DOI: https://doi.org/10.57233/ihcfs.002

ISBN: 978-978-68-07775

BOOK OF PROCEEDINGS

IHCFS – 2025 WEBSITE: fos.fugusau.edu.ng

1ST INTERNATIONAL HYBRID CONFERENCE OF FACULTY OF SCIENCE

(A PUBLICATION OF FACULTY OF SCIENCE, FEDERAL UNIVERSITY GUSAU, NIGERIA)

ADSORPTION OF NAPHTHALENE FROM AQUEOUS SOLUTION USING NATURAL AND SURFACTANT- MODIFIED BENTONITE CLAYS, ISOTHERM AND KINETIC STUDIES

Arzika, A. T., Adili, A. T., Abubakar, L., Ibrahim, K., Shehu, H., and Hassan, S.

Department of Chemistry, Shehu Shagari Collage of Education, Sokoto

Corresponding author; arzikatambuwa86@gmail.com phone +2348068938228

ABSTRACT

Bentonite clay, owing to its exceptional adsorption properties, has gained significant attention in environmental remediation. This study investigates the modification of natural bentonite clay with Benzyl Trimethylammonium (BTMA) surfactants to enhance its efficacy in removing naphthalene from aqueous solutions. The natural bentonite clay was sourced from (FIIRO) lagos. Initial characterization of the unmodified and surfactant-modified clays was conducted using X-ray diffraction (XRD), and Fourier Transform Infrared (FTIR) analyses. Batch adsorption experiments were performed to evaluate the effects of adsorbent dosage, solution pH, and initial naphthalene concentration, kinetics, and adsorption isotherms. The results obtained indicated that the BTMA-modified bentonite exhibited highest percentage naphthalene removal (91.03%) followed by and the unmodified bentonite (89.90%) clay. Adsorption isotherm data were best described by the Freundlich model, with correlation coefficients of, 0.9847, and 0.7342 for BTMA-modified and unmodified bentonite clays, respectively, suggesting multilayer adsorption. Kinetic studies revealed that the pseudo-second-order model provided the best fit, with correlation coefficients of 0.9958, and 0.8167 for BTMA-modified and unmodified bentonite clays respectively indicating chemisorption. In conclusion, surfactant-modified bentonite clays demonstrate promising potential as effective adsorbents for PAH-contaminated water remediation applications.

Keywords: Adsorption, Naphthalene, Bentonite, Surfactant-modified, Isotherm-models,

1. INTRODUCTION

Water contamination by organic pollutants, particularly polycyclic aromatic hydrocarbons (PAHs), poses a major public health and environmental challenge (Singh *et al.,* 2022). Naphthalene, a simple but significant PAH, is frequently detected in contaminated industrial effluents, petroleum wastes, and urban runoff. Its persistent and toxic nature calls for cost-effective and efficient removal techniques (Olu-owolabi *et al.*, 2016). Several techniques have been employed to remove pollutants that have negative effects on our health and environment (Yue *et al.*, 2025). Among available methods; chemical oxidation, biodegradation phytoremediation, and thermal methods, adsorption has gained more attention due to its simplicity, low cost, high efficiency, reusability and suitability in treating both inorganic and organic pollutant (like PAHs) even at low-concentration (Haider *et al.,* 2022).

Several variety of low cost adsorbents such as biological materials and nanomaterial was employed (Obi, 2014; Zongzheng *et al.,* 2025; Das *et al.*, 2015; Gładysz-płaska *et al.*, 2017). However, most of these suffer one limitation or another such as low removal efficiency, secondary pollutant, technicality, low stability, bleeding, low mechanical strength, durability and re-usability, These have led to the search for more efficient and low cost adsorbents (Chang-mao *et al.,* 2020).

Natural clay materials, especially bentonite, are widely used as adsorbents due to their good binding ability, locally available, absent of secondary pollutant, potential for reuse(Haider, 2022).

Bentonite consists mainly of montmorillonite, a 2:1 layered aluminosilicate with negatively

DOI: https://doi.org/10.57233/ihcfs.002

ISBN: 978-978-68-07775

BOOK OF PROCEEDINGS

charged sheets capable of exchanging cations and adsorbing molecules (Aran *et al.,* 2008). However, its adsorption performance toward hydrophobic organic compounds is limited. Modification with surfactants, particularly quaternary ammonium salts, enhances clay hydrophobicity and expands interlayer spacing, thereby improving affinity for non-polar pollutants.

This study investigates natural bentonite clay and bentonite modified with Benzyltrimethyl ammonium chloride (BTMA-Cl), as an an adsorbent for removal of naphthalene from aqueouse solution. The research also evaluates adsorbent characterization, adsorption performance, effects of operational parameters, isotherm modeling, and adsorption kinetics.

2. MATERIALS AND METHODS

2.1 Materials

The natural bentonite clay was obtained from from FIIRO, Lagos. The chemicals used are analytical grade included BTMA-Cl, NaCl, methanol, $CuSO_4 \cdot 5H_2O$, ethylenediamine, and reagents for pH adjustment. All solutions were prepared using distilled water.

2.2 Cation Exchange Capacity (CEC) of the Clay

The CEC of the clay was measured by adsorption of copper diamine complex $[Cu(en)_2]^{2+}$ method (Aran *et al.*, 2008). 100 mg of the Clay sample was added in 8 ml of the 0.01 M cupper complex solution, and shaken for 30 min and centrifuged at 2000 rpm for 15 M. 3 ml of the supernatant was mixed with 1 ml of 1 M tris buffer solution, the absorbance was determined on a UV-Vis spectrometer. The CEC value of the clay was calculated from the difference between the initial and equilibrium concentration of the copper complex (Alshameri *et al.,* 2017).

2.3 Preparation and Modification of bentonite clay

The natural bentonite clay was sieved through 76 Nm mesh sieve , washed, dried and saturated with 1 M NaCl to obtain Na-bentonite (Na-BC). The Na-BC was modified by agitating it with BTMA-Cl surfactant solution. After washing and drying, the BTMA-modified bentonite (BTMA-MBC) was ground and stored for analysis. (Gładysz-płaska *et al., 2017*; Wo *et al.*, 2017; Apreutesei *et al.*, 2008).

2.4 Characterization of the surfactant modified clay adsorbent

The modified clay samples were characterized by the following instruments; X-ray diffraction (XRD) to determine structural changes, especially basal spacing, and FTIR spectroscopy to identify functional groups and confirm surfactant incorporation. (Andrunik, 2019).

2.5 Adsorption experiment

The Adsorption was studied using batch adsorption method (Emmanuel *et al*., 2016; El-nahhal & Safi, 2004; Mohammad *et al.*, 2008; Ade *et al.,* 2021). The parameters investigated was effect of contact time (0 - 180 min), the effect initial pH of naphthalene solution(2-10), the effect of adsorbate concentration, the effect of initial concentration (10–50 mg/L) and the Effect of adsorbent dose (0.3–1.3 g) (OBI, 2014; Das *et al*., 2016 and Onwuka *et al.*, 2020). All the experiments were conducted using 40 mL of naphthalene solution at room temperature on a mechanical shaker at 200 rpm, the supernatants were centrifuged at 2000 rpm for 10 min and were analyzed using UV-visible spectrophotometer (274 nm). The adsorption capacity (q_e) and the percentage adsorption (Removal efficiency) was calculated using equation 2.2 and 2.3 (Crisafully *et al.*, 2008).

$$\frac{(Co-Ce)V}{W} \text{ .....2.1}$$

$$\text{Adsorption (\%)} = \frac{(c_o-c_e)}{c_o} \text{ x 100. ..... 2.2}$$

DOI: https://doi.org/10.57233/ihcfs.002

ISBN: 978-978-68-07775

BOOK OF PROCEEDINGS

IHCFS – 2025 WEBSITE: fos.fugusau.edu.ng

2.6 Adsorption isotherm and kinetic studies

Three adsorption isotherm models, namely Langmuir (equation. 2.3) Freundlich (equation. 2.4) and Tempkin isotherm (equation. 2.5) were used

Langmuir model proposed that the maximum adsorption capacity consists of a monolayer adsorption and that the adsorption energy is distributed homogenously over adsorbent surface and there is no interaction between adsorbed molecules, (Awad *et al.,* 2019).

$\frac{c_e}{q} = \frac{1}{q_m}Ce + \frac{1}{k1q_m}$ .....equation 2.3 (a)

The Langmuir isotherm can be shown *via* a dimensionless constant separation factor (RL) known as the equilibrium parameter, which is obtained from equation 2.3. (b)

Table: 2.1 Effect of separation factor on isotherm shape

RL Value	Type of isotherm
R_L>1	Unfavorable Adsorption
R_L=1	Linear Adsorption
0<R_L<1	Favourable Adsorption
R_L=0	Irreversible Adsorption

The R_L value indicates the nature and the feasibility of adsorption process as shown in table 2.1.

$$R_L = \frac{1}{1+qm*k1} \quad \text{.....2.3. (b)}$$

Freundlich Isotherm model assume a heterogeneous surface of the adsorbent with non-uniform distribution $\ln q_e = \ln k_f + 1/n \ln C_e$ 2. 4

Where K_f (L/g) is the Freundlich constant and n indicates the intensity level of the adsorption

Tempkin isotherm shows the effect of some indirect adsorbent/adsorbate interactions on the adsorption $q_e = B1\ln K_t + B_1 \ln C_e$ 2. 5

Where K_t is the Tempkin isotherm constant (L/g) and $B_1 = RT/b$. Also, b is the Tempkin constant. **Adsorption kinetics** employed are pseudo-first-order kinetics (equation. 2.7), pseudo-second-order kinetics (equation. 2.8), and Elovich equation (equation. 2.9).

$$\ln (q_e - q_t) = \ln q_e - k_1 t \text{ .....} \quad 2.6$$

$$t/q_t = 1/kq_e^2 + t/q_e \text{ .....} \quad 2.7$$

$$q_t = \frac{1}{\alpha}\ln(\alpha\ \beta) + \frac{1}{\alpha}\ln t \quad \text{.....2.8}$$

3.0 RESULTS AND DISCUSSION

3.1 Cationic exchange capacity of modified and unmodified bentonite clay

The CEC results obtained is reported in table 3.1, The CEC value of the UM-BC obtained is 73.6 meq/100g, this indicate that the UM-BC contain higher organic matter.

Table 3.1 CEC Result of modified and unmodified bentonite clay

Clay	CEC (meq/100g)
Natural Bentonite Clay	73.6±0.059
BTMA -MBC clay	93.30±0.067

DOI: https://doi.org/10.57233/ihcfs.002

ISBN: 978-978-68-07775

BOOK OF PROCEEDINGS

IHCFS – 2025 WEBSITE: fos.fugusau.edu.ng

Upon modification, the CEC increased to 93.3 (table 3.1) indicating the cat ionic surfactant increases the absorption capacity of the clay by expanding the interlayer spacing of the clay.

3.2 FTIR Result of BTMA-MBC and UM-BC

The FTIR spectra (Fig 3.1a and b) of the unmodified bentonite clay (Fig 3.a) show a number of bands observed at 3684.5cm^{-1} and 3623cm^{-1} are assigned to OH stretching vibrations in Si-OH and Al-OH groups of the tetrahedral and octahedral sheets. The band at 1645.6 correspond to OH frequency in water molecule (Abdullah, *et al*., 2017); (Kahraman & Pehlivan, 2017). The IR bands at 775 and 693 cm^{-1} are attributed to cristobalite and quartz respectively (Al-Essa, 2018).

After modification, an additional pair of peaks were observed (fig. 3.1b) at 30375cm^{-1} and 14555cm^{-1} which is assign to C-H and C=C in aromatic ring respectively. Due to these observations in the IR spectra it is thought that the cat ion of the clay had been replaced by BTMA, this observation is in agreement with the previous studies (Kahraman, 2017); (Rozik *et al*., 2014)

3.3 XRD Result for the modified and unmodified bentonite clay

The XRD patterns of clays (Fig. 3.2 a). show the 2Ɵ at 6.7 Å, 11.4 Å, 20.7 Å, and 23.7Å were assigned to montmorillonite which is the major mineral of bentonite clay, the characteristic peaks at 2Ɵ reflection assign to quartz at 26.4 for quartz designated as impurity (Mohammad *et al.* 2023).

The successful modification the obtained XRD pattern (Fig 3.2 b) revealed the positions of the peaks were shifted to 6.04 Å, 9.7 Å, 18.5 Å, 21.72 Å with the corresponding d-values of 14.621, 9.110, 4.792, 4.088, (Elkhalifah *et al.,* 2021) reported similar result.

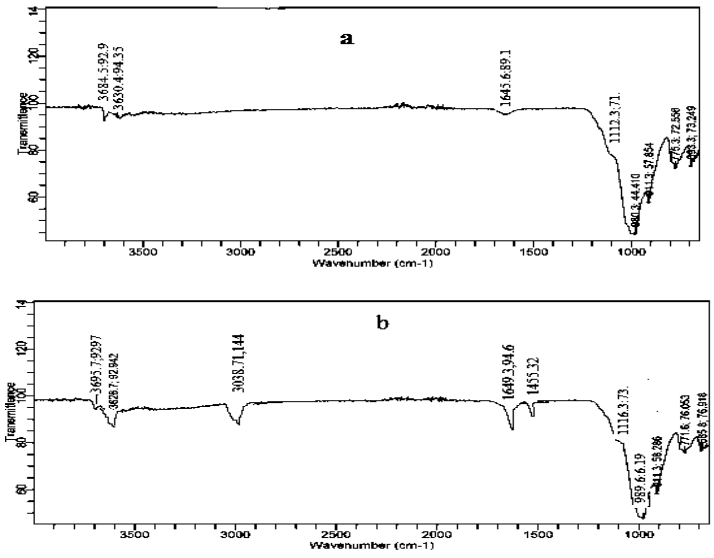


Figure 3.1 FTIR spectra of (a) UM-BC, (b) BTMA-MBC

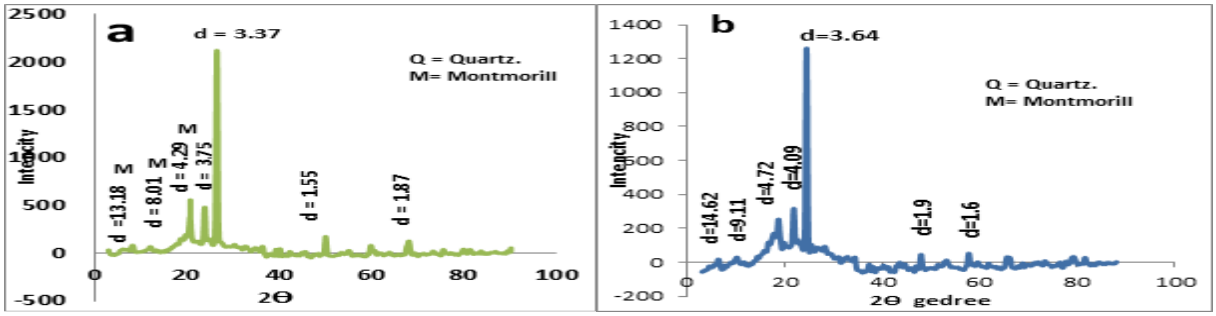


Figure 3.2 XRD diffractograms of (A) UM-BC, BTMA-MBC (B)

DOI: https://doi.org/10.57233/ihcfs.002

ISBN: 978-978-68-07775

BOOK OF PROCEEDINGS

IHCFS – 2025 WEBSITE: fos.fugusau.edu.ng

3.4 Effect of operating parameters on the naphthalene adsorption

3.4.1 Effect of contact time and adsorbent dose on naphthalene removal

Fig. 3.4 (a) presented the effect of contact time on the removal efficiency of naphthalene by BTMA-MBC and UM-BC clays, the removal efficiency by BTMA-MBC rapidly increased as contact time increased and attained maximum at around 90 min with 94.05% adsorption. For UM-BC the maximum adsorption was reached maximun at 120 min with 68.34% adsorption. It was observed that there is rapid adsorption at the initial uptake time because of the availability of the free active side on the clay after a certain time, the gradual occupation of the active sites slowed down the adsorption process. Therefore, the time chosen for the subsequent experiment were 90 min for BTMA modified clay and 120 min for UM-BC clay.

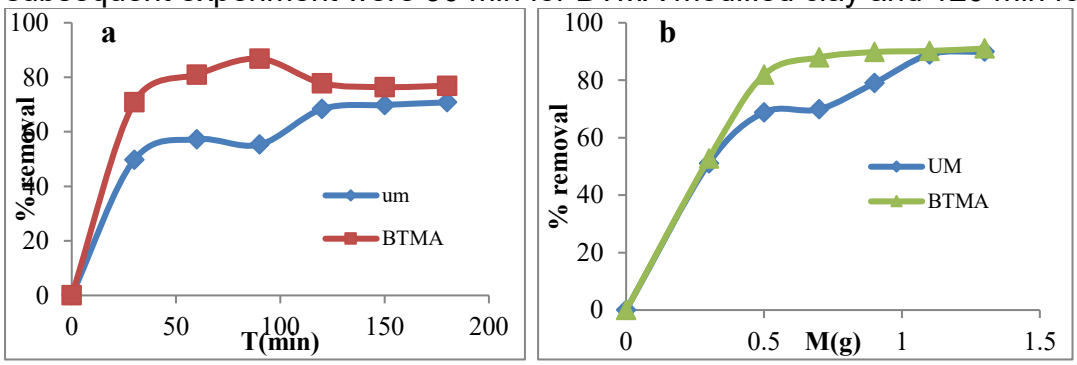


Figure 3.4.1 Effect of contact time (a) Adsorbent dose (b) on the removal efficiency of Naphthalene by BTMA-MBC and UM-BC Clay (Volume = 40 ml, Co = 10 mg/L and adsorbent dosage = 0.5 g)

Fig 3.4 b shows the effect of adsorbent doses. The increased in clay adsorbent dosage from 0.2 to 1.3g resulted in the corresponding increase in the adsorption from 52.76 and 51.1% to 91.03 and 81.90% for BTMA-MBC and UM-BC respectively, this is due to total increase in total surface area. Therefore based on this result, 1.3g of the clay gives optimum adsorption and was used for all the subsequent experiment.

3.4.2 Effect of solution pH and solution concentration

Fig. 3.4.c shows the effect of pH on the Adsorption of naphthalene by BTMA-MBC and UM-BC, the maximum adsorption was observed at pH close to neutral at pH of 6.0 with the percentage adsorption of 81.37 and 78.56 respectively, similar result was reported by Obi *et al*., (2021) and Das *et al.,* (2020).

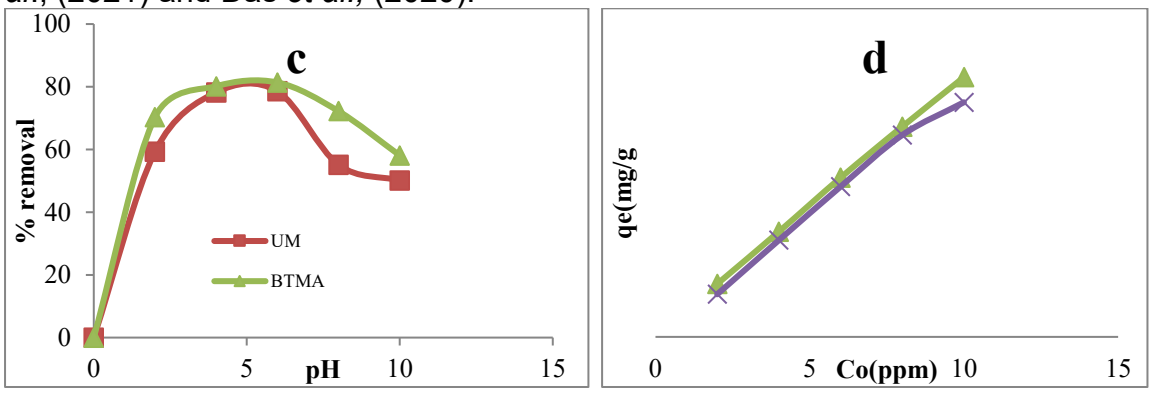


Figure 3.4.2 (c) the effect of pH on the removal efficiency naphthalene by BTMA-MBC and UM-BC Contact time = 90 min for BTMA-MBC 120 min for UM-BC, Co = 10 mg/L, adsorbent dosage = 1.3 g. (d) the effect of initial concentration on the removal efficiency naphthalene

DOI: https://doi.org/10.57233/ihcfs.002

ISBN: 978-978-68-07775

BOOK OF PROCEEDINGS

IHCFS – 2025 WEBSITE: fos.fugusau.edu.ng

by BTMA-MBC and U-BC. Contact time = 90 min for BTMA-BC and 120 min for UM-BC bentonite, adsorbent dosage = 1.3g and pH 6.

Fig.3.4.d shows the effect of solution concentration by BTMA-MBC and UM-BC clay. The adsorption increase with increasing initial concentration, this can be attributed to the increase in the concentration gradient which acted as a driving force for the adsorption

3.5 Kinetic of naphthalene Adsorption on the Clay

Three kinetic models; pseudo-first-order Fig. 3.5.a, pseudo-second-order Fig.3.5.b, and Elovich Fig. 3.5.c were used to evaluate the adsorption data. The pseudo second order shows best fit (BTMA-MBC: R^2 = 0.9958, UM-BC: R^2 = 0.8167) This suggests chemisorption dominates, involving electron sharing/exchange. Elovich shows good fit for modeling adsorption (BTMA-MBC R^2 = 0.8934 UM-BC R^2 = 0.8251) and showed good correlation and multilayer chemisorption while first order shows bad fit. The Overall, BTMA-MBC had faster adsorption and higher rate constants (Table 3.2) show the summary .

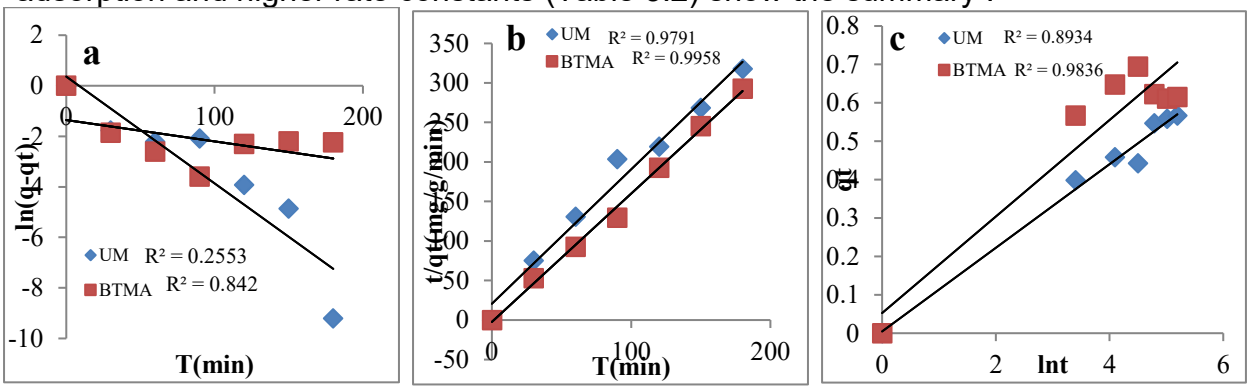


Figure 3.5 Pseudo–first–order (a) –second–order (b) and Elovich (c) adsorption kinetics models of Naphthalene on BTMA-MBC and UM-BC.

Table 3.2 Summary of Kinetics Results for Naphthalene Adsorption on HDTMA-MBC and UM-BC

Kinetic Models	Parameters	BTMA-MBC	UM-BC
	q	1.0009	0.995
PFO	k_1	0.012	0.0054
	R^2	0.025	0.842
	q^2	0.0203	0.0007
PSO	k_2	29.887	9.4873
	R^2	0.9958	0.8167
ELOV	α	18.7266	217.39
	β	2.26042	1.4825
	R^2	0.8934	0.8251

3.6 Adsorption isotherm for Naphthalene adsorption

Three Adsorption isotherm; Langmuir, Freundlich and Tempkin were used to describe the adsorption (Fig. 3.6 a,b, and c) The summary of constants and the correlation coefficients of the fitted data are given in table 3.3.

DOI: https://doi.org/10.57233/ihcfs.002

ISBN: 978-978-68-07775

BOOK OF PROCEEDINGS

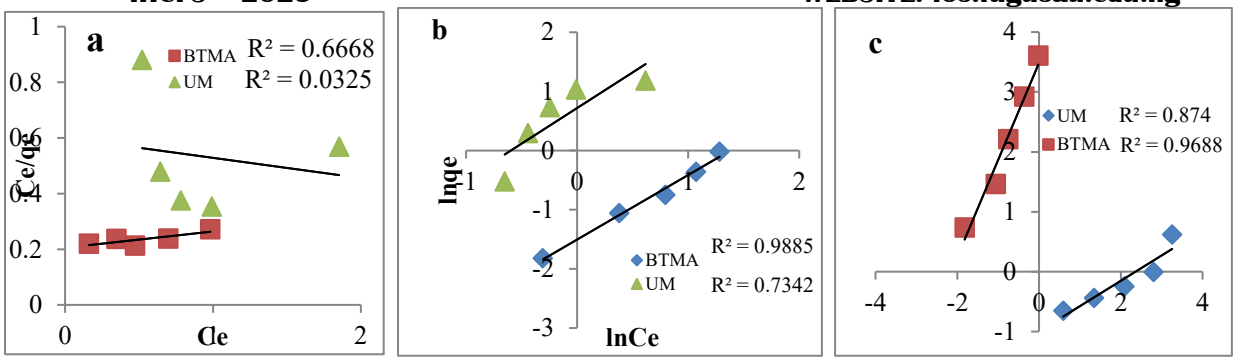


Figure 4.13 Langmuir (a), Freundlich (b) and Tempkin (c) isotherm models for BTMA-MBC and UM-BC clay

Freundlich model shows best fit with R^2 for BTMA-MBC and UM-BC of 0.9847 and 0.7342 respectively, indicating that the adsorption is heterogeneous surface, Multilayerd and Favorable adsorption (n > 1). The summary of all the constants and R^2 obtained was given in table 4.5.

Table 4.5 Summary of Adsorption isotherm results for Naphthalene Adsorption on HDTMA-MBC, BTMA-MBC and UM-BC

	Langmuir				Freundlich			Tempkin		
	R^2	q(mg/g)	b(L/mg)	RL	R^2	Kf(mg/g)	n	R^2	B	k
BTMA	0.4951	9.5238	0.3648	0.2599	0.9847	3.7158	1.74	0.9657	2.187	6.145
UMBC	0.0325	13.793	22.793	0.0045	0.7342	1.839	0.048	0.874	0.999	1.527

4.0 CONCLUTIONS AND RECOMMENDATIONS

4.1 CONCLUTIONS

In this study, the potentials of surfactant (Benzyltrimethyl ammonium chloride) modified bentonite clays for the removal of naphthalene (a representative model for PAH) from aqueous solution was investigated. Batch adsorption was conducted at 5 to 50 mg/L of naphthalene concentration and 0.3 to 1.3 g of the surfactant modified and unmodified natural bentonite clays.

The results show that BTMA-modified bentonite significantly enhances naphthalene adsorption compared to unmodified with Maximum removal of 90-94% for BTMA-MBC and 68-82% for UM-BC. Surfactant modification increased CEC and interlayer spacing, leading to better adsorption performance. Optimum conditions for best adsorption are at pH of 6, Contact time: 90–120 min Adsorbent dose: 1.3 g. Adsorption follows Freundlich isotherm and Pseudo-second-order kinetics. Therefore BTMA-MBC is a promising low-cost material for removing PAHs from contaminated water.

4.2 RECOMMENDATIONS

Research was considering the use of modification bentonite clay and its potentials for the removal of naphthalene from water at scale to explore the potential applications. The potential regeneration and reuse of the PAH-loaded modified bentonite should be explored to achieve low-solid waste production during the treatment process.

REFERENCE

Ade Priyanto, Malik, F., Muhdarina, & Awaluddin, A. (2021). Adsorption and characterization of activated sugarcane bagasse using sodium hydroxide. *Indonesian Journal of Chemical Research,* *8*(3), 202–209. http://ojs3.unpatti.ac.id/index.php/ijcr

Andrunik, M., & Badja, T. T. (2019).

Modification of bentonite with cationic and nonionic surfactants: Structural and textural features. *Materials, 12*(22), 3772. https://doi.org/10.3390/ma12223772

Aran, D., Maul, A., & Masfaraud, J. (2008). A spectrophotometric measurement of soil cation exchange capacity based on cobaltihexamine chloride absorbance. *Comptes Rendus Geoscience, 340*, 865–871. https://doi.org/10.1016/j.crte.2008.07.015

Awad, A. M., Shaikh, S. M. R., Jalab, R., Gulied, M. H., Nasser, M. S., Benamor, A., & Adham, S. (2019). Adsorption of organic pollutants by natural and modified clays: A comprehensive review. *Separation and Purification Technology, 228*, 115719. https://doi.org/10.1016/j.seppur.2019.115719

Chang-Mao, H., Chin-Pao, H., Chiu-Wen, C., & Hsin, W. (2020). Activation of percarbonate by water treatment sludge-derived biochar for the remediation of PAH-contaminated sediments. *Environmental Pollution, 265*(Part B), 114914. https://doi.org/10.1016/j.envpol.2020.114914

Das, P., Goswami, S., & Maity, S. (2020). Removal of naphthalene present in synthetic wastewater using novel G/GO nanosheet synthesized from rice straw: Comparative analysis, isotherm, and kinetics. *Frontiers of Nanoscience and Nanotechnology, 2*(1), 38–42. https://doi.org/10.15761/FNN.1000107

Elkhalifah, A. E., Murugesan, T., & Bustam, M. A. (2011). Characterization of different cationic forms of montmorillonite by FTIR, XRD, and TGA techniques. *National Postgraduate Conference*, 1–6.

El-Nahhal, Y. Z., & Safi, J. M. (2024). Adsorption of phenanthrene on organoclays from distilled and saline water. *Journal of Colloid and Interface Science, 269*(2), 265–273. https://doi.org/10.1016/S0021-9797(03)00607-6

Fasih Ullah Haider, Wang, X., Zulfiqar, U., Farooq, M., Hussain, S., Mehmood, T., Naveed, M., Li, Y., Liqun, C., Saeed, Q., Ahmad, I., & Mustafa, A. (2022). Biochar application for remediation of organic toxic pollutants in contaminated soils: An update. *Ecotoxicology and Environmental Safety, 248*, 114322. https://doi.org/10.1016/j.ecoenv.2022.114322

Gładysz-Płaska, A., Lipke, A., Tarasiuk, B., & Makarska-Białokoz, M. (2017). Naphthalene sorption on red clay and halloysite modified by quaternary ammonium salts. *Adsorption Science & Technology, 35*(5–6), 464–472. https://doi.org/10.1177/0263617417696090

Lamichhane, S., Krishna, K. C. B., & Sarukkalige, R. (2016). Polycyclic aromatic hydrocarbons (PAHs) removal by sorption: A review. *Chemosphere, 148*, 336–353. https://doi.org/10.1016/j.chemosphere.2016.01.036

Milicevic, S. T., Milic, M., & Sonja, S. (2017). Competitive adsorption of polycyclic aromatic hydrocarbons on organo-zeolites. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-017-9711-8

Mohammad, A., Yahya, R., Saleh, F., & Zubair, A. (2023). Adsorption of acenaphthene using date seed activated carbon. *Journal of Environmental Science and Technology, 4*(1), 10–15.*

Obi, C., & Okoye, I. P. (2021). Kinetic evaluation of naphthalene removal using acid-modified and unmodified bentonite clay mineral. *Journal of Applied Sciences and Environmental Management, 18*(1), 143–149.*

Olu-Owolabi, B. I., Alabi, A. H., Unuabonah, E. I., Diagboya, P. N., Böhm, L., & Düring, R. (2016). Calcined biomass-modified bentonite clay for removal of aqueous metal ions. *Journal of Environmental*

Chemical Engineering, 4(1), 1376–1382. https://doi.org/10.1016/j.jece.2016.01.044

Singha, S., Ashesha, A., Devia, N. L., & Yadav, I. C. (2022). A comprehensive review on occurrence, source, effect, and measurement techniques of polycyclic aromatic hydrocarbons in India. *Microchemical Journal, 108005*. https://doi.org/10.1016/j.microc.2022.108005

Unuabonah, E. I., Olu-Owolabi, B. I., Böhm, L., & Düring, R.-A. (2016). Adsorption of polynuclear aromatic hydrocarbons from aqueous solution: Agrowaste-modified kaolinite vs. surfactant-modified bentonite. *Bulletin of the Chemical Society of Ethiopia, 30*(3), 369–376. https://doi.org/10.4314/bcse.v30i3.5

Wo, M., Muir, B., Żi, K., Bajda, T., Kowalik, M., & Franus, W. (2017). Experimental study on the removal of VOCs and PAHs by zeolites and surfactant-modified zeolites. *Energy & Fuels.* https://doi.org/10.1021/acs.energyfuels.7b01124

Yue, F., Yi, Y., Wang, Y., Diao, Y., Diao, Z.-H., & Zhenguo, C. (2025). A comparative review of modified biochar-based advanced oxidation process for environmental pollution remediation: Efficiency, mechanism, toxicity assessment. *Journal of Environmental Management, 387*, 125872. https://doi.org/10.1016/j.jenvman.2025.125872