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Mai Lien Tran

RECEIVED
16 July 2026

CITE THIS ARTICLE

Tran, M.L., 2027. Modification of H₃PO₄-activated Pomelo peel biochar with cetyltrimethylammonium bromide for methyl orange removal: Adsorption performance and mechanism. *Nature Environment and Pollution Technology*, 26(1), D1960.

<https://doi.org/10.46488/NEPT.2027.v26i01.D1960>

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PUBLICATION STATUS

PEER REVIEW
Completed

ONLINE VERSION
Prepublished

FINAL ISSUE
March 2027

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Modification of H₃PO₄-activated Pomelo peel biochar with cetyltrimethylammonium bromide for methyl orange removal: Adsorption performance and mechanism

Mai Lien Tran[†]

Institute of Environmental Science, Engineering and Management, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam

[†]Corresponding author: Mai Lien Tran; tranmailien@iuh.edu.vn

ORCID ID: 0000-0001-8110-1548

Abstract

The biochar obtained from pomelo peel with phosphoric activation (A-PBC) was modified using a cationic surfactant, cetyltrimethylammonium bromide (CTAB). The percentage of CTAB in biochar significantly affects the physicochemical characteristics of the obtained biochar. The specific surface area of CTAB-modified biochar could remarkably increase up to 2150.61 m²/g. The surface charge of biochar significantly changed with point zero charge pH_{pzc} = 6.49. The biochar modified with 2 wt% of CTAB (CTAB2@A-PBC) was the best adsorbent for methyl orange (MO) removal. The maximum adsorption capacity of MO calculated by the Langmuir model reached 534.23 mg/g at 30 °C. The result of the isotherm study indicates that the adsorption process of MO on the modified biochar is well fitted with Langmuir and Temkin models, meaning homogeneous rather than heterogeneous adsorption. The kinetic result revealed that the Elovich kinetic model could predict the adsorption process better than the pseudo-first model as well as the pseudo-second model. It suggests that the MO adsorption mechanisms by CTAB2@A-PBC could be involved by electrostatic attraction, pore-filling, π - π interaction, and hydrogen bonding.

Keywords

Pomelo peel biochar; CTAB modification; Methyl orange adsorption; Methyl orange removal

1. INTRODUCTION

Organic dyes are among the most popular pollutant groups in the world. They have been applied to change the color of multiple products such as paper, textiles, leather, etc. Dye manufacturing is estimated to produce 700,000 tons annually (Kusumlata et al. 2024). The dyes are produced to be stable with time, or when exposed to sunlight and detergents. Therefore, dyes released during production, processing, and after utilization could consistently remain in the environment and contaminate water sources. Dyes in water bodies pose a threat to aquatic life and

adversely affect human health (Singha et al. 2021). Dyes can absorb and reflect sunlight, reducing photosynthetic efficiency and impacting aquatic life. Being non-biodegradable substances, dyes can enter the food chain and accumulate in fatty tissues of organisms (Mehra et al. 2021). Chromophores like the carbonyl (C=O), azo (–N=N–), nitro (NO₂) groups, etc., which give dyes' color, are highly carcinogenic and probably cause extreme problems to human health (Islam et al. 2023).

To eliminate dyes, various methods have been investigated, including physical, chemical, biological, advanced oxidation process (AOP), and hybrid methods, which have been declared for high efficiency in dye removal. For instance, brilliant green dye and azo dye Acid Orange 7 could be removed more than 90% by using adsorbents (Baidya and Kumar 2021; Perez-Calderon et al. 2023). Chemical methods such as coagulation-flocculation, precipitation, and oxidation also showed high efficiency in methylene blue removal (Ihaddaden et al. 2022), solophenyl blue (Januário et al. 2021), or acid black 194 (Gómez-García and Dobrosz-Gómez 2024), etc. Biological treatments present eco-friendly and sustainable methods and also provide advantages compared to traditional treatments (Singh et al. 2022). Recently, AOPs are a novel trend to remove not only dyes but also other organic pollutants (Liu et al. 2021). AOPs can be highly effective at degrading even persistent dyes; however, some AOPs generate secondary byproducts. Each method had its advantages and disadvantages. Therefore, some efforts by combining physical, chemical, biological, and AOPs (hybrid methods) to overcome limitations and enhance efficiency (Ahmed et al. 2021; Renita et al. 2021; Kim et al. 2022). Among various methods, adsorption has been widely applied to treat dyes as well as other organic pollutants. Key advantages of adsorption over other methods could be simple and cost-effective, eco-friendly, no secondary pollutants, effective against various pollutants, and adaptable to integrate with other methods (Osagie et al. 2021).

A variety of adsorbents have been developed for dye removal including activated carbon (Husien et al. 2022), clays (Cigeroglu et al. 2024), zeolites (Hammood et al. 2021), cellulose-based adsorbents (Kausar et al. 2023), magnetic nanoparticles (Panda et al. 2021), polymer-based adsorbents (Goswami et al. 2023), biochar (Praveen et al. 2022), and composite adsorbents (Abu-Nada et al. 2021). Biochar is often prepared by a process to convert biomass, such as agricultural waste, wood, food waste, or animal waste, into a carbon-rich material. Biochars formed by traditional methods usually have low efficiency in the adsorption of pollutants because of their low specific surface area and fewer active sites. To improve these properties, physical and chemical activation have been applied. For example, sawdust biochar could be activated by sonication, resulting in increased Cu (II) adsorption capacity from 91.74 to 112.36 mg/g (Eleryan et al. 2024). Microwave pyrolysis was applied to synthesize activated carbon derived from biomass (Durán-Jiménez et al. 2024), which showed high CO₂ and basic blue 9 dye adsorption. Chemical activations are modifications biochars by using chemicals such as acids, alkalis, salts, and polymers. Chemical modifications generally offer several advantages over physical methods, especially in improving biochar's surface properties and functionality for specific applications (Wang and Wang 2019).

In our previous study, the biochar derived from pomelo peel and activated by phosphoric acid (A-PBC) showed an excellent adsorbent of methylene blue (MB) (Tran 2024). It exhibited a high specific surface area of 1192.18 m²/g. The adsorption capacity of MB reached 385.11 mg/g. One of the adsorption mechanisms for MB adsorption was the electrostatic attraction between its positive charge and the negatively charged biochar surface. The result

about the point of zero charge of A-PBC also indicated that its surface was negatively charged in the range of 2 to 12, inferring that the biochar presents electrostatic attraction to positively charged objects and electrostatic repulsion to negatively charged objects. To overcome this repulsion and broaden applicability, the biochar underwent modification with cetyltrimethylammonium bromide (CTAB), a cationic surfactant, to reduce negative charge density on the biochar surface. The introduction of CTAB onto biochars was reported to enhance not only the interaction between biochars and anionic pollutants but also the specific surface area of biochars (Hanif et al.).

In this study, the biochar (A-PBC) was introduced with CTAB at different mass ratios. The physicochemical characteristics of CTAB-modified biochars were analyzed using XRD, FTIR, SEM, BET, and pH_{pzc} measurements. Then, the adsorption efficiency toward methyl orange (MO), which is a typical azo anionic dye that contains a negative sulfonic group ($-\text{SO}_3$) was studied. Finally, the adsorption mechanism was proposed based on studying the isotherm and kinetic models.

2. MATERIALS AND METHODS

2.1. Materials

Methyl orange (MO, $\text{C}_{14}\text{H}_{14}\text{N}_3\text{NaO}_3\text{S}$), phosphoric acid (H_3PO_4), sodium hydroxide (NaOH), hydrochloric acid (HCl), and potassium chloride (KCl) were purchased from Xilong Scientific (Shantou, China). Cetyltrimethylammonium bromide (CTAB, $\text{C}_{19}\text{H}_{42}\text{BrN}$) was supplied by Bio Basic (Markham, Canada). All solutions were prepared using deionized (DI) water.

2.2. Preparation of CTAB-biochar

First, pomelo peel biochar activated by H_3PO_4 (A-PBC) was prepared as in our previous study (Tran 2024). A-PBC was then modified with CTAB. 0.5 g of A-PBC was added to 100 mL of different concentration CTAB solutions. After being gently stirred overnight, the mixtures were filtered and triple-washed with DI water. The obtained modified biochars, denoted as CTAB1@A-PBC, CTAB2@A-PBC, and CTAB5@A-PBC, corresponding to CTAB concentrations of 0.05, 0.1, and 0.25 g/L, respectively, were oven-dried at 60°C . The CTAB biochars were stored in sealed glass bottles.

2.3. Characterization

Surface morphology of all adsorbents was examined by scanning electron microscopy (SEM, S-4800, Hitachi, Tokyo, Japan). The phase of adsorbents was analyzed by X-ray diffraction (LabX XRD-6100, Shimadzu, Tokyo, Japan). Fourier transform infrared spectroscopy (FT-IR, Spectrum 10.5.2, PerkinElmer, Bucks, England) was utilized for functional group determination in the adsorbents. The specific surface area and pore size were determined using the Brunauer–Emmett–Teller method (Nova Station C, Quantachrome Instruments, Florida, USA). To determine the pH at the point of zero charge (pH_{pzc}), the salt addition method was applied (Kosmulski et al. 2019). For this purpose, 20 mg of adsorbent was added to a 0.05 M KCl solution having a pH adjusted in the range of 2 to 12 (pH_i). Following 24 hours of shaking, the final pH values were recorded. The ΔpH , representing the change in pH

(initial vs. final) was determined and graphically presented as a function of pH. The pH at which ΔpH equals zero is defined as the pH_{pzc} .

2.4. Adsorption experiments

The adsorption of MO onto the synthesized adsorbents was investigated under batch conditions. It was carried out by adding a certain amount of adsorbent to a 250-mL Erlenmeyer flask that contains 100 mL of an MO solution. The solution was stirred at 160 rpm. At desired time intervals, the samples were taken and passed through a 0.45- μm membrane filter (Finetech, Taiwan). The remaining concentration of MO was analyzed by measuring the maximum absorbance at a fixed wavelength of 465 nm, using an ultraviolet-visible spectrophotometer (Genesys 10S, Thermo Scientific, Madison, WI, USA). All experiments were performed in triplicate.

The removal efficiency (R) of MO was determined using the formula:

$$R(\%) = \frac{(C_0 - C_t)}{C_0} \times 100 \quad (1)$$

where C_0 is the initial MO concentration, and C_t (mg/L) is MO concentration at time t .

The quantity of MO adsorbed on the adsorbent was calculated as follows:

$$q_t = \frac{(C_0 - C_t) \times V}{m} \quad (2)$$

where q_t (mg/g) represents the adsorption capacity at t (min), V (L) refers to the volume of solution, and m (g) represents the adsorbent mass used.

2.5. Adsorption isotherm

The adsorption isotherms of MO on CTAB2@A-PBC were conducted at ambient temperature (303 K). Particularly, 0.01 g biochar was dispersed in 100 mL solutions with different MO concentrations ranging from 30 to 120 mg/L. The pH of the solution was optimized through the addition of 0.1 M HCl or 0.1 M NaOH solutions. The mixtures were stirred at 160 rpm for 120 min to reach equilibrium. The remaining MO concentrations were analyzed as described above.

The experimental results were then analyzed and fitted using common models including Langmuir, Freundlich, Temkin, Dubinin-Radushkevich (DR), and Sips isotherms (Al-Ghouti and Da'ana 2020). The equations of the five isotherms are as follows:

Langmuir isotherm equation:

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

Freundlich isotherm equation:

$$q_e = K_F C_e^{1/n_F} \quad (4)$$

Temkin isotherm equation:

$$q_e = \frac{RT}{b_T} \ln a_T C_e \quad (5)$$

DR isotherm equation:

$$q_e = q_{DR} \exp\left(\frac{(RT \ln(1 + 1/C_e))^2}{-2E^2}\right) \quad (6)$$

Sips isotherm equation:

$$q_e = \frac{q_s (K_s C_e)^{n_s}}{1 + (K_s C_e)^{n_s}} \quad (7)$$

where q_e (mg/g) is the adsorbed MO at equilibrium, q_m (mg/g) is the maximum monolayer adsorption capacity, K_L (L/mg) is the Langmuir isotherm constant, K_F ((mg/g)(L/mg)^{1/n}) is the Freundlich isotherm constant, n_F is Freundlich exponent of adsorption intensity, a_T is Temkin isotherm constant (L/g), b_T is Temkin constant related to the heat sorption (J/mol), R is the ideal gas constant (8.314 J/mol.K), T (K) is the temperature in Kelvin, q_{DR} (mg/g) is the highest adsorbed amount of DR model, E (kJ/mol) the energy, q_s (mg/g) is the Sips isotherm's highest adsorbed amount, K_s (L/mg) and n_s are Sips constants.

2.6. Adsorption kinetics

To evaluate the adsorption kinetics, 0.01 g of CTAB2@A-PBC was dispersed in a 100 mL solution of 50 mg/L MO at the optimal pH value. The adsorption kinetics of the MO on CTAB2@A-PBC were studied and modeled using Pseudo first-order (PFO), Pseudo second-order (PSO), Elovich, and intraparticle diffusion equations (Wang and Guo 2020). The nonlinear kinetics expressions of these models are presented in equations (8), (9), (10), (11), respectively.

$$q_t = q_e (1 - e^{-k_1 t}) \quad (8)$$

$$q_t = \frac{q_e^2 k_2 t}{1 + q_e k_2 t} \quad (9)$$

$$q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln t \quad (10)$$

$$q_t = k_{ip} t^{0.5} + C_{ip} \quad (11)$$

where q_t (mg/g) is the amount of MO adsorbed at time t (min), q_e (mg/g) is the adsorption capacity at equilibrium, k_1 (min^{-1}) is the PFO rate sorption constant, k_2 (g/mg.min) is the PSO rate sorption constant, α (mg/g.min) is the initial adsorption rate, β (g/mg) is the extent of surface coverage and activation energy for chemisorption, k_{id} ($\text{mg/g.min}^{0.5}$) is the intraparticle diffusion rate constant, C_{id} is the constant.

2.7. Recycling test

To assess the reusability and recovery efficiency of the CTAB2@A-PBC adsorbent, consecutive adsorption-desorption cycles were conducted. The MO-loaded biochar was eluted using a mixed solvent of ethanol and DI water (1:1 v/v) containing 0.01 M NaOH. After phase separation, the biochar was repeatedly rinsed with DI water until reaching a neutral pH and dried at 60°C overnight before subsequent adsorption cycles.

3. RESULTS AND DISCUSSION

3.1. Characterizations

XRD characterization was applied to analyze the crystal structure and phase composition of both pristine (A-PBC) and modified (CTAB2@A-PBC) biochars. As illustrated in **Fig. 1**, two peaks were detected at 22.8° and 43.4°, corresponding to the (002) and (101) planes in graphite structure, respectively. It suggests the existence of amorphous carbon in the samples (Egbedina et al. 2023). Compared with A-PBC, the intensity of the peak at 22.8° of CTAB2@A-PBC remarkably decreased. This implies that the crystallinity of CTAB2@A-PBC is lower than that of A-PBC or the crystal size of CTAB2@A-PBC is smaller than that of A-PBC. The change in the crystallinity degree of CTAB2@A-PBC indicates that the presence of CTAB could decrease the aggregated structure of A-PBC. This could result in an increased surface area and a greater number of active sites for the adsorbate molecules (Salehi et al. 2020).

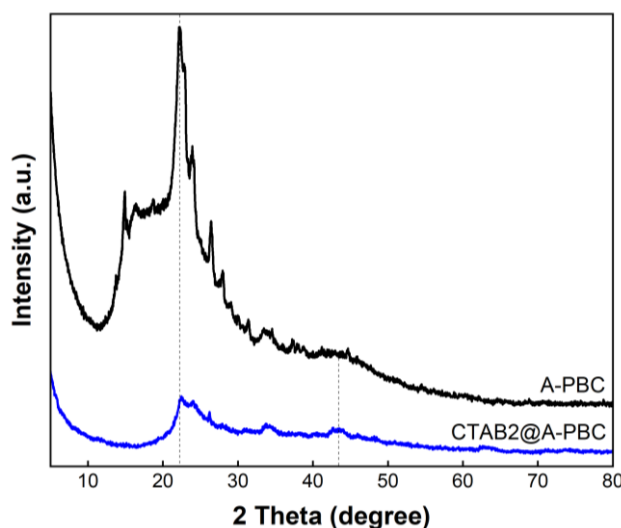


Fig. 1. XRD patterns of biochars.

To further explore the modifications in functional groups on biochars, FT-IR spectra are presented in **Fig. 2**. Broad bands at $3500 - 3200 \text{ cm}^{-1}$ were associated with the vibration of the hydroxyl ($-\text{OH}$). Compared with FT-IR spectrum of A-PBC, the peak intensity in the spectrum of CTAB2@A-PBC was weakened, indicating the hydroxyl ($-\text{OH}$) might participate in CTAB and A-PBC combination. The peaks at 2919 and 2841 cm^{-1} in CTAB2@A-PBC indicate the symmetric and antisymmetric bond stretching of $\text{C}-\text{H}$ of methyl in biochar modified with CTAB (Liu et al. 2021). The peak detected in the range of $1607-1563 \text{ cm}^{-1}$ may correspond to the $\text{C}=\text{O}$ stretching vibration in carboxyl group or $\text{C}=\text{C}$ aromatic vibration (Tran 2024). The peak observed at 1401 cm^{-1} is due to the $\text{C}-\text{O}$ stretching vibration of carboxyl group (Zeng et al. 2021), which is present in A-PBC but absent in CTAB2@A-PBC, suggesting that CTAB might modify the origin biochar at carboxyl group position. The new peak at 1239 cm^{-1} indicates the vibration of the $\text{C}-\text{N}$ bond (Mathurasa and Damrongsiri 2018), confirming the presence of CTAB on A-PBC. After MO adsorption, a broad peak appears at $1138 - 595 \text{ cm}^{-1}$ may associate with the stretching vibrations of $-\text{S}=\text{O}$ and $-\text{C}-\text{H}$ of the benzene ring in MO molecule (Cyril et al. 2019), indicating MO was adsorbed in CTAB2@A-PBC surface. In addition, shifts were observed in vibration peaks assigned to $\text{C}=\text{O}$, $\text{C}=\text{C}$, and $\text{O}-\text{H}$ after MO adsorption.

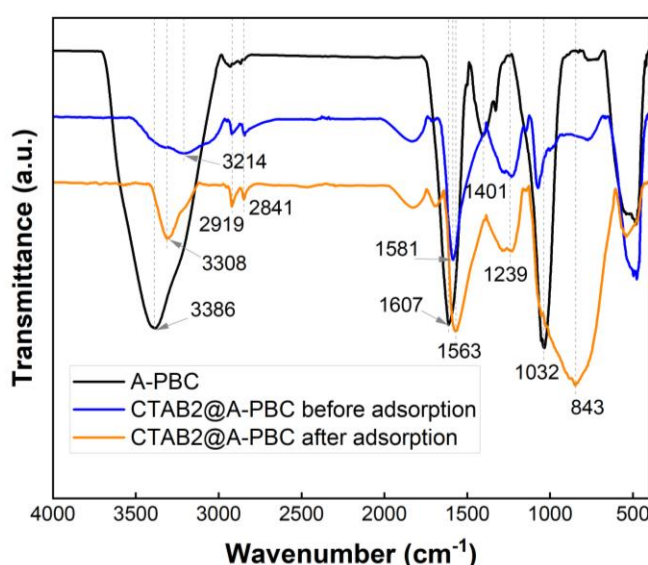


Fig. 2. FTIR spectra of biochars before and after adsorption

The morphology of biochars can be described by SEM (**Fig. 3**). It can be seen that the surface structure of biochars modified by CTAB (**Fig. 3b,c,d**) was different from that of A-PBC biochar (**Fig. 3a**). A-PBC presents more blocky structures and an irregular size distribution on the surface. After being modified with CTAB, the biochar surface reveals smaller-sized particles with more pores, which could lead to an enhancement of the surface area and pore volume of these biochars. The difference in morphology of SEM images in **Fig. 3b, c**, and **d** indicates that the percentage of CTAB is crucial to the change in biochar's surface properties. With 2 wt% of CTAB, the obtained biochar (CTAB2@A-PBC) appears to have the smallest particles and more pores on the surface. This change is expected to improve the adsorption of MO, which was confirmed in the next section. After the adsorption process, the biochar's surface was changed (**Fig. 3e**), indicating the MO molecules were adsorbed onto the biochar.

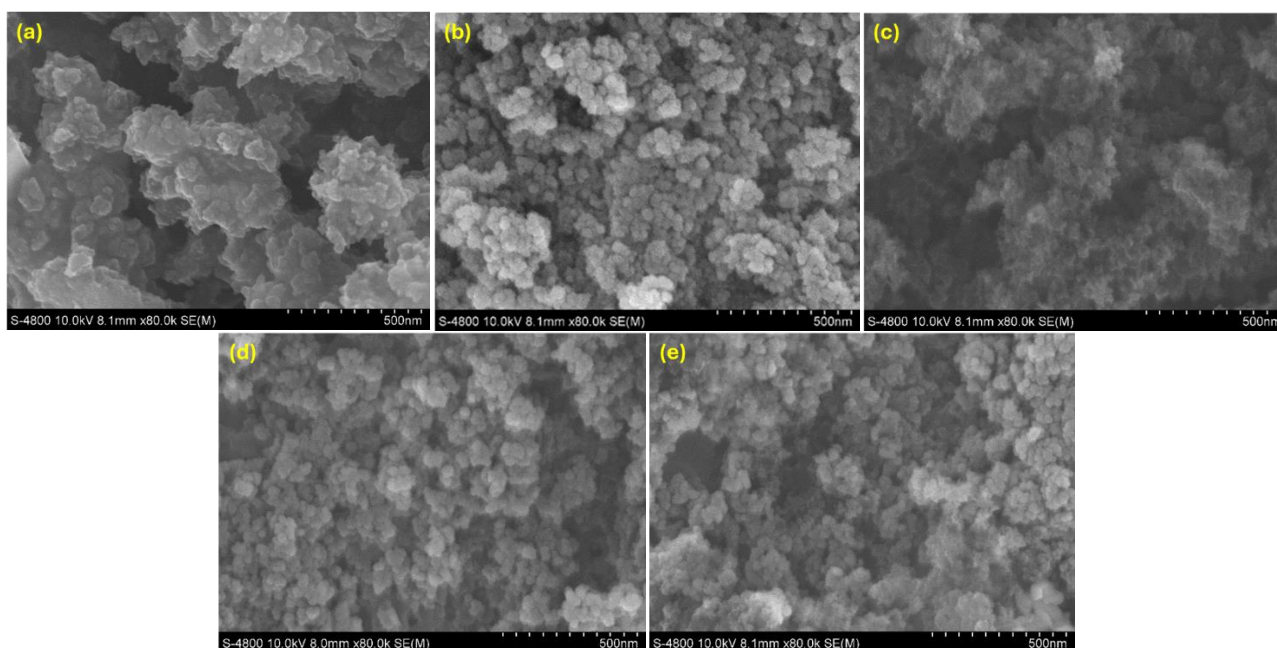


Fig. 3. SEM images of biochars modified by CTAB (a) A-PBC, (b) CTAB1@A-PBC, (c) CTAB2@A-PBC, (d) CTAB5@A-PBC, (e) CTAB2@A-PBC – after adsorption

Specific surface area, pore volume, and diameter play a critical role in the adsorption process. The BET results of the original biochar and modified biochar with CTAB are shown in **Fig. 4** and **Table 1**. It is apparent that the modification of biochar with CTAB did not make a change in the adsorption-desorption isotherms. All samples display hybrid type I/IV isotherms with the type H3 hysteresis loop (**Fig. 4a**) (Al-Ghouti and Da'ana 2020), confirming the existence of hierarchical micro-mesoporous structures with interparticle slit-shaped pores in these biochars. The pore size distribution curves (**Fig. 4b**) reveal that the pore diameters predominantly range from 10 to 50 Å, with a narrow peak centered around 20 Å. Concurrently, the average pore diameters obtained from the analysis range between 0.9728 and 1.0135 nm (**Table 1**), indicating a predominantly microporous structure with complementary mesoporosity. Notably, CTAB modification significantly enhanced both the specific surface area and micropore volume of biochar materials. Particularly, when 1 wt% of CTAB was applied, the pore volume increased from 0.029 cm³/g (A-PBC) to 0.043 cm³/g (CTAB1@A-PBC), reaching a peak of 0.074 cm³/g for CTAB2@A-PBC. This trend strictly corresponds to the specific surface area, which increased from 1192.18 m²/g to a maximum of 2150.61 m²/g. The enhancement in textural properties can be attributed to the surfactant action of CTAB, which reduces particle aggregation and stabilizes the newly formed porous framework during synthesis, as corroborated by SEM observations. However, a further increase in CTAB content to 5 wt% (CTAB5@A-PBC) resulted in a slight decrease in both micropore volume (0.067 cm³/g) and surface area (2010.06 m²/g). This decline is likely due to the accumulation of excess CTAB molecules, which block a portion of the microporous channels.

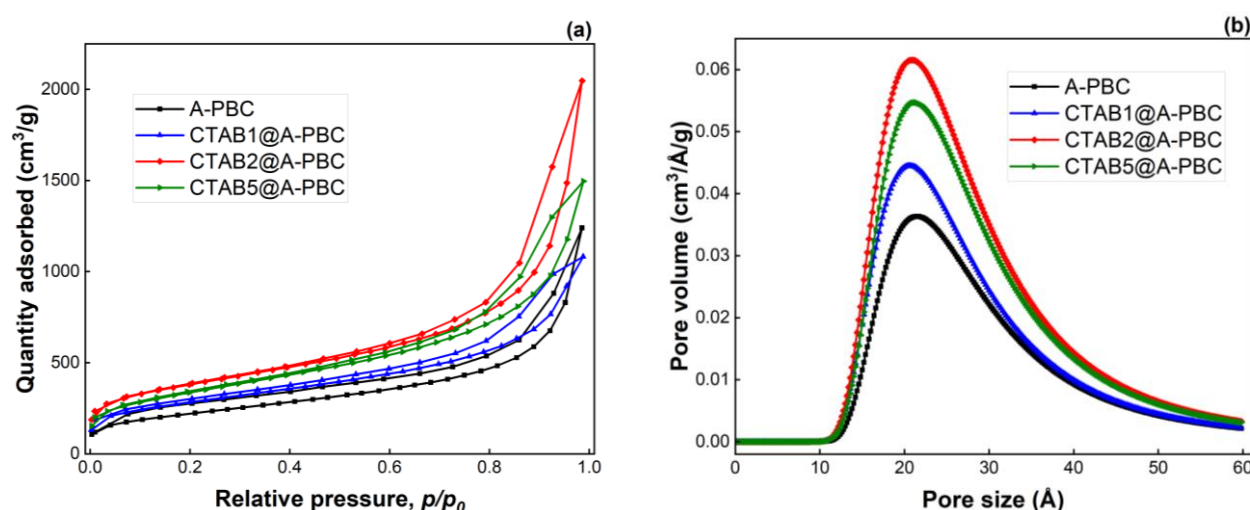


Fig. 4. N₂ adsorption-desorption (a) and pore size distribution (b) of as-prepared biochars

Table 1. Textural properties of different biochars

Sample	Specific surface area	Micropore volume	Average pore diameter
	(m ² /g)	(cm ³ /g)	(nm)
A-PBC	1192.18	0.029	1.0135
CTAB1@A-PBC	1697.93	0.043	0.9985
CTAB2@A-PBC	2150.61	0.074	0.9728
CTAB5@A-PBC	2010.06	0.067	0.9813

3.2. Adsorption of MO on biochars modified by CTAB

The removal efficiency of MO by different as-prepared biochars has been investigated. As shown in **Fig. 6**, biochars modified with CTAB present higher MO adsorption efficiency. Particularly, 55.26% of MO was removed by A-PBC after 90 min adsorption process. This increased to 67.68% for biochar modified with 1 wt% of CTAB (CTAB1@A-PBC). When increasing CTAB to 2 wt%, the MO removal increased to 70.38%. However, the removal efficiency decreased to 63.91% when CTAB was 5 wt%. The enhanced MO removal efficiency with biochars modified by CTAB could be due to the change in surface charge in CTAB presence. CTAB was reported as a cationic surfactant (Hoshyar et al. 2021). It was facilely adsorbed on the surface of A-PBC, resulting in a decrease in the negative charge of A-PBC and the repulsion interaction between anionic MO dye and the adsorbents, resulting in higher adsorption efficiency. In addition, another important point is that the modification of biochar using CTAB gave a rise in the surface area and pore size (**Fig. 4**), thus increasing the removal of MO.

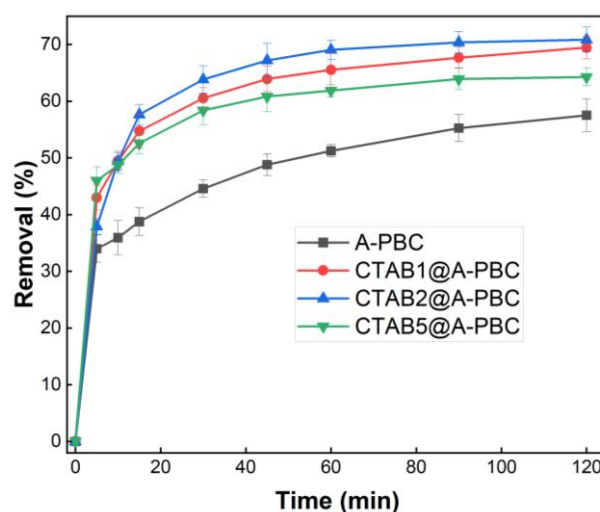


Fig. 6. MO adsorption efficiency of synthesized biochars. Conditions: initial MO concentration (50 mg/L), natural pH, and adsorbent dosage (0.1 g/L)

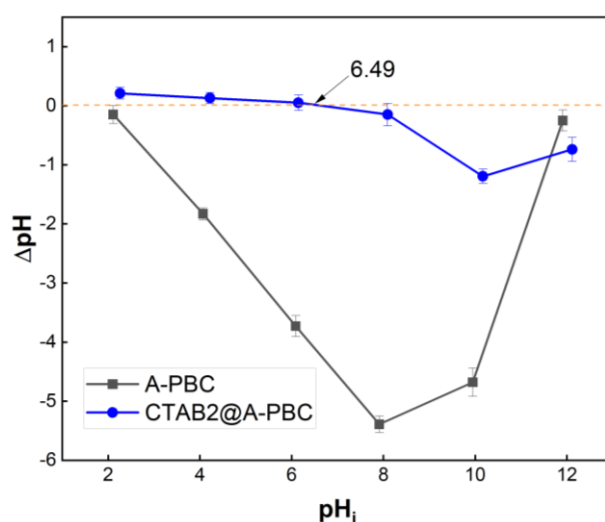


Fig. 7. Point of zero charge of biochars with and without CTAB modification

3.3. Effect of pH on MO adsorption

The solution pH is essential to the adsorption process as it influences the adsorbent's surface charge as well as the dissociation of the MO species. The adsorption tests at pH 4.01, 6.14, 8.13, and 10.11 (**Fig. 8**) showed an increase in MO removal with removals of 94.64, 91.05, 74.16, and 70.86% after a 60-min adsorption process, respectively. This phenomenon can be interpreted through an analysis of the isoelectric point of the adsorbent (pH_{pzc}) and the ionized MO species as influenced by pH. The pH_{pzc} value of CTAB2@A-PBC shown in **Fig. 7** is 6.49. At $\text{pH} < 6.49$, it is assumed that the adsorbent surface carries a positive charge, facilitating electrostatic attraction with negative species. Conversely, at $\text{pH} > 6.49$, the adsorbent surface turns negative and exhibits repulsion force with those species. As reported by Jia et al. (Jia et al. 2020), MO exists mainly in deprotonated form at $\text{pH} > 4$; this strong electrostatic repulsion between the negatively charged surface and the anionic dye species accounts for the diminished adsorption capacity observed under alkaline conditions. At a solution pH

between 4 and 6.5, the adsorbent surface becomes positively charged, leading to high removal of MO. Since the MO removal at pH 4 and 6 at equilibrium was not significantly different, pH 6 was chosen as the optimal pH for the adsorption.

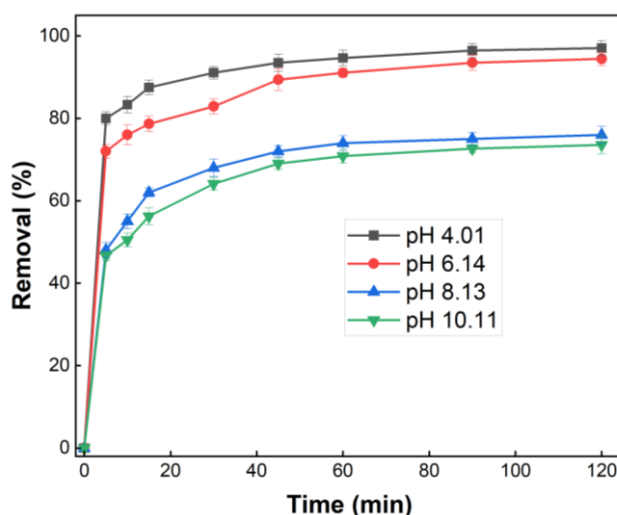


Fig. 8. Effect of initial solution pH on MO adsorption by CTAB2@A-PBC. Conditions: initial MO concentration (50 mg/L) and adsorbent dosage (0.1 g/L)

3.4. Adsorption isotherms

The adsorption isotherm of MO on CTAB2@A-PBC by Langmuir, Freundlich, Temkin, Dubinin-Radushkevich (D-R), and Sips isotherm models are displayed in **Fig. 8**. The fitting parameters of these models are presented in **Table 2**. The statistical significance of the models, such as standard error (SE) and $\text{adj.}R^2$ was summarized. Obviously, the experimental data exhibited an excellent correlation with the Langmuir model with $\text{adj.}R^2 > 0.99$. This reveals single-layer adsorption of MO on the CTAB2@A-PBC surface. The predicted highest adsorption capacity based on this model was 534.23 mg/g. The equilibrium parameter, $R_L = \frac{1}{(1+C_0K_L)}$, provides insight into the favorability of the adsorption process. According to the R_L values, adsorption can be categorized as follows: $R_L > 1$ suggests unfavorable adsorption, $R_L = 1$ implies a linear process, $R_L = 0$ indicates irreversible adsorption, while adsorption is classified as favorable when $0 < R_L < 1$ (Chen et al. 2019). In these experiments, the values were between 0 and 1 for the investigated C_0 range, indicating the adsorption process of MO on the adsorbent occurred favorably. As for Freundlich model, it presented $\text{adj.}R^2 = 0.8359$ and $\text{SE} = 28.53$, suggesting that this model was not fitted very well with the experimental data. This implies that adsorption occurs predominantly homogeneously rather than heterogeneously on the surface. To describe how the adsorbate interacts with the adsorbent, the Temkin model was applied. As presented in **Fig. 8** and **Table 2**, the Temkin model exhibited a strong fit with the experimental data ($R^2 > 0.97$). This suggests that electrostatic interaction was among the key adsorption mechanisms of MO on CTAB2@A-PBC. The experimental data were additionally verified using the DR model. The relatively high R^2 value (> 0.97) reveals a function of the porous structure of the adsorbent (Choudhary and Paul 2018). The E value (< 8 kJ/mol) suggested physisorption. However, isotherm models primarily provide mathematical descriptions of adsorption equilibria rather than definitive molecular mechanisms. Therefore, it must

be evaluated alongside kinetic fitting and characterization spectral data to establish a realistic mechanism. The Sips model integrates elements of both the Langmuir and Freundlich models. The isotherm exponent, $n_s = 1.26$, indicates that the isotherm was more Langmuir in nature. From the analysis of all the isotherms, the isotherms can be arranged with respect to R^2 (in descending order): Langmuir, Sips, Temkin, Dubinin-Radushkevich, Freundlich.

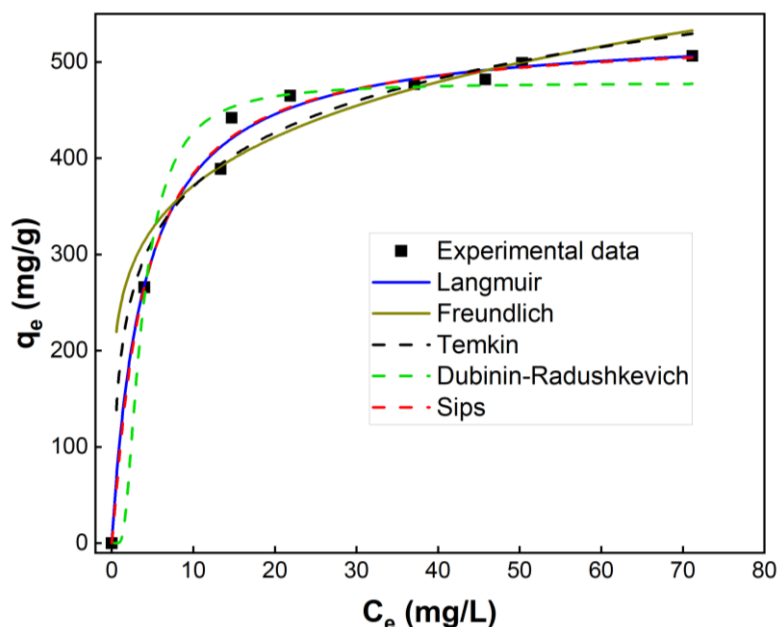


Fig. 8. Adsorption isotherm data and fitted models of MO on CTAB2@A-PBC

Table 2. Isotherm model parameters derived from experimental data

Isotherm Model	Model Parameters				Adj. R^2	Model Equation
	Symbol	Unit	Value	SE		
Langmuir	$q_{\max}$	mg/g	534.23	9.67	0.9932	$q_e = \frac{133.56 \times C_e}{1 + 0.25 \times C_e}$
	K_L	L/mg	0.25			
	R_L	-	0.118-			
			0.032			
Freundlich	K_F	(mg/g)(L/mg) $^{1/n}$	243.18	28.53	0.8359	$q_e = 243.18 \times C_e^{0.18}$
	n_F	-	5.44			
Temkin	a_T	L/g	9.68	6.51	0.9779	$q_e = 81.03 \times \ln(9.68 \times C_e)$
	b_T	J/mol	31.09			
Dubinin-Radushkevich	q_{DR}	mg/g	478.51	11.04	0.9728	$q_e = 478.51 \times e^{-12.66 \times e^2}$
	K_{DR}	mol 2 /KJ 2	12.66			
	E	kJ/mol	0.19			
Sips	q_s	mg/g	531.02	15.52	0.9922	$q_e = \frac{136.39 \times C_e^{1.26}}{1 + 0.26 \times C_e^{1.26}}$
	K_s	L/g	0.34			
	n_s	-	1.26			

3.5. Adsorption kinetic studies

Kinetic studies offer valuable information on the mechanisms and dynamics of the adsorption process. The experimental data of the MO adsorption on CTAB2@A-PBC were fitted to the PFO, PSO, Elovich, and intraparticle diffusion models, as shown in **Fig. 9** and **Table 3** presents the fitting parameters. The fitness of models could be estimated based on the R^2 values. As shown in **Table 3**, R^2 values are almost larger than 0.95, indicating good agreement of experimental data with all models. However, the higher R^2 value of the Elovich model (0.9982) compared with 0.9632 (PFO model) and 0.9884 (PSO model) means that the Elovich kinetic model predicts the adsorption process better than the others. Based on the Elovich model's assumptions, the surface of the modified biochar possesses energetic heterogeneity with a distribution of activation energies. This heterogeneity drives complex adsorption dynamics, which combine dominant chemisorptive interactions at specific surface sites with multi-layer diffusion rather than a simple single-site chemical reaction (Naggar et al. 2023). For further understanding of the major limitations in the adsorption process, the intraparticle diffusion model was investigated. **Fig. 9b** shows two stages of linearity, indicating that the adsorption process is not entirely regulated by intraparticle diffusion (Choudhary and Paul 2018). The first stage is controlled by mass transfer in the external barrier, while the second stage is dominated by the intra-particle diffusion. Moreover, the observation that the plot did not intersect the origin suggests the adsorption rate was likely limited by the external diffusion step (Chen et al. 2019).

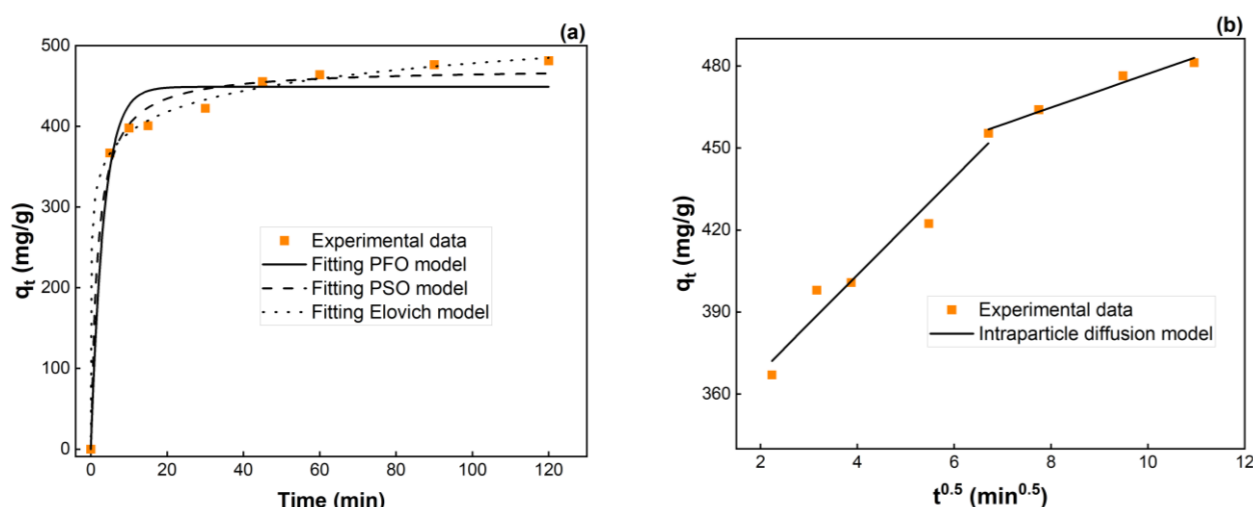


Fig. 9. Sorption kinetic studies of MO on CTAB2@A-PBC fitted by: (a) PFO, PSO, and Elovich models and (b) intraparticle diffusion model

Table 3. Adsorption kinetic parameters of MO on CTAB2@A-PBC

Kinetic model	Parameter	Unit	Value
PFO	$q_{e,cal}$	mg/g	449.04
	$q_{e,exp}$	mg/g	481.20
	Adj- R^2	-	0.9632
PSO	$q_{e,cal}$	mg/g	472.33
	$q_{e,exp}$	mg/g	481.20
	Adj- R^2	-	0.9884

Elovich	α	mg/g.min	134423
	β	g/mg	0.0268
	Adj- R^2	-	0.9982
Intraparticle diffusion	$k_{d,1}$	mg/g.min ^{0.5}	17.82
	Adj- R^2	-	0.9429
	$k_{d,2}$	mg/g.min ^{0.5}	6.16
	Adj- R^2	-	0.9569

3.6. Possible mechanism

From the analyzed results, the adsorption mechanism of MO on the modified biochar could be involved by the combination of several interactions, including electrostatic attraction, π - π interaction, pore filling, and hydrogen bonding (**Fig. 10**). The electrostatic attraction happened between the positively charged biochar surface and negatively charged MO molecules. The original biochar (A-PBC), which had a negative surface, became much more positive after modification by cation surfactant (CTAB) (**Fig. 7**). This resulted in enhanced attraction of negative molecules such as MO molecules. The π - π interaction mechanism was reported as a dominant adsorption mechanism for organic pollutants. Here, π - π interaction occurred between π -electron system of graphene sheet within the biochar and π -electron system of MO molecules. The pore-filling mechanism could be inferred from the size of molecules and pores in biochar. CTAB and MO molecular widths reported were 0.17 and 0.55 nm, respectively (Javadian et al. 2013; Chaukura et al. 2017). Compared with the average pore diameter of A-PBC (~1.01 nm; **Table 1**), the smaller width suggests that CTAB could be distributed into the pores of A-PBC during the preparation of CTAB@A-PBC. The CTAB2@A-PBC material with a pore size of mainly 2 nm (**Fig. 4b**) and an average pore diameter of 0.97 nm (**Table 1**) indicated that MO molecules could go freely into the biochar pores. Hydrogen bonding interaction could happen between H atoms on the biochar surface and N and O atoms of MO. **Fig. 2** shows that the vibration peak of -OH was shifted after adsorption of MO, indicating the occurrence of hydrogen bonding interaction in adsorption mechanisms. To sum up, characterization results including FT-IR, pH_{pzc} , and a high specific surface area (2150.61 m²/g, **Table 1**) corroborate the hybrid physisorption and chemisorption mechanism indicated by the DR isotherm and Elovich kinetic model.

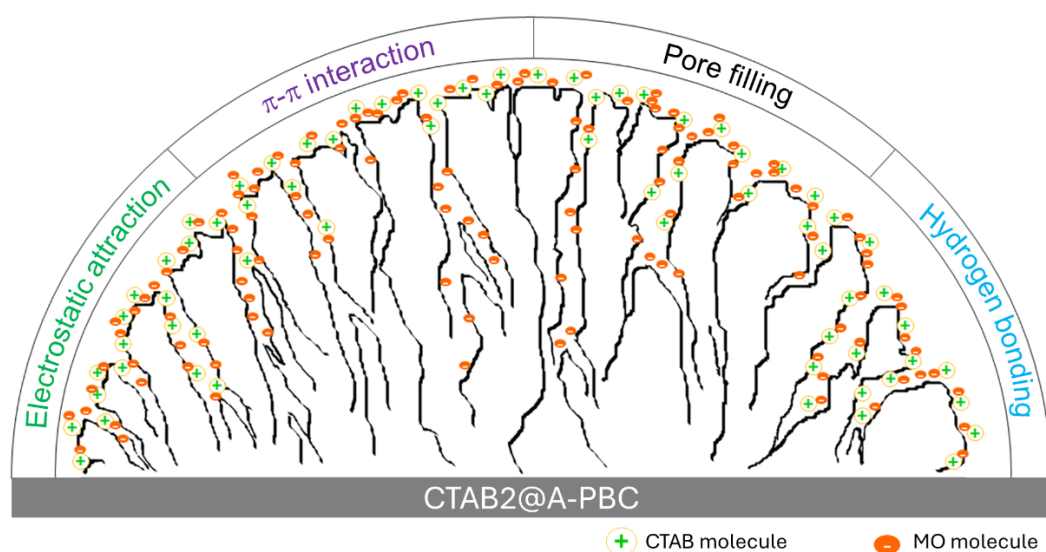


Fig. 10. Possible adsorption mechanism of MO on CTAB@A-PBC

3.7. Comparison of MO removal by CTAB2@A-PBC with the literature

Recently, biochars used as adsorbents to remove dyes such as MO have been investigated. These biochars were prepared from multiple biomass. To improve the treatment efficiency of pollutants, pristine biochars were modified in various ways. As shown in **Table 4**, biochars reported by Hou et al. (Hou et al. 2021), Lee et al. (Lee et al. 2024), and Hamad et al. (Hamad et al. 2024) could be physically activated, presenting high MO removal efficiency of 449, 220, and 113.3 mg/g. For chemical modification, biochars could be magnetized (Hu et al. 2024), functionalized with EDTA and chitosan (Zhang et al. 2022, Cheng et al. 2024), and coated or doped by chemicals (Mao et al. 2023; Zhang et al. 2024). Those biochars showed excellent MO adsorption performance in which magnetic chitosan-functionalized waste carton biochar (Cheng et al. 2024) could reach an adsorption capacity of 644.0 mg/g. The prepared biochar in this study (CTAB2@A-PBC) could be compared to other modified biochars on its MO removal efficiency. It is evident that the MO adsorption capacity of CTAB2@A-PBC attained 534.23 mg/g at room temperature is relatively high to those of other adsorbents. Moreover, the facility in preparation for CTAB2@A-PBC promises real applications.

Table 4. Comparison of MO removal efficiency by different adsorbents

Adsorbents	Adsorption capacity (mg/g)	References
Magnetic pepper straw biochar	437.18	(Hu et al. 2024)
EDTA and chitosan bi-functionalized magnetic bamboo biochar	305.4	(Zhang et al. 2022)
N-doped lotus root biochar	449	(Hou et al. 2021)
N-doped hierarchical biochar	567.7	(Mao et al. 2023)
Magnetic chitosan-functionalized waste carton biochar	644.0	(Cheng et al. 2024)
Activated birchwood pellets biochar	220	(Lee et al. 2024)
Hydrochar nanoparticles biosorbent	113.3	(Hamad et al. 2024)

Cu ₂ O/Ag-coated wood-based biochar composites	178.63	(Zhang et al. 2024)
CTAB2@A-PBC	534.23	This study

3.8. Reusability

The reusability performance of the modified biochar over five adsorption-desorption cycles is illustrated in **Fig. 11**. In the initial run, the material exhibited a high removal efficiency of 94.5%, which gradually decreased to 80.3% and 70.5% in the first and second reuse cycles, respectively. By cycle 4, the uptake efficiency dropped to 46.5%, reflecting a progressive decline in performance across continuous regeneration steps. This attenuation can be attributed to the incomplete desorption of dye molecules from internal pores, alongside the potential loss of active binding sites during repeated washing. Nevertheless, CTAB2@A-PBC maintained reasonable adsorption capabilities through the first few cycles, demonstrating its moderate stability for practical wastewater treatment.

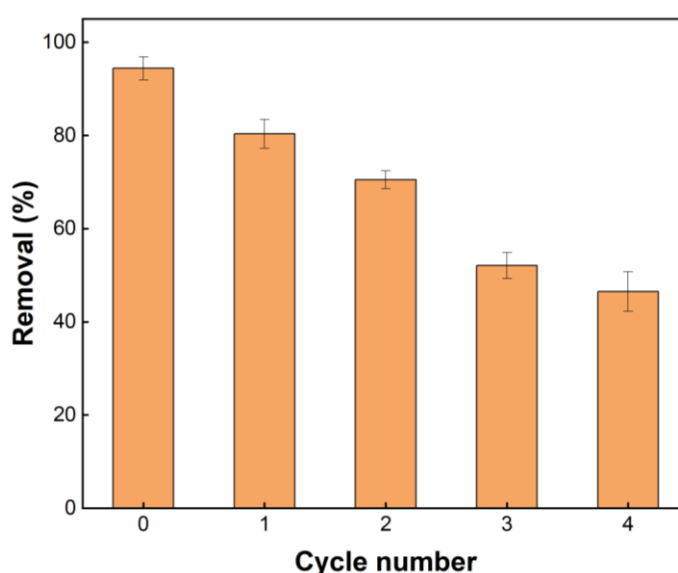


Fig. 11. Regeneration performance of CTAB2@A-PBC. Conditions: initial MO concentration (50 mg/L), pH 6.0, adsorbent dosage (0.1 g/L), and contact time 150 min

4. CONCLUSIONS

CTAB could be applied to modify biochar successfully. The presence of CTAB on the biochar not only improves the specific surface area but also changes the charge density of the biochar's surface. Compared with A-PBC, the surface area of CTAB2@A-PBC increased almost two times. The pore volume also increased from 1.998 to 3.303 cm³/g. The change in physicochemical characteristics of CTAB-modified biochar resulted in good adsorption performance for MO, an anionic dye. The pH of the solution can affect the MO removal efficiency due to the change in the biochar's surface charge. The isotherms and kinetics studies also indicated that there were both physical and chemical interactions between MO and biochar. Besides, the external diffusion of MO controlled the adsorption rate. The results of this research demonstrated that the biochar modification by using CTAB could produce an

excellent adsorbent for anionic pollutants such as MO. The enhanced physicochemical characteristics of the modified biochar suggest high potential for capturing negatively charged species as well as other classes of contaminants. While CTAB2@A-PBC exhibited high adsorption performance under controlled batch conditions, further validation using real wastewater containing complex organic matter and competing ions is required to fully assess its practical feasibility.

5. ACKNOWLEDGMENTS

The author sincerely thanks the Institute of Environmental Science, Engineering and Management, Industrial University of Ho Chi Minh City for facilitating facilities and equipment to help complete this study.

6. REFERENCES

1. Abu-Nada, A., Abdala, A. and McKay, G., 2021. Removal of phenols and dyes from aqueous solutions using graphene and graphene composite adsorption: a review. *Journal of Environmental Chemical Engineering*, 9, 105858. <https://doi.org/10.1016/j.jece.2021.105858>
2. Ahmed, S., Mofijur, M., Nuzhat, S., Chowdhury, A.T., Rafa, N., Uddin, M.A., Inayat, A., Mahlia, T., Ong, H.C. and Chia, W.Y., 2021. Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *Journal of Hazardous Materials*, 416, 125912. <https://doi.org/10.1016/j.jhazmat.2021.125912>
3. Al-Ghouti, M.A. and Da'ana, D.A., 2020. Guidelines for the use and interpretation of adsorption isotherm models: A review. *Journal of Hazardous Materials*, 393, 122383. <https://doi.org/10.1016/j.jhazmat.2020.122383>
4. Baidya, K.S. and Kumar, U., 2021. Adsorption of brilliant green dye from aqueous solution onto chemically modified areca nut husk. *South African Journal of Chemical Engineering*, 35, pp33-43. <https://doi.org/10.1016/j.sajce.2020.11.001>
5. Chaukura, N., Murimba, E.C. and Gwenzi, W., 2017. Synthesis, characterisation and methyl orange adsorption capacity of ferric oxide–biochar nano-composites derived from pulp and paper sludge. *Applied Water Science*, 7, pp2175-2186. <https://doi.org/10.1007/s13201-016-0392-5>
6. Chen, S., Qin, C., Wang, T., Chen, F., Li, X., Hou, H. and Zhou, M., 2019. Study on the adsorption of dyestuffs with different properties by sludge-rice husk biochar: adsorption capacity, isotherm, kinetic, thermodynamics and mechanism. *Journal of Molecular Liquids*, 285, pp62-74. <https://doi.org/10.1016/j.molliq.2019.04.035>
7. Cheng, Y., Li, A., Shi, W. and Zhao, L., 2024. Magnetic chitosan-functionalized waste carton biochar composites for efficient adsorption of anionic and cationic dyes. *Chemical Engineering Journal*, 481, 148535. <https://doi.org/10.1016/j.cej.2024.148535>
8. Choudhary, B. and Paul, D., 2018. Isotherms, kinetics and thermodynamics of hexavalent chromium removal using biochar. *Journal of Environmental Chemical Engineering*, 6, pp2335-2343. <https://doi.org/10.1016/j.jece.2018.03.028>

9. Cigeroglu, Z., El Messaoudi, N., Şenol, Z.M., Baskan, G., Georgin, J. and Gubernat, S., 2024. Clay-based nanomaterials and their adsorptive removal efficiency for dyes and antibiotics: a review. *Materials Today Sustainability*, 26, 100735. <https://doi.org/10.1016/j.mtsust.2024.100735>
10. Cyril, N., George, J.B., Joseph, L. and Sylas, V., 2019. Catalytic degradation of methyl orange and selective sensing of mercury ion in aqueous solutions using green synthesized silver nanoparticles from the seeds of *Derris trifoliata*. *Journal of Cluster Science*, 30, pp459-468. <https://doi.org/10.1007/s10876-019-01508-9>
11. Durán-Jiménez, G., Rodriguez, J., Stevens, L., Kostas, E.T. and Dodds, C., 2024. Microwave pyrolysis of waste biomass and synthesis of micro-mesoporous activated carbons: The role of textural properties for CO₂ and textile dye adsorption. *Chemical Engineering Journal*, 488, 150926. <https://doi.org/10.1016/j.cej.2024.150926>
12. Egbedina, A.O., Ugwuja, C.G., Dare, P.A., Sulaiman, H.D., Olu-Owolabi, B.I. and Adebawale, K.O., 2023. CTAB-activated Carbon from Peanut Husks for the Removal of Antibiotics and Antibiotic-resistant Bacteria from Water. *Environmental Process*, 10, 20. <https://doi.org/10.1007/s40710-023-00636-9>
13. Eleryan, A., Aigbe, U.O., Ukhurebor, K.E., Onyancha, R.B., Eldeeb, T.M., El-Nemr, M.A., Hassaan, M.A., Ragab, S., Osibote, O.A. and Kusuma, H.S., 2024. Copper (II) ion removal by chemically and physically modified sawdust biochar. *Biomass Conversion and Biorefinery*, 14, pp9283-9320. <https://doi.org/10.1007/s13399-022-02918-y>
14. Gómez-García, M.Á. and Dobrosz-Gómez, I., 2024. The scope of alum coagulation-flocculation assisted by slaked lime for the treatment of industrial wastewater containing highly concentrated Acid Black 194 dye. Optimization, molecular weight distribution and toxicity analysis. *Results in Engineering*, 23, 102676. <https://doi.org/10.1016/j.rineng.2024.102676>
15. Goswami, M.K., Srivastava, A., Dohare, R.K., Tiwari, A.K. and Srivastav, A., 2023. Recent advances in conducting polymer-based magnetic nanosorbents for dyes and heavy metal removal: fabrication, applications, and perspective. *Environmental Science and Pollution Research*, 30, pp73031-73060. <https://doi.org/10.1007/s11356-023-27458-4>
16. Hamad, N., Galhoum, A.A., Saad, A. and Wageh, S., 2024. Efficient adsorption of cationic and anionic dyes using hydrochar nanoparticles prepared from orange peel. *Journal of Molecular Liquids*, 409, 125349. <https://doi.org/10.1016/j.molliq.2024.125349>
17. Hammood, Z.A., Chyad, T.F. and Al-Saedi, R., 2021. Adsorption performance of dyes over zeolite for textile wastewater treatment. *Ecological Chemistry and Engineering S*, 28, pp329-337.
18. Hanif, M.A., Ibrahim, N., Dahalan, F.A. and Ali, U.F.M., 2023. Biochar Modification with Cetyltrimethylammonium Bromide (CTAB) For Utilization in The Adsorption Process: A Mini-Review. *FKTA Postgraduate Colloquium*.
19. Hoshyar, S.A., Barzani, H.A., Yardım, Y. and Şentürk, Z., 2021. The effect of CTAB, a cationic surfactant, on the adsorption ability of the boron-doped diamond electrode: Application for voltammetric sensing of Bisphenol A and Hydroquinone in water samples. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 610, 125916. <https://doi.org/10.1016/j.colsurfa.2020.125916>

20. Hou, Y., Liang, Y., Hu, H., Tao, Y., Zhou, J. and Cai, J., 2021. Facile preparation of multi-porous biochar from lotus biomass for methyl orange removal: Kinetics, isotherms, and regeneration studies. *Bioresource Technology*, 329, 124877. <https://doi.org/10.1016/j.biortech.2021.124877>
21. Hu, J., Mi, B., Chen, L., Yuan, Y., Zhang, J. and Wu, F., 2024. An economical preparation strategy of magnetic biochar with high specific surface area for efficient removal of methyl orange. *International Journal of Biological Macromolecules*, 276, 134156. <https://doi.org/10.1016/j.ijbiomac.2024.134156>
22. Husien, S., El-taweel, R.M., Salim, A.I., Fahim, I.S., Said, L.A. and Radwan, A.G., 2022. Review of activated carbon adsorbent material for textile dyes removal: Preparation, and modelling. *Current Opinion in Green and Sustainable Chemistry*, 5, 100325. <https://doi.org/10.1016/j.crgsc.2022.100325>
23. Ihaddaden, S., Aberkane, D., Boukerroui, A. and Robert, D., 2022. Removal of methylene blue (basic dye) by coagulation-flocculation with biomaterials (bentonite and *Opuntia ficus indica*). *Journal of Water Process Engineering*, 49, 102952. <https://doi.org/10.1016/j.jwpe.2022.102952>
24. Islam, T., Repon, M.R., Islam, T., Sarwar, Z. and Rahman, M.M., 2023. Impact of textile dyes on health and ecosystem: A review of structure, causes, and potential solutions. *Environmental Science and Pollution Research*, 30, pp9207-9242. <https://doi.org/10.1007/s11356-022-24398-3>
25. Januário, E.F.D., Vidovix, T.B., Bergamasco, R. and Vieira, A.M.S., 2021. Performance of a hybrid coagulation/flocculation process followed by modified microfiltration membranes for the removal of solophenyl blue dye. *Chemical Engineering and Processing*, 168, 108577. <https://doi.org/10.1016/j.cep.2021.108577>
26. Javadian, S., Ruhi, V., Heydari, A., Asadzadeh Shahr, A., Yousefi, A. and Akbari, J., 2013. Self-assembled CTAB nanostructures in aqueous/ionic liquid systems: effects of hydrogen bonding. *Industrial and Engineering Chemistry Research*, 52, pp4517-4526. <https://doi.org/10.1021/ie302411t>
27. Jia, Y., Ding, L., Ren, P., Zhong, M., Ma, J. and Fan, X., 2020. Performances and mechanism of methyl orange and Congo red adsorbed on the magnetic ion-exchange resin. *Journal of Chemical and Engineering Data*, 65, pp725-736. <https://doi.org/10.1021/acs.jced.9b00951>
28. Kausar, A., Zohra, S.T., Ijaz, S., Iqbal, M., Iqbal, J., Bibi, I., Nouren, S., El Messaoudi, N. and Nazir, A., 2023. Cellulose-based materials and their adsorptive removal efficiency for dyes: A review. *International Journal of Biological Macromolecules*, 224, pp1337-1355. <https://doi.org/10.1016/j.ijbiomac.2022.10.220>
29. Kim, S., Nam, S.N., Jang, A., Jang, M., Park, C.M., Son, A., Her, N., Heo, J. and Yoon, Y., 2022 Review of adsorption–membrane hybrid systems for water and wastewater treatment. *Chemosphere*, 286, 131916. <https://doi.org/10.1016/j.chemosphere.2021.131916>
30. Kosmulski, M., Mączka, E. and Ruchomski, L., 2019. Two types of electrokinetic behavior of solid particles in the presence of anionic surfactants. *Journal of Colloid and Interface Science*, 533, pp34-41. <https://doi.org/10.1016/j.jcis.2018.08.050>

-
31. Kusumlata, Ambade, B., Kumar, A., Gautam, S., 2024. Sustainable Solutions: Reviewing the Future of Textile Dye Contaminant Removal with Emerging Biological Treatments. *Limnological Review*, 24, pp126-149. <https://doi.org/10.3390/limnolrev24020007>
 32. Lee, H., Fiore, S. and Berruti, F., 2024. Adsorption of methyl orange and methylene blue on activated biocarbon derived from birchwood pellets. *Biomass and Bioenergy*, 191, 107446. <https://doi.org/10.1016/j.biombioe.2024.107446>
 33. Liu, L., Chen, Z., Zhang, J., Shan, D., Wu, Y., Bai, L. and Wang, B., 2021. Treatment of industrial dye wastewater and pharmaceutical residue wastewater by advanced oxidation processes and its combination with nanocatalysts: A review. *Journal of Water Process Engineering*, 42, 102122. <https://doi.org/10.1016/j.jwpe.2021.102122>
 34. Liu, W., Ren, D., Wu, J., Wang, Z., Zhang, S., Zhang, X. and Gong, X., 2021. Adsorption behavior of 2, 4-DCP by rice straw biochar modified with CTAB. *Environmental Technology*, 42, pp3797-3806. <https://doi.org/10.1080/09593330.2020.1743367>
 35. Mao, Y., Cai, B., Huang, M., Liu, X., Zhang, W. and Ma, Z., 2023. A sustainable preparation strategy for the nitrogen-doped hierarchical biochar with high surface area for the enhanced removal of organic dye. *Biochar*, 5, 70. <https://doi.org/10.1007/s42773-023-00269-z>
 36. Mathurasa, L. and Damrongsiri, S., 2018. Low cost and easy rice husk modification to efficiently enhance ammonium and nitrate adsorption. *International Journal of Recycling of Organic Waste in Agriculture*, 7, pp143-151. <https://doi.org/10.1007/s40093-018-0200-3>
 37. Mehra, S., Singh, M. and Chadha, P., 2021. Adverse impact of textile dyes on the aquatic environment as well as on human beings. *Toxicology International*, 28, 165. <https://doi.org/10.18311/ti/2021/v28i2/26798>
 38. Naggar, A.H., Seaf-Elnasr, T.A., Thabet, M., El-Monaem, E.M.A., Chong, K.F., Bakr, Z.H., Alsohaimi, I.H., Ali, H.M., El-Nasser, K.S. and Gomaa, H., 2023. A hybrid mesoporous composite of SnO₂ and MgO for adsorption and photocatalytic degradation of anionic dye from a real industrial effluent water. *Environmental Science and Pollution Research*, 30, pp108247-108262. <https://doi.org/10.1007/s11356-023-29649-5>
 39. Osagie, C., Othmani, A., Ghosh, S., Malloum, A., Esfahani, Z.K. and Ahmadi, S., 2021. Dyes adsorption from aqueous media through the nanotechnology: A review. *Journal of Materials Research and Technology*, 14, pp2195-2218. <https://doi.org/10.1016/j.jmrt.2021.07.085>
 40. Panda, S.K., Aggarwal, I., Kumar, H., Prasad, L., Kumar, A., Sharma, A., Vo, D.V.N., Van Thuan, D. and Mishra, V., 2021. Magnetite nanoparticles as sorbents for dye removal: a review. *Environmental Chemistry Letters*, 19, pp2487-2525. <https://doi.org/10.1007/s10311-020-01173-9>
 41. Perez-Calderon, J., Marin-Silva, D.A., Zaritzky, N. and Pinotti, A., 2023. Eco-friendly PVA-chitosan adsorbent films for the removal of azo dye Acid Orange 7: Physical cross-linking, adsorption process, and reuse of the material. *Advanced Industrial and Engineering Polymer Research*, 6, pp239-254. <https://doi.org/10.1016/j.aiepr.2022.12.001>

42. Praveen, S., Jegan, J., Bhagavathi Pushpa, T., Gokulan, R. and Bulgariu, L., 2022. Biochar for removal of dyes in contaminated water: an overview. *Biochar*, 4, 10. <https://doi.org/10.1007/s42773-022-00131-8>
43. Renita, A.A., Vardhan, K.H., Kumar, P.S., Ngueagni, P.T., Abilarasu, A., Nath, S., Kumari, P. and Saravanan, R., 2021. Effective removal of malachite green dye from aqueous solution in hybrid system utilizing agricultural waste as particle electrodes. *Chemosphere*, 273, 129634. <https://doi.org/10.1016/j.chemosphere.2021.129634>
44. Salehi, E., Askari, M., Velashjerdi, M. and Arab, B., 2020. Phosphoric acid-treated spent tea residue biochar for wastewater decoloring: batch adsorption study and process intensification using multivariate data-based optimization. *Chemical Engineering and Processing*, 158, 108170. <https://doi.org/10.1016/j.cep.2020.108170>
45. Singh, A., Pal, D.B., Mohammad, A., Alhazmi, A., Haque, S., Yoon, T., Srivastava, N. and Gupta, V.K., 2022. Biological remediation technologies for dyes and heavy metals in wastewater treatment: New insight. *Bioresource Technology*, 343:126154. <https://doi.org/10.1016/j.biortech.2021.126154>
46. Singha, K., Pandit, P., Maity, S. and Sharma, S.R., 2021. Harmful environmental effects for textile chemical dyeing practice, in: Ibrahim, N., Hussain, C.M. (eds.), *Green chemistry for sustainable textiles*, Elsevier, pp. 153-164.
47. Tran, M.L., 2024. One-step preparation of activated pomelo peel biochar by using H₃PO₄ for removal of methylene blue: performance, isotherm, and kinetic studies. *Biomass Conversion and Biorefinery*, 15, pp1-13. <https://doi.org/10.1007/s13399-024-05848-z>
48. Wang, J. and Guo, X., 2020. Adsorption kinetic models: Physical meanings, applications, and solving methods. *Journal of Hazardous Materials*, 390, 122156. <https://doi.org/10.1016/j.jhazmat.2020.122156>
49. Wang, J. and Wang, S., 2019. Preparation, modification and environmental application of biochar: A review. *Journal of Cleaner Production*, 227, pp1002-1022. <https://doi.org/10.1016/j.jclepro.2019.04.282>
50. Zeng, H., Zeng, H., Zhang, H., Shahab, A., Zhang, K., Lu, Y., Nabi, I., Naseem, F. and Ullah, H., 2021. Efficient adsorption of Cr (VI) from aqueous environments by phosphoric acid activated eucalyptus biochar. *Journal of Cleaner Production*, 286, 124964. <https://doi.org/10.1016/j.jclepro.2020.124964>
51. Zhang, H., Li, R. and Zhang, Z., 2022. A versatile EDTA and chitosan bi-functionalized magnetic bamboo biochar for simultaneous removal of methyl orange and heavy metals from complex wastewater. *Environmental Pollution*, 293, 118517. <https://doi.org/10.1016/j.envpol.2021.118517>
52. Zhang, Y., Chen, J., Wang, Y., Dou, H., Lin, Z., Gao, X., Chen, X. and Guo, M., 2024. Cu₂O/Ag-coated wood-based biochar composites for efficient adsorption/photocatalysis synergistic degradation of high-concentration azo dyes. *Applied Surface Science*, 647, 158985. <https://doi.org/10.1016/j.apsusc.2023.158985>

7. BACKGROUND INFORMATION FOR RECORD (NOT TO BE PRINTED)

Funding: The author did not receive support from any organization for the submitted work.