J. Mater. Environ. Sci., 2025, Volume 15, Issue 5, Page 881-893

Journal of Materials and Environmental Science ISSN : 2028-2508 e-ISSN : 2737-890X CODEN : JMESCN Copyright © 2025, University of Mohammed Premier Oujda Morocco

http://www.jmaterenvironsci.com



Adsorption of cationic and anionic dyes in single and binary systems using activated carbon derived from agricultural waste

¹Musa Husaini* and ²Muhammad Bashir Ibrahim

¹Department of Pure and Industrial Chemistry, Faculty of Physical Sciences College of Natural and Pharmaceutical Sciences, Bayero University Kano (BUK), P.M.B. 3011, Kano, Nigeria

²Department of Pure and Industrial Chemistry, Faculty of Physical Sciences College of Natural and Pharmaceutical Sciences, Bayero University Kano (BUK), P.M.B. 3011, Kano, Nigeria

*Corresponding author, Email address: <u>musahusaini36@gmail.com</u>

Received 14 Mar 2025, **Revised** 28 Apr 2025, **Accepted** 29 Apr 2025

Keywords:

✓ Adsorption;

✓ Anionic dye;

✓ Cationic dye;
✓ Binary system;

✓ *Kinetics*;

Kinetics,
 Thormodynamics

✓ Thermodynamics;

Citation: Husaini, M. and Ibrahim, M. B. (2025). Adsorption of cationic and anionic dyes in single and binary adsorption of cationic and anionic dyes onto activated carbon derived from agricultural waste. J. Mater. Environ. Sci., 16(5), 881-893

Abstract: Single and competitive studies were conducted to investigate the elimination of positively charged methylene blue (MB) and negatively charged methyl orange dye using activated carbon sourced from sweet detar seed shells. The adsorbent properties were analyzed using scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and pH point of zero charge (pHpzc) analysis. Various factors like pH (2-12), contact time (5 - 150)minutes), adsorbent weight (0.1 - 0.7 g), initial concentration (20 - 500 mg/L) and temperature (303 – 323 K), were examined for their influence on the adsorption process. The experimental findings showed that optimal dye adsorption occurred at pH of 2 and 12 for anionic MO and cationic MB dye, with equilibrium achieved after 60 minutes for both dyes. Competitive adsorption revealed higher adsorption capacities than single adsorption, suggesting synergistic interaction. Mathematical models were used to analyse isotherms and kinetics, with the pseudo-second order model fitting the kinetics data well. The equilibrium data aligned with the Freundlich model, representing dye uptake onto the adsorbent. Thermodynamic analysis indicated that the adsorption was a spontaneous and exothermic process.

1. Introduction

Numerous synthetic dyes have been employed across the textile, pharmaceutical, and food industries. However, discharging the wastewater from these industries poses a significant risk to both human health and the environment. Therefore, it is essential to eliminate dye pollutants from aqueous solutions (Chan *et al.*, 2017; Akartasse *et al.*, 2022; N'diyae *et al.*, 2022; Kusumlata *et al.*, 2024). Among several techniques available for this purpose, including ion exchange and membrane filtration, adsorption stands out as the most commonly used method. Various adsorbents, including activated carbons, biological adsorbents, biomaterials and polymeric adsorbents, have been extensively utilized to remove dyes from aqueous solutions (Elharti *et al.*, 2012; Yahyaei and Azizian 2014; Aaddouz *et al.*, 2023; Abouri *et al.*, 2024). Using cost-effective and waste agricultural materials as adsorbents has emerged as a practical solution for treating contaminated water. Researchers worldwide have shown significant interest in utilizing activated carbon derived from agricultural waste for wastewater treatment (Santhi *et al.*, 2014). Recent studies have demonstrated that different agricultural material

containing varying amounts of unburned carbon can function as activated carbon, effectively adsorbing various pollutants from aqueous solutions (Dhahri *et al.*, 2023; Blachnio *et al.*, 2020; Rohilla *et al.*, 2018). Indeed, real wastewater systems often contain a combination of cationic and anionic dyes, and interactions between different dyes may occur during the adsorption process (Guo *et al.*, 2018). Consequently, researching multi-component adsorption poses a significant challenge compared to single-component adsorption (Idan *et al.*, 2017). While a considerable amount of research data exists on single-component adsorption, there is limited literature available on the topic of multi-component adsorption (Jayalakshmi *et al.*, 2019). Thus, there is a pressing need to develop cost-effective adsorbents that can effectively handle multiple contaminants due to their widespread occurrence in real industrial waste (Zhang *et al.*, 2019).

Therefore, the primary objective of this research is to investigate the simultaneous adsorption of multiple dyes, namely Methylene blue (MB) and methyl orange (MO), from a binary dye solution using an adsorbent sourced from inexpensive materials. By doing so, this study aims to address the challenges associated with treating complex mixtures of pollutants and pave the way for more efficient and economical methods of water purification. Sweet data seed shell activated carbon was utilized as an adsorbent for both individual and simultaneous removal of dyes from aqueous solutions.

2. Methodology

2.1 Adsorbent Preparation

The adsorbent sample was prepared following the method described by Husaini *et al.* (2023a). Sweet detar seed shell samples were collected, cleaned with tap-water to remove any impurities, and dried for 72 hours. The dried sample was ground into granules and soaked in a 30% phosphoric acid solution for 24 hours. Afterward, it was dried before undergoing carbonization at 400°C for 2 hours in a furnace. The activated samples were washed with distilled water until they reached a neutral pH and then dried in an oven at 105°C until a constant weight was achieved. Finally, the sample was sieved, and the resulting material was stored in an air-tight container prior to experiment.

2.2 Adsorbent Characterization

Various analytical techniques were employed to examine the surface morphology and chemical characteristics of the sample. The adsorbent's FTIR spectra were recorded using an FTIR spectrophotometer (Cary 630; Agilent Technologies) in the range of 4000-600 cm⁻¹ (Husaini *et al.*, 2020). Additionally, SEM images of the samples were taken using a scanning electron microscope (PRO: X: Phenonm World 800-07334) at an acceleration voltage of 10 kv and 500x enlargement (Husaini and Ibrahim 2019). To understand the distribution of charges on the adsorbent surface, the pH of the zero charge point (pH_{pzc}) was determined using the salt addition method (Bakatula *et al.*, 2018).

2.3 Chemicals

In this study, all chemicals utilized were of analytical-grade and were used as they were without additional purification. The adsorbate employed consisted of a mixture of two dyes: MB and MO purchased from Sigma Aldrich. The chemical structures of these dyes are illustrated in Figure 1. These dyes were acquired in their commercial purity and used without any further purification. Methylene blue and methyl orange dyes were selected as the model adsorbates for this study, in order to assess the effectiveness of sweet detar seed shell as a natural adsorbent.



Figure. 1: Structure of (a) Methylene blue (b) Methyl orange

2.4 Adsorbate Preparation

To prepare stock solutions of each dye, 1g of the respective dye was dissolved in 1 liter distilled water, resulting in a concentration of 1000 mg/L. The binary dye solution, consisting of MB and MO, was also prepared in the same manner, with a mass ratio of 1:1. From the stock solution, experimental solutions of lower concentrations were subsequently generated through successive dilution. These solutions were used for constructing the calibration curve and conducting adsorption studies.

2.5 Adsorption Experiments

The adsorption experiments were conducted in batch mode by mixing a specified dose of the adsorbent with 50 ml of dye solution in Erlenmeyer flasks. These flasks were then shaken at 200 rpm at a specific temperature using an incubator shaker (New Brunswick Scientific; Innova 4000). The initial solution pH was adjusted to the desired value using 0.1 M HCl and 0.1 M NaOH. Various operating variables were investigated in individual experiments, including the weight of the adsorbent (ranging from 0.1 to 0.7 g), initial dye concentration (ranging from 20 to 500 mg/L), contact time (ranging from 5 to 150 minutes), pH (ranging from 2 to 12), particle size (ranging from 75 to 900 μ m) and temperature (ranging from 30 to 50°C). After predetermined time intervals, the adsorbent was separated through filtration using filter paper (Whatman No. 1). The concentration of unadsorbed dye in the filtrate was analyzed using a UV-Vis spectrophotometer (Perkin Elmer; Labda 35) at the absorption maxima of 664.20 nm and 464.5 nm for MB and MO respectively. For the binary dye system, the experimental procedures and conditions used were the same as those described for the single dye systems. The experiments were replicated three times, and the presented results are the averages. The amount of dye adsorbed at equilibrium, qe (mg/g) and percentage removal were calculated using equation 1 and 2 (Husaini *et al.*, 2023b and c).

$$qe = \frac{(C_0 - C_e) \times v}{m}$$
 Eqn. 1
R (%) = $\frac{C_0 - C_e}{C_0} \times 100$ Eqn. 2

Where Co and Ce (mg/L) represent the initial and final dye concentrations, respectively. V (L) represents the volume of the dye solution, and m (g) is the mass of the adsorbent.

3. Results and Discussion

3.1 Adsorbent Characterization

The surface texture and porosity of the adsorbent material were examined using SEM, which provided important insights of adsorbent morphological structure. Figure 2a shows the irregular and porous structure of the adsorbent. However, after MB and MO adsorption (Figures 2b and 2c), the porous surfaces appeared to decrease, indicating that the dye molecules were accommodated within the adsorbent pores. To further understand the activated carbon's surface functionalities, FTIR analysis

was conducted (Figure 3a). The presence of peaks at various wave numbers suggested the existence of various functional groups in the adsorbent as presented in Table 1. Notably, the spectra after adsorption exhibited significant changes in the occurrence or position of some peaks, which may indicate interactions between the dye molecules and the adsorbent surface (Giwa *et al.*, 2015).



Figure 2. SEM Micrograph for (a) SDAC (b) SDAC-MB (c) SDAC-MO



Figure 3. FT-IR spectra SDAC before and after Adsorption of MB and MO

Tabla	1 Eunstianal	anoun oha	much hafam	and often	adagention	of adapthatas	onto CDAC
rame	I. FUNCTIONAL	2100000008	rived before		ausorbuon	or ausorbales	OHIO SDAU
		0					

Vibrati	onal Frequenc	cies	
Before	MB-loaded	MO-loaded	Functional Groups
Absorption			
3651	3633	3677	O-H stretching vibration in alcohol (3700-3584)
2910	2851	2905	C-H stretching vibration in alkane (3000-2840)
2248	2260	2250	$C \equiv C$ stretching vibration in alkyne (2260-2100)
2117	2199	2113	$C \equiv C$ stretching vibration in alkyne (2260-2190)
1704	1794	1701	C = O stretching of carboxylic acid (1720-1706)
1685	1680	1681	C = O stretching of ketone (1685-1666)
1550	1547	1547	N-O stretching of nitro groups (1550-1500)
1110	1130	1115	C-O stretching of alcoholic groups (1124-1087)
873	863	878	C-H bending vibration of 1,3-disubstituted
			(880±20)
747	750	745	C-H bending vibration of monosubstituted
			(750±20)

3.2 Adsorption Studies

3.2.1 Influence of Contact Time

As the adsorption process depends on time, it is essential to explore how quickly substances are adsorbed in the design of the process. Faster adsorption rates lead to lower operational costs, making the adsorbent more suitable for large-scale applications (Istratie *et al.*, 2019). To determine the optimal time required to maximize the removal of dye molecules and understand the adsorption kinetics, the impact of the contact time between the adsorbates and adsorbent was investigated. Figure 4a illustrates that the adsorption capacity increases for both individual and binary systems as the contact time between the adsorbent increases. This is because longer contact time allows the dye molecules to establish stronger bonds with the adsorbent (Mahaninia *et al.*, 2015).

The graph indicates that the increase in adsorption capacity becomes insignificant after 60 minutes for MB and MO. Therefore, 60 minutes was defined as the equilibrium time for the respective dyes, and this equilibrium time was the same in both systems. Figure 4a also suggests that the sorption of dyes follows a three-step mechanism. In the early rapid step, numerous vacant sites on the adsorbent are accessible for dye uptake. In the later, slower step, the movement of dyes into the pores creates repulsion between the dye molecules on the solid and the bulk phases. Finally, in the equilibrium step, the removal process nearly stops because no vacant sites are available on the adsorbent to accommodate additional adsorbates (Mokkapati *et al.*, 2016).



Figure 4. (a) Influence of Time (b) Influence of Concentration

3.2.2 Influence of Initial Concentration

The initial concentration of the adsorbate plays a crucial role in determining the diffusion and mass transfer dynamics of dye sorption onto the adsorbent. Figure 4b illustrates the impact of the initial concentration on the removal efficiency of the adsorbates. Higher initial concentration provides the necessary driving force to overcome mass transfer resistance for the transport of dyes between the aqueous phase and the surface of adsorbent (Duran *et al.*, 2011). As observed from the plot, the percentage of the dyes removed decreases due to the saturation point of the adsorbent that limit its capacity to adsorb more dye molecule, this results in lower percentage removal compared to the cases with lower initial concentrations (Husaini *et al.*, 2024a).

3.2.3 Impact of Adsorbent Weight

The quantity of adsorbent used in the adsorption process is essential as it determines the adsorbentadsorbate ratio and also affects cost considerations (Wanyonyi *et al.*, 2014). The variation in the percentage of dyes remove with different adsorbent weights in both single and binary solutions is presented in Figure 5a. The results indicated that the percentage removal increase as the adsorbent dose increased until it reached optimum at 0.6 g and later decreased. The increase in percentage removal with an increase in adsorbent weight suggests that more actives sites become available for dye molecules to be adsorbed, resulting in increased removal efficiency (Cheruiyot *et al.*, 2019; Yunusa *et al.*, 2021).



Figure 5. (a) Impact of Dosage (b) Influence of pH

3.2.4 Influence of Solution pH

MB and MO are cationic and anionic dyes existing as positive and negative charged ions in aqueous environments. Consequently, the extent of their adsorption is mainly governed by the net surface charge on the adsorbent, which is influenced by the solution pH. The impact of solution pH on the uptake of dyes is illustrated in Figure 5b. It was observed that the adsorption capacity increased with higher solution pH for cationic dye and lower pH for anionic dye. The maximum uptake of MB occurred at higher pH while that of MO at lower pH in both single and binary systems. This indicates that the adsorption of dye cations is favored under basic pH conditions while that of anionic at acidic pH condition (Husaini *et al.*, 2023d and e). This phenomenon can be better understood through the characteristic known as the pH of the point of zero charge (pH_{pzc}) of the adsorbent, which was determined to be 6.9 and 5.9 (Figure 6). At pH > pH_{pzc} (6.9) upon base activation, the adsorbent surface becomes deprotonated due to the presence of excess hydroxyl ions, resulting in an enhanced affinity between the dye cations and the negatively charged surface of the adsorbent through electrostatic attraction, leading to maximum uptake of MB dye. Conversely, at pH < pH_{pzc} (5.9) upon acid activation, the adsorbent surface becomes positively charged due to the protonation of the adsorbent surface, resulting in rapid MO dye adsorption (Banerjee *et al.*, 2016).





3.3 Adsorption Kinetics

To examine the dynamic sorption behavior of the dyes on adsorbent, the pseudo first-order and pseudo second-order models were utilized to simulate the kinetic data, expressed by Equations 3 and 4 respectively.

$$\ln (q_e - q_t) = \ln q_e - k_1 t$$
Eqn. 3
$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$
Eqn. 4

Where qt and qe represent the amount of dyes adsorbed on the adsorbent at any instance t and at equilibrium, respectively, while k_1 and k_2 are the corresponding rate constants.

Based on the interrelationship coefficient (\mathbb{R}^2), the kinetic data showed a better fit to the pseudo second-order model than the pseudo first-order model for all the dye systems (Figures 7a and b). The kinetic parameters are summarized in Table 2. Notably, the predicted qe values align closely with the experimental values for the pseudo second-order model. The rate constant, k_2 , for MB and MO in binary dye systems is higher than that for mono-adsorbate systems, indicating a synergistic effect in the adsorption system. Additionally, the rate constant for MB is higher than that for MO in both single and binary dye systems, indicating that the adsorption process for MB is faster than for MO in both mono- and binary-dye solutions (Luo *et al.*, 2015).



Figure 7. (a) Pseudo first order (b) Pseudo second order Plot

Kinetic Model	Parameters	MB	MB(MB+MO)	MO	MO(MO+MB)
Pseudo-first order	$k_1 \times 10^{-2} \text{ (min}^{-1}\text{)}$	0.20	3.00	0.30	2.10
	$q_{e exp} (mg/g)$	9.78	9.81	9.52	9.90
	$q_{e cal} (mg/g)$	0.63	0.79	0.60	1.19
	\mathbb{R}^2	0.0316	0.4458	0.6166	0.6528
Pseudo-second order	$K_2 \times 10^{-2} (g/mg min)$	8.00	13.00	7.80	8.16
	$q_{e \exp} (mg/g)$	9.78	9.81	9.52	9.90
	$q_{e cal} (mg/g)$	9.89	9.82	9.62	9.90
	\mathbb{R}^2	1.0000	0.9998	0.9999	0.9998

3.4 Adsorption Isotherms

The adsorption isotherms are essential for understanding the interaction of sorbate molecules on the adsorbent surface. In this study, the Langmuir and Freundlich isotherm models were used to analyze both systems and their linear forms are represented by Equations 5 and 6:

$$\frac{1}{q_e} = \frac{1}{q_{max}K_LC_e} + \frac{1}{q_{max}}$$
 Eqn. 5

 $\ln q_e = \ln K_f + \frac{1}{n} \ln C_e$

Eqn. 6

Here, qe (mg/g) and Ce (mg/L) represent the dye uptake and concentration at equilibrium, respectively. q_{max} (mg/g) and K_L (L/mg) are Langmuir isotherm constants that express the maximum adsorption capacity and adsorption free energy, respectively. K_F (L/mg) and n are the Freundlich isotherm constants providing information about adsorption capacity and adsorption yield, respectively.

The characteristic parameters of the Freundlich and Langmuir models are summarized in Table 3. Based on the interrelationship coefficients, it is evident that the Freundlich model fits the experimental data quite well for all the dyes. This implies that: (a) The adsorbent surface is heterogeneous; (b) The adsorption sites on the adsorbent are not energetically equivalent; (c) The adsorbed dye molecules are organized as a multilayer; and (d) There are interactions between the adsorbed dye molecules (Husaini *et al.*, 2024b; Rabiu *et al.*, 2023). The Freundlich constant, n, provides information about the favorability of the process. When the value of n > 1 or n < 1, it indicates that the adsorption is associated with a favorable physical or chemical process, respectively. In all the systems studied, the value of n is > 1, indicating convenient physical adsorption.

System	La	Freundlich Parameters					
	q _m (mg/g)	$K_L(L/mg)$	R_L	\mathbb{R}^2	K _F (L/mg)	n	\mathbb{R}^2
MB	81.30	0.33	0.13	0.9534	2.30	1.92	0.9946
MB(MB+MO)	65.79	0.84	0.06	0.8979	20.77	2.08	0.9963
MO	96.15	7.25	0.01	0.9757	12.30	1.72	0.9927
MO(MO+MB)	60.98	1.12	0.04	0.8740	20.73	2.08	0.9897

 Table 3. Adsorption Isotherm Parameters

3.5 Adsorption Thermodynamics

Thermodynamic parameters such as changes in enthalpy (Δ H), entropy (Δ S), and Gibbs free energy (Δ G) are essential for understanding the nature of any adsorption process. These parameters were calculated to assess the spontaneity, thermal characteristics, and favorability of the sorption. Equations (7-9) were used to evaluate their values under the employed experimental conditions:

$\Delta G = \Delta H - T \Delta S$	Eqn. 7
$\Delta G = -RT lnKc$	Eqn. 8
$\mathrm{Kc} = \frac{C_{ads}}{C_{e}}$	Eqn. 9

Here, C_{ads} and Ce (mg/dm³) are the dyes equilibrium concentration on the adsorbent and in the liquid phase. K_c is constant for adsorption equilibrium, R is the universal gas constant (8.314 j/ mol K), and T is the absolute temperature in kelvin (K). Equation 7 was used to obtain the ΔG values at different temperatures.

The graph in Figure 8 was utilized to assess the magnitudes of ΔS and ΔH . The estimated values for ΔG , ΔH , and ΔS during the adsorption of dyes by the adsorbent were recorded in Table 4.



The negative ΔG values indicated that the sorption process was spontaneous and thermodynamically favorable. Moreover, the spontaneity of the process decreased with higher temperatures. The ΔG values obtained fall within the range for physisorption processes (-20 to 0 kJ/mol) rather than chemisorption processes (-80 to 400 kJ/mol). The negative ΔH value suggests that the process was exothermic, while the negative ΔS values indicate the decrease in order of the dye molecules on the adsorbent surface (Adeyemo *et al.*, 2017; Akazdam *et al.*, 2017; Husaini *et al.*, 2019; Vojnović *et al.*, 2023; Nogueira *et al.*, 2023).

	•						
System	- ΔH	- ΔS	$-\Delta G (kJ/mol)$				
	(kJ/mol)	(J/K)	303 K	308 K	313 K	318 K	323 K
MB	73.32	217.73	7.570	6.485	5.400	4.315	3.230
MB(MB+MO)	11.79	295.18	8.678	7.203	5.728	4.253	2.778
MO	54.63	159.42	6.451	5.656	4.861	4.066	3.271
MO(MO+MB)	1.517	382.62	10.415	8.542	6.632	4.722	2.812

 Table 4. Thermodynamic Parameters

3.6 Co-adsorption Behavior of Dyes

Combining cationic MB and anionic MO dyes in the binary solution leads to a mutually beneficial enhancement in percentage removal. The uptake of both dyes rises significantly across various initial pH levels compared to single dye systems. This synergy suggests that pollutant removal is aided by forces beyond simple adsorbent and adsorbate interactions. The smaller and lighter MB molecule has higher mobility and easier access to the negative adsorbent surface. At different pH levels, the presence of MB molecules attracts MO molecules, leading to a notable increase in uptake capacity. The self-association of MB contributes to a push-pull mechanism for MO removal (Piccin *et al.* 2012).

Conclusion

The adsorption of methylene blue (MB) and methyl orange (MO) onto sweet detar seed shell activated carbon was examined in both individual and combined systems. The optimal conditions for achieving maximum dye uptake were determined as follows: pH of 2 and 12 for MO and MB dye, adsorbent weight of 0.5 g, contact time of 60 minutes, and a temperature of 303K. The sorption kinetics aligned with the pseudo second order model. Equilibrium data indicated that the Freundlich model was suitable for describing dye uptake onto the adsorbent. Thermodynamic analysis demonstrated that the

adsorption process was spontaneous and exothermic. In the binary system, the relative adsorption capacity pointed to synergistic mechanism. the findings confirmed that sweet detar seed shell activated carbon is a viable alternative adsorbent for removing cationic and anionic dye from aqueous solutions.

Acknowledgement: Department of Pure and Industrial Chemistry, Bayero University Kano is acknowledged. Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest. *Compliance with Ethical Standards:* This article does not contain any studies involving human or animal subjects.

References

- Aaddouz M., Azzaoui K., Akartasse N., Mejdoubi E., et al., (2023). Removal of Methylene Blue from aqueous solution by adsorption onto hydroxyapatite nanoparticles, Journal of Molecular Structure, 1288, 135807, <u>https://doi.org/10.1016/j.molstruc.2023.135807</u>
- Abouri M., Benzaouak A., Zaaboul F., Sifou A., et al. (2024). Efficient Catalytic Reduction of Organic Pollutants Using Nanostructured CuO/TiO₂ Catalysts: Synthesis, Characterization, and Reusability. *Inorganics*. 12(11), 297. <u>https://doi.org/10.3390/inorganics12110297</u>
- Adeyemo, A.A., Adeoye, I.O. & Bello, O.S. Adsorption of dyes using different types of clay: a review. *Appl. Water Sci.*, 7, 543–568 (2017). <u>https://doi.org/10.1007/s13201-015-0322-y</u>
- Akartasse N., Azzaoui K., Mejdoubi E., et al. (2022), Environmental-Friendly Adsorbent Composite Based on Hydroxyapatite/Hydroxypropyl Methyl-Cellulose for Removal of Cationic Dyes from an Aqueous Solution, Polymers, 14(11), 2147; https://doi.org/10.3390/polym14112147
- Akazdam S., Chafi M., Yassine W., Gourich B. (2017), Removal of Acid Orange 7 Dye from Aqueous Solution Using the Exchange Resin Amberlite FPA-98 as an Efficient Adsorbent: Kinetics, Isotherms, and Thermodynamics Study, J. Mater. Environ. Sci. 8 (8), 2993-3012
- Bakatula E. N., Richard D., Neculita C. M., & Zagury G. J. (2018). Determination of point of zero charge of natural organic materials. *Environmental Science and Pollution Research*, 25(8), 7823–7833. https://doi.org/10.1007/s11356-017-1115-7
- Banerjee S., Sharma G. C., Gautam R. K., *et al.* (2016). Removal of Malachite Green, a hazardous dye from aqueous solutions using Avena sativa (oat) hull as a potential adsorbent. *Journal of Molecular Liquids*, 213, 162–172. https://doi.org/10.1016/j.molliq.2015.11.057
- Blachnio M, Derylo-Marczewska A, Charmas B, Zienkiewicz-Strzalka M, Bogatyrov V, Galaburda M. (2020). Activated Carbon from Agricultural Wastes for Adsorption of Organic Pollutants. *Molecules*. 25(21), 5105. <u>https://doi.org/10.3390/molecules25215105</u>
- Chan L., Cheung W., Allen S., & McKay G. J. H. (2017). Equilibrium adsorption isotherm study of binary basic dyes onto bamboo-derived activated carbon. *HKIE Transactions*, 24(4), 182– 192. https://doi.org/10.1080/1023697X.2017.1348283
- Cheruiyot G. K., Wanyonyi W. C., Kiplimo J. J., & Maina E. N. (2019). Adsorption of toxic crystal violet dye using coffee husks: equilibrium, kinetics, and thermodynamics study. *Scientific African*, 5(11), 62–71. https://doi.org/10.1016/j.sciaf.2019.e00109
- Dhahri R., Ben Mosbah M., Khiari R., et al. (2023). Activated Carbon from Agricultural Waste for the Removal of Pollutants from Aqueous Solution. In: Khiari R., Jawaid M., Belgacem M.N. (eds) Annual Plant: Sources of Fibres, Nanocellulose and Cellulosic Derivatives. Composites Science and Technology. Springer, Singapore. <u>https://doi.org/10.1007/978-981-99-2473-8_16</u>
- Duran C., Ozdes D., Gundogdu A., & Senturk H. B. (2011). Kinetics and isotherm analysis of basic dyes adsorption onto almond shell (Prunus dulcis) as a low-cost adsorbent. *Journal of Chemical & Engineering Data*, 56(5), 2136–2147. https://doi.org/10.1021/je101243m

- Elharti M., Legrouri K., Khouya E., Hannache H., Fakhi S., *et al.* (2012), Preparation of Adsorbent Material from Moroccan Oil Shele of Timahdit: Optimization of Parameters Processes and Adsorption Tests, *Der Pharma Chemica*, 4(5), 2130-2139
- Giwa A. A., Oladipo M. A., & Abdulsalam K. A. (2015). Adsorption of Rhodamine B from single, binary, and ternary dye systems using sawdust of Parkia biglobosa as adsorbent: isotherm, kinetics, and thermodynamics studies. *Journal of Chemical and Pharmaceutical Research*, 7(2), 454–475. https://doi.org/10.13140/RG.2.1.3475.3366
- Guo H., Bi C., Zeng C., Ma W., Yan L., Li K., & Wei K. (2018). Camellia oleifera seed shell carbon as an efficient renewable bio-adsorbent for the adsorption removal of hexavalent chromium and methylene blue from aqueous solution. *Journal of Molecular Liquids*, 249, 629–636. https://doi.org/10.1016/j.molliq.2017.11.084
- Husaini M. B., Ibrahim M. B. (2019). Thermodynamic and kinetic study on the corrosion of aluminium in hydrochloric acid using benzaldehyde as corrosion inhibitor. *International Journal of Engineering and Manufacturing*, 9(6), 53–64. https://doi.org/10.5815/ijem.2019.06.06
- Husaini M., Usman B., & Ibrahim M. B. (2019). Inhibitive effect of glutaraldehyde on the corrosion of aluminum in hydrochloric acid solution. *Journal of Science and Technology*, 11(2), 8–16. https://doi.org/10.1016/j.scitec.2019.02.003
- Husaini M., Usman B., & Ibrahim M. B. (2023a). Adsorption studies of methylene blue using activated carbon derived from sweet detar seed shell. *ChemSearch Journal*, 14(1), 21–32. https://doi.org/10.4314/csj.v14i1.3
- Husaini M., Usman B., Ibrahim M.B. (2023b). Combined computational and experimental studies for the removal of anionic dyes using activated carbon derived from agricultural waste. *Applied J. Environ. Engin. Sci.*, 9(4), 245–258. https://doi.org/10.1080/20421338.2023.2162345
- Husaini M., Usman B., & Ibrahim M. B. (2023c). Competitive adsorption of Congo red dye from aqueous solution onto activated carbon derived from black plum seed shell in single and multicomponent system. *African Journal of Management and Engineering Technology*, 1(2), 76–89. https://doi.org/10.11648/j.ajmet.20230102.11
- Husaini M., Usman B., & Ibrahim M. B. (2023d). Kinetic and thermodynamic evaluation on removal of anionic dye from aqueous solution using activated carbon derived from agricultural waste: equilibrium and reusability studies. *Applied Journal of Environmental Engineering Science*, 9, 124–138. https://doi.org/10.1080/20421338.2023.2162346
- Husaini M., Usman B., Ibrahim M.B. (2023e) Modeling and equilibrium studies for the adsorption of Congo red using Detarium microcarpum seed shell activated carbon. *Applied Journal of Environmental Engin. Sci.*, 9, 147–162. https://doi.org/10.1080/20421338.2023.2180251
- Husaini M., Usman B., & Ibrahim M. B. (2023f). Thermodynamic and equilibrium evaluation for anionic dye adsorption using utilized biomass-based activated carbon: regeneration and reusability studies. Arabian Journal of Chemical and Environmental Research, 10(1), 1–116. https://doi.org/10.1007/s44153-023-00007-w
- Husaini M., Usman B., & Ibrahim M. B. (2024a). Biosorption of methyl orange dye in single, binary, and ternary systems onto gingerbread plum seed shell activated carbon. *Journal of the Turkish Chemical Society*, 11(2), 655–664. https://doi.org/10.18596/jotcs.1179829
- Husaini M., Usman B., & Ibrahim M. B. (2024b). Experimental and quantum chemical evaluation for methylene blue adsorption onto activated carbon. *African Journal of Management and Engineering Technology*, 2(1), 51–62. https://doi.org/10.11648/j.ajmet.20240201.14

- Husaini M., Usman B., Ibrahim M. A., & Ibrahim M. B. (2020). Effect of aniline as corrosion inhibitor on the corrosion of aluminium in hydrochloric acid solution. *Research Journal of Chemical* and Environmental, 24(2), 99–106. https://doi.org/10.21303/2304-2237.2020.003175
- Idan I. J., Abdullah L. C., Mahdi D. S., Obaid M. K., & Jamil S. N. A. B. M. (2017). Adsorption of anionic dye using cationic surfactant-modified kenaf core fibers. *Open Access Library Journal*, 4(07), 1–18. https://doi.org/10.4236/oalib.1104195
- Istratie R., Stoia M., Păcurariu C., & Locovei C. (2019). Single and simultaneous adsorption of methyl orange and phenol onto magnetic iron oxide/carbon nanocomposites. *Arabian Journal of Chemistry*, 12(8), 3704–3722. https://doi.org/10.1016/j.arabjc.2017.09.004
- Jayalakshmi R., & Jeyanthi J. (2019). Simultaneous removal of binary dye from textile effluent using cobalt ferrite-alginate nanocomposite: performance and mechanism. *Microchemical Journal*, 145, 791–800. https://doi.org/10.1016/j.microc.2019.03.032
- Kusumlata, Ambade B., Kumar A., Gautam S. (2024). Sustainable Solutions: Reviewing the Future of Textile Dye Contaminant Removal with Emerging Biological Treatments. *Limnological Review*. 24(2), 126-149. <u>https://doi.org/10.3390/limnolrev24020007</u>
- Luo X., Zhang Z., Zhou P., Liu Y., Ma G., & Lei Z. (2015). Synergic adsorption of acid blue 80 and heavy metal ions (Cu²⁺/Ni²⁺) onto activated carbon and its mechanisms. *Journal of Industrial and Engineering Chemistry*, 27, 164–174. https://doi.org/10.1016/j.jiec.2015.04.019
- Mahaninia M. H., Rahimian P., & Kaghazchi T. (2015). Modified activated carbons with amino groups and their copper adsorption properties in aqueous solution. *Chinese Journal of Chemical Engineering*, 23(1), 50–56. https://doi.org/10.1016/j.cjche.2014.10.010
- Mokkapati R. P., Mokkapati J., & Ratnakaram V. N. (2018). Kinetic, isotherm and thermodynamics investigation on adsorption of divalent copper using agro-waste biomaterials, Musa acuminata, Casuarina equisetifolia L. and Sorghum bicolor. *Polish Journal of Chemical Technology*, 18(2), 68–77. https://doi.org/10.2478/pjct-2018-0010
- N'diaye A.D., Kankou M.S.A., Hammouti B., Nandiyanto A.B.D., Al Husaeni D.F. (2022). A review of biomaterial as an adsorbent: From the bibliometric literature review, the definition of dyes and adsorbent, the adsorption phenomena and isotherm models, factors affecting the adsorption process, to the use of typha species waste as adsorbent. *Communications in Science and Technology*, 7(2), 140-153. https://doi.org/10.21924/cst.7.2.2022.977
- Nogueira D. Ad. R., Zanela T.M.P., Machado M.V., Almeida C.A.P., Marangoni R. (2023) Adsorption Process of Methyl Orange Dye onto Zinc Hydroxide Nitrate: Kinetic and Thermodynamic Studies. *Colorants*, 2(3), 565-577. <u>https://doi.org/10.3390/colorants2030028</u>
- Piccin J., Gomes C., Feris L., Utterres M. (2012). Kinetics and isotherms of leather dye adsorption by tannery solid waste. *Chem. Engin. J.*, 183, 30–38. https://doi.org/10.1016/j.cej.2012.01.072
- Rabiu M. A., Husaini M., Usman B., & Ibrahim M. B. (2023). Adsorption of basic magenta dye from aqueous solution using raw and acid-modified yam peel as adsorbent. *Bayero Journal of Pure* and Applied Sciences, 14(1), 460–466. https://doi.org/10.4314/bajopas.v14i1.78
- Rohilla L., Garg V., Mallick S., & Setia G. (2018). An experimental investigation on the effect of particle size into the flowability of fly ash. *Powder Technology*, 330, 164–173. https://doi.org/10.1016/j.powtec.2017.10.051
- Santhi T., Prasad A.L., Manonmani S. (2014) A comparative study of microwave and chemically treated Acacia nilotica leaf as an eco-friendly adsorbent for the removal of rhodamine B dye from aqueous solution. *Ar. J. Chem.*, 7(4), 494–503. https://doi.org/10.1016/j.arabjc.2013.10.016

- Vojnović B., Cetina M., Franjković P., Sutlović A. (2022) Influence of Initial pH Value on the Adsorption of Reactive Black 5 Dye on Powdered Activated Carbon: Kinetics, Mechanisms, and Thermodynamics. *Molecules*. 27(4), 1349. <u>https://doi.org/10.3390/molecules27041349</u>
- Wanyonyi W. C., Onyari J. M., & Shiundu P. M. (2014). Adsorption of Congo red dye from aqueous solutions using roots of Eichhornia crassipes: kinetic and equilibrium studies. *Energy Procedia*, 50, 862–869. https://doi.org/10.1016/j.egypro.2014.06.109
- Yahyaei B., Azizian S. (2014). Rapid adsorption of binary dye pollutants onto the nanostructured mesoporous alumina. J. Molec. Liq., 199, 88–95. https://doi.org/10.1016/j.molliq.2014.08.007
- Yunusa U., Husaini M., Ibrahim A. K., Abdullahi Y., & Abdullahid T. (2021). Hexavalent chromium removal from simulated wastewater using biomass-based activated carbon. *Algerian Journal* of Engineering and Technology, 4, 030–044. https://doi.org/10.5281/zenodo.5571755
- Zhang X., Qin C., Gong Y., Song Y., et al. (2019). Co-adsorption of an anionic dye in the presence of a cationic dye and a heavy metal ion by graphene oxide and photoreduced graphene oxide. RSC Advances, 9(10), 5313–5324. https://doi.org/10.1039/C8RA10163A

(2025); <u>http://www.jmaterenvironsci.com</u>