^{-1} . The observed value of positive entropy change ($\Delta S^\circ = 26 \text{ J mol}^{-1} \text{ K}^{-1}$) implies a rising in randomness at the solid–liquid interface during adsorption. The increase in entropy may be

attributed to the displacement of water molecules initially associated with both the hydrated dye molecules and the adsorbent surface during adsorption, thereby increasing the degrees of freedom and randomness at the solid–liquid interface (Agarwala and Mulky 2023; Osman *et al.* 2023).

Effect of Desorption Cycles on the Regeneration of KOH-Activated BPAC

The regeneration performance of the KOH-activated BPAC was assessed in five consecutive adsorption–desorption cycles, and the results are given in Fig. 14. The findings reveal that desorption efficiency reduced slowly from 71.3% in the first cycle to 60.5% after the fifth cycle, demonstrating a progressive decline in the regeneration performance of the adsorbent with repeated use. The uppermost desorption efficiency was found in the first regeneration cycle. The observed relatively high desorption efficiency within the first cycle indicates that a substantial fraction of the adsorbed dye was released during treatment with the desorbing solution. With increase in the number of regeneration cycles, the desorption efficiency slowly declined up to fifth cycles. The slow decline in desorption efficiency may be as a result of the incomplete removal of dye molecules from the adsorption sites during each regeneration cycle.

The reduction in regeneration performance may also be linked with small chemical and structural changes in the activated carbon caused by repeated adsorption and desorption as successive regeneration treatments can cause alterations on the surface functional groups, causing partial pore blockage due to the accumulation of irreversibly adsorbed dye molecules or reduce pore accessibility (Al-Sareji *et al.* 2024). The findings revealed that the adsorbent still retained a relatively high desorption efficiency of 60.5% after five consecutive cycles, corresponding to a reduction of only 10.8% from the initial cycle. Nevertheless, due to the fact that adsorption capacity and RY 145 removal efficiency were not independently determined after each regeneration cycle, the present results were not interpreted as direct evidence of quantitative retention of adsorption capacity or long-term operational stability. Additional cyclic adsorption–desorption works involving measurement of adsorption capacity or removal efficiency after each cycle would be required to establish the reusability of BPAC more conclusively.

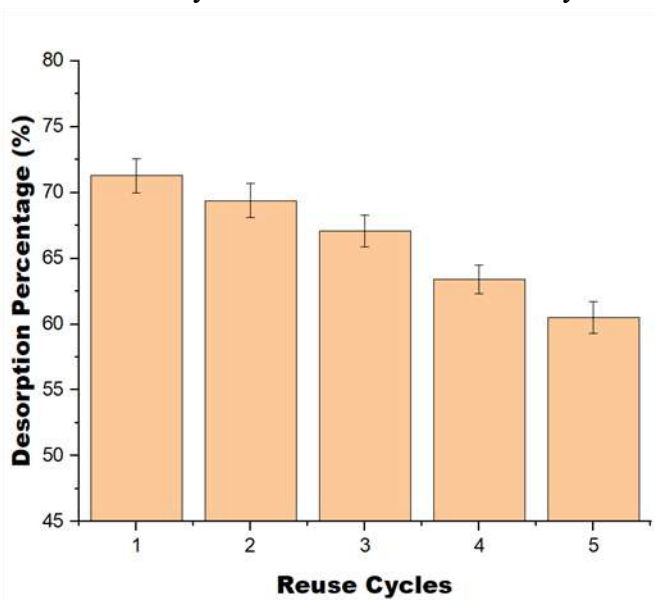


Fig. 14. Desorption studies on the regeneration of KOH-activated BPAC

Proposed Adsorption Mechanism for the Uptake of RY 145 by BPAC

The uptake of RY 145 onto BPAC is proposed to involve a combination of surface interactions and transport processes rather than a single dominant mechanism. The information obtained from FTIR, EDX, pHPZC, kinetic, textural, and thermodynamic methods offer evidence that is consistent with several possible contributions; though, these techniques do not independently establish the occurrence or relative magnitude of each individual interaction. The FTIR spectrum shows that BPAC contained oxygen-containing surface functionalities, while the presence of a peak around 1170 cm^{-1} after adsorption is consistent with the availability of sulfonate-associated vibrations from RY 145 on the adsorbent surface. The elemental findings provide further evidence for dye retention through the appearance of sulfur and nitrogen after adsorption. Nevertheless, these findings reveal the likely association of RY 145 with BPAC rather than proving a particular molecular interaction.

The adsorption behavior dependence on solution pH suggests that electrostatic interactions may contribute to RY 145 uptake. The value of pH_{PZC} measured for BPAC was 5.65 and at pH values beneath the pH_{PZC} protonation of surface functionalities may produce a more positively charged surface, which would be electrostatically favorable for interaction with the negatively charged sulfonate groups of RY 145. The better removal observed under acidic conditions is thus consistent with a contribution from electrostatic attraction.

However, the reduction in adsorption with rising pH does not imply that electrostatic attraction is the only mechanism involved. With pH values likely to be greater than pH_{PZC} , including pH 8, the surface of BPAC is expected to become mainly negatively charged, while RY 145 remains an anionic dye. As such, electrostatic repulsion would thus be expected to oppose adsorption, and despite this unfavorable electrostatic condition, 54.7% removal was still attained at pH 8 compared with 78.4% at pH 2. This residual adsorption indicates that non-electrostatic contributions may become increasingly relevant as electrostatic attraction weakens. Most especially, hydrogen bonding between oxygen-containing surface functionalities and suitable functional groups of RY 145 may contribute to dye retention. Likewise, the aromatic carbon domains identified in the BPAC structure may permit π - π interactions with the aromatic moieties of RY 145.

The observed porous structure of BPAC may also enhance adsorption by providing accessible pathways and internal surface area for dye transport. The N_2 adsorption-desorption assessment yielded a BET surface area of $135\text{ m}^2\text{ g}^{-1}$, whereas the pore-size analysis suggested considerable pore development within the small mesopore range. Additionally, findings from kinetic analysis further suggest that intraparticle diffusion contributes to the removal process, although the non-zero intercept of the intraparticle-diffusion plot indicates that diffusion is not the sole rate-controlling step. The results from thermodynamic investigation also provide supporting evidence towards RY 145 removal concerning the nature of adsorption. The negative value of ΔG° suggests that the uptake process is thermodynamically favorable under the investigated conditions, while the relatively low positive ΔH° value is consistent with an energetically modest adsorption process.

Generally, the uptake of RY 145 by BPAC is thus proposed to result from the likely combined and condition-dependent contributions of hydrogen bonding, electrostatic attraction, possible π - π interactions, and diffusion into accessible pores/pore confinement. Electrostatic attraction is likely to be more favorable under acidic conditions lower than the pH_{PZC} ; however, the noticeable uptake seen at pH 8 suggests that non-electrostatic

interactions and surface/pore accessibility may sustain adsorption even when electrostatic repulsion is expected.

Limitations of the Study

The employment of banana peels as a precursor gives an avenue for valorisation of an agricultural residue. Nevertheless, this study was performed using synthetic single-solute RY 145 solutions and thus, does not establish the performance of BPAC in complex textile wastewater. Moreover, although the precursor is an agricultural waste, BPAC preparation involves KOH activation, acid washing/neutralization, and thermal treatment; thus, claims concerning low production cost or environmental sustainability cannot be conclusively established from the present data alone. Accordingly, further studies should investigate BPAC using real textile wastewater, examine the impact of competing ions and dissolved organic matter, quantify chemical and energy consumption during adsorbent preparation, and conduct techno-economic and life-cycle assessments.

Furthermore, the present study did not include a non-KOH-activated banana-peel carbon developed from the same precursor as a matched control. Thus, the individual contribution of KOH activation to the observed adsorption capacity, removal efficiency, and surface characteristics cannot be quantitatively separated from the effects of carbonization and the overall adsorbent preparation process. Though the observed porous and surface characteristics of BPAC are consistent with the established effects of chemical activation, a direct activated-versus-non-activated comparison would be required to experimentally quantify the contribution of KOH activation. Thus, future work should include a matched non-KOH-activated control and, preferably, comparative surface-area and pore-structure measurements to establish the specific effect of activation on RY 145 adsorption.

CONCLUSIONS

The elimination of RY 145 dye from contaminated water was studied using KOH-activated BPAC and the major findings were as follows:

1. Banana peels wastes were used for the development of the activated carbon *via* carbonization, which yielded a porous, oxygen-rich, and amorphous-structured adsorbent as revealed by scanning electron microscope (SEM), Fourier transform infrared (FTIR) spectroscopy, and X-ray diffraction (XRD) characterizations.
2. Batch adsorption experiments showed that contact time, pH, initial dye concentration, and adsorbent dosage greatly affected RY 145 dye removal.
3. Studies from the kinetics analysis revealed that intraparticle diffusion model contributed substantially to RY 145 uptake; however, the non-zero intercept demonstrated that intraparticle diffusion was not the sole rate-controlling step, whereas equilibrium data fitted well with the Langmuir isotherm model demonstrating a maximum adsorption capacity of 159 mg g⁻¹.
4. Thermodynamic investigation showed sorption was spontaneous ($\Delta G^\circ < 0$), endothermic ($\Delta H^\circ = 7.211 \text{ kJ mol}^{-1}$), and associated with increased randomness ($\Delta S^\circ = 26 \text{ J mol}^{-1} \text{ K}^{-1}$).

5. The regeneration study demonstrated that BPAC retained appreciable desorption capability over five consecutive cycles, with the desorption efficiency decreasing from 71.3% in the first cycle to 60.5% in the fifth cycle.
6. Thus, BPAC is a promising biomass-derived adsorbent for the removal of Reactive Yellow 145 from textile dye-contaminated wastewater.

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