



Efficient Removal of Organic Pollutants Using Magnetic Biochar Derived from Corn Husk

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Abstract: The development of cost-effective and sustainable adsorbents for dye-contaminated wastewater remains a critical environmental challenge. In this study, a magnetic biochar composite (M/BCH) was synthesized from corn husk biomass through FeCl₃ impregnation followed by pyrolysis at 600 °C for 4 h. The physicochemical characteristics of the pristine biochar (BCH) and the magnetic composite were systematically investigated using XRD, FTIR, SEM/EDS, and N₂ adsorption-desorption techniques. XRD and FTIR analyses confirmed the successful incorporation of Fe₂O₃ into the carbon matrix, while SEM/EDS mapping revealed uniform Fe distribution (~12 wt.%). Textural analysis showed that Fe₂O₃ deposition reduced the BET surface area and pore volume, indicating partial pore occupation. The adsorption performance of BCH and M/BCH for methylene blue (MB) and methyl red (MR) was evaluated over varying contact times, initial concentrations, adsorbent dosages, and shaking speeds. BCH exhibited relatively higher MB adsorption, attributed to its higher surface area and mesoporous structure, whereas M/BCH showed higher MR removal compared to BCH due to modified surface chemistry, improved electrostatic interactions, and additional mechanisms such as complexation and π - π interactions. The M/BCH composite reached adsorption equilibrium within 120 min and showed increasing dye uptake with higher adsorbent dosage and shaking speed. Importantly, its magnetic properties enabled rapid and efficient post-treatment separation. Overall, the findings demonstrate that corn husk-derived M/BCH was an effective, multifunctional, magnetically separable adsorbent with potential for wastewater treatment applications.

Keywords: Biochar; corn husk; magnetic composite; methylene blue; methyl red.

1. Introduction

Large quantities of wastewater are continuously generated from textile, leather, paper, and plastic industries, with dye-laden effluents, particularly those containing synthetic dyes such as methylene blue and methyl red, representing a major environmental concern due to their toxicity and persistence in aquatic systems [1]. Dyeing wastewater commonly exhibits high concentrations of aromatic organic pollutants, intense chromaticity, alkaline pH, and recalcitrant constituents [2]. Consequently, unintended or uncontrolled discharge of such effluents into natural water bodies can lead to severe ecological deterioration. Addressing dye-contaminated wastewater has therefore become a critical issue in environmental engineering and remains one

of the most challenging aspects of industrial wastewater management. A diverse array of treatment approaches has been explored for dye elimination, including advanced oxidation processes (AOPs), photocatalytic degradation, membrane separation, biological treatment, and adsorption [3]. Among these, adsorption is frequently highlighted as a practical and efficient approach, owing to its operational simplicity, cost-effectiveness, and robustness toward toxic or chemically complex pollutants. Commercial activated carbon remains the benchmark adsorbent; however, its relatively high cost and regeneration limitations hinder large-scale application. To overcome these barriers, growing research efforts have focused on developing low-cost, value-added, or waste-derived sorbents as sustainable alternatives for dye removal from industrial wastewater [4, 5].

Biochar is a carbon-rich material generated under oxygen-limited conditions through slow or fast pyrolysis. It can be produced from a wide range of lignocellulosic and organic biowastes, including woody residues, agricultural by-products, animal wastes, and biosolids. Due to its elevated porosity, extensive surface area, and predominantly negative surface charge, biochar has become a viable, low-cost adsorbent for the removal of organic and inorganic pollutants from aqueous systems [6, 7]. Despite these advantages, many commercial biochars remain costly due to their feedstock sources and the additional regeneration or reactivation procedures required, which limit their wider practical use. Corn husk, the fibrous outer layer surrounding the maize cob, represents an abundant lignocellulosic residue. Current disposal techniques, such as open burning and landfilling, exacerbate environmental degradation by disposing of waste-rich biomass resources. Given that maize is the second most widely cultivated crop globally and that approximately 14% of the plant mass consists of husk, this agricultural waste offers substantial potential as an inexpensive carbon precursor for biochar production. In addition to their use as precursors for biochar production, corn husks and other agricultural residues have been widely explored for value-added applications, such as biomass densification and the development of renewable materials. Furthermore, biochar derived from various waste sources has demonstrated promising potential in environmental and agricultural applications, highlighting its versatility and sustainability [8,9].

Iron oxide (Fe_2O_3) has been widely explored in various technological and environmental applications, including magnetic media, biosensing, imaging, and energy systems. Importantly, Fe_2O_3 shows a strong affinity for a range of pollutants, including heavy metals, organic dyes, and pharmaceuticals [10,11]. Its magnetic properties also allow spent particles to be easily recovered from aqueous systems, enabling the recyclability of the adsorbent. However, nanoscale Fe_2O_3 tends to aggregate in water due to its high surface energy, thereby reducing surface area and diminishing adsorption efficiency. To overcome these limitations, combining Fe_2O_3 nanoparticles with a carbonaceous support, such as biochar, can enhance stability, dispersion, and functional performance. In this study, a magnetic biochar composite (M/BCH) was synthesized using corn husk mixed with FeCl_3 and subjected to pyrolysis at 600°C for 4 h to obtain a multifunctional magnetic sorbent. The physicochemical characteristics of the resulting M/BCH were systematically examined. Its adsorption performance toward two model organic dyes, methylene blue (MB) and methyl red (MR), with different chemical structures (Figure 1), was investigated by evaluating the effects of adsorbent type, dosage (M/V, g/L), initial dye concentration, contact time, and shaking speed.

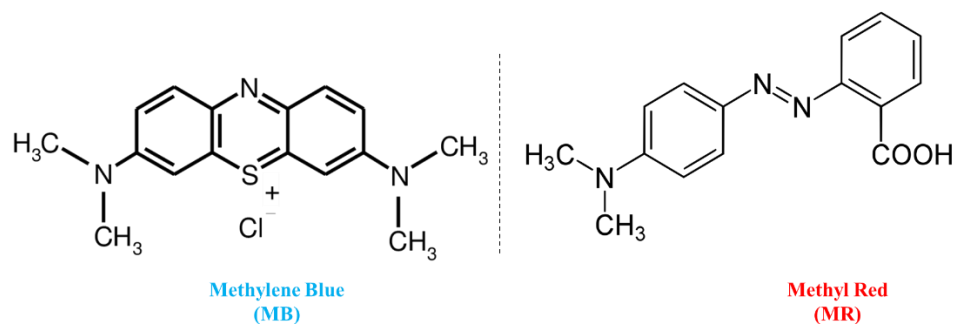


Figure 1. Chemical structure of methylene blue and methyl red.

2. Materials and Methods

2.1 Chemicals and reagents for preparation of adsorbents

Corn husk residue (CH) was collected from Chiang Mai province, Thailand. Iron (III) chloride hexahydrate (analytical grade 99.9%, $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$), Methylene blue ($\text{C}_{16}\text{H}_{18}\text{N}_3\text{SCL}$, 319.85 g/mol) and Methyl red ($\text{C}_{15}\text{H}_{15}\text{N}_3\text{O}_2$, 269.30 g/mol) were purchased from Sigma-Aldrich. All chemicals were of analytical grade and were used without further purification.

2.2 Preparation of adsorbents

2.2.1 Preparation of biochar derived from corn husk (BCH)

The corn husk biomass was initially rinsed thoroughly with deionized water to remove surface dust, soil residues, and other soluble contaminants that could affect carbonization efficiency. The material was dried at 110 °C for 12 h post-washing to eliminate residual moisture and ensure stable thermal behavior during pyrolysis. The dried biomass was milled and sieved to achieve a uniform particle size of less than 100 μm , thereby enhancing heat transfer and facilitating effective carbon conversion during thermal processing. Pyrolysis was performed in a muffle furnace at 600 °C for 4 h with a heating rate of 5 °C min^{-1} under limited oxygen to facilitate char formation. Approximately 20 g of dried corn husk biomass was used in each pyrolysis batch. Pyrolysis was carried out in a laboratory-scale muffle furnace under oxygen-limited conditions without an external carrier or inert gas flow. The produced biochar was naturally cooled to room temperature and kept in a desiccator to prevent moisture uptake before subsequent modification steps. After pyrolysis, the BCH sample was ground and sieved to obtain particles within the 0.5–1 mm range.

2.2.2 Preparation of magnetic biochar derived from corn husk (M/BCH)

The magnetic corn-husk biochar/ Fe_2O_3 composite was synthesized by impregnating corn-husk powder with an FeCl_3 solution, followed by high-temperature pyrolysis. An FeCl_3 solution was prepared by dissolving 40 g of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ in 60 mL of deionized water. The impregnation process was performed using approximately 20 g of corn husk powder mixed with 60 mL of FeCl_3 solution. The corn husk powder was then soaked in this solution for 2 h to allow adequate adsorption of iron precursors. Following impregnation, the mixture was air-dried at 80 °C for 2 h. The biomass underwent pyrolysis in a furnace at 600 °C for 4 h, with a heating rate of 5 °C/min. The obtained biochar/ Fe_2O_3 composite was lightly ground and sieved to obtain particles in the 0.5–1 mm range. The resulting biochar derived from corn husk was designated as M/BCH. The samples were rinsed multiple times with deionized water, subsequently dried at 80 °C, and stored in a desiccator for future use.

2.3 Characterization of adsorbents

The structural information of the materials was obtained by powder X-ray diffraction (XRD) analysis on an Empyrean 3 Panalytical diffractometer, using $\text{CuK}\alpha$ radiation at 40 kV and 40 mA. Fourier-transform infrared spectroscopy (FTIR) was used to identify functional groups in the composites, using a Perkin-Elmer spectrometer with the KBr method. Sixty-four scans throughout the range of 400–4000 cm^{-1} at a resolution of 4 cm^{-1} were averaged for each spectrum. The SEM micrographs were captured at 1,500 $\times$ magnification using a JEOL JSM-IT800. Elemental mapping and confirmation of iron distribution were further supported by energy-dispersive X-ray spectroscopy (EDS). N_2 adsorption-desorption was measured at -196 °C using an Anton Paar Nova 600 to determine the textural characteristics of the materials. The mass of the sample, initially approximately 40 mg, was precisely recorded after pretreatment at 150 °C for 2 h.

2.4 Adsorption study

The adsorption behavior of methylene blue (MB) and methyl red (MR) on corn husk-derived biochar materials (BCH and M/BCH) was evaluated using batch experiments. A known mass of adsorbent was added to 50-mL Erlenmeyer flasks containing 10 mL of dye solution, and the mixtures were agitated under controlled conditions using a mechanical shaker. The influence of several operational parameters, including contact time (0–120 min), adsorbent dosage (1–10 g/L), initial dye concentration (100–140 mg/L), and shaking speed (100–150 rpm) was systematically investigated. All adsorption experiments were conducted at the natural pH of the dye solutions without pH adjustment. The initial pH values were approximately 6.5 for methylene blue

and 5.0 for methyl red. After the adsorption process, the residual concentrations of MB and MR were quantified using a UV-vis spectrophotometer (Jasco V-730) at wavelengths of 664 nm and 444 nm, respectively. Each sample was measured in triplicate to ensure analytical reliability. At each sampling interval, approximately 0.5 mL of solution was withdrawn for UV-vis analysis. The adsorption capacity (q_e) was determined using Eq. (1). Calibration curves were constructed using six concentration points, yielding the following regression equations: MB, $y = 0.0189x - 0.0165$ ($R^2 = 0.9990$); MR, $y = 0.0091x - 0.00286$ ($R^2 = 0.9976$), where x represents the dye concentration (mg/L), and y denotes the absorbance.

$$\text{Adsorption capacity: } q_e = \frac{(C_0 - C_e)V_i}{W} \quad (1)$$

In this equation, q_e denotes the equilibrium adsorption capacity (mg/g, based on dry adsorbent). C_0 and C_e refer to the initial and equilibrium dye concentrations in the solution (mg/L). V_i represents the volume of the initial dye solution (L), and W corresponds to the mass of the dried adsorbent used (g).

2.5 Kinetic study

The dried adsorbent was added to the MB and MR solution in the 250 mL Erlenmeyer flask. The initial concentrations of the MB and MR solutions were fixed at 100 mg/L. Samples were collected at different time intervals for UV-vis analysis until equilibrium was reached. Pseudo-first-order and pseudo-second-order kinetic models were evaluated according to Eqs. (2)–(3) to postulate the mechanism of MB and MR adsorption on the synthesized adsorbents.

Pseudo-first-order model:

$$q_t = q_e (1 - e^{-K_1 t}) \quad (2)$$

Pseudo-second-order model:

$$q_t = K_2 \frac{q_e^2 t}{1 + K_2 q_e t} \quad (3)$$

where q_t is the adsorption capacity at any time (mg/g_{dried adsorbent}); K_1 (/min) and K_2 (g/(mg min)) are the rate constants of the pseudo-first-order and pseudo-second-order models, respectively.

2.6 Isotherm study

The adsorption isotherm data were measured *via* the procedure described in Section 2.4. The initial concentrations of MB and MR were varied between 100 and 140 mg/L.

3. Results and Discussion

3.1 Characterization of biochar adsorbents

X-ray diffraction (XRD) was used to characterize the crystalline and amorphous phases of the biochar-based materials. Figure 2 displays the diffraction patterns of the corn husk biochar (BCH) and the magnetic corn husk biochar composite (M/BCH). The BCH sample exhibited a broad diffraction band within the 2θ range of approximately 15–30°, indicating its predominantly amorphous carbon structure. In contrast, the M/BCH composite retained this amorphous background while displaying additional sharp diffraction peaks at 33.3°, 35.6°, 50.2°, and 57.2°, corresponding to crystalline Fe_2O_3 [12]. The presence of these well-defined peaks indicates the successful incorporation of iron oxide into the biochar matrix. Due to the increased intensity of the crystalline Fe_2O_3 peaks, the amorphous hump appears less prominent in the M/BCH pattern compared to pristine BCH. This result suggested that Fe_2O_3 particles were well dispersed on the biochar structure, resulting in a low intensity of the amorphous structure but a high intensity of the Fe_2O_3 crystal structure when analyzed by XRD.

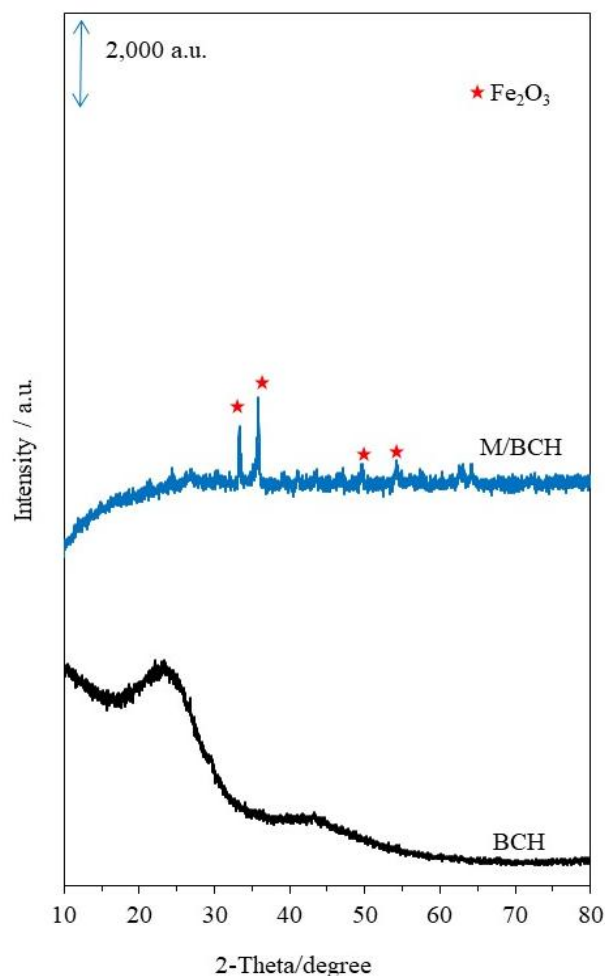


Figure 2. XRD analysis of biochar derived from corn husk, BCH, and M/BCH composite.

The FTIR spectra of the corn husk biochar (BCH) and the magnetic biochar composite (M/BCH) are presented in Figure 3. For BCH pyrolyzed at 600 °C, a broad absorption band at 3394 cm⁻¹ was observed, which is attributed to O–H stretching vibrations associated with phenolic hydroxyl and alcoholic functionalities [13]. The band at 1693 cm⁻¹ corresponds to C=O stretching of carboxyl or conjugated carbonyl groups [14], while the feature at 1597 cm⁻¹ is assigned to aliphatic C=C stretching [14]. In the case of M/BCH, the band observed at 1629 cm⁻¹ is more likely attributed to O–H bending vibrations of adsorbed water and/or C=C stretching in the carbon structure rather than Fe₂O₃-related vibrations [15]. It is well established that Fe–O stretching vibrations of Fe₂O₃ typically appear in the fingerprint region below 700 cm⁻¹. However, this region is not clearly resolved in the present FTIR spectrum, limiting further interpretation. Therefore, the incorporation of Fe₂O₃ into the biochar matrix is primarily confirmed by XRD analysis and SEM-EDS mapping rather than FTIR alone. However, the M/BCH composite exhibited reduced intensities of the characteristic peaks associated with the carbonaceous functional group of biochar. This result corresponded to the XRD data in Figure 2. This result confirmed that Fe₂O₃ particles were deposited on the biochar surface with good dispersion.

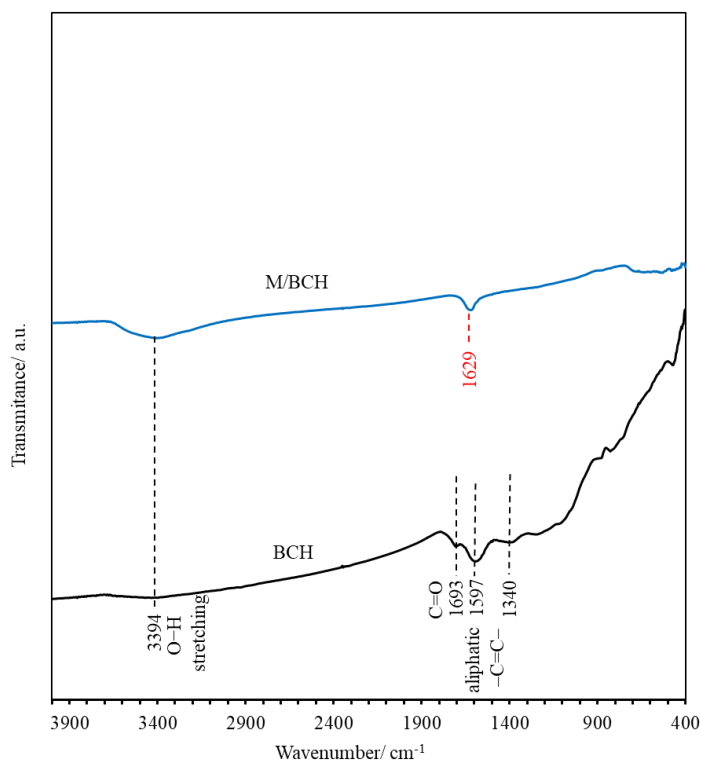


Figure 3. FTIR spectra of biochar derived from corn husk, BCH, and M/BCH composite.

The morphological characteristics of BCH and M/BCH were examined by scanning electron microscopy (SEM), as shown in Figure 4. Both samples displayed a porous carbon framework, which is commonly generated during pyrolysis as volatile components are released. In contrast to pristine BCH, the surface of the M/BCH composite showed a high level of finely dispersed Fe content. Energy-dispersive X-ray spectroscopy (EDS) mapping further confirmed the distribution of Fe across the carbon surface. While no detectable Fe signal appeared in the pristine BCH, the M/BCH composite contained approximately 12 wt.% of Fe content, demonstrating the effectiveness of anchoring the Fe particles uniformly on the biochar surface.

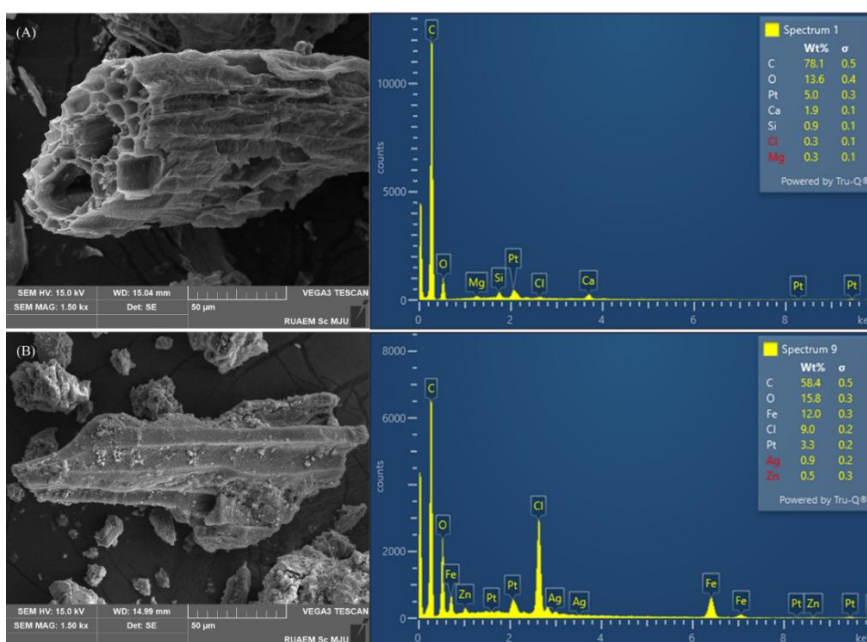


Figure 4. SEM-EDS image of biochar derived from corn husk (A) BCH and (B) M/BCH composite at magnification of 1,500x.

Figure 5 illustrates the N₂ adsorption–desorption isotherms and the corresponding pore size distributions of the BCH and M/BCH materials. Based on the IUPAC classification, both samples exhibit type IV isotherms with H-type hysteresis loops over a relative pressure range of approximately 0.45–0.95. This behavior is indicative of mesoporous structures formed through capillary condensation, as shown in Figure 5A. The pore size distribution profiles (Figure 5B) show a single dominant pore diameter centered at 3.7 nm for BCH and 3.2 nm for M/BCH, further confirming the mesoporous nature of the materials. As summarized in Table 1, the M/BCH composite with Fe content of 12%wt (SEM-EDS result) exhibited a lower BET surface area, total pore volume, and pore diameter (40.3%, 31.25%, and 12.6% reduction, respectively) in comparison with those of the initial BCH. These results suggest that Fe₂O₃ particles deposited within the pore structure of biochar derived from corn husk, leading to a drastic loss of textural properties [15].

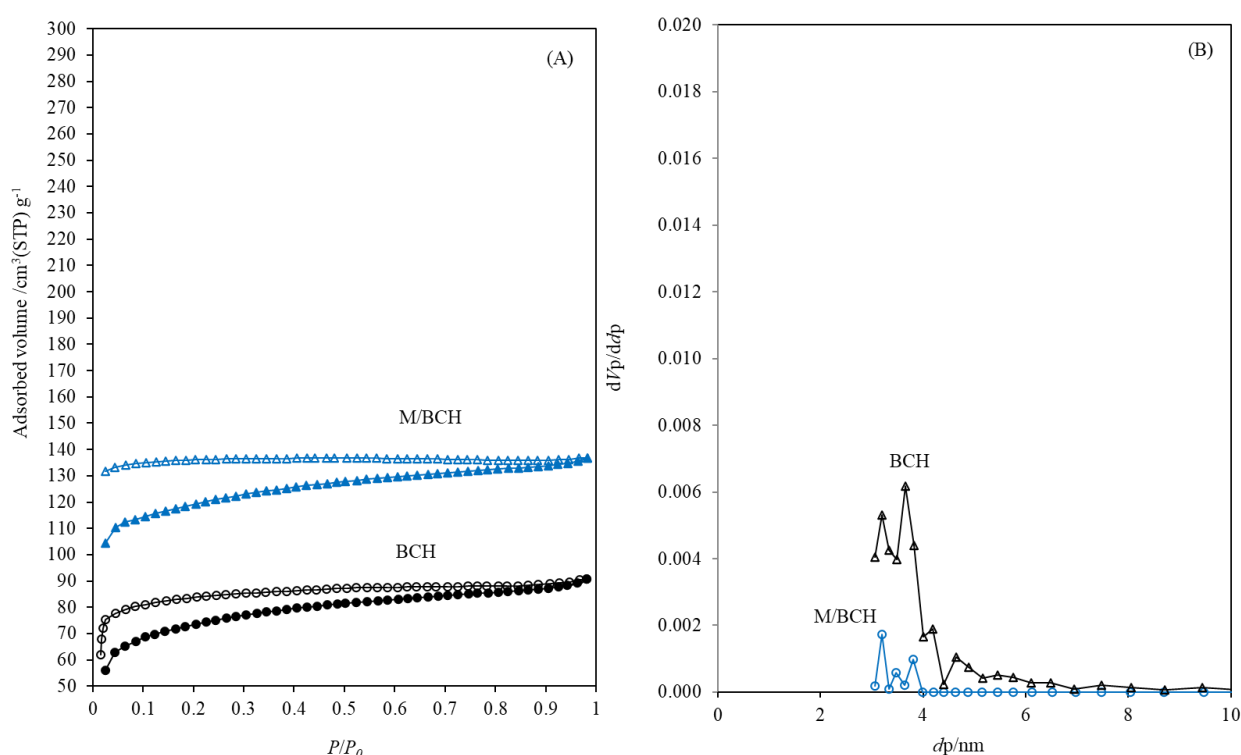


Figure 5. N₂ adsorption–desorption isotherms (A) and BJH pore size distribution (B) of BCH and M/BCH composite.

Table 1. Textural characteristics of BCH and M/BCH composite.

Sample	S_{BET}^a (m ² g ⁻¹)	D_p^b (nm)	V_t^c (cm ³ g ⁻¹)
BCH	269.58	3.65	0.16
M/BCH	160.93	3.19	0.11

^aBET surface area

^bPore diameter, evaluated by the BJH method

^cTotal pore volume, evaluated by the volume adsorbed at $P/P_0 = 0.99$

3.2 Adsorption study for the removal of dyes

The biochar derived from corn husk (BCH) and the magnetic biochar composite (M/BCH) were evaluated as adsorbents for the removal of methylene blue (MB) and methyl red (MR) from aqueous solutions. The adsorption capacities and removal efficiencies for both dyes are summarized in Figure 6A–B. As shown in Figure 6A, BCH exhibited higher adsorption capacity and removal efficiency than the M/BCH composite, which is consistent with the BET surface area values reported in Table 1. These findings indicate that the mesoporous structure and larger specific surface area of BCH facilitate enhanced adsorption. The adsorption

behavior may be influenced by electrostatic interactions depending on the solution pH and the ionization state of the MB dye molecules. Additional non-electrostatic interactions such as π - π stacking, n - π interactions, and hydrogen bonding further facilitate MB attachment to the composite surface [16]. However, the M/BCH composite exhibited a good magnetic property for separation from the solution, as shown in Figure 7, whereas the BCH material could not show the magnetic property. Although all experiments were conducted in triplicate, no formal statistical tests (e.g., t-tests or ANOVAs) were performed. Therefore, the observed differences between BCH and M/BCH should be interpreted as comparative trends rather than statistically validated differences.

In contrast, the M/BCH composite demonstrated greater adsorption capacity and removal efficiency for methyl red than the pristine BCH, as illustrated in Figure 6B. This trend aligns with the findings of Dong et al. [17], who reported that biochar-iron mineral composites exhibit enhanced performance in the removal of methyl orange. The addition of Fe_2O_3 to the biochar structure enhanced the adsorption of methyl red (MR) through multiple mechanisms. Therefore, the enhanced adsorption of methyl red by M/BCH may be associated with several interactions between the adsorbent surface and dye molecules. These may include electrostatic attraction, π - π interaction between aromatic structures, and hydrogen bonding. It should be noted that no advanced characterization techniques, such as post-adsorption FTIR, XPS, or total organic carbon (TOC) analysis, were performed. Therefore, the dominant adsorption mechanism cannot be conclusively identified and requires further investigation. These mechanisms are proposed based on the literature and the material's physicochemical characteristics and were not directly verified in this study. So, the adsorption behavior should be interpreted as a combination of possible interactions rather than a single confirmed mechanism.

Based on the comparative results shown in Figures 6 and 7, the M/BCH composite was selected for further parametric investigation due to its magnetic separability and enhanced performance toward methyl red. Therefore, subsequent studies on contact time, initial concentration, adsorbent dosage, and shaking speed were conducted using M/BCH as the representative adsorbent.

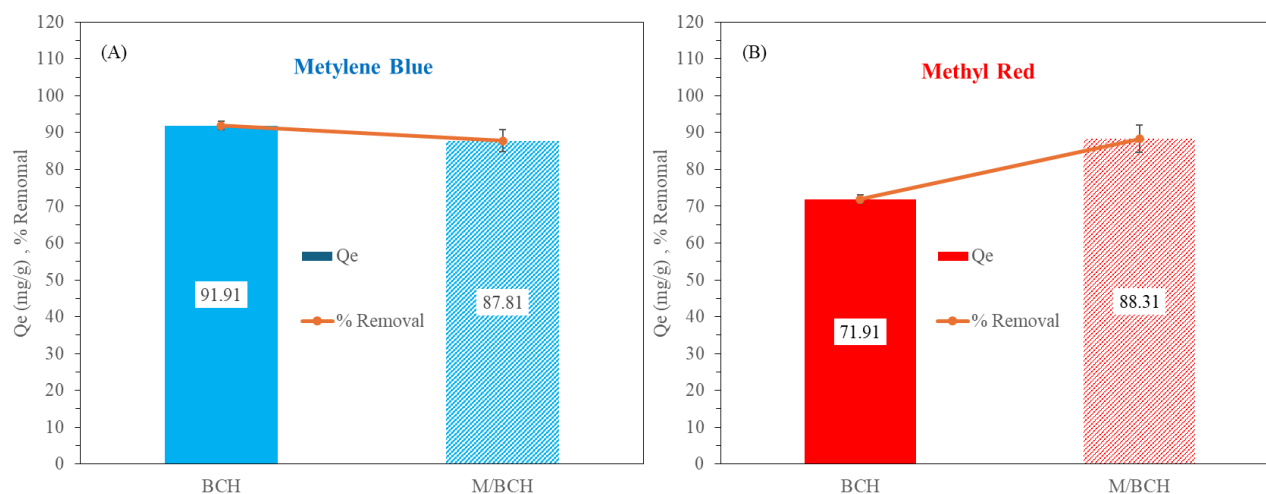


Figure 6. Comparison of adsorption performance of pristine biochar (BCH) and magnetic biochar (M/BCH) for (A) methylene blue (MB) and (B) methyl red (MR) under identical conditions (initial concentration: 100 mg/L, adsorbent dosage: 1 g/L, contact time: 120 min, shaking speed: 100 rpm).

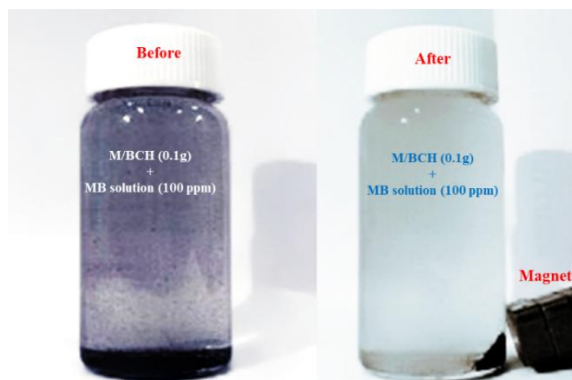


Figure 7. The adsorption MB solution (100 mg/L) using the M/BCH composite before and after magnetic separation.

The adsorption performance of the M/BCH composite toward MB and MR was examined by evaluating the effects of contact time, initial dye concentration, adsorbent dosage (M/V, g/L), and shaking speed, as presented in Figure 8. The influence of contact time is shown in Figure 8A. A rapid uptake of both dyes occurred during the first 100 min, after which the adsorption rate gradually stabilized, reaching equilibrium at approximately 120 min. The effect of initial dye concentration was assessed as depicted in Figure 8B. When the initial concentrations increased from 100 to 140 mg/L, the adsorption capacities of the M/BCH composite decreased by approximately 19.04% for MB and 12.07% for MR. Given that the M/V ratio remained constant, this decline suggests that the available active sites associated with Fe_2O_3 and surface functional groups were limited in number [18,19]. Consequently, higher initial dye concentrations led to greater competition between MB and MR molecules for adsorption sites.

The influence of adsorbent dosage (M/V) on the adsorption of MB and MR is shown in Figure 8C. Increasing the M/V ratio from 1 g/L to 10 g/L increased the adsorption capacities by approximately 20.04% and 28.07% for MB and MR, respectively. This improvement is attributed to the greater number of active sites provided by the higher adsorbent dosage, while the dye concentration and solution volume (10 mL, 100 mg/L) remained constant. Based on these results, an adsorbent dosage of 10 g/L was identified as optimal under the laboratory-scale conditions used in this study (10 mL solution volume). It should be noted that the reported adsorption performance and optimal dosage are based on laboratory-scale batch experiments and may not directly represent large-scale or continuous treatment systems. Figure 8D shows the effect of shaking speed on adsorption performance. Increasing the shaking speed from 100 to 150 rpm improved the adsorption capacities of both dyes. Enhanced agitation promotes better dispersion of the adsorbent particles and increases the frequency of collisions between dye molecules and the M/BCH composite, thereby accelerating adsorption. However, it should be noted that pH-PZC measurement and systematic pH-dependent studies were not conducted in this work. Therefore, the proposed adsorption mechanisms involving electrostatic interactions are inferred from the literature and should be interpreted with caution. In addition, the regeneration and reusability of the M/BCH composite were not evaluated in this study. Therefore, while the magnetic property enables rapid separation from solution, the adsorbent's long-term stability and recyclability require further investigation.

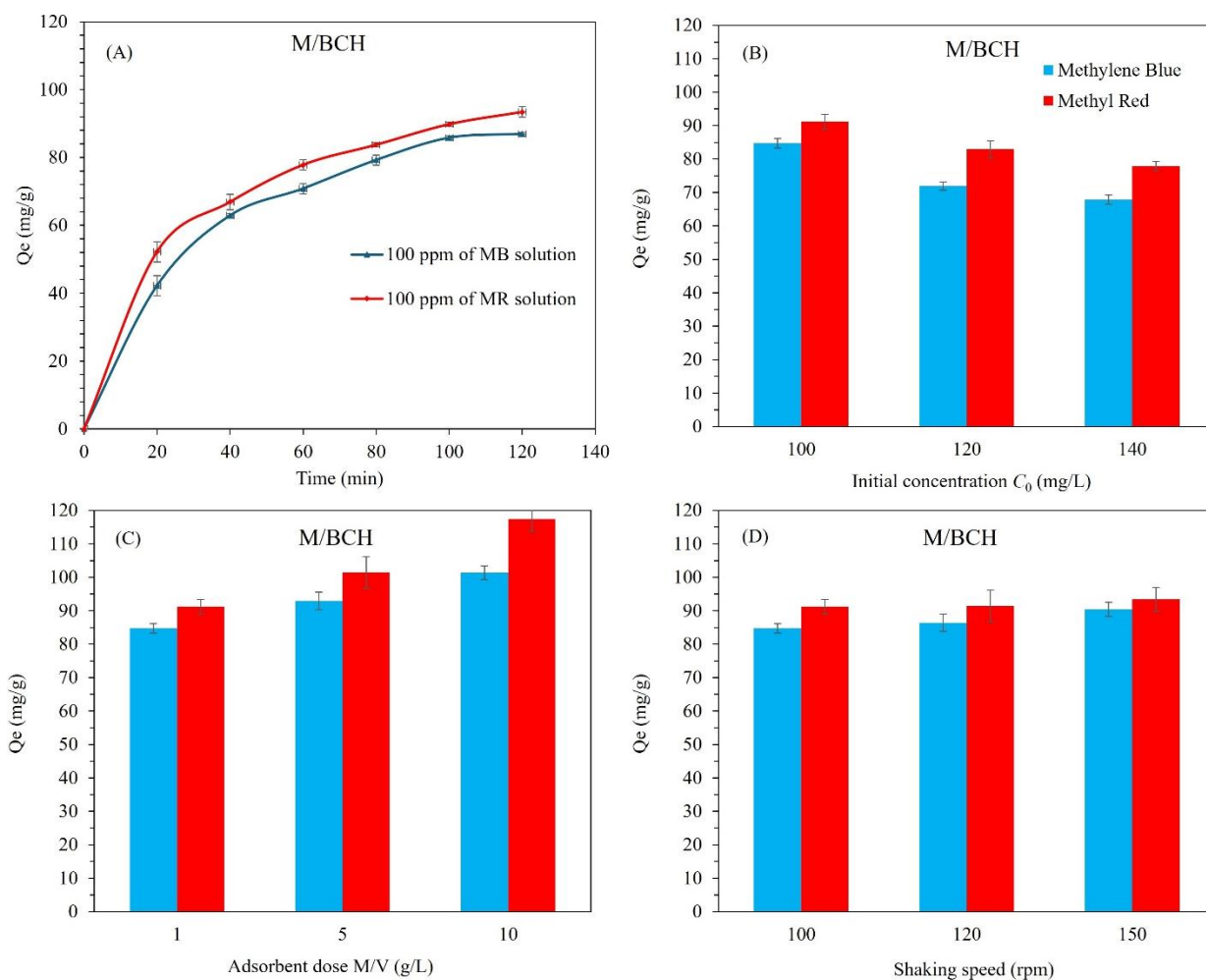


Figure 8. Effect of (A) contact time, (B) initial concentration, (C) adsorbent dose, and (D) shaking speed on methylene blue and methyl red removal.

3.3 Adsorption kinetics and isotherm modeling

The adsorption behavior of methylene blue and methyl red onto M/BCH was further evaluated using kinetic and isotherm models to understand the governing mechanisms better. The kinetic data were analyzed using pseudo-first-order (PFO) and pseudo-second-order (PSO) models (Figure 9A–B), and the fitted parameters are summarized in Table 2. It was observed that the PSO model described the experimental data more accurately for both dyes, as reflected by higher R^2 values and better agreement between calculated and experimental q_e values. ($R^2 = 0.9979$ for MB and 0.9979 for MR) compared to the PFO model. In addition, the q_e values estimated from the PSO model showed better agreement with the experimental values. This result suggests that the adsorption process is better described by the pseudo-second-order model, which is commonly associated with surface-related interactions. However, the deviation between calculated and experimental q_e values indicates that a single kinetic model cannot fully explain the system. This implies that other factors, such as pore diffusion and surface heterogeneity, may also contribute to adsorption.

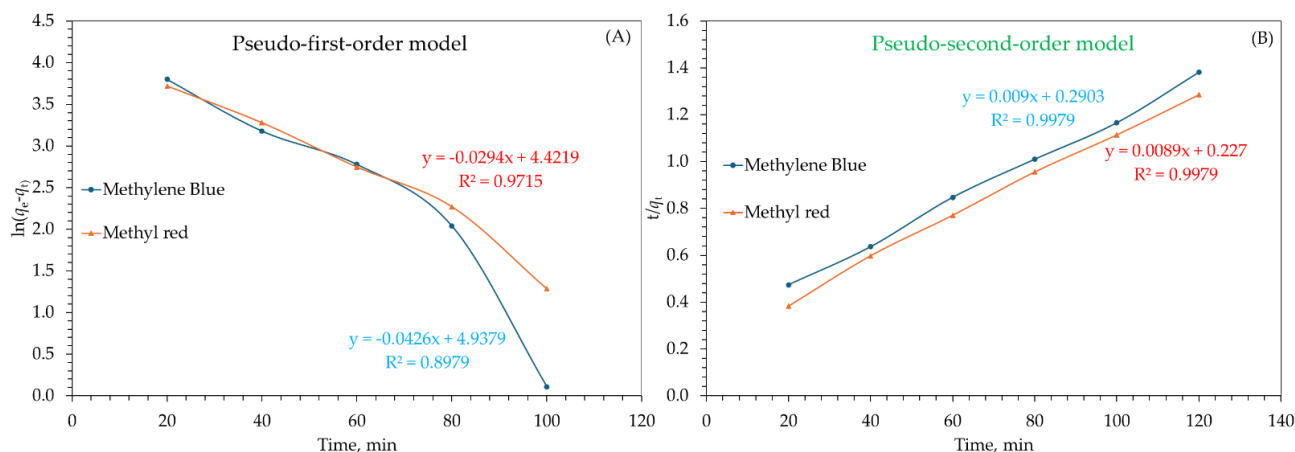


Figure 9. Fitting data to a pseudo-first-order kinetic model (A) and a pseudo-second-order kinetic model (B) for methylene blue and methyl red adsorption onto M/BCH adsorbent.

Table 2. Kinetic parameters for methylene blue and methyl red adsorption onto M/BCH adsorbent.

Dye	Model	k	q_e (calc) (mg/g)	q_e (exp) (mg/g)	R^2
Methylene blue	Pseudo-first-order	0.0426 min ⁻¹	139.47	86.90	0.8979
	Pseudo-second-order	2.78×10 ⁻⁴ g mg ⁻¹ min ⁻¹	111.35	86.90	0.9979
Methyl red	Pseudo-first-order	0.0415 min ⁻¹	147.32	93.40	0.9715
	Pseudo-second-order	3.10×10 ⁻⁴ g mg ⁻¹ min ⁻¹	118.22	93.40	0.9979

For equilibrium analysis, the adsorption data were fitted to the Langmuir and the Freundlich isotherm models, and the results are presented in Table 3. The Langmuir model showed slightly higher R^2 values than the Freundlich model for both MB and MR, indicating a better overall fit to the experimental data. Nevertheless, some of the calculated parameters, particularly the Langmuir constant (K_L), exhibited non-ideal values. This suggests that adsorption occurs on a heterogeneous surface with multiple interaction mechanisms rather than in an ideal monolayer. Similarly, the Freundlich parameter (n) did not clearly reflect typical adsorption behavior. These observations suggest that the adsorption system does not strictly follow the ideal assumptions of either model. Such inconsistency between fitting quality and parameter validity indicates that the adsorption of MB and MR onto M/BCH is likely governed by multiple mechanisms rather than a single ideal process. Possible interactions include electrostatic attraction, π - π interactions between aromatic structures, and surface interactions involving iron oxide species. It should also be noted that the isotherm study was conducted within a relatively narrow concentration range (100–140 mg/L), which may limit the robustness of model fitting and affect parameter interpretation. Overall, the combined kinetic and isotherm results indicate that adsorption on M/BCH involves multiple mechanisms within a heterogeneous system. This behavior is typical for biochar-based composites and reflects the complex nature of their surface properties.

Table 3. Isotherm parameters for methylene blue and methyl red adsorption onto M/BCH adsorbent.

Dye	Freundlich			Langmuir		
	K_F ((mg/g)(mL/mg) ^{1/n})	n	R^2	K_L (mg/mL)	q_{max} (mg/g)	R^2
Methylene blue	1,784.7	1.5	0.9525	-0.0219	45.37	0.9963
Methyl red	1,500	1.3	0.9480	-0.018	52.18	0.9950

To further evaluate the performance of the M/BCH composite, a comparison with previously reported adsorbents is presented in Table 4. The results indicate that the adsorption capacity of M/BCH for methylene blue is lower than that of pristine BCH and several engineered adsorbents, which can be attributed to the reduction in surface area resulting from Fe₂O₃ incorporation. However, M/BCH demonstrates improved performance toward methyl red compared to BCH, suggesting that surface modification enhances interactions with anionic dyes. Although some reported materials exhibit higher adsorption capacities, they often involve more complex synthesis routes or higher production costs. In contrast, the M/BCH composite developed in this study offers advantages such as low-cost biomass feedstock, simple preparation, and magnetic separability. It should also be noted that the $q_{\max}$ values obtained in this study were derived from a relatively narrow concentration range, and therefore should be interpreted as approximate values rather than absolute maximum capacities.

Table 4. Comparison of the adsorption capacities of M/BCH with those of reported biochar-based adsorbents.

Adsorbent	Dye	$q_{\max}$ (mg/g)	Key feature	Reference
BCH	Methylene blue	91.91	High surface area	This work
M/BCH	Methylene blue	45.37	Magnetic, Fe ₂ O ₃ -modified	This work
M/BCH	Methyl red	52.18	Enhanced anionic dye removal	This work
Magnetic biochar (banana peel)	Methylene blue	72.5	Fe-modified biochar	[12]
Biochar/Fe ₂ O ₃ composite	Methyl orange	65.3	Electrostatic interaction	[17]
Ag-biochar composite	Methylene blue	110.4	Catalytic adsorption	[13]
Activated carbon	Methylene blue	150–400	Commercial adsorbent	[4,5]

4. Conclusions

This study successfully synthesized a magnetic biochar composite (M/BCH) from corn husk, an abundant agricultural residue, and demonstrated its effectiveness as a recoverable adsorbent under laboratory-scale conditions. Structural analyses confirmed the effective incorporation of Fe₂O₃ nanoparticles onto the biochar surface, resulting in distinct changes in functional groups, morphology, and surface textural properties. Although the deposition of Fe₂O₃ reduced the BET surface area relative to pristine BCH, it significantly improved adsorption performance toward methyl red through enhanced electrostatic attraction, complexation, hydrogen bonding, and π - π interactions. Batch adsorption experiments revealed that the M/BCH composite achieved rapid dye uptake with equilibrium attained at approximately 120 min. Adsorption capacity increased with higher adsorbent dosage and shaking speed but decreased with elevated initial dye concentration due to active-site limitations. In comparison, BCH remained more effective for methylene blue removal due to its higher surface area, whereas M/BCH was more suitable for anionic dye treatment. Notably, the strong magnetic response of M/BCH enabled facile separation from aqueous media. The results demonstrate that corn husk-derived M/BCH is an effective and magnetically recoverable adsorbent under laboratory-scale conditions. While the material shows promising performance, further studies on regeneration, pH-dependent behavior, and multi-component systems are necessary to assess its practical applicability better. These findings provide a useful foundation for the future development of low-cost, sustainable biochar-based adsorbents for real wastewater treatment.

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