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Adsorption of bromocresol purple onto combined modified maize husk and maize cob: kinetic and equilibrium studies

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Highlights

- Phosphoric acid-activated maize husk–maize cob (MMH–MMC) adsorbents was developed.
- FTIR confirmed enhanced new surface functional groups post-activation.
- Adsorption capacity increased with contact time and initial BCP concentration.
- Langmuir isotherm ($R^2 = 0.978$) best described equilibrium; maximum capacity was 14.95 mg/g.
- Pseudo-second-order kinetics confirmed chemisorption as the rate-controlling step.

Abstract

This research examined the feasibility of employing a modified maize husk–maize cob (MMH–MMC) adsorbent for the removal of bromocresol purple (BCP) from water in batch adsorption settings. The raw materials were chemically modified with phosphoric acid, and Fourier-transform infrared (FTIR) spectroscopy was employed to characterize the surface functional groups of the raw precursors and modified adsorbents. The effects of operational parameters, including initial dye concentration as function of contact time and adsorbent dosage, were evaluated. The adsorption kinetics were analyzed using the pseudo-first-order, pseudo-second-order, and Elovich models. The pseudo-second-order model offered the best fit, suggesting that it most accurately depicted the adsorption process, even though all kinetic models sufficiently explained the experimental data. Equilibrium data were evaluated through the Langmuir, Freundlich, and Temkin isotherm models. The Langmuir model exhibited the highest concordance with the experimental data, achieving a correlation coefficient (R^2) of 0.978 and a peak adsorption capacity ($q_{\max}$) of 14.95 mg g⁻¹. The findings indicate that the MMH–MMC combined adsorbent is a viable and efficient economical material for extracting bromocresol purple from water solutions.

Keywords: Low-cost material, modified maize husk, modified maize cob, bromocresol purple, adsorption, isotherms, kinetics

1.0 INTRODUCTION

Water is regarded as a universal solvent because it is essential for life. It is an integral part of the ecosystem. It is also indispensable in maintaining ecological stability and supporting the livelihoods of thousands of millions of people. However, rapid industrialization, urban expansion and population growth have resulted in the incessant discharge of insufficient treated wastewater into natural water bodies, leading to serious environmental pollution (Kanu et al., 2011). Industrial effluents often contain numerous contaminants, including acids, hazardous organic and inorganic substances and colorants that can adversely affect water quality (Aljerf, 2018; Kanu et al., 2011). Among the various classes of water contaminants, synthetic dyes are of particular environmental concern because they impart intense colour to receiving water bodies, thereby mitigate light penetration and disrupting photosynthetic activity of aquatic organism. Some of the synthetic dyes, which generate these colours are crystal violet, Congo red (CR), thymol blue (TB), malachite green (MG), methylene blue (MB) and Triphenylmethane (TPM). The latter exhibit different structures, including phenol red (PR) and bromo-based dyes namely bromophenol blue (BPB), bromochlorophenol blue (BCPB), bromocresol blue (BCB), and bromocresol purple (BCP) (Chmelová et al., 2015). BCP comes from TPM family, with relative molecular mass of 540.2 g/mol. BCP is a versatile substance, as it can be used as a pH indicator, a two-colour indicator or a dye (Aljerf, 2018; Rehim et al., 2020). Most BCP in water streams is generated from textile s, pulp and paper, tanneries, and pharmaceuticals. Regardless of their origins, dyes remain visible even in trace amounts (mg/L to $\mu\text{g/L}$), and this can lead to substantial ecological disruption (Aljerf, 2018; Benkhaya et al., 2017; El-dars et al., 2015). Dye utilization has led to considerable environmental pollution owing to their persistent nature and poor biodegradation. The presence of BCP in aquatic environments is undesirable because of its persistence of and potential ecotoxicological impacts. Consequently, the development of efficient, economical and environmentally sustainable technologies for the removal of BCP from wastewater remains a crucial research priority (Agarwala & Mulky, 2023).

Over the past several years, many separation techniques have been utilized in treatment of dye-contaminated wastewater namely filtering, coagulation, advanced oxidation, ozonation, electrochemical oxidation and adsorption (PiasKowsKi et al., 2018). They can be used individually, with each other, or in conjunction with biological processes. Although these separation methods can achieve satisfactory dye removal under specific conditions, many are constrained by a number of issues. For instance, advanced oxidation/reduction processes, may follow ambiguous reaction pathways, leading to the creation of undesirable residual compounds in treated water. Membrane separation entails huge capital and operational expenditures, rendering it financially burdensome. Likewise, ion exchange is comparatively costly and may be less efficient for eliminating specific contaminants. Lastly, coagulation–flocculation presents significant disadvantages, such as the production of substantial quantities of sludge necessitating additional treatment and disposal, as well as its comparatively low efficacy in eliminating acidic dyes from wastewater (Kim et al., 2003; Ndive, 2021). The adsorption process has become one of the most adaptable and efficient techniques owing to its

straightforwardness, efficacy, and ecological sustainability (Aljerf, 2018; Hameed et al., 2008; Lala et al., 2023). Furthermore, the process can be operated effortlessly, and it produces desirable results without requiring sophisticated equipment. These merits have encouraged persistence research into the development of efficient and inexpensive adsorbent materials from renewable resources (Aljerf, 2018; Hameed et al., 2008; Ogidi et al., 2019). According to Agarwala and Mulky (2023), adsorption technique is as widely proven and effective approach to remove colour substance from wastewater. It employs a wide range of abandoned materials, which highly suitable for dye removal from aqueous solutions. These materials serve as separating agents that are capable of taking dye from one phase (liquid medium) to another phase (solid surface). Many waste materials have been used for water purification including clay mineral, chitosan, zeolite, plant-based and industrial wastes, nano-particles and agricultural biomass (Yu and Han, 2015). Before selecting any of these materials as precursor for adsorbent development, other factors that need to put into consideration are renewability, suitability for large-scale wastewater treatment, existence of essential functional groups, and the cost of activation or modification.

In terms of availability and cost, agricultural waste is widely available, and often requires little or no cost of acquisition, making it an economical attractive adsorbent precursor. They are generated throughout all stages of farm operations, including pre-harvesting, harvesting and post-harvesting or processing (Yu and Han, 2015). In addition to these advantages, agricultural wastes are known to be very rich in functional groups such hydroxyl, carboxyl, and amide groups, since they are carbohydrate-based materials, which influence the binding of pollutants to the surface (Bouguettoucha et al., 2016; Sohrabi & Ameri, 2016). Shaq et al. (2023) also explained the favorable physiochemical characteristics of agro-waste make it an excellent adsorbent for wastewater treatment. In accordance with Goncalves *et al.* (2025), various low-cost adsorbents have been explored, and agricultural waste-derived materials have attracted considerable attention due to their renewability and biodegradability.

Among agricultural wastes, maize residues are one of the most abundant lignocellulosic by-products, generated during harvesting and processing (Jayapal and Devi, 2011; Kapoor *et al.*, 2016). In many developing countries, particularly Nigeria, they are often underutilized, openly dumped, or burned, contributing to environmental pollution despite their considerable potential as value-added materials. Following consumption, maize cobs are commonly discarded as waste despite their potential as valuable raw materials for various applications, particularly for the production of low-cost adsorbents. The high carbon content composition make them excellent precursors for adsorbents development (Sangoremi, 2025), and recent scientific interest has focused on valorizing these residues through modern ligno-cellulose biotechnology and wastewater treatment applications (Kapoor *et al.*, 2016).

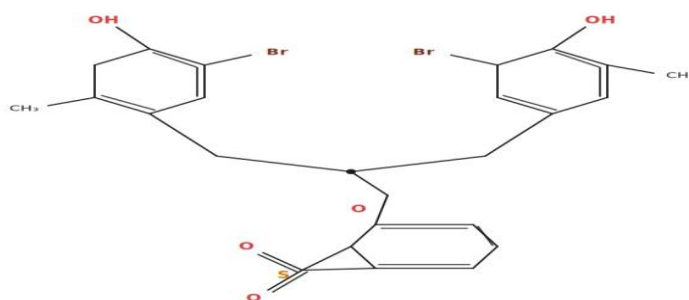
Maize husk and maize cob have been widely used separately as adsorbents for the removal of various dye pollutants from aqueous solutions. Although maize husk and maize cob originate from the same agricultural source, their adsorption performances may differ because of differences in their physiochemical properties. Furthermore, limited attention has been devoted to investigating the synergistic adsorption performance of combined maize husk and maize cob. Although a few studies have investigated the uses of combined adsorbents for several dyes, including chicken feather composites for methylene blue (Adeyi et al., 2024), raw bentonite clay-activated carbon composites for BCP (Ibrahim, 2018), and a bentonite-carbon composites for BCP and MB (El-dars *et al.*, 2015), with no report on the combined use of chemically modified maize husk and maize cob especially for the removal of BCP. Therefore, the present study investigates the possibility of using chemically modified maize husk and maize cob as a composite adsorbent for the removal of bromocresol purple (BCP) from aqueous solution. The effects of physical variables such as initial dye concentration, contact time and

adsorbent dosage have been inspected. Besides, the adsorption equilibrium isotherms and kinetics have been investigated.

2.0 Materials and Method

2.1 Materials

All reagents used in this study, including distilled water, sodium hydroxide (NaOH), and phosphoric acid (H_3PO_4) were supplied by Merck, while BCP dye employed was procured from Sigma-Aldrich, and structurally illustrated in scheme 1.



Scheme 1. Chemical structure of Bromocresol Purple

2.2 Adsorbents collection, Pre-treatment and chemical modification

Maize husk and maize cob were collected from a farm near Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Oyo State, Nigeria. The acquired precursors underwent some steps such as sorting (to remove other materials attached to it) and sample washing (to eliminate adhering dust particles). Subsequently, the samples were sundried for 3 days. Prior to particle size reduction, dried maize husk was cut into smaller sizes using a pair of scissors to reduce risk and ensures smoother operation during size reduction, while maize cob sample was ground with a mortar and pestle. Subsequently, the maize husk and maize were then reduced to small-sized particles with the aid of an electrical blender. The sample particles were sieved using a rotary shaker to obtain a grain size of 250 μm . The samples were thoroughly washed with deionized water and placed in the oven for drying for about 3-4 hr at 50 $^{\circ}\text{C}$, after which it was pre-treated.

One hundred grams (100) g each of the dried maize husk and maize cob were individually submerged in 1000 mL of 1M phosphoric acid (H_3PO_4). The suspensions were agitated for 3-5 minutes to achieve complete wetting and uniform impregnation of the biomass. Thereafter, the samples were left to impregnate at room temperature (25 ± 2 $^{\circ}\text{C}$) for 24 h. At the end of the first impregnation period, the spent phosphoric acid solution was decanted and replaced with afresh 1000 mL 1M phosphoric acid. The impregnation process was then continued for additional 24 hr under the same conditions to enhance the interaction between the lignocellulosic matrixes.

Following impregnation, the modified samples were separated by filtration and washed sequentially with 500 mL of 1 M NaOH solution. The filtrates were separated and residues obtained were dried in the oven 50 $^{\circ}\text{C}$ for 3-4 hr. The chemically modified maize husk and maize cob were stored separately in airtight, opaque plastic containers. The modified maize

husk and modified maize cob were designated as MMH and MMC, and were used as adsorbents for the present study. Characterizing the surface functional groups of the adsorbent is crucial to identify the nature of changes induced by modification and understand their implications for adsorption behaviour. The FTIR spectra of raw and modified adsorbents were obtained using Nicolet 5700 spectrometer with DTGS detector, at a spectral resolution of 4 cm⁻¹ over the wave number range from 4000 to 400 cm⁻¹. Prior to analysis, the equipment was calibrated using a standard polystyrene film and wavenumber accuracy was checked and verified, with deviations kept within ± 1 cm⁻¹.

2.3 Simulation of wastewater containing dye pollutant

The simulated wastewater was prepared in such a way that its composition would closely resemble that of actual dye wastewater. The dye-containing wastewater was prepared through a dissolution approach as follows: BCP-polluted wastewater was simulated by dissolving 1 g of dye in 1 L of distilled water in a well-calibrated standard volumetric flask. The various concentrations of the dye, spanning from 50 to 250 mg L⁻¹, were formulated by diluting the stock solution with distilled water in accordance with the standard procedures outlined by Almadani and Bayda (2019).

2.4 Batch Adsorption

The removal of BCP from simulated dye-containing wastewater by the combination of modified adsorbents was discussed in this section. The experimental conditions were summarized in Table 2. All experiments were executed in duplicate with an allowable experimental error of $\pm 5\%$, and the average value was reported as representative. The experimental procedure followed an established batch adsorption protocol (Akinyemi *et al.*, 2024). Dye solution of known concentrations, pH pre-adjusted using NaOH, were dispensed in 100 mL aliquots of dye into 12 individually well-labelled 150 mL Erlenmeyer flasks used as reaction vessels. Contingent upon the parameter being examined, a specified amount or various specified amounts of modified adsorbents were added to the dye solutions in the corresponding flasks. The flasks were arranged in the BR-23FH bio-shaker, and the agitation speed was set at 180 rpm for a period of 15 minutes. The pH was fixed at constant 5.5 throughout of the experiments.

The parameters varied were: (a) initial dye concentration of the respective dye solution (50-250 mgL⁻¹) with contact time varied 0 to 180 minutes at 15-minutes sampling intervals, using a fixed mass 1.0 g of modified adsorbent (0.5 g of each MMH and MMC) (b) the dosage (mass) of modified (0.2-1.2 g) with a constant initial concentration 100 mg/L, where each dosage was obtained by combining equal masses of MMH and MMC. For each effect studied, at the end of agitation period, the mixtures were allowed to settle for 1 minute before being centrifuged. The supernatant were subsequently filtered using 0.45 μ m filter papers and transfer into sampling bottles prior to UV-Vis spectrophotometric analysis. The bromocresol purple adsorption capacity and removal efficiency (dye uptake) are calculated from the equations 1 and 2, respectively, while eqn. 3 is employed in batch equilibrium study (Agarry *et al.*, 2014).

$$q_t = (c_o - C_t) \frac{v}{m} \quad 1$$

$$R = \frac{c_o - C_e}{c_o} \times 100\% \quad 2$$

$$q_e = (c_o - C_e) \frac{v}{m}$$

3

q_t is the time-dependent form, while q_e is the equilibrium-only form adsorption capacity ; R depicts removal efficiency; C_o , C_t and C_e (mg/L) stand for initial, residual and equilibrium concentrations; v (mL) denotes volume of dye solution and m (g) represents mass of modified adsorbents (MMH and MMC).

Table 1: Summary of experimental conditions for adsorption studies

Parameter	Effect of Dosage	Effect of initial Concentration
Biosorbent dosage (g)	0.2-1.2	1.0
Solution volume (mL)	100	100
Initial concentration (mg/L)	100	50-250
pH	5.5	5.5
Temperature (°C)	25 °C	25 °C
Contact time (min)	0-180	0-180
Agitation (rpm)	180	180
Sampling interval (min)	15	15

2.5 Kinetics and isotherm studies

Kinetic studies reveal whether an adsorption process is governed by chemisorption or physisorption (Melichová and Hromada, 2013), whereas adsorption isotherms describe the behaviours of the system once equilibrium has been reached. Both approaches were applied in fitting the experimental data obtained in this study. The kinetic models considered in this study comprised pseudo-first-order (PFO), pseudo-second-order (PSO) (Ho & McKay, 1999), and Elovich models, while the three isotherm models were analyzed namely Langmuir, Freundlich, and Temkin, and these model exhibit different working principles. The principle of each model is founded on distinct assumptions: the Langmuir model associates maximum adsorption with a saturated monolayer of sorbate molecules on the active sites of the adsorbent surface, Freundlich model posits that heterogeneous adsorption arises from the variety of adsorption sites, whereas the Temkin model accounts for the interaction between the heat of adsorption and the external surface of the adsorbent. The kinetic and isotherm models, along with their corresponding equations, are displayed in Tables 4 and 6. While the closeness between the calculated equilibrium adsorption capacity (q_e cal) and experimental equilibrium adsorption capacity (q_e exp) was considered in comparing determine the PFO and PSO models, the suitability of each model was primarily assessed based on the coefficient of determination (R^2), derived from the linear plots. Since R^2 values range from 0 and 1, values closer to 1 indicate a stronger proximity between the model predictions and the experimental data.

3.0 Results

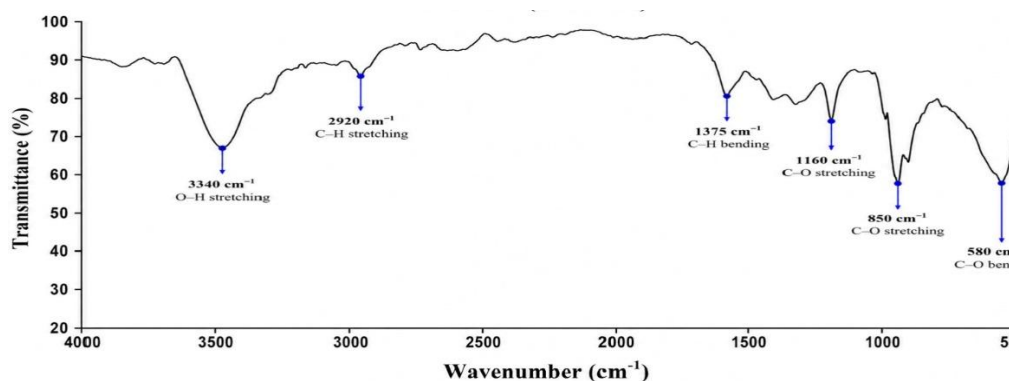
In this section, the key characteristic FTIR peaks of the raw and modified materials are fully discussed to identify the functional groups present and the changes resulting from the modification process. The effects of control variables on the adsorption process are also examined. Furthermore, the adsorption equilibrium isotherms and kinetic models are discussed in detail to elucidate the adsorption behaviour and the underlying mechanisms of the process.

3.1 Surfaces functional groups determination by FTIR analysis

A comparative assessment of the surface chemistry of untreated and modified adsorbents is a fundamental step in adsorption research. FTIR spectroscopy was utilized to identify the functional groups present on the surface of the adsorbents and to monitor changes induced by the modification process. The resulting spectra of untreated and modified maize husk and maize cob are presented in Fig. 2-3. For ease of identification, the FTIR spectra of the raw and modified materials were represented in blue and green, respectively.

3.1.1 FTIR analysis of Maize Husk

The FTIR spectra of maize husk, scanned in the range of $4000\text{--}400\text{ cm}^{-1}$, is illustrated Fig.1. The analysis revealed a few characteristics absorption peaks and functional groups associated with the lignocellulosic structure of the adsorbent. The untreated maize husk displayed a broad absorption band at 3340 cm^{-1} , attributed to the O–H stretching vibration of hydroxyl groups. After being modified, this band remain unchanged. The C–H stretching vibration of aliphatic groups was observed at 2920 cm^{-1} in the untreated sample and shifted slightly to 2921 cm^{-1} after modification, suggesting that the aliphatic carbon framework remained largely intact. A distinct absorption band at 1644 cm^{-1} in the treated maize husk corresponds to C=O stretching of carbonyl groups or absorbed water. This peak reduced in intensity after modification, indicating changes in the carbonyl groups. The CH bending vibration was observed at 1375 cm^{-1} in both samples, suggesting that this functional group was retained after chemical treatment. The C–O stretching band shifted from 1160 cm^{-1} in the untreated maize husk to 1027 cm^{-1} in the modified sample. This change reflects changes in alcohol and ether functional groups. Additionally, the low-frequency C–O bending band shifted from 600 cm^{-1} to 580 cm^{-1} , confirming structural modification of the maize husk. The FTIR analysis revealed the pertinent functional group present on the surface of maize husk, which includes hydroxyl carboxyl, and carbonyl, which could play a major role in the removal of BCP from aqueous solution (Agarry et al., 2014). These functional groups may interact with sorbate active sites either through hydrogen bonding or electrostatic interaction.



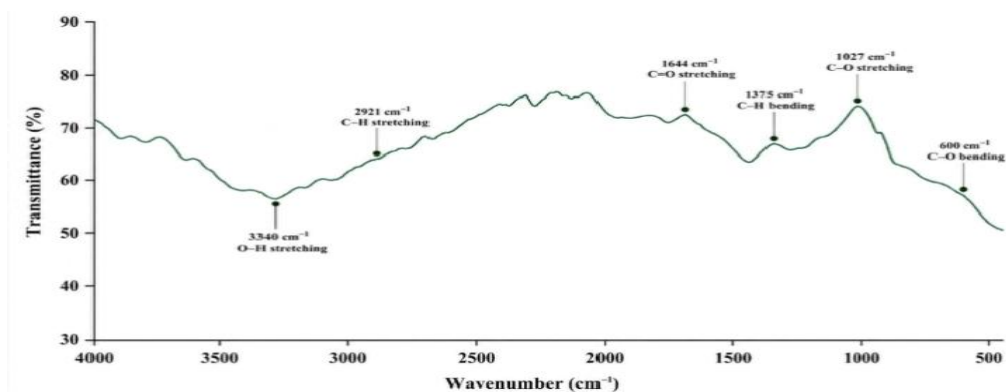
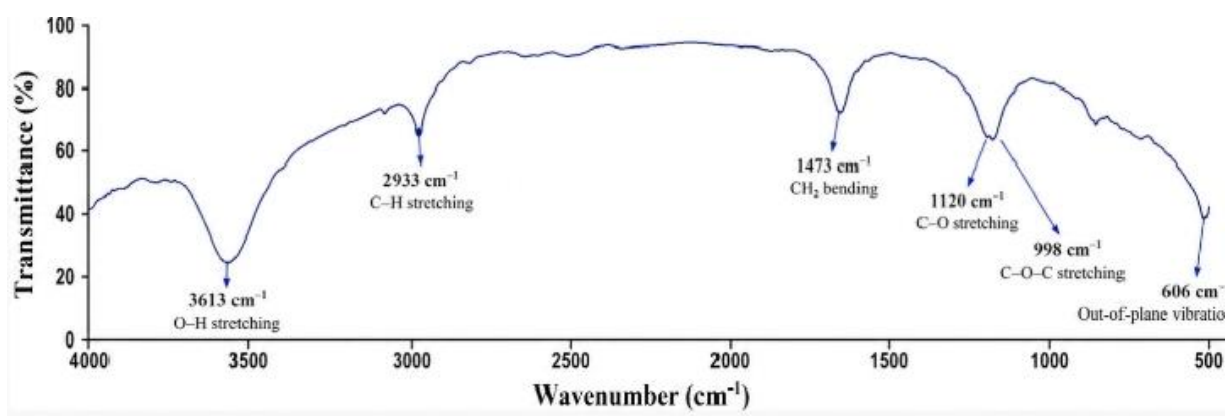


Fig. 1. FTIR spectrum of (a) untreated maize husk and modified maize husk

3.1.2 FTIR analysis of Maize Cob

Fig. 2 depicts the FTIR spectra of maize cob before and after phosphoric acid modification. The observed absorption bands confirm the lignocellulosic nature of the material and reveal structural changes following chemical treatment. A broad absorption band at 3613 cm^{-1} in the untreated maize cob, assigned to O–H stretching of hydroxyl groups in cellulose, hemicellulose, and lignin, shifted to 3340 cm^{-1} after modification. The shift and broadening indicate enhanced hydrogen bonding and changes in the hydroxyl environment due to phosphoric acid treatment. The C–H stretching vibration of aliphatic groups was observed at 2933 cm^{-1} for the untreated sample and 2926 cm^{-1} for the modified sample, suggesting that the hydrocarbon backbone remained unaltered after modification. The CH_2 bending band shifted from 1473 cm^{-1} to 1375 cm^{-1} , indicating partial alteration of lignin and hemicellulose structures. Similarly, the C–O stretching band shifted from 1120 cm^{-1} to 1160 cm^{-1} , reflecting changes in oxygen-containing functional groups, while the C–O–C stretching vibration shifted from 998 cm^{-1} to 850 cm^{-1} , confirming modification of ether linkages within the lignocellulosic matrix. The low-wavenumber band also shifted from 606 cm^{-1} in the untreated sample to 580 cm^{-1} in the modified maize cob, indicating changes in C–O bending vibrations and further confirming structural modification.



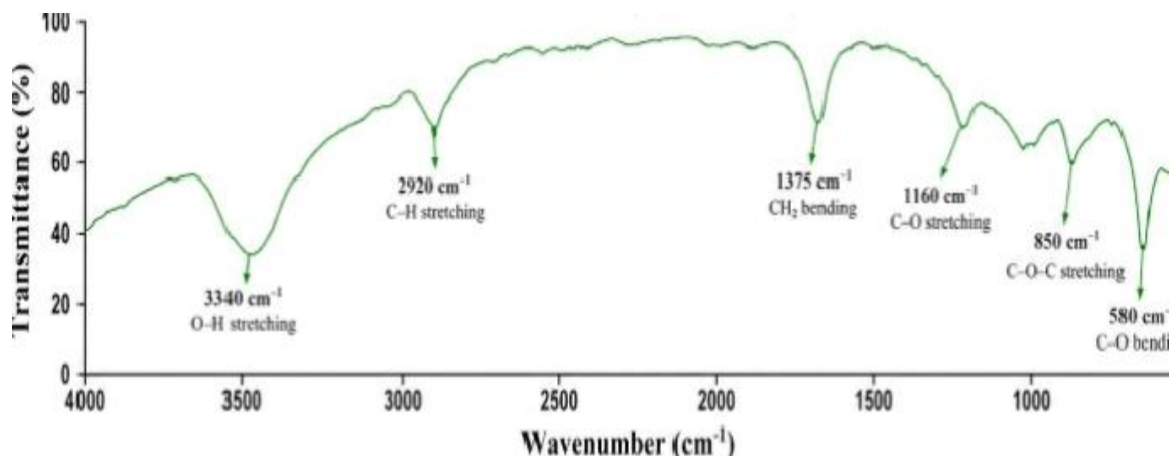


Fig.2. FTIR spectrum of (a) untreated maize cob and (b) treated maize cob

3.1.3 Comparison of FTIR Results for Modified Maize Husk and Modified Maize Cob

The FTIR spectra of maize husk and maize cob revealed that both materials possess the characteristic functional groups of lignocellulosic biomass, including hydroxyl (O–H), aliphatic (C–H), carbonyl (C=O), and ether (C–O–C) groups, which are important for adsorption (Kayranli, 2021). However, phosphoric acid modification affected the two materials differently. For maize husk, the O–H stretching band shifted from 3440 to 3340 cm^{-1} , whereas for maize cob it shifted from 3613 to 3340 cm^{-1} , indicating stronger hydrogen bonding and successful modification in both materials. The C–H stretching vibration showed only slight shifts in maize husk (2921–2926 cm^{-1}) and maize cob (2933–2926 cm^{-1}), suggesting that the aliphatic backbone remained largely unchanged after treatment. A significant distinction is the existence of the 1644 cm^{-1} (C=O stretching) band in maize husk, which is lacking in maize cob, suggesting that maize husk possesses a higher concentration of carbonyl-containing functional groups that could enhance dye adsorption. On the other hand, maize cob exhibited a more pronounced shift in the C–O stretching region (1120–1160 cm^{-1}) and the C–O–C stretching region (998–850 cm^{-1}), suggesting greater modification of ether linkages by phosphoric acid. In summary, both substances were effectively altered, as demonstrated by the changes in their distinctive absorption bands. Conversely, the modified maize husk retained more oxygen-containing functional groups, particularly carbonyl groups, which can provide additional active sites for adsorption. Concurrently, the modified maize cob experienced more significant structural changes in its ether and alcohol groups, indicating a greater degree of chemical activation. The advantageous surface chemistries of the two substances facilitate their joint application as a combine adsorbent for the efficient extraction of bromocresol purple from water solutions.

3.2 Adsorption of BCP onto modified adsorbents

3.2.1 Influence of contact time and initial dye concentration on BCP adsorption

Investigating the effect of contact time as a function of initial dye concentrations is essential in adsorption studies because these parameters determine both the equilibrium contact time and the equilibrium adsorption capacity (q_e). Fig. 3 depicts the adsorption of BCP across

a spectrum of initial concentrations, ranging from 50 to 250 mg/L at a temperature of 298 K as a function of contact duration. As shown in Fig. 3, the adsorption capacity increased with increasing initial dye concentration, whereas a contrary trend was noted in the removal efficiency as concentrations heightened (Fig. 4). As the initial BCP concentration increased from 50 to 250 mg/L, the adsorption uptake of MMH-MMC increased from 4.3 to 12.5 mg/g. This shows that a higher concentration enhances driving force to surmount all the opposition forces of the dye between the aqueous and solid phases (Aljerf, 2018). Olukayode et al. (2025) also explained that at low initial dye concentrations, the high ratio available active sites on the adsorbent to the number of dye molecules present in solution led to a lower adsorption capacity, as the limited number of dye molecules was insufficient to fully use up available sites. Additionally, rapid change in concentrations increase the frequency of collision between dyes ion and the MH-MC facilitates the sorption process. As the initial BCP concentrations progress from 50 to 250 mg/L, the removal efficiency declined from 86 % to 50 % (Fig. 4).

The influence of contact time on the removal of BCP by the modified MMH-MMC at initial concentrations range from 50 to 250 mg/L and at 298 K displayed rapid uptake of dye in the first 15 minutes. At 15 minutes, although the time is short, high percentage removal was observed, and this could be due to high degree of affinity of MMH-MMC for dye molecules pointing towards chemisorption. The adsorption rate diminished progressively, achieving equilibrium at 150 minutes for initial concentrations ranging from 50 to 100 mg/L. In BCP solutions with initial concentrations ranging from 150 to 250 mg/L, equilibrium was achieved after 165 minutes. The equilibrium time indicates there is no further observable change in adsorption uptakes as active sites have become saturated, and no available space for adsorption of BCP on active sites of MH-MC.

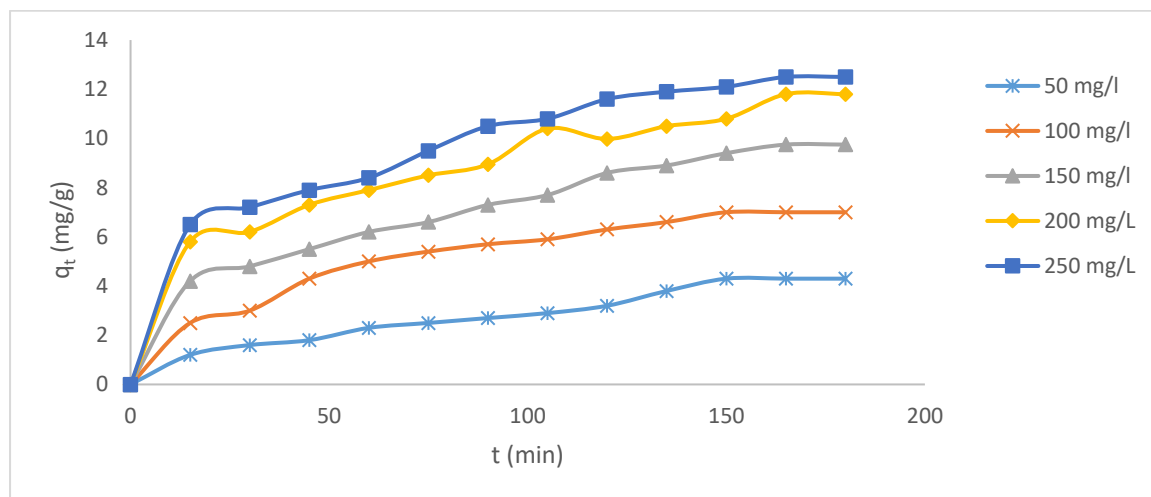


Fig.3. Adsorption uptake as a function contact time with varying initial BCP concentration over adsorption uptake (experimental conditions: adsorbent dosage = 1.0 g; volume =100 mL; $P^H = 5.5$, Temperature =298 K, agitation =180 rpm)

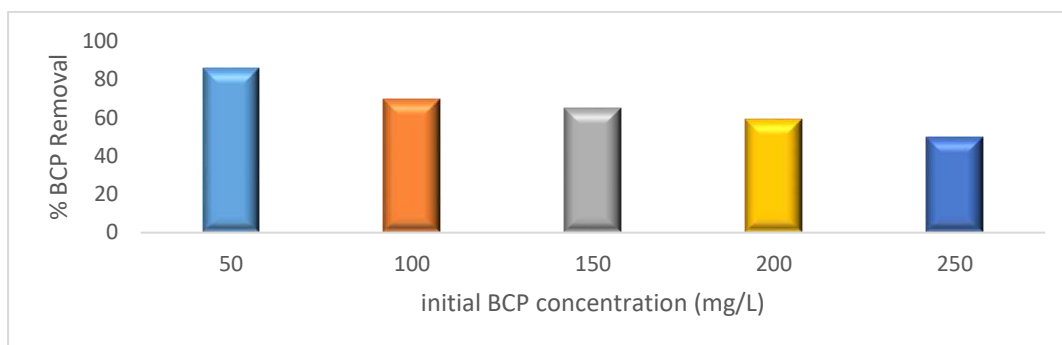


Fig 4. Influence of initial BCP concentration on adsorption uptake (experimental conditions: adsorbent dosage = 1.0 g; volume =100 mL; P^H = 5.5, Temperature =298 K, agitation =180 rpm)

3.2.2 Effect of adsorbent dosage on the removal efficiency of BCP

The variability in BCP removal efficacy relative to adsorbent dosage is depicted in Fig. 5. The percentage of BCP removal efficiency increased from 43.5 % to 84.3 % as the dosage of adsorbent increased from 0.2 g to 1.2 g. this improvement is attributed to the increased surface area and greater availability of active adsorption sites, which enhanced the uptake of BCP molecules (Elijah *et al.*, 2020; Murmu *et al.*, 2018). Furthermore, FTIR analysis confirmed the presence of aromatic C=C groups associated with lignin, indicating that π - π interactions between the aromatic rings of BCP and the aromatic structures of the adsorbent also contributed to adsorption (Camargos *et al.*, 2025). Similar observations have been reported for the adsorption of bromocresol purple using zeolites (Aljerf, 2018) and raw bentonite (Ibrahim, 2018). Comparable dosage-dependent behaviour has also been observed during the adsorption of bromocresol green onto rice husk (Elijah *et al.*, 2020), methylene blue onto pine tree foliage (Yagub *et al.*, 2012), and methylene blue on corncob activated with phosphoric acid (El-sayed *et al.*, 2014). These findings demonstrates that the developed MMH-MMC combined adsorbent exhibits effective adsorption performance and folows adsorption pattern commonly reported for similar adsoebent systems.

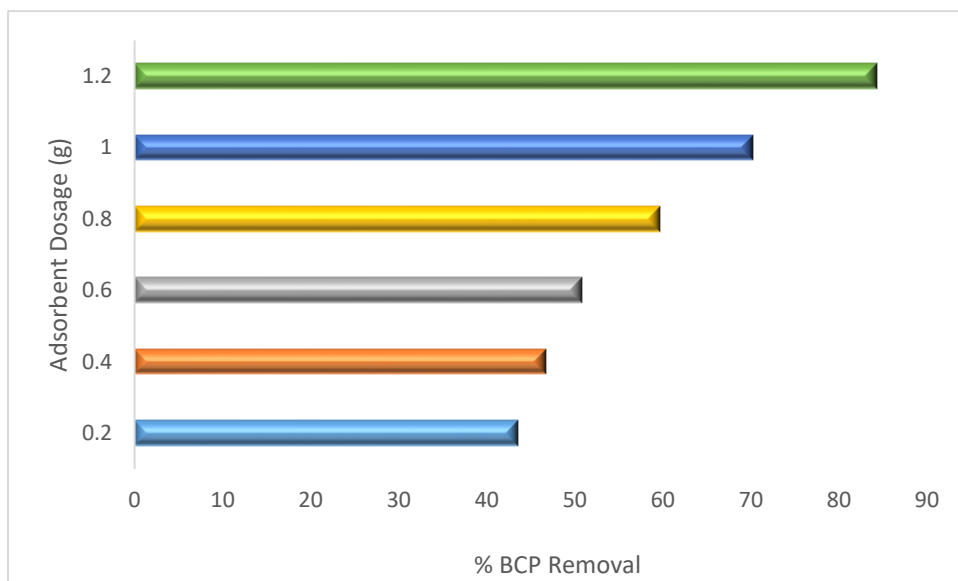


Fig 5. Influence of dosage on percentage removal of BCP (experimental conditions: initial BCP concentration of 100 mg/L; MMH-MMC dosage (0.2-1.2 g); solution volume of 100 mL; PH 5.5; temperature of 25 °C; and shaker speed of 180 rpm)

3.3 Kinetics of adsorption of BCP

Kinetic modelling of experimental adsorption data offers understanding regarding the optimizing the process, velocity of dye molecule elimination from the solution, the time necessary to reach equilibrium, and the mechanistic routes that dictate the adsorption process (Aljerf, 2018; Akinyemi *et al* 2024; Forgacs and Cserha, 2004). Adsorption kinesis is imperative factors for better choice of precursors to be utilized as adsorbent (Amran *et al.*, 2011). The adsorption kinetics of bromocresol purple (BP) onto MMH-MMC combined adsorbent at varying initial concentrations (50-250 mg/L) were analyzed using pseudo-first-order (PFO) pseudo-second-order (PSO) and Elovich kinetic models (Table 4). All kinetic parameters derived from model fitting are displayed in Table 5. In this study, the most appropriate kinetic model was established utilizing combined evaluation criteria combining the highest regression coefficient (R^2), the proximity between the computed equilibrium adsorption capacity q_e (cal) and the experimental adsorption capacity q_e (exp).

3.3.1 Pseudo-first-order and Pseudo-second-order models fittings of adsorption of BCP

The parameters of PFO and PSO are summarized in Table 3. These parameters were evaluated via the plot of linearized expression of the models (Table 2). PFO kinetic parameters were evaluated using linearized plot of $\ln(q_e - q_t)$ (mg/g) versus time (t) (Fig.6). In multiple cases, PFO is chiefly involved at particular points in the adsorption processes, and the model commonly fails to accurately represent the full duration of contact time. Thus, this rationale is insufficient for dismissal and should consistently be evaluated alongside other kinetic models, as numerous elements like the characteristics of the dye, the properties of the adsorbent, the interaction between dye and adsorbent, and the modification mode of the adsorbent contribute to this typical behaviour. The data presented in Table 5 reveals that the correlation coefficients are notably elevated in certain instances (150-250 mg/L), and the computed q_e is consistently

lower than the experimental q_e across the entire contact time spectrum, suggesting that the adsorption of BCP on modified MMH-MMC is unlikely to follow a pseudo-first-order kinetics for the initial concentrations examined. This study is in consistent with the research of (El-dars et al., 2015), Ibrahim (2018), and Tavakkoli et al. (2014) regarding the adsorption of BCP onto alternative adsorbents.

Fig. 7 illustrates the linearized plot of the PSO model (Table 2), while the model parameters are detailed in Table 3. The PSO kinetic parameters, rate constants k_2 and equilibrium adsorption capacity q_e , were evaluated from intercepts and slopes of linear plots, respectively. In the context of pseudo-second-order kinetics, the calculated q_e values closely align with the experimental values, and a regression coefficient exceeding 0.97 demonstrates that the model is applicable to the entire adsorption process, thereby confirming the chemisorption of BCP onto modified MMH-MMC. This indicates that chemisorption governed the adsorption process and served as the rate-limiting step. This indicates that the adsorption process was chiefly influenced by valence interactions involving the exchange of electrons between the dye molecules and the active sites on the adsorbents. This observation coincides with previous investigations (Aljerf, 2018; El-dars *et al.*, 2015; Ibrahim, 2018; Tavakkoli *et al.*, 2014).

Table 2: Kinetic models Model, equations, definition and Parameters

Model	Linear equation	Plot	Definition/Unit	Parameter
Pseudo-first-order	$\ln(q_e - q_t) = \ln q_e - k_1 t$	$\ln(q_e - q_t) \text{ vs } t$	q_t (mg/g):	R^2
			amount adsorbed at time,	K_1
			k_1 (L/min): PFO rate constant	q_e
Pseudo-second-order	$\frac{t}{q_t} = \left(\frac{1}{k_2 \times q_e^2} \right) + \left(\frac{1}{q_e} \times t \right)$	$\frac{t}{q_t} \text{ vs } t$	k_2 (g/mg. min): PSO rate constant	R^2
				K_2
				q_e
Elovich	$q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln(t)$	$q_t \text{ vs } \ln(t)$	α (mg/g. min): initial adsorption rate	R^2
				α
			β = desorption constant	β

Table 3: Kinetic Model parameters evaluated for each initial concentrations for adsorption of BCP onto MH-MC adsorbent

Models/concentration	50 mgL ⁻¹	100 mgL ⁻¹	150 mgL ⁻¹	200 mgL ⁻¹	250 mgL ⁻¹
q_e experimental (mg/g)	4.3	7.0	9.75	11.8	12.5
Pseudo-first-order					
k_1 (min ⁻¹)	0.133	0.1659	0.301	0.1928	0.3341
q_e (Mgg ⁻¹)	2.95	3.29	9.67	6.57	9.68
R^2	0.7042	0.6411	0.9054	0.9276	0.9641
Pseudo-second-order					
k_2 (gmg ⁻¹ min ⁻¹)	0.0029	0.00361	0.0027	0.0039	0.0032
q_e (mgg ⁻¹)	5.40	8.13	11	12.7	13.7
R^2	0.82	0.9594	0.944	0.9629	0.9724
Elovich					
α (mgg ⁻¹ min ⁻¹)	0.36	0.83	1.219	1.7436	1.99
β (mgg ⁻¹)	1.188	0.690	0.52688	0.448	0.41
R^2	0.8215	0.9412	0.938	0.9636	0.973

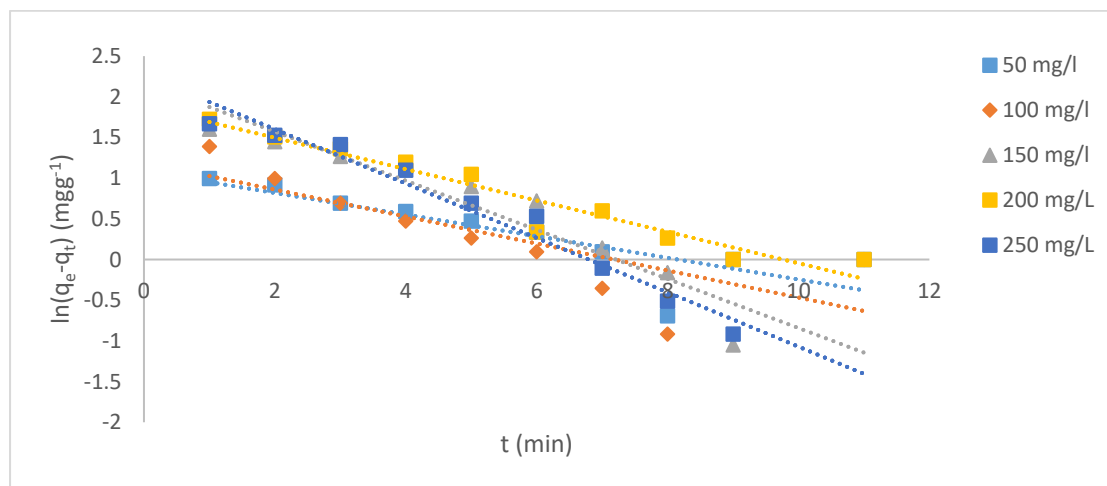


Fig 6. Pseudo-first-order kinetic fitting (experimental settings: biosorbent of mass 1.0 g; 100 mL of solution; P^H 5.5; temperature maintained at 25 °C; and shaker speed of 180 rpm)

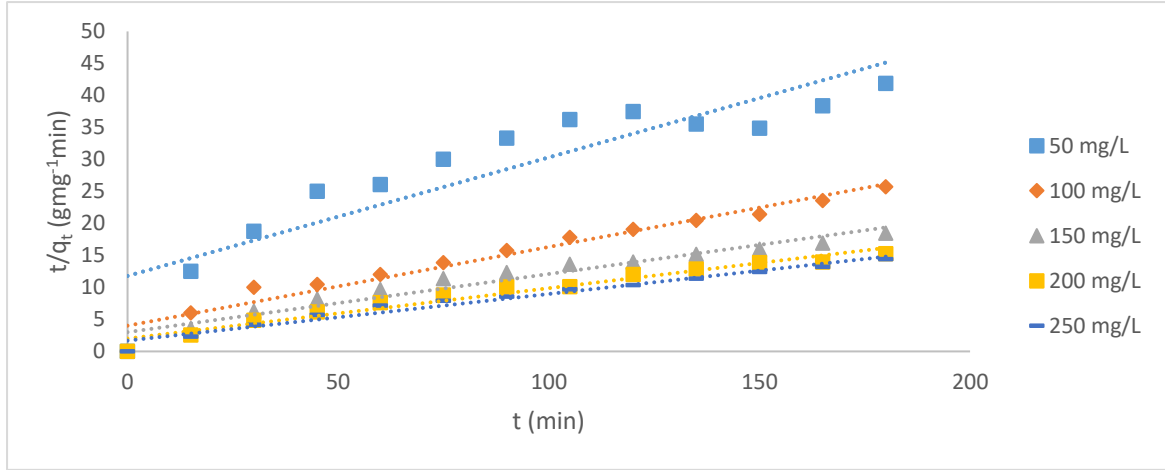


Fig 7. Pseudo-second-order kinetic model plot (experimental settings: adsorbent mass 1.0 g; 100 mL of solution; P^H level of 5.5; temperature maintained at 25 °C; and shaker speed = 180 rpm)

3.3.2 Elovich kinetic model

The Elovich model also showed good fitting performance (Fig. 8), especially at higher concentrations. The parameter α (initial adsorption rate) rose with higher concentrations, signifying a more rapid initial absorption at elevated dye concentrations owing to a more potent mass transfer driving force. Conversely, β decreased as concentration increased, suggesting changes in surface interaction during adsorption (Table 5). The correlation coefficients (R^2) varied from 0.8215 to 0.973, with the maximum value recorded at 200 and 250 mg/L, indicating a favourable with the experimental data. Based on R^2 values, the model agreed with the PSO kinetic model, indicating that film mass-transfer did not play a significant role in the adsorption process and could therefore be neglected. Consequently, the adsorption of BCP onto MMH-MMC was controlled by chemisorption.

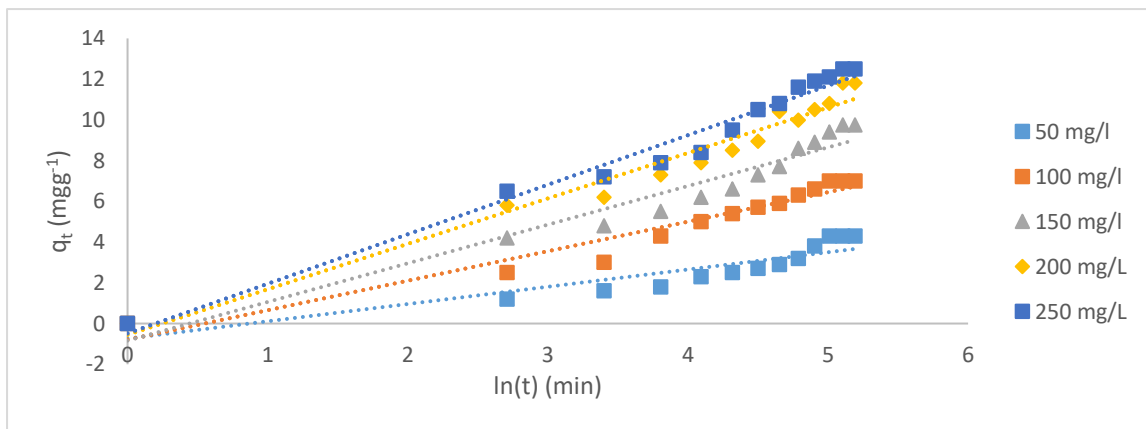


Fig 8. Elovich kinetic model fitting (experimental settings: adsorbent of mass 1.0 g , 100 mL of solutions; P^H level of 5.5; temperature maintained at 25 °C; and shaker velocity of 180 rpm)

3.4 Adsorption Isotherms of bromocresol purple

To further elucidate the equilibrium behaviours of the adsorption process, the experimental data were fitted to three widely applied isotherm models: Langmuir, Freundlich and Temkin. The linearized equation of each model were plotted, and the values obtained through comparison with equations are presented in Table 4, while fig. 11-13 show the isotherms. These parameters are important for optimizing batch adsorption process design and performance.

Figure 9 shows a straight line graph of C_e/q_e versus C_e , indicating adsorption following the Langmuir model. Table 6 displays the values of the Langmuir parameters $q_{\max}$ and K_L , which were computed using the plot's slope and intercept, respectively. The values of R_L depend on the initial concentration (C_0) and Langmuir constant (k_L), and was found to be between 0.088 and 0.327 as shown in Table 4, this implies that BCP is effectively and favorably adsorbed onto MMH-MMC. The reduced values R_L were noted at elevated beginning concentrations, suggesting that adsorption became increasingly advantageous with rising initial dye concentration (Kamga, 2019). This result also indicates the feasibility of using these materials for the removal of BCP dye. The standard adsorption process to occur when R_L value is between 0 and 1. In this study R_L values fell within this favourable range across all initial concentrations tested, confirming that the adsorption of BCP onto MMH-MMC was favourable rather than irreversible or unfavorable.

Moreover, the Langmuir isotherm predicted a maximum adsorption capacity that was marginally higher than the experimentally obtained q_e value, while the correlation coefficient ($R^2 = 0.9779$) demonstrated a strong fit, indicating that the model suitably represents the adsorption system. The exceptional concordance of the Langmuir isotherm with the empirical findings can be attributed to the even distribution of minuscule active sites on the MH-MC surface, as the Langmuir equation presupposes a uniform surface. The best fit affirms the monolayer coverage of BCP onto MMH-MMC particles.

The linear relationship between $\ln q_e$ and $\ln C_e$ is depicted in Fig. 10. The values of parameters K_f and n evaluated from the slope and the intercept, respectively, are presented in Table 6. The value of n was greater than 1 ($1/n$ value for MMH-MMC is 0.39) (Table 4). Based on this, there is a strong indication that the adsorption of BCP onto MMH-MMC is favourable, and modified adsorbent (MMH-MMC) is feasible for the adsorption process. Also, in terms of correlation coefficients, the high R^2 (0.9773) value suggests that the adsorption process follows the Freundlich isotherm model. However, when compared with the value obtained from the Langmuir model, the Langmuir model demonstrated a high regression coefficient, signifying a more accurate alignment compared to the experimental data.

Fig. 11 illustrates the linear representation of the Temkin model. The parameters b_T and K_T were evaluated from the slope and intercept of the linearized form of Eqn. 8. The Temkin parameters indicate that the adsorption of BCP onto the biosorbent was favorable, as reflected by the relatively high binding constant A , which suggests appreciable adsorbate-adsorbent affinity and the regression coefficient $R^2 = 0.944$. The low value of B indicates low heat of adsorption, which implies that the adsorption may be predominantly physical in nature. The low value of B , which corresponds to heat of adsorption, was low due to temperature at which the experiment was carried out.

Table 4: isotherm models and their evaluated parameters for the sorption of BCP

Model	Linear equation	Plot	Definition/Unit	Parameter	Value
Langmuir	$\frac{C_e}{q_e} = \frac{1}{q_{max}k_L} + \frac{C_e}{q_{max}}$	$\frac{C_e}{q_e} \text{ vs } C_e$	K_L (L/mg): Langmuir constant q_{max} (mg/g): Maximum adsorption	R^2	0.9779
				K_L	0.041
				q_{max}	14.95
Freundlich	$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e$	$\ln q_e \text{ vs } \ln C_e$	K_f (L mg ⁻¹) ^{1/n} : Freundlich constants n: heterogeneity factor	R^2	0.9777
				k_f	1.972
				1/n	2.52
Temkin	$q_e = \frac{RT}{b_T} \ln(A) + \frac{RT}{b_T} \ln C_e$	$q_e \text{ vs } \ln C_e$	B_T (kJmol ⁻¹): sorption energy variation K_T (L/mg): sorption potential	R^2	0.9440
				b_T	0.312
				K_T	7940.93

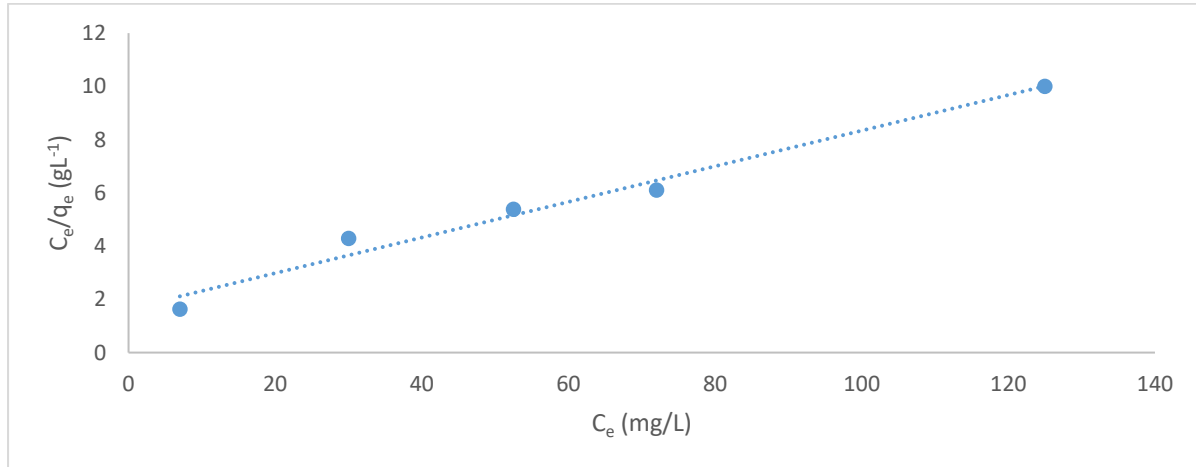


Fig. 9. The Langmuir isotherm plot (experimental settings: adsorbent of mass 1.0 g; 100 mL of solution; P^H level of 5.5; temperature maintained at 25 °C; and shaker rate of 180 rpm)

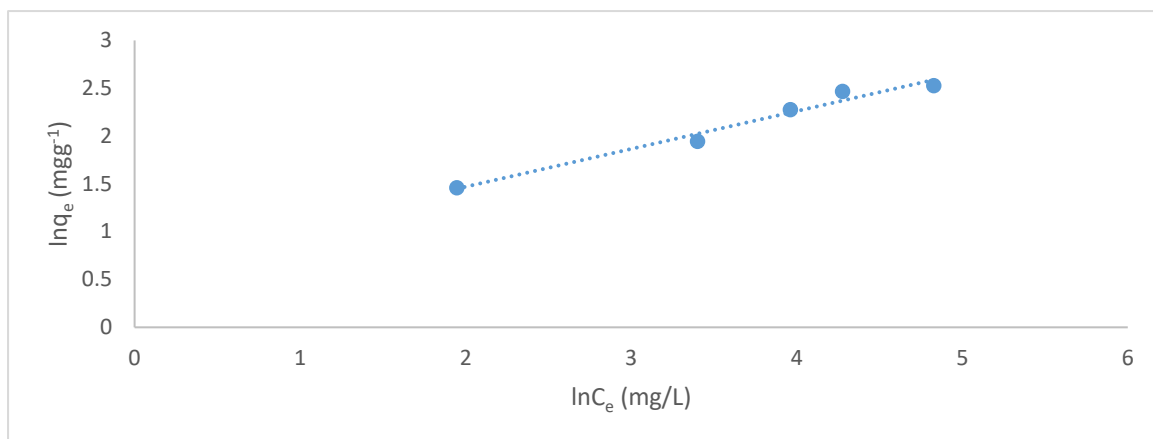


Fig. 10 The plot of the Freundlich isotherm (experimental settings: 1.0 g of adsorbent; 100 mL of solution; pH level of 5.5; temperature maintained at 25 °C; and shaker velocity of 180 rpm).

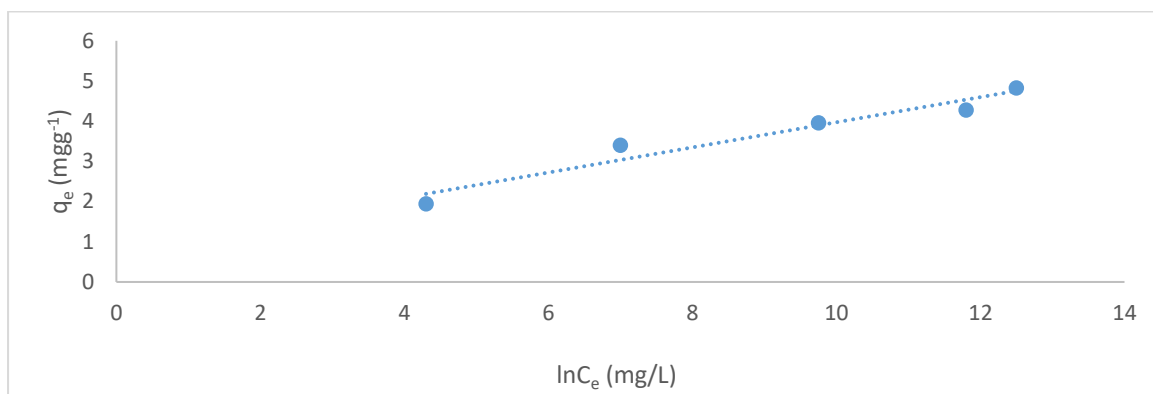


Fig. 11. The Temkin isotherm plot (experimental settings: adsorbent of mass 1.0 g; 100 mL of solution; P^H level of 5.5; temperature of 25 °C; and shaker speed of 180 rpm)

3.5 Comparison of Maximum adsorption capacity of sorption of BCP dye onto MMH and MMC with previous studies based on adsorbents and related dye

The adsorption capacity ($q_{\max}$) derived from the isotherm model is a widely accepted indicator for benchmarking the performance of newly developed adsorbents against materials reported in the literature. In the present study, the H₃PO₄-activated maize husk–maize cob (MMH-MMC) combined adsorbent achieved a $q_{\max}$ of 14.95 mg g⁻¹ for bromocresol purple (BCP) removal under the experimental conditions of p^H 5.5, temperature 298 K, and adsorbent dose of 1.0 g. Table 5 presents a comparative summary of this value alongside those reported for related adsorbents and structurally analogous dyes in published literature.

Among adsorbents investigate specifically for BCP removal, the MMH-MMC biosorbent developed in this study (14.95 mg g⁻¹) substantially outperformed both raw attapulgite (4.99 mg g⁻¹) and thermally activated bentonite (0.03 mg g⁻¹). Thermally activated bentonite's incredibly low adsorption capacity indicates that thermal activation by itself is less efficient in producing the surface functional groups needed for effective BCP adsorption. On the other hand, H₃PO₄ activation enhances pore development and encourages the formation of

phosphate-containing functional groups, which improves dye-adsorbent interactions. Similarly, the adsorption capacity of the developed MMH-MMC adsorbent is approximately three times higher than that of raw attapulgite, demonstrating the effectiveness of phosphoric acid modification.

The highest adsorption capacity reported for BCP adsorption was 175.5 mg g⁻¹, achieved using a clinoptilolite-solid waste (CL-SW) composite Aljerf (2018). However, this value was obtained using an adsorbent dose of 60.4 g, approximately sixty times higher than the 1.0 g employed in the present study. Furthermore, the preparation of the CL-SW composite involves mineral processing and blending with solid waste, making it more resource-intensive than the simple phosphoric acid activation employed in this work. Consequently, although the adsorption capacity of CL-SW is considerably higher, the present MMH-MMC adsorbent offers a simpler, more economical, and potentially more sustainable alternative for BCP removal.

Comparison with adsorbents investigated for structurally related sulfonated dyes further demonstrates the performance of the developed adsorbent. For bromocresol green (BCG), Murmu et al. (2018) reported 25 mmol g⁻¹ using H₂SO₄-activated *Phragmites karka*. Although the adsorption capacity of the H₃PO₄-activated MMH-MMC adsorbent (14.95 mg g⁻¹) is lower than this value, phosphoric acid activation is generally preferred for lignocellulosic materials because of its lower corrosivity, safer handling characteristics, and ability to introduce phosphate functional groups that enhance dye adsorption (Singh et al., 2011).

A particularly relevant comparison is with raw maize husk, which exhibited an adsorption capacity of 16.077 mg g⁻¹ for methylene blue (Pezhhanfar et al., 2021). The adsorption capacity obtained in the present study (14.95 mg g⁻¹) for the relatively larger and more structurally complex BCP molecule is therefore highly competitive. This observation suggests that phosphoric acid activation effectively enhances the surface properties of the MMH-MMC adsorbent, generating sufficient active sites to overcome the steric limitations associated with larger dye molecules.

Overall, although the maximum adsorption capacity of the developed MMH-MMC adsorbent is moderate compared with some highly engineered adsorbents, the present study demonstrates that simple phosphoric acid activation of abundant maize husk and maize cob can produce an effective, low-cost, environmentally sustainable, and practically scalable adsorbent for BCP removal from wastewater without the need for energy-intensive activation processes.

Table 5. Comparison of maximum adsorption capacity of the developed MMH-MMC adsorbent with other adsorbents reported for dye removal

Adsorbent	Method of activation	Dye	Temperature (K)	P ^H	Adsorbent dose (g)	q _m (mgg ⁻¹)	Reference
MMH-MMC	Chemical activation	BCP	298	5.5	1.0	14.95	This study
Attapulgite surface	Raw	BCP	298	-	0.8	4.99	(Jadoo <i>et al.</i> , 2025)
Bentonite	Thermal activation	BCP	313	-	0.2	0.03	(El-dars <i>et al.</i> , 2015)
Clinoptilolite and solid waste (CL-SW)	Raw/minimal	BCP	298	6.5	60.4	175.5	(Aljerf, 2018)

Maize husk	Raw	MB	RT	6.5	0.7	16.077	Pezhhanfar et al., (2021)
<i>Phragmites karka</i>	Chemical activation by sulphuric acid	BCG	303	0.5	0.1	25 mmolg ⁻¹	(Murmu et al., 2018)

BCP=Bromocresol purple; BCG= Bromocresol green; BPB=bromophenol Blue; MB= Methylene blue; RT= Room Temperature; - = not reported; **Highlight row= present study**

4. Discussion

The FTIR results confirm that phosphoric acid activation induced significant modifications to the surface chemistry of both maize husk and maize cob. The formation of new peaks and shifts in existing bands, particularly in the O–H and C–O regions, indicate the creation of new active functional sites on the adsorbent surface (Foo and Hameed, 2010). These modifications are consistent with the known mechanism of phosphoric acid activation, which promotes dehydration and condensation reactions in lignocellulosic materials, enhancing pore development and surface functionality (Chukwuemeka et al., 2021).

The observed increase in adsorption capacity with rising initial BCP concentration is consistent with the driving force hypothesis: higher concentrations reduce the energy barrier for mass transfer from solution to adsorbent, thereby enhancing adsorption (Hameed & Ahmad, 2009). The plateau behaviour observed at equilibrium at 150 min and 165 min indicates saturation of available adsorption sites, a pattern widely reported for adsorbent-dye systems (Aljerf, 2018; El-dars et al., 2015; Tavakkoli et al., 2014). The decreasing percentage removal at higher initial concentrations reflects competitive site occupation and eventual surface saturation, a thermodynamically expected outcome in fixed-dosage systems.

The superior fit of the Langmuir isotherm ($R^2 = 0.978$) compared to Freundlich ($R^2 = 0.977$) and Temkin ($R^2 = 0.944$) suggests that BCP adsorption onto MMH–MMC primarily occurs through monolayer coverage on homogeneously distributed active sites. The R_L values (0.088–0.327) confirm favourable adsorption behaviour across all tested initial concentrations (Kamga, 2019). The maximum adsorption capacity of 14.95 mg/g, while modest relative to activated carbon-based adsorbents, compares favourably with other low-cost biosorbents reported for BCP removal. The low value of B_T in the Temkin model suggests physisorption plays a contributing role alongside chemisorption.

The kinetic analysis conclusively identifies the PSO model as the most appropriate descriptor of BCP adsorption onto MMH–MMC, with the model's predicted q_e values closely matching experimental observations. The PSO model implies that chemisorption is the rate-limiting step, involving electron sharing or exchange between BCP molecules and active surface functional groups on MMH–MMC (Ho & McKay, 1999). This aligns mechanistically with the FTIR findings of O–H and C–O functional groups that can establish hydrogen bonds and coordinate interactions with the polar and ionic components of BCP. The Elovich model's good fit at higher concentrations ($R^2 = 0.973$ at 250 mg/L) suggests that at elevated BCP concentrations, multi-layer adsorption and increasing site heterogeneity become more prominent (Sev, 2024). The kinetic ranking (PSO > Elovich > PFO) is consistent with previous studies on BCP removal (Aljerf, 2018; El-dars et al., 2015; Tavakkoli et al., 2014).

The dosage-dependent increase in removal efficiency (43.5–84.3%) reflects the expected relationship between biosorbent mass, total surface area, and number of available

active sites (Elijah et al., 2020; Murmu et al., 2018). The observed levelling off at higher dosages is a common feature in batch adsorption systems where excess adsorbent leads to particle aggregation, reducing effective surface area (Hameed & Ahmad, 2009).

Overall, the MMH–MMC adsorbents demonstrates meaningful adsorption capability for BCP from simulated wastewater. The synergistic combination of maize husk and maize cob in a single composite matrix leverages the complementary lignocellulosic properties of both materials. Future work should investigate thermodynamic parameters, explore the performance in real industrial effluents, and assess regeneration/reusability cycles to establish practical feasibility.

5. Conclusions

This research illustrated the effective creation and utilisation of phosphoric acid-activated maize husk–maize cob (MMH–MMC) adsorbents for the extraction of bromocresol purple (BCP) from water. The results revealed the following key findings:

- FTIR spectroscopy demonstrated the formation and restructuring of new surface functional groups due to phosphoric acid activation.
- Adsorption capacity improved with increased contact time, reaching equilibrium at 150–165 minutes, and with higher initial BCP concentrations (4.3–12.5 mg/g for 50–250 mg/L). Removal efficiency also increased with greater adsorbent dosage, ranging from 43.5% to 84.3% over 0.2 to 1.2 grams.
- The Langmuir isotherm model accurately predicted the equilibrium data ($R^2 = 0.978$), with a maximum adsorption capacity of 14.95 mg/g and RL values ranging from 0.088 to 0.327, indicating favourable adsorption conditions.
- The pseudo-second-order kinetic model effectively characterized the adsorption kinetics.
- The MMH–MMC combined adsorbent offers a viable, economical, and eco-friendly solution for the extraction of dyes from wastewater, aiding in the utilization of plentiful agro-industrial by-products.

Ethics Statement

This study did not involve human participants, animal subjects, or any data requiring ethical approval. All experiments were conducted with commercially available and field-collected plant materials in accordance with standard laboratory practices.

Declaration of Competing Interests

The authors proclaim the absence of any financial or personal interests that might have swayed the findings discussed in this paper.

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Data Availability Statement

The data underpinning the outcomes of this investigation can be requested from the corresponding author under reasonable conditions.

References

- Adeyi, V. A., Agarry, S. E., Akinjobi, T. A., 5 Agboola, T. T., Afolabi, T. J., And Alade, A. O. . (2024). Corresponding Author E-mail: *LAUTECH Journal of Civil and Environmental Studies*, 13(01), 11–25. <https://doi.org/10.36108/laujoces/4202.31.0120>
- Agarwala, R., & Mulky, L. (2023). *Adsorption of Dyes from Wastewater : A Comprehensive Review*. 3, 326–335. <https://doi.org/10.1002/cben.202200011>
- Aljerf, L. (2018). *High-efficiency extraction of bromocresol purple dye and heavy metals as chromium from industrial effluent by adsorption onto a modified surface of zeolite : Kinetics and equilibrium study*. 225(April), 120–132. <https://doi.org/10.1016/j.jenvman.2018.07.048>
- Almadani, E. A., & Bayda, A. (2019). *KINETIC STUDY OF THE ADSORPTION OF THE REMOVAL OF*. 7(December), 144–149. <https://doi.org/10.5281/zenodo.3597637>

- Amran, M., Salleh, M., Khalid, D., Azlina, W., Abdul, W., & Idris, A. (2011). *Cationic and anionic dye adsorption by agricultural solid wastes : A comprehensive review*. 280, 1–13. <https://doi.org/10.1016/j.desal.2011.07.019>
- Azeez G. Akinyemi, Abass O. Alade, A. O. A., & Olabiyi, S. B. (2024). Kinetics Analysis of Crystal Violet Adsorption from Aqueous Solution onto Flamboyant Pod Biochar. *Journal of the Turkish Chemical Society*, 7, 105–122.
- Benkhaya, S., Harfi, S. El, & Harfi, A. El. (2017). *Classifications , properties and applications of textile dyes : A review*. 3, 311–320.
- Bouguettoucha, A., Reffas, A., Chebli, D., Mekhalif, T., & Amrane, A. (2016). *Novel activated carbon prepared from an agricultural waste , Stipa tenacissima , based on ZnCl₂ activation — characterization and application to the removal of methylene blue*. 3994(February). <https://doi.org/10.1080/19443994.2015.1137231>
- Camargos, C. H. M., Yang, L., Jackson, J. C., Tanganini, I. C., Francisco, K. R., Ceccantonini, S. R., Rezende, C. A., & Faria, A. F. (2025). Lignin and Nanolignin : Next-Generation Sustainable Materials for Water Treatment [Review-article]. *ACS Applied Bio Materials*, 8, 2632–2673. <https://doi.org/10.1021/acsabm.4c01563>
- Chmelová, D., & Č, M. O. (2015). *EFFECT OF METAL IONS ON TRIPHENYLMETHANE DYE DECOLORIZATION BY LACCASE FROM TRAMETES VERSICOLOR*. 2, 191–200. <https://doi.org/10.1515/nbec-2015-0026>
- Chukwuemeka, J. M., Nwabanne, J. T., & Ugonabo, V. I. (2021). *Response Surface Optimization of Corn Husk Fiber Mercerization Using NaOH*. 20(3), 62–82. <https://doi.org/10.9734/JERR/2021/v20i317284>
- El-dars, F. M. S. E., Ibrahim, H. M., Farag, H. A. B., Abdelwahhab, M. Z., & Shalabi, M. E. H. (2015). *Using bentonite carbon composite material for adsorption of bromocresol purple and methylene blue*. 6(10).
- El-sayed, G. O., Yehia, M. M., & Asaad, A. A. (2014). Assessment of activated carbon prepared from corncob by chemical activation with phosphoric acid. *Water Resources and Industry*, 7–8, 66–75. <https://doi.org/10.1016/j.wri.2014.10.001>
- Elijah, O. C., Collins, O. N., Obumneme, O. C., & Jessica, N. (2020). *Application of Modified Agricultural Waste in the Adsorption of Bromocresol Green Dye*. 7(1), 15–24. <https://doi.org/10.9734/AJOCS/2020/v7i119011>
- Foo, K. Y., & Hameed, B. H. (2010). *Insights into the modeling of adsorption isotherm systems*. 156, 2–10. <https://doi.org/10.1016/j.cej.2009.09.013>
- Forgacs, E., & Cserha, T. (2004). *Removal of synthetic dyes from wastewaters : a review*. <https://doi.org/10.1016/j.envint.2004.02.001>
- Hameed, B. H., & Ahmad, A. A. (2009). *Batch adsorption of methylene blue from aqueous solution by garlic peel , an agricultural waste biomass*. 164, 870–875. <https://doi.org/10.1016/j.jhazmat.2008.08.084>
- Hameed, B. H., Mahmoud, D. K., & Ahmad, A. L. (2008). *Sorption equilibrium and kinetics of basic dye from aqueous solution using banana stalk waste*. 158, 499–506.

<https://doi.org/10.1016/j.jhazmat.2008.01.098>

- Ho, Y. S., & McKay, G. (1999). *Pseudo-second order model for sorption processes*. 34, 451–465.
- Ibrahim, M. B. (2018). *KINETICS AND THERMODYNAMICS STUDIES FOR THE REMOVAL OF BROMOCRESOL PURPLE USING RAW BENTONITE CLAY AND ACTIVATED CARBON FROM Vachellia achellia nilotica POD AS ADSORBENTS* * Rukayya Abdulganiyu Abdul. 11(1), 17–26.
- Ishaq, M., Chippa, R. C., Sharma, A., & Ali, G. (2023). *Agro-Waste as a Potential Source for the Development of Adsorbents in Water and Wastewater Treatment*. 10(6), 10–18.
- Jadoo, S. A., Sadiq, K. A., Zaki, A. N., Jamur, J. M. S., & Jassim, S. (2025). *Adsorption of Bromocresol Purple Dye from Aqueous Solutions onto Attapulgite Surface*. 29(12), 2457–2467. <https://doi.org/12.1579/Rjce.31.01.2026.01>
- Jiwan Singh, a N. S. Mishra, a Uma, b Sushmita Banerjee, c and Y. C. S. b. (2011). *Comparative studies of physical characteristics of raw and modified sawdust for their use as adsorbents for removal of acid dye*. 6, 2732–2743.
- Kamga, F. T. (2019). Modeling adsorption mechanism of paraquat onto Ayous (Triplochiton scleroxylon) wood sawdust. *Applied Water Science*, 9(1), 1–7. <https://doi.org/10.1007/s13201-018-0879-3>
- KANU, IJEOMA and ACHI, O. K. (2011). *INDUSTRIAL EFFLUENTS AND THEIR IMPACT ON WATER QUALITY OF*. 1(1), 75–86.
- Kayranli, B. (2021). Journal of King Saud University – Science Mechanism of interaction and removal of zinc with lignocellulosic adsorbents , closing the cycle with a soil conditioner. *Journal of King Saud University - Science*, 33(8), 101607. <https://doi.org/10.1016/j.jksus.2021.101607>
- Kim, S., Park, C., Lee, J., & Kim, S. (2003). *COD Reduction and Decolorization of Textile Effluent Using a Combined Process*. 95(1), 102–105.
- Krzysztof PiasKowsKi, renata ŚwidorsKa-dąbrowsKa, and P. K. zarzycKi, & Koszalin. (2018). *Dye Removal from Water and Wastewater Using Various Physical, Chemical, and Biological Processes*. 10, 1371–1384.
- Lala, M. A., Olomowewe, Z. O., & Tirimisiyu, A. (2023). Maize cob-derived activated carbon as an adsorbent for the removal of nickel (II) cation from aqueous solution : optimization and kinetic studies. *Arab Journal of Basic and Applied Sciences*, 30(1), 573–582. <https://doi.org/10.1080/25765299.2023.2266230>
- Melichová, Z., & Hromada, L. (2013). *Adsorption of Pb 2 + and Cu 2 + Ions from Aqueous Solutions on Natural Bentonite*. 22(2), 457–464.
- Murmu, B. M., Behera, S. S., Das, S., Mohapatra, R. K., Bindhani, B. K., & Parhi, P. K. (2018). *Extensive investigation on the study for the adsorption of Bromocresol Green (BCG) dye using activated Phragmites karka*. 25(September), 409–420.
- Ndive, J. N. (2021). *Investigation of the Adsorption Potentials of an Organic Adsorbent for*

- Phenol Removal from Aqueous Solution*. 20(5), 124–134.
<https://doi.org/10.9734/JERR/2021/v20i517318>
- Ogidi, O. I., Okereke, J. N., & Anyalogbu, E. A. (2019). *Effectiveness of Composites of Corn Cobs , Coconut Husks and Breadfruit Peels in Purifying Selected Paint Effluents*. VI(X), 236–248.
- Pezhhanfar, S., Zarei, M., & Shekaari, T. (2021). Introduction of maize cob and husk for wastewater treatment ; evaluation of isotherms and artificial neural network modeling. *Journal of the Iranian Chemical Society*. <https://doi.org/10.1007/s13738-021-02301-0>
- Rehimi, Z., Ayadi, H., & Halladja, S. (2020). *Synthesis and characterization of Fe₃O₄ – MWCNTs adsorbent : application for bromocresol purple dye removal in aqueous medium*. 10, 31–37.
- S. E. Agarry a, O. O. O. a & O. A. A. a a. (2014). *Biosorptive Removal of Cadmium (II) Ions From Aqueous Solution by Chemically Modified Onion Skin : Batch Equilibrium , Kinetic and Thermodynamic Studies*. December, 37–41.
<https://doi.org/10.1080/00986445.2013.863187>
- Sev, F. (2024). *Investigation of Adsorption Capacity , Kinetics and Thermodynamics in The Removal of Textile Dye in Wastewater*.
- Sohrabi, H., & Ameri, E. (2016). *Adsorption equilibrium , kinetics , and thermodynamics assessment of the removal of the reactive red 141 dye using sesame waste*. 57, 19443994. <https://doi.org/10.1080/19443994.2015.1087345>
- Tavakkoli, H., Ghaemi, A., & Mostofizadeh, M. (2014). *Full Length Research Paper Synthesis and Evaluation Catalytic Efficiency of Perovskite-Type Oxide Nanopowders in Removal of Bromocresol Purple from Aqueous Solution*. 2(7), 340–351.
- Yagub, M. T., Sen, T. K., & Ang, H. M. (2012). *Equilibrium , Kinetics , and Thermodynamics of Methylene Blue Adsorption by Pine Tree Leaves*. 5267–5282.
<https://doi.org/10.1007/s11270-012-1277-3>
- Yu, C., & Han, X. (2015). *Adsorbent Material Used In Water Treatment-A Review*. Iwmecs, 290–293.