

Research Article

Efficient Removal of Methyl Red from Aqueous Solutions Using Chemically Modified Bentonite Clays: A Study of Adsorption Dynamics

Shailesh Kumar¹ , Ashok Kumar Jha^{1, 2, *} ¹University Department of Chemistry, Tilka Manjhi University, Bhagalpur, India²Kamleshwari Prasad College, Madhepura University, Madhepura, India

Abstract

The extensive discharge of synthetic organic dyes from the textile and leather industries has become a major environmental concern due to their toxic, persistent, and non-biodegradable nature. Among these pollutants, methyl red dye poses significant risks to aquatic ecosystems and human health. The present study aims to evaluate the adsorption efficiency of cetyltrimethylammonium bromide (CTAB)-modified bentonite as a low-cost and effective adsorbent for the removal of methyl red from aqueous solutions. Bentonite powder was modified using 0.5 mol L⁻¹ CTAB to enhance its surface properties and adsorption capacity. Batch adsorption experiments were carried out at pH 7 with initial dye concentrations ranging from 10 to 30 ppm. The adsorption process was monitored using UV–Vis spectrophotometry at a wavelength of 360 nm. The experimental results demonstrated excellent adsorption performance, with removal efficiencies exceeding 98% across all studied concentrations. A maximum removal efficiency of 99.62% was achieved at an initial concentration of 30 ppm within 90 minutes of contact time. The superior adsorption behavior is attributed to the increased surface area, mesoporous structure, and improved surface functionality resulting from CTAB modification. Structural and functional characterization using X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) confirmed successful modification of bentonite and the interaction between dye molecules and active surface sites. Overall, the findings indicate that CTAB-modified bentonite is a promising, economical, and environmentally friendly adsorbent for the efficient removal of organic dyes from wastewater, offering potential application in sustainable wastewater treatment processes.

Keywords

Bentonite, Methyl Red, Adsorption, Dye Removal, Wastewater Treatment

1. Introduction

The advent of synthetic organic dyes has revolutionized industries such as textiles, paper, leather, and cosmetics. Among these, azo dyes like methyl red are particularly no-

table for their extensive industrial applications and the environmental challenges they pose. Structurally, organic dyes are characterized by aromatic rings and chromophoric groups,

*Correspondence: Ashok Kumar Jha (ashokjha39@gmail.com)

Received: 15 February 2026; Accepted: 4 March 2026; Published: 21 April 2026



which impart the desired colour properties while also contributing to their resistance to degradation [1]. Persistence of the dye results in widespread contamination. Many dyes and their degradation products, such as aromatic amines, are classified as toxic, carcinogenic, and mutagenic. Long-term exposure to the dyes may cause liver damage and skin disorders [2].

Water pollution caused by dye effluents has become a global concern due to the sheer volume of dye usage and the inadequacy of conventional wastewater treatment technologies in removing these complex organic compounds [3, 5].

Bhagalpur, often hailed as the Silk City of India, is a major hub for silk production and textile dyeing. The regions of Nathnagar and Champnagar are central to this industry, with numerous small-scale and medium-scale units engaged in dyeing silk fabrics. These industries predominantly use synthetic dyes to achieve vibrant and lasting colours on silk, ensuring the products meet both domestic and international demand.

The effluents coming out of dye work contain not only dyes but also a plethora of toxic chemicals used during processing, including heavy metals, surfactants, and auxiliary agents. The resulting contamination not only impacts the local environment but also poses challenges for agricultural activities as well as the adjoining the river Ganges.

In agricultural settings, dye-contaminated water impacts soil health by altering its pH and reducing its fertility. The persistent nature of dyes hinders microbial activity in the soil, which is critical for nutrient cycling. Additionally, plants irrigated with such water exhibit reduced growth, lower yields, and, in some cases, accumulation of toxic substances in edible parts, posing risks to food safety. Aquatic environments are among the most affected by dye pollution.

Bentonite, a type of clay predominantly composed of montmorillonite, is renowned for its high surface area, cation exchange capacity, and swelling properties [6-8]. The mesopores present in the Bentonite can be one of the important factors for the adsorption potential. These characteristics make it an excellent adsorbent of dyes and heavy metals. The Rajmahal hills of Jharkhand, India, are a significant source of high-quality bentonite, rich in silica, alumina, and trace elements. The geochemical profile of Rajmahal Bentonite underscores its potential as an adsorbent in wastewater treatment. While raw bentonite has shown promise in removing contaminants from water, its adsorption capacity for organic dyes can be significantly enhanced through chemical modification [9-12]. These modifications alter the clay's surface properties, increasing its affinity for dye molecules and improving its overall adsorption efficiency [13].

Cetyltrimethylammonium bromide (CTAB), a cationic surfactant, is widely used to modify bentonite for enhanced adsorption capabilities. CTAB treatment increases the hydrophobicity of bentonite and introduces functional groups that interact more effectively with organic dye molecules, and also increases the surface area. This modification transforms bentonite from a general-purpose adsorbent into a specialized material tailored for dye removal applications [14, 15].

The CTAB-modified bentonite exhibits improved adsorption performance due to the formation of an organophilic surface, which interacts strongly with the hydrophobic regions of dye molecules. This makes it particularly effective for removing methyl red from aqueous solutions, even at low concentrations [16, 17].

2. Materials and Methods

2.1. Chemicals and Reagents

Methyl red dye ($C_{15}H_{15}N_3O_2$), a common azo dye, was procured from Merck. Cetyltrimethylammonium bromide (CTAB), a cationic surfactant used for modifying bentonite, was of analytical grade. All solutions were prepared using double-distilled water to ensure the absence of impurities.

2.2. Bentonite Sample Collection and Preparation

Raw bentonite samples were collected from the Rajmahal hills region in Jharkhand, India. The samples were dried at 105°C for 24 hours to remove moisture and then ground and sieved through a 100-mesh sieve to obtain a uniform particle size.

2.3. Chemical Modification of Bentonite with CTAB

For chemical modification, bentonite was treated with CTAB as follows:

- 1) A 0.5 M CTAB solution was prepared by dissolving the required amount in distilled water.
- 2) Bentonite (10 g) was added to the CTAB solution and stirred at 300 rpm for 6 hours at 60°C .
- 3) The mixture was allowed to settle, and the supernatant was discarded.
- 4) The modified bentonite was washed with distilled water to remove excess surfactant and then dried at 80°C for 12 hours.
- 5) The CTAB-modified bentonite was stored in an airtight container for further experiments.

Absorbance of the dye is known from the U.V. double beam spectrophotometer Systronic model 2203. Percentage decolouration of the dye is calculated from the formula [18-21].

$$\% \text{ decolouration} = \frac{C_i - C_t}{C_i} \times 100$$

Where C_i is the initial concentration and C_t is the concentration after time t .

3. Results and Discussions

From Figure 1 and Table 1, it has been clearly shown that

the percentage removal increases up to 45 minutes and the saturation of the equilibrium is attained at 60 minutes for the initial concentration of 5 ppm at pH 8. The graph between absorbance and time at a wavelength of 360 nm has been shown in Figure 2 for an initial concentration of 10 ppm methyl red

dye. it is clearly observed from the graph that absorbance decreases as time increases. Figure 3 shows the combined effect of absorbance and percent decolouration for different initial concentrations and contact time.

Table 1. Absorbance and percentage removal for different concentrations at of methyl red solutions.

Initial Concentration in PPM	pH	Time	Absorbance	% Removal
5	8	15	0.09	98.2
		30	0.061	98.78
		45	0.06	98.8
		60	0.065	98.7
		90	0.095	98.1
10	8	15	0.107	98.93
		30	0.113	98.87
		45	0.121	98.79
		60	0.112	98.88
		90	0.102	98.98
15	8	15	0.134	99.1
		30	0.128	99.146
		45	0.122	99.186
		60	0.118	99.213
		90	0.115	99.233
20	8	15	0.133	99.55
		30	0.104	99.48
		45	0.122	99.39
		60	0.121	99.395
		90	0.129	99.355
25	8	15	0.208	99.168
		30	0.101	99.154
		45	0.038	99.848
		60	0.09	99.64
		90	0.144	99.424
30	8	15	0.15	99.5
		30	0.139	99.53
		45	0.139	99.56
		60	0.122	99.59
		90	0.133	99.62

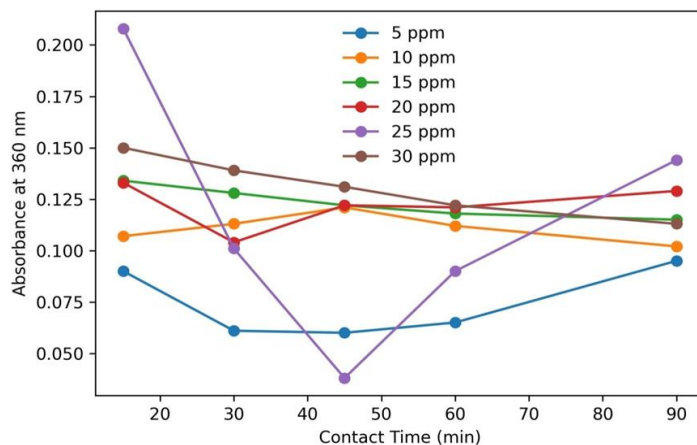


Figure 1. Absorbance versus Contact time for different initial concentrations of methyl red solution at 360nm.

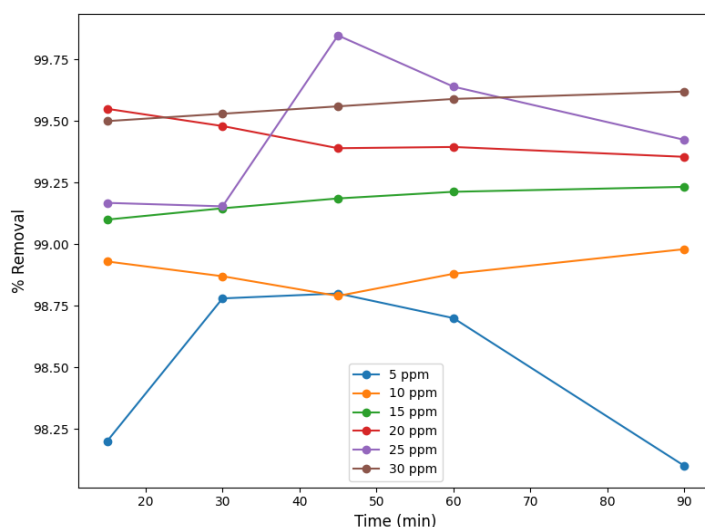


Figure 2. Percentage removal versus contact time for different initial concentrations of methyl red solutions at 360 nm.

Experimental data show that CTAB-modified Bentonite has the capacity to decolourise methyl red dye. CTAB increases the Bentonite surface area after modification.

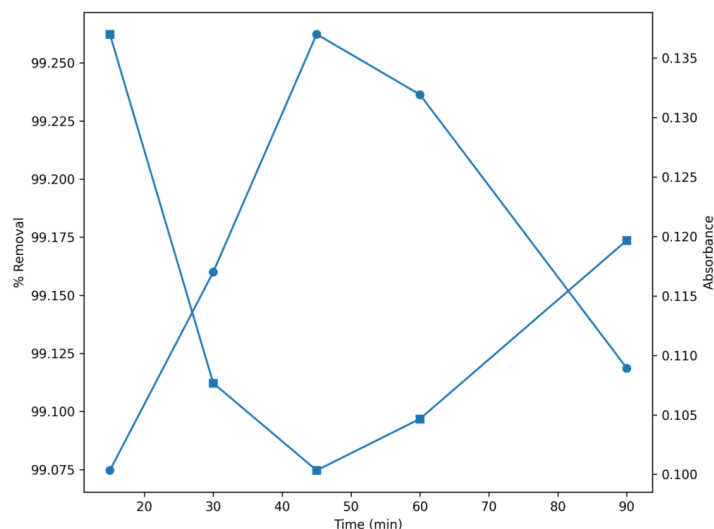


Figure 3. Combined effect of contact time on absorbance and percentage removal at different initial dye concentrations (5–30 ppm) at pH 8.



Figure 4. Sem Image of Barmer Bentonite (BB2).

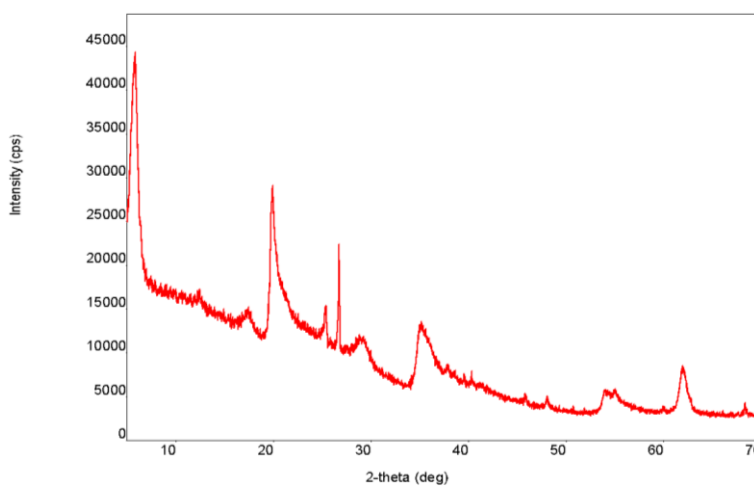


Figure 5. XRD pattern of CTAB-modified bentonite confirming the montmorillonite structure and interlayer modification.

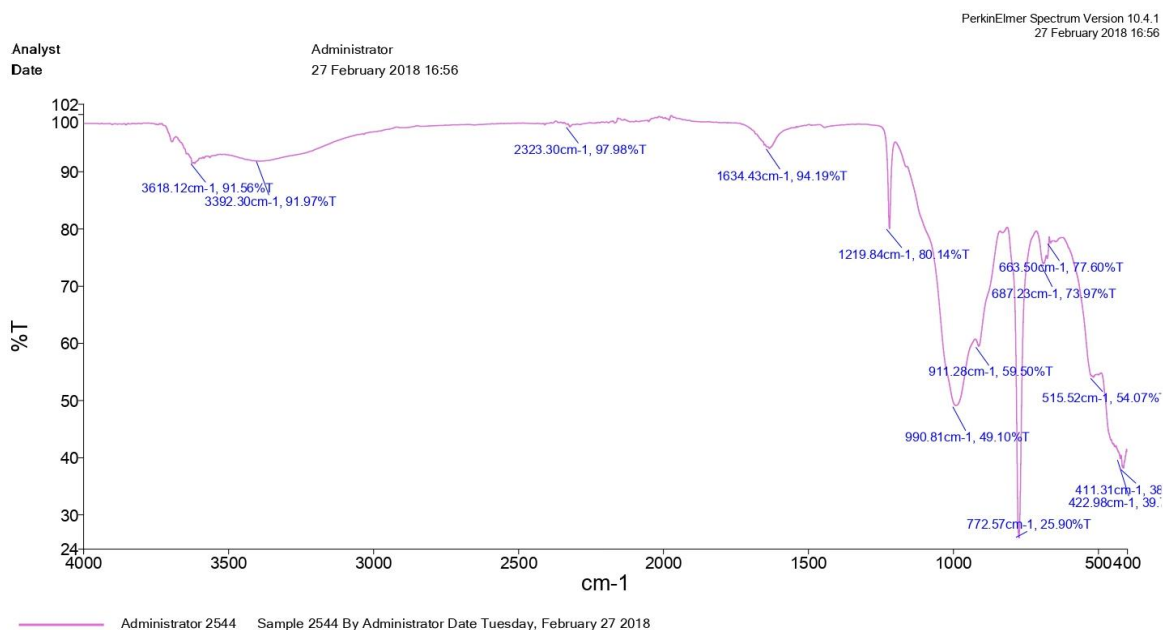


Figure 6. FTIR spectra of raw and CTAB-modified bentonite showing functional group interactions after chemical modification.

Bentonite is characterized by SEM images, XRD, and FTIR. These data confirm the Presence of the montmorillonite unit in Bentonite. SEM images show the morphological structure of the surface of Bentonite (Figure 4). The FTIR peaks around 3600 cm^{-1} show the presence of OH^- in the lattice. (Figure 6). Si – O – Si linkage stretching vibration takes place at around 1600 cm^{-1} and Al – O – Al bending at the peak 524 cm^{-1} . The peak at 692 cm^{-1} shows the presence of SiO_2 . The intensity peaks at a glancing angle of 2θ degrees show the diffraction patterns like that of the montmorillonite unit (Figure 5).

4. Conclusion

Modified bentonite has emerged as a potential adsorbent of methyl red dye due to increased surface area and mesopores present in the bentonite powder. This may be adopted as an eco-friendly and low-cost adsorbent for the dye.

Abbreviations

CTAB	Cetyltrimethylammonium Bromide
SEM	Scanning Electron Microscopy

Author Contributions

Shailesh Kumar: Data curation, Formal Analysis, Investigation, Methodology, Validation

Ashok Kumar Jha: Conceptualization, Formal Analysis, Resources, Supervision, Validation, Visualization, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] United States Environmental Protection Agency. (n.d.). Environmental criteria and assessment office reports. U.S. Environmental Protection Agency.
- [2] Ahmed, M. A., Ahmed, M. A., & Mohamed, A. A. (2023). Adsorptive removal of dyes using modified clay materials. *RSC Advances*, 13, 5337. <https://doi.org/10.1039/D2RA07883J>
- [3] Bhatt, A. S., Sakaria, P. L., Vasudevan, M., Pawar, R. R., Sudheesh, N., Bajaj, H. C., & Mody, H. M. (2012). Adsorption of an anionic dye from aqueous medium by organoclays: Equilibrium, kinetic, and thermodynamic studies. *RSC Advances*, 2, 8663-8671.
- [4] Akçay, M. (2015). Adsorptive removal of basic dyes by surfactant-modified bentonite clay. *Process Safety and Environmental Protection*, 95, 215-225.
- [5] Springer, J. (2022). Adsorption characteristics of methyl red dye by Na_2CO_3 -treated jute fibre. *Applied Water Science*, 12, 179.
- [6] Jha, A. K., & Mishra, B. (2012). Removal of fluoride by Bentonite minerals of Rajmahal Hills. *Journal of the Indian Chemical Society*, 89(4), 519.
- [7] Jha, A. K. (2018). Bentonite for chemical industries. *Journal of the Indian Chemical Society*, 95, 35.
- [8] Jha, A. K., Mishra, A. K., Kumari, V., & Mishra, B. (2011). Softening of Hard Water by Bentonite Mineral. *Asian Journal of Water, Environment and Pollution*, 8(4), 93.
- [9] Majumder, S., & Jha, A. K. (2020). Kinetic and Adsorption Study for Removal of Arsenic from Aqueous Medium by Low-Cost Bentonite of Rajmahal Hills and Hazaribagh, Jharkhand. *Nature Environment and Pollution Technology*, 19(5), 1847. <https://doi.org/10.46488/nept.2020.v19i05.008>
- [10] Jha, A. K. (2016) Bentonite minerals and their TGA, DSC, and PXRD studies. *Journal of the Indian Chemical Society*, 93(4), 437.
- [11] Jha, A. K., Mishra, K. K., & Majumder, S. (2020). "Application of Bentonite and Modified Bentonite as Green Adsorbent for Cadmium Removal from Aqueous Medium". *Journal of the Indian Chemical Society*, 97(9B), 1604.
- [12] Majumder, S., & Jha, A. K. (2020). Removal of Cr and Mn from aqueous medium using bentonites and their derivatives. *Journal of Chemical Sciences*, 132, 135. <https://doi.org/10.1007/s12039-020-01838-6>
- [13] Modified bentonite adsorption of organic pollutants of dye wastewater. (2017). *Materials Chemistry and Physics*, 202, 266-276.
- [14] Application of modified clays as an adsorbent for the removal of Basic Red 46 and Reactive Yellow 181. (2016). *Desalination and Water Treatment*, 57(29), 13561-13572.
- [15] Ho, Y. S., & McKay, G. (1999). Pseudo-second-order model for sorption processes. *Process Biochemistry*, 34(5), 451-465. [https://doi.org/10.1016/S0032-9592\(98\)00112-5](https://doi.org/10.1016/S0032-9592(98)00112-5)
- [16] Bulut, E., Özacar, M., & Şengil, İ. A. (2012). Adsorption characteristics, isotherm, kinetics, and diffusion of modified natural bentonite for removing diazo dye. *Chemical Engineering Journal*, 187, 79-88.
- [17] Fernandes, J. V., Rodrigues, A. M., Menezes, R. R., & Neves, G. d. A. (2020). Adsorption of an anionic dye on acid-functionalized bentonite. *Materials*, 13, 3600. <https://doi.org/10.3390/ma13163600>
- [18] Zihui Huang, Yuzhen Li, Wenjun Chen, Jianhui Shi, Ning Zhang, Xiaojin Wang, Zhen Li, Lijhen Gao, Yuxin Zhang. Modified bentonite adsorption of organic pollutants in dye wastewater. (2017). *Materials Chemistry and Physics*, 202, 266-276.
- [19] Bousemat, H., Ziane-Hezil, S., Benatmane, S., Bessaha, F., Bessaha, G., Çoruh, A., Sillanpää, M., & Khan, M. A. (2025). Experimental and modeling studies for simultaneous removal of anionic dyes using activated clay. *Scientific Reports*, 15, Article 30039. <https://doi.org/10.1038/s41598-025-30039-9>

- [20] Gupta V. K. & Ali I. (2004). *Removal of lead and chromium from wastewater using bagasse fly ash—a sugar industry waste.* Journal of Colloid and Interface Science, 271, 321-328.
<https://doi.org/10.1016/j.jcis.2003.11.007>
- [21] Özcan, A., & Özcan, A. S. (2005). Adsorption thermodynamics of dyes. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 266, 73-81.
<https://doi.org/10.1016/j.colsurfa.2005.05.008>