Applications of Copper and Iron Oxide Nanoparticles for Ampicillin Antibiotic Removal from Wastewater

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***Abstract*—In the present study, copper oxide (CuO) and iron oxide (FeO) nanoparticles were employed as adsorbent materials for the removal of ampicillin from aqueous solutions. Experimental observations indicated that both nanoparticles exhibited significant adsorption potential toward ampicillin. The maximum adsorption capacities were calculated as 126.6 mg/g for copper oxide nanoparticles and 129.9 mg/g for iron oxide nanoparticles. Equilibrium analysis revealed that the adsorption behavior was best represented by the Freundlich isotherm model, suggesting multilayer adsorption on a heterogeneous surface. Kinetic investigations further indicated that the adsorption process is mainly controlled by a chemisorption mechanism. The removal of ampicillin is likely governed by several interactions, including surface complexation, electrostatic attraction, and hydrogen bonding between the adsorbent surface and antibiotic molecules. Thermodynamic evaluation demonstrated that the adsorption process is spontaneous and thermodynamically favorable. In addition, both CuO and FeO nanoparticles showed satisfactory regeneration ability, maintaining considerable adsorption efficiency for up to three successive reuse cycles.**

***Index Terms*—Antibiotics, copper oxide NPs, iron oxide NPs, synthesis and characterization, adorption studies.**

I. INTRODUCTION

Antibiotics are biologically active chemical substances that can originate from natural sources or be synthetically produced. These compounds are widely utilized because they are capable of destroying microorganisms or inhibiting the growth of bacteria and fungi. The worldwide consumption of antibiotics is estimated to be approximately 100,000–200,000 tons each year (Nasseh et al., 2020). Among the commonly used antibiotics, ampicillin is widely prescribed due to their broad-spectrum antimicrobial activity, affordability, and easy availability (Liu et al., 2023; Rahman & Varshney, 2021). In recent years, the global consumption of pharmaceutical compounds for the prevention and treatment of diseases in humans as well as animals has increased considerably. This growth is mainly associated with the rising occurrence of infectious and chronic health conditions (El-Bindary et al., 2022; Rahman & Raheem, 2022 a, b). Consequently, several pharmaceutical residues, including antibiotics, analgesics, and antipyretic drugs, have been frequently detected in different aquatic environments such as rivers, lakes, and groundwater sources (Elhalil et al., 2018).

Their extensive use in medical treatments results in their frequent release into the environment. A considerable fraction of these pharmaceuticals is not completely metabolized within living organisms, and the remaining residues are discharged into natural water bodies through excretion and wastewater streams. The accumulation of antibiotic residues in the environment has raised serious ecological concerns, including toxicity to aquatic organisms, possible carcinogenic effects, and the development of antibiotic-resistant microorganisms (Bal-Öztürk et al., 2021; Shurbaji et al., 2021).Several physicochemical treatment methods, such as advanced oxidation processes, membrane filtration, and adsorption, have been investigated for the removal of antibiotics from contaminated water systems (El-Bindary et al., 2020; Nguyen & Tran, 2021; Loganathan et al., 2023). Among these approaches, adsorption has gained significant attention because of its operational simplicity, cost efficiency, high removal efficiency, reusability of adsorbents, and ability to selectively remove contaminants even from complex aqueous matrices (Ngoc et al., 2021; AlHazmi et al., 2022; Rahman & Raheem, 2022).

A variety of adsorbent materials, including copper- and iron-based oxides, have been investigated for the removal of different pollutants, including antibiotics, from aquatic systems (Rahman & Raheem, 2022; Rahman & Raheem, 2023). Copper and iron oxides belong to the class of magnetic metal oxides and have attracted considerable interest due to their excellent adsorption properties and ease of separation (Kamranifar et al., 2019; Naghizadeh et al., 2020). In particular, copper oxide and iron oxide nanoparticles have gained increasing attention because of their wide applications in electronics, biomedical fields, and wastewater treatment processes as efficient adsorbent materials (Kumari et al., 2023; Salih&Mahmood, 2023). Therefore, the present study focuses on investigating the effectiveness of copper oxide and iron oxide nanoparticles for the removal of ampicillin from wastewater.

II. MATERIALS AND METHODS

Materials: All chemicals and reagents used in the experimental work were procured from Sigma Aldrich Chemicals Pvt. Ltd., India, Himedia laboratory Pvt. Ltd., SD fine-Chem Ltd, Mumbai. The antibiotic ampicillin was purchased from Yarrow Chemicals (India) with purity higher than 98%. All procured chemicals were of analytical grade. Deionised water (DW) was procured from the market. All stocks and experimental solutions were prepared using deionised water.

Preparation of antibiotic in aqueous solutions

The antibiotic used for adsorption studies in the present work wasampicicillin and commercially available as fine dust. The standard stock solutions of antibiotic were prepared (500 mg/L) by dissolving required amount of respective antibiotic from which test solution are prepared for each antibiotic by successive dilution. The solution was stored in a dry and dark place at 20^{0}C temperature for no longer than two days before use.

Batch experiments

The adsorption efficiency of the prepared nanoadsorbents was investigated by batch adsorption studies. In a conical flask (250 ML), different adsorbent dosages were agitated along with antibiotics (10-50 mg/50ml) at 150 rpm room temperature in dark condition. After attaining the equilibrium the adsorbent was separated via centrifugation and aqueous phase containing antibiotic were examined by employing UV-spectrophotometer. The parameters included different contact time (30-180 min), pH (2-8), adsorbent dosage (0.1- 1.0 gm) and initial concentrations (10-50 mg/L) were examined for their effect on antibiotic adsorption (Nasseh et al., 2019). The removal efficiency of antibiotics by prepared adsorbents is calculated according to the equations as Nasseh et al., 2019.

Adsorption isotherms

Adsorption isotherms are used to explain the relationship between the amount of adsorbate adsorbed onto the adsorbent surface (qe) and the equilibrium concentration of the adsorbate left behind in solution (Ce) at a constant temperature (Nasseh et al., 2019). Several isotherm models such as Langmuir adsorption isotherm and Freundlich adsorption isotherm have been used to explain this relationship.

Adsorption kinetics

In order to analyze the rate of adsorption of antibiotics on prepared nanoadsobents, the Lagergren first order and pseudo second order were applied to adsorption data.

Reusability Analysis

The reuse potential of the fabricated nano adsorbents was also estimated through various successive adsorptions desorption cycles for the removal of antibiotics from aqueous system. After completion of the batch adsorption experiments, the nanoadsorbents were taken out from the aqueous medium via centrifugation and cleaned with ethanol and distilled water several times, and then dried in an oven at 100°C for a few hours. The regenerated nanoadsorbents were reused in further adsorption studies to assess their performance over multiple cycles.

III. RESULTS AND DISCUSSION

Batch Experiments

Influence of Adsorbent Dose: The effect of adsorbent dosage on Ampicillin removal was examined using copper oxide and iron oxide nanoparticles doses ranging from 0.01 to 0.04 g per 50 mL of solution at per 50 mL of solution. A blank ampicillin solution without adsorbent was also analyzed to account for any possible adsorption on the container walls. All other experimental conditions were maintained constant, including pH 3.0, initial ampicillin concentration was of 10 mg L^{-1}, contact time of 60 min, and temperature of 27 ± 3°C.

For the CuO nanoparticles adsorbent, the percentage removal of ampicillin increased from 77.94% to 98.16% as the adsorbent dose was raised (Fig. 1). A similar result was observed with the iron oxide nanoparticles, where ampicillin removal percentage increased from 73.74 to 94.16%,(Fig. 2). This enhancement can be attributed to the greater availability of surface area and active adsorption sites on the nanocomposite, which promotes more effective antibiotics uptake. Beyond a dosage of 0.030 g per 50 mL, the system reached equilibrium, indicating that further increases in adsorbent amount did not result in significant improvement in ampicillin removal due to saturation of the available ampicillin and ampicillin molecules.The enhancement in antibiotic uptake with increasing adsorbent dose can be attributed to the greater availability of active surface area and a higher number of adsorption sites (Al-Musawi et al., 2023; Mahmodi sheikh sarmast, 2024).

Overall, the Copper oxide nanoparticles demonstrated superior adsorption performance compared to Iron oxide nanoparticles. This improved efficiency is likely due to the introduction of additional functional groups and binding sites on the surface of the copper and iron oxide nanoparticles, which promote stronger interactions with ampicillin.

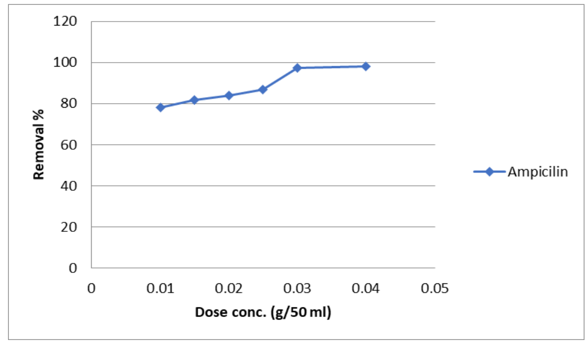

Figure1: Effect of adsorbent dose on removal of ampicillin using copper oxide nanoparticles

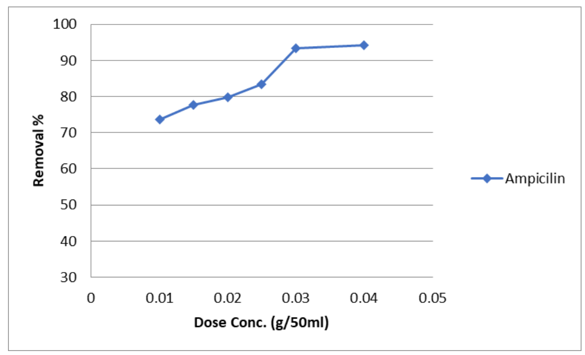

Figure2: Effect of adsorbent dose on removal of ampicillin using iron oxide nanoparticles

Influence of Initial Concentration on Its Removal: The effect of the initial ampicillin concentration on adsorption was investigated under fixed experimental conditions, including pH 3.0, temperature of 27 ± 3 °C, adsorbent dosage of 0.03 g per 50 mL, contact time of 120 min, and shaking speed of 180 rpm. The adsorption performance of CuO and Fe_2O_3 nanoparticles were evaluated over ampicillin concentration range of 10-100 mg L^{-1}. The percentage removal of ampicillin decreased noticeably with increasing initial concentration, dropping from 96.44% to 52.58% using CuOnanoparticles, however, it was 98.54% to 54.68% using Fe_2O_3 nanoparticles. The variations in removal efficiency are illustrated in Fig. 3 and 4, respectively. At lower ampicillin removal concentrations, most of the ampicillin molecules can readily occupy the available adsorption sites, leading to high removal efficiency. However, at higher concentrations, the number of ampicillin molecules exceeds the available binding sites, leaving a larger fraction of ampicillin unabsorbed in the solution, which results in a lower overall removal percentage.

This behavior can be attributed to the increasing concentration gradient, which provides a stronger mass-transfer driving force for ampicillin antibiotic molecules to move from the solution to the adsorbent surface (Mahmodi sheikh sarmast, 2024).

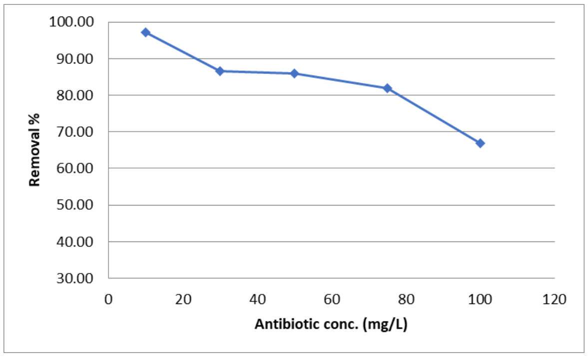

Figure3: Effect of initial antibiotic concentration on removal of ampicillin using copper oxide nanoparticles

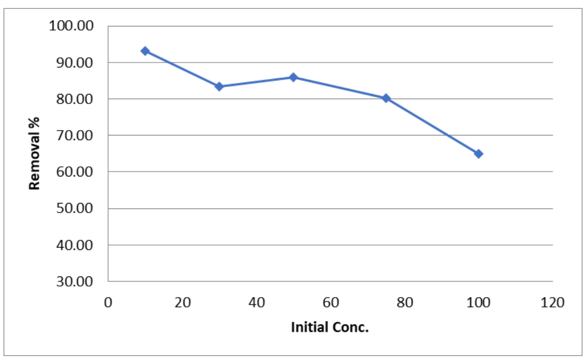

Figure 4: Effect of initial antibiotic concentration on removal of ampicillin using iron oxide nanoparticles

Contact time influence of ampicillin removal:
The effect of contact time on ampicillin adsorption was evaluated by varying the interaction period between the adsorbent and adsorbate from 30 min to 180 min under fixed experimental conditions (pH 3.0 for copper oxide nanoparticles and pH 2 for iron oxide nanoparticles, adsorbent dose 0.03 g per 50 mL, ampicillin concentration 10 mg L^{-1}, temperature 27±3 °C, and shaking speed 180 rpm). As shown in Figures 5 and 6removal of ampicillinantibiotic rapidly increased. Theampicillin removal percentage increased from 78.7 to 99.1%, during copper oxide nanoparticles used as adsorbent however ampicillin removal percentage increased from 76.2 to 98.5% during ironoxide nanoparticles used as adsorbent

At the initial stage of adsorption, a large number of vacant active sites were available on the both adsorbent surface, allowing rapid ampicillin uptake. As time progressed, these sites became increasingly occupied, causing the adsorption rate to slow until equilibrium was reached. After saturation, further TC uptake became limited due to reduced availability of binding sites and increasing repulsive interactions between adsorbed and free antibiotic molecules (Rajapaksha et al., 2022; Mahmodi sheikh sarmast, 2024).

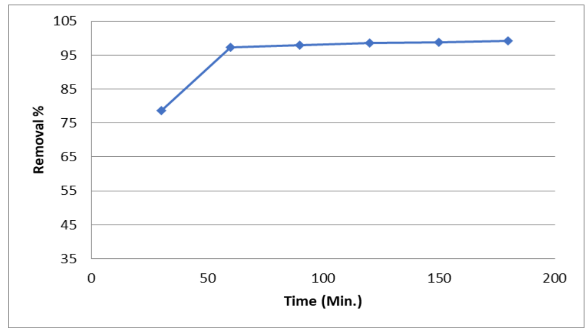

Figure 5: Effect of time on removal of ampicillin using copper oxide nanoparticles

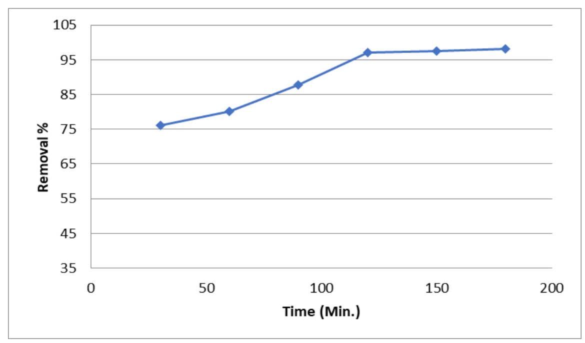

Figure 6: Effect of time on removal of ampicillinusing iron oxide nanoparticles

pH influence on the removal of ampicillin
Solution pH is one of the most influential parameters in adsorption studies because it controls the surface chemistry, ionization, and speciation of both the adsorbent and the adsorbate in aqueous systems. To examine the role of pH in ampicillin removal, batch experiments were performed using ampicillin solution adjusted to pH values between 2.0 and 8.0 (Fig7, 8). The studies were performed using an adsorbent dose of 0.025 g per 50 mL of antibiotic solution with an initial concentration of 50 mg·L^{-1}, maintained at room temperature for a contact time of 2 h. The effect of solution pH on the adsorption

performance toward the ampicillin removal was investigated within the pH range of 2-8. In case of CuO nanoparticles, an increase in pH from 2.0 to 3.0 led to an improvement in ampicillin removal efficiency removal of both the antibiotics rapidly increased from pH 2 to 3 and after pH up to pH 8 it decrease due to high anionic concentration of both antibiotic and adsorbents. The ampicillin removal percentage increased from 83.38 to 97.96% when pH changes from 2 to 3, when pH further increase from pH 3 to pH 8 the removal percentage decrease up to 79.82%, during copper oxide nanoparticles used as adsorbent.

In iron oxide nanoparticles, the ampicillin removal percentage increased from 80.92 to 94.66% when pH changes from 2 to 3, when pH further increase from pH 3 to pH 8 the removal percentage decrease up to 72.82%. The enhanced ampicillin adsorption observed under acidic conditions can be attributed to favorable interactions such as hydrogen bonding, , π–π stacking, cation–π interactions and electron donor–acceptor forces between antibiotic molecules and copper oxide as well as iron oxide nano adsorbent surfaces as in Fig 15-16. Conversely, at higher pH values, the increasing proportion anionic antibiotic species weakens their interaction with the negatively charged adsorbent, leading to reduced adsorption. This trend is consistent with previously reported adsorption behavior of antibiotics, where changes in ionization strongly affect adsorption performance (Al-Musawi et al., 2023).

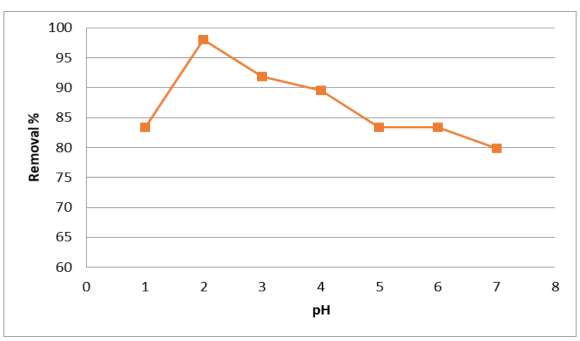

Figure 7: Effect of pH on removal of ampicillin using copper oxide nano-particles.

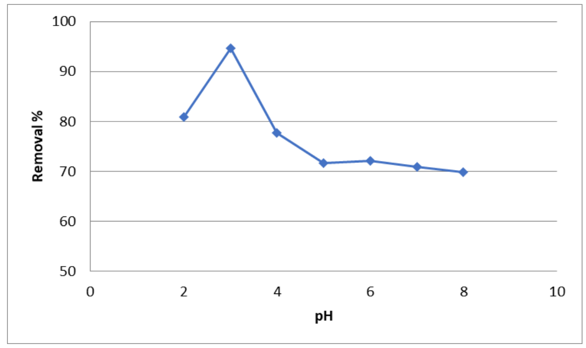

Figure 8: Effect of pH on removal of ampicillin using iron oxide nanoparticles

Influence of Temperature on TC Removal:

The influence of temperature on the adsorption of ampicillin antibiotic was investigated over a temperature range of 10-50 °C at a fixed antibiotic concentration of 50 mg/L and a contact time at 120 minutes. As depicted in Fig. 9-10 antibiotic exhibited a similar response to changes in temperature. An increase in temperature led to a noticeable improvement in antibiotic removal efficiency, with ampicillin removal rising from 51.54% to 98.04% using copper oxide nanoparticles as adsorbent while with ampicillin removal rising from 45.36% to 95.14% using iron oxide nanoparticles as adsorbent.

This enhancement in adsorption performance with increasing temperature can be attributed to improved interaction between antibiotic molecules and the active sites on the adsorbent surface. Higher temperatures increase the kinetic energy of antibiotic molecules, thereby enhancing their mobility and diffusion within the aqueous phase and facilitating greater access to adsorption sites. Elevated temperatures enhance the kinetic energy and mobility of ampicillin molecules, facilitating their diffusion across the liquid boundary layer and into the pores of the adsorbent. Moreover, thermal energy may promote the formation of additional active sites by disrupting internal bonds within the adsorbent structure, thereby improving adsorption performance (Mahmodi sheikh sarmast, 2024).

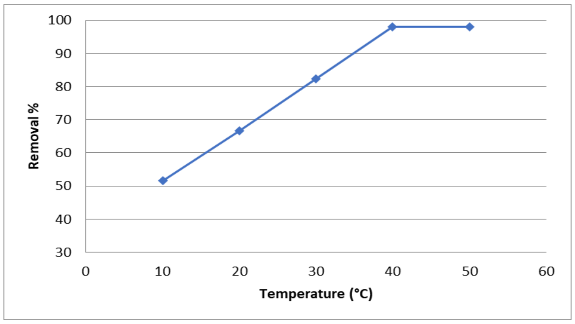

Figure 9: Effect of temperature on removal of ampicillin using copper oxide nanoparticles

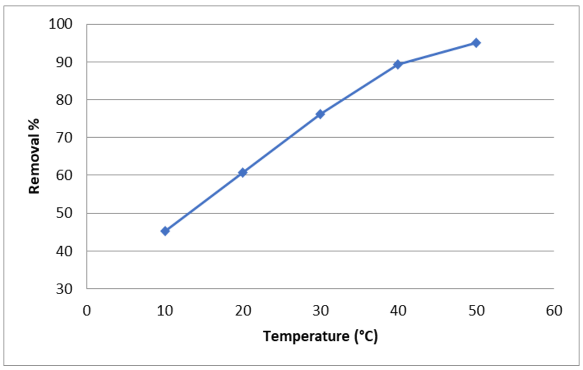

Figure 10: Effect of temperature on removal of ampicillin using iron oxide nanoparticles

IV. THERMODYNAMIC STUDIES

Thermodynamic parameters, including changes in standard entropy (ΔS°), Gibbs free energy (ΔG°), and enthalpy (ΔH°), for the adsorption of cationic antibiotics onto copper oxide and iron oxide nanoparticles were evaluated through experiments conducted at different temperatures. These parameters were determined using established thermodynamic relationships, as reported in the literature (table 1). The corresponding equations employed for the analysis are given below:

$$\Delta G^0 = -RT lnK_d \quad (1)$$

$$K_d = \frac{C_a}{C_e} \quad (2)$$

$$lnK_d = -\frac{\Delta H^0}{RT} + \frac{\Delta S^0}{R} \quad (3)$$

Here, Kd represents the equilibrium constant, R is the universal gas constant (8S.314 J mol⁻¹ K⁻¹), and T (K) denotes the absolute temperature. The term (mg/L) corresponds to the amount of ampicillin antibiotic adsorbed onto the nanoadsorbent surface at equilibrium. The values of standard enthalpy change (ΔH°) and standard entropy change (ΔS°) were calculated from the slope and intercept, respectively, of the linear plots of lnKd versus 1/T1 (Fig. 11-12).

As summarized in Table 1, the positive ΔH° values for ampicillin antibiotic indicate that the adsorption process is endothermic in nature, suggesting that the uptake of ampicillin occurs predominantly through a physical adsorption mechanism (Al-Musawi et al., 2023). Furthermore, the positive ΔS° values 289.05 J mol^{-1} K^{-1} for ampicillinby copper oxide nanoparticles and 210.98 J mol^{-1} K^{-1} for ampicillin antibiotic by iron oxide nanoparticles reflect an increase in randomness and mobility at the solid–solution interface, which favors the adsorption of antibiotic molecules. The negative values of ΔG° for ampicillin confirm that the adsorption process is thermodynamically feasible and spontaneous under the studied conditions, as presented in Table 1.

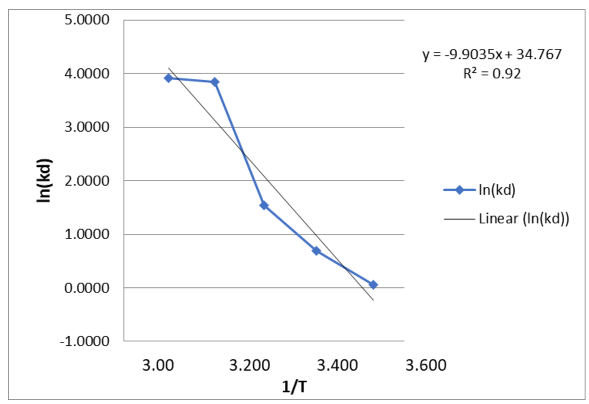

Figure 11: Thermodynamic plot for ampicillin removal by Copper oxide nanoparticles

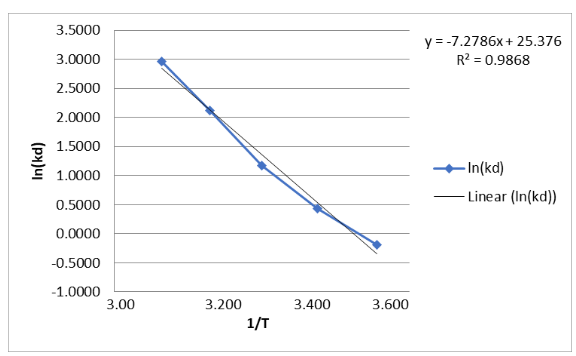

Figure 12: Thermodynamic plot for ampicillin removal by iron oxide nanoparticles

Table 1: Thermodynamic parameters description of ampicillin adsorption by copper oxide and Iron oxide nanoparticles

Copper oxide nanoparticles				Iron Oxide nanoparticles		
Temp.				Ampicillin		
(K)	ΔGº	ΔSº	ΔHº	ΔGº	ΔSº	ΔHº
	(k J mol-1)	(J mol-1K-1)	(k J mol-1)	(k J mol-1)	(J mol-1K-1)	(k J mol-1)
283	-0.14	289.05	82.34	0.44	210.98	60.51
293	-4.46			-1.06		
303	-3.86			-2.94		
313	-10.06			-5.53		
323	-10.51			-7.96		

V. KINETIC MODELING

The adsorption kinetics of both ampicillin antibiotic onto the synthesized copper oxides and iron oxides nanoparticles were systematically investigated using the pseudo-first-order kinetic model originally proposed by Lagergren (1898) and the pseudo-second-order kinetic model developed by McKay and Ho (1999). These models were applied to quantitatively describe the adsorption rate behavior and to identify the dominant rate-controlling mechanisms governing the adsorption process. The linearized forms of the pseudo-first-order and pseudo-second-order kinetic equations are presented as follows:

$$\log(q_e - q_t) = \log q_e - \left(\frac{k_1}{2.303}\right) t \quad (4)$$

$$t/q_t = 1/k_2 q_e^2 + t/q_e \quad (5)$$

$$q_t = k_{id} t^{1/2} + C \quad (6)$$

Where qe (mg g^{-1}) represents the adsorption capacity at equilibrium and qt (mg g^{-1}) denotes the adsorption capacity at any time t. The rate constants k1 (min^{-1}) and k2 (g mg^{-1} min^{-1}) correspond to the pseudo-first-order and pseudo-second-order kinetic models, respectively. The kinetic parameters obtained from both models are summarized in Table 2 and were evaluated by fitting the experimental data to the linearized forms of the respective kinetic equations using linear regression analysis. Figures 13-16 illustrate the plots associated with the pseudo-first-order and pseudo-second-order models. For the pseudo-first-order model, the parameters k1 and qe were determined from the slope and intercept of the plot of log(qe-qt) versus t, whereas for the pseudo-second-order model, these parameters were obtained from the linear plot of t/qt versus t. The calculated equilibrium adsorption capacities qe (cal) derived from the pseudo-first-order model were consistently lower than the experimentally determined values qe (exp) for both antibiotics, indicating a poor fit of this model to the experimental data. In contrast, the pseudo-second-order model exhibited significantly higher regression coefficients (R^2=0.998) and (R^2=0.997) for ampicillin antibiotic, respectively on to both copper oxide nanoparticles and iron oxide nanoparticles, along with a close agreement between qe(cal) and qe (exp). These findings clearly demonstrate that the adsorption kinetics of ampicillin onto copper oxide nanoparticles and iron oxide nanopartcles are better described by the pseudo-second-order kinetic model, suggesting that the adsorption process is predominantly governed by chemisorption mechanisms involving valence forces through electron sharing or exchange.

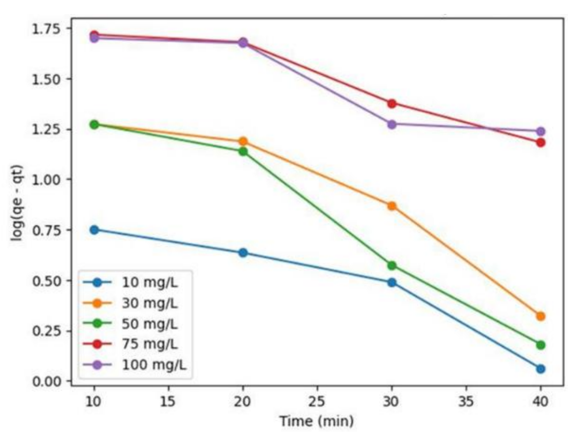

Figure13: Comparative Psedo-first order kinetic plot of ampicillin using copper oxide nanoparticles

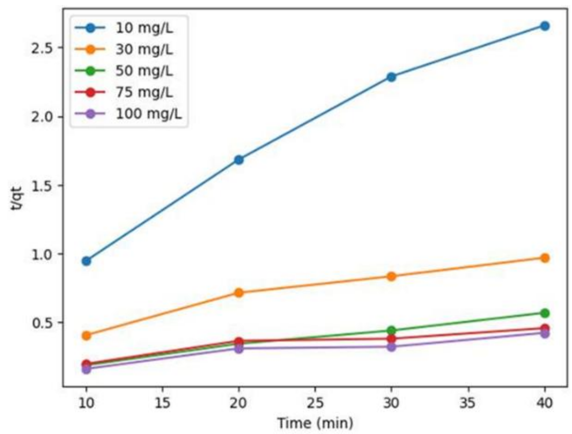

Figure14: Comparative Psedo-second order kinetic plot of ampicillin using copper oxide nanoparticles

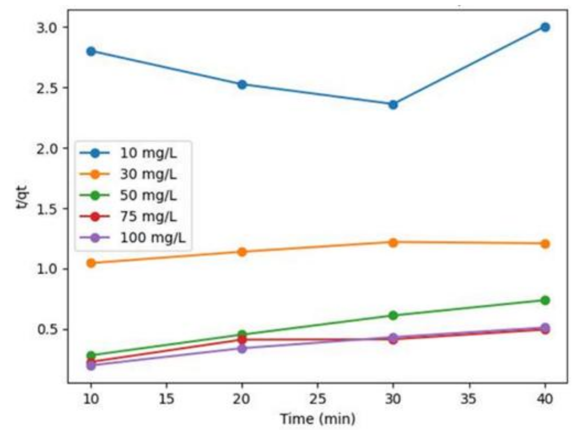

Figure16: Comparative Psedo-second order kinetic plot of ampicillin using iron oxide nanoparticles

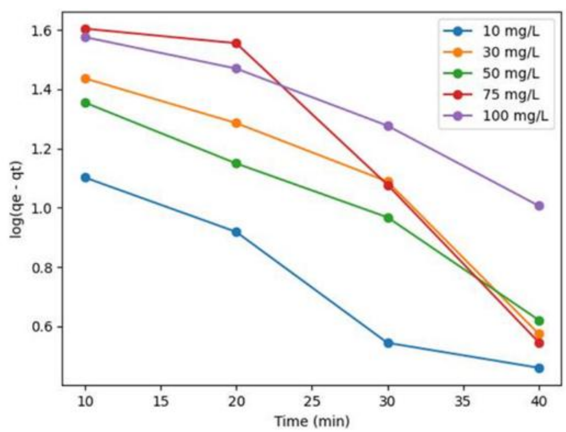

Figure15: Comparative Psedo-first order kinetic plot of ampicillin using iron oxide nanoparticles

Table 2: Ampicillin adsorption kinetic models parameters description on copper oxide nanoparticles

kinetic model's parameters		Ampicillin (mg//L)									
		Copper oxide nanoparticles					Iron Oxide nanoparticles				
		10	30	50	75	100	10	30	50	75	100
Pseudo-first Order	k_1(min^{-1})	0.046	0.041	0.040	0.037	0.034	0.032	0.030	0.025	0.023	0.022
	qe(cal)	15.87	42.91	70.88	101.62	110.24	15.32	36.02	57.41	83.65	87.55
	R^2	0.973	0.965	0.958	0.951	0.944	0.968	0.961	0.957	0.949	0.943
Pseudo-second Order	k_2(g/mg /min)	0.021	0.015	0.013	0.011	0.010	0.018	0.017	0.016	0.014	0.013
	qe(cal)	16.18	43.29	71.66	102.41	111.5	16.15	36.83	58.48	87.84	88.63
	R^2	0.998	0.997	0.996	0.995	0.994	0.997	0.996	0.995	0.994	0.993
Exp. Data	qe (exp)	16.20	43.33	71.70	102.45	111.57	16.18	36.87	58.53	84.80	88.70

VI. ADSORPTION ISOTHERM MODELING

The adsorption behavior and the nature of interactions between the adsorbent surface and antibiotics molecules were analyzed using adsorption isotherm models. To elucidate the equilibrium characteristics of ampicillin adsorption onto copper oxide and iron oxide nanoparticles, the Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich (D–R) isotherm models were fitted to the experimental adsorption data. These models provide insight into surface heterogeneity, adsorption capacity, and the energetics of the adsorption process. The linearized form of the Langmuir isotherm model is expressed as follows.

$$\frac{C_e}{q_e} = \frac{1}{q_{max}b} + \frac{C_e}{q_{max}} \quad (7)$$

Where b (L/mg) is the Langmuir constant, q max (mg/g) is the maximum monolayer adsorption capacity.

Freundlich isotherms model (Freundlich, 1906) may be represented by the equation:

$$\log q_e = \log K_f + \frac{1}{n}\log C_e \quad (8)$$

In the Freundlich isotherm model, Kf represents the Freundlich constant associated with the adsorption capacity of the adsorbent, while 1/n is the heterogeneity factor that reflects the adsorption intensity and surface heterogeneity. For a favorable adsorption process, the value of 1/n should lie between 0 and 1. A value of 1/n proaching zero indicates a highly heterogeneous adsorbent surface, whereas 1/n suggests that the adsorption process is predominantly chemisorptive in nature. Conversely, values of 1/n are indicative of cooperative adsorption behavior (Al-Musawi et al., 2023). The Temkin–Pyzhev isotherm model (Temkin and Pyzhev, 1940), which accounts for adsorbent–adsorbate interactions and assumes a linear decrease in the heat of adsorption with surface coverage, is expressed as:

qe=BlnKT+BlnKe

where:

R (8.314 J mol⁻¹ K⁻¹) is the universal gas constant, T (K) is the absolute temperature, and B=RT, with b (J mol⁻¹) representing the Temkin constant related to the heat of adsorption. The parameter KT (L g⁻¹) denotes the Temkin equilibrium binding constant. The isotherm model parameters and corresponding correlation coefficients for ampicillin antibiotic are summarized in Table 3, while the linearized plots of the Langmuir, Freundlich, and Temkin isotherm models are illustrated in Fig. 17-22.Among the evaluated models, the Langmuir isotherm exhibited the highest correlation coefficients, with R2=0.972 for ampicillin antibiotic on copper oxide nanoparticles as adsorbents, and R2=0.968 for ampicillin antibiotic on iron oxide nanoparticles, indicating superior fitting compared to the Freundlich and Temkin models. This observation suggests that the adsorption of both ampicillin antibioticonto copper oxide and iron oxide nanoparticles occurs predominantly via monolayer formation on a homogeneous surface.

The maximum monolayer adsorption capacities q max for ampicillin antibiotic was determined to be 126.6 mg g⁻¹ on copper oxide nanoparticles as adsorbents while maximum monolayer adsorption capacities q max for ampicillin antibiotic was determined to be 129.9 mg g⁻¹ on to iron oxide nanoparticles. A comparative evaluation of the adsorption capacities of antibiotic reported for various adsorbents is presented in Table 4. The relatively high adsorption capacities obtained in the present study demonstrate that copper oxide and iron oxide nanoparticles are promising and efficient adsorbents for the removal of ampicillin antibiotic from simulated wastewater systems. Similar results were reported by many researchers (Al-Musawi et al., 2023; Mahmodi sheikh sarmast, 2024).

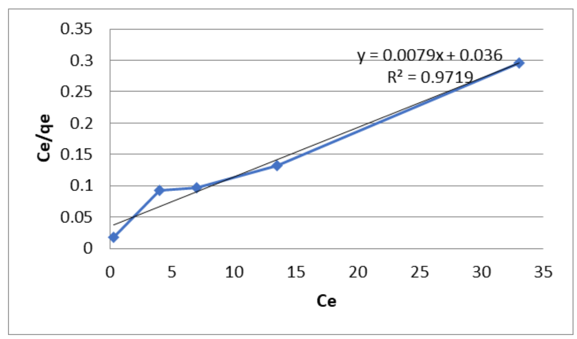

Figure 17: Langmuir Adsorption isotherm plot for ampicillin removal by copper oxide nanoparticles

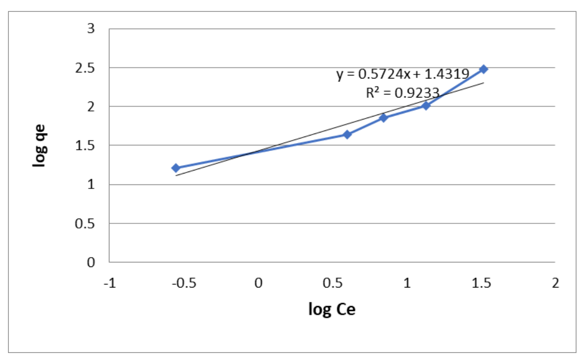

Figure 18: Freundlich adsorption isotherm plot for ampicillin removal by copper oxide nanoparticles

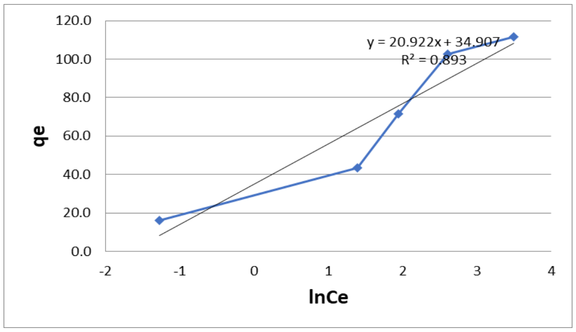

Figure 19: Temkin and Pyzhev adsorption isotherm plot for ampicillin removal by copper oxide nanoparticles

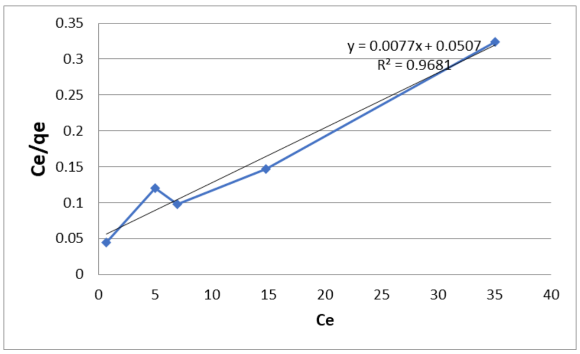

Figure 20: Langmuir Adsorption isotherm plots for ampicillin removal by ferric oxide nanoparticles

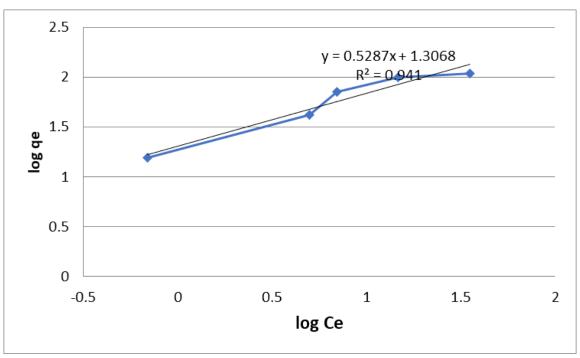

Figure 21: Freundlich adsorption isotherm plots for ampicilin removal by ferric oxide nanoparticles

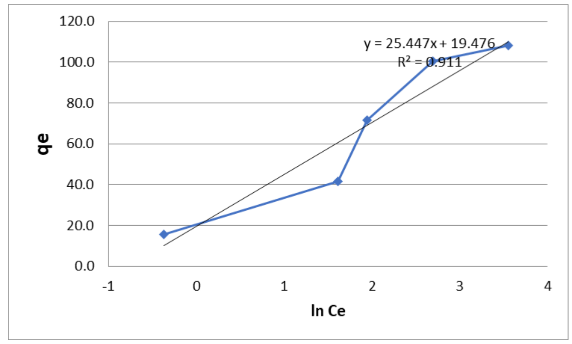

Figure 22: Temkin and Pyzhev adsorption isotherm plots for ampicilin removal by ferric oxide nanoparticles

Table 3: Adsorption isotherms model parameters description of ampicillin antibiotic adsorption using copper oxide nanoparticles

Isotherms models	Parameters values		
		Copper oxide nanoparticles	Iron oxide nanoparticles
		Ampicillin (mg/L)	
Langmuir	qmax(mg/g)	126.6	129.9
	b(L/mg)	0.219	0.015
	R2	0.972	0.968
Freundlich	1/n	1.75	1.89
	Kf (mg/g)	27.03	20.27
	R2	0.923	0.941
Temkin and Pyzhev	B	119.21	98.01
	KT (L/mg)	5.303	2.15
	R2	0.893	0.911

Table 4: Comparison of adsorption capacity of synthesized nanomaterials for ampicillin antibiotics

Sl. No.	Adsorbent material	Target Antibiotic	Maximum adsorption capacity (mg·g⁻¹)	Reference
	SBA-15	Ampicillin	237	Nairi et al., 2017
	Polydopamine/zirconium (IV) iodate	Ampicillin	100.0	Rahman, N., &Varshney, 2020
	Fe_3O_4/graphene oxide/aminopropyltrimethoxysilane (FGOA) nanocomposites	Ampicillin	294	Ha et al., 2021
	Iron and cerium nanoparticles (C-Fe/Ce)	Ampicillin	27.61	Gómez-Vilchis et al., 2022

	Activated carbon prepared from the Azollafiliculoides fern (ACAF)	Ampicillin	114.3	Al-Musawi et al., 2023
	Activated biochar	Ampicillin	53.81	Yu et al., 2024
	Silver incorporated with chitosan and Fe_3O_4 nanoparticles	Ampicillin	49.50	Mahmodi sheikh sarmast, 2024
	Iron oxide nanoparticles	Ampicillin	129.9	Current Study
	Copper oxide nanoparticles	Ampicillin	126.6	Current Study

VII. DESORPTION AND REUSABILITY

The regenerated copper oxide and iron oxide nanoparticles were used for adsorption study of both ampicillin antibiotic up to three reuse cycles. In the first round of copper oxide nanoparticles, the removal ampicillin was97.96% that was greater than the iron oxide nanoparticles where the removal ampicillin was found 93.64% and 90.82%. But in next round,the removal efficiency for theantibioticwas significantlydecreasedand at theend ofthird round it was reached upto 74.35%forampicillin for copper oxide nanoparticles and 66.29%as shownin Figures 23for iron oxide nanoparticles. This studysuggests that the adsorbent has potential to purge the antibiotics from aqueous solutions after reuse. It can be applicable for waste water treatment.

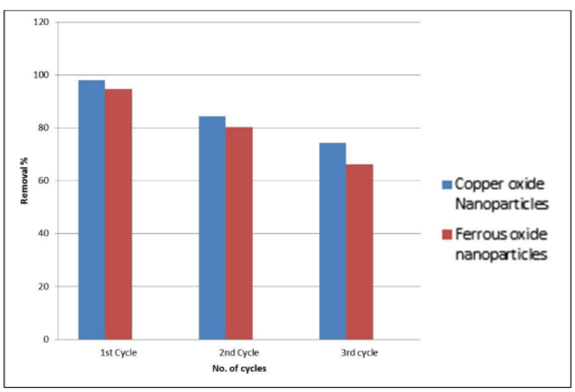

Figure 23: Reuse efficiency of nanoparticles for ampicillin antibiotic removal

VIII. CONCLUSION

In the current study Copper oxide and iron oxide nanoparticles are prepared, which was subsequently applied for the removal of ampicillin antibiotic from aqueous media. The experimental findings demonstrated that the developed nanocomposite possesses significant adsorption capability for ampicillin in water samples, achieving a maximum adsorption capacity of 126.6 mg/g and 129.9 mg/g for copper oxide and iron oxide nanoparticles. Equilibrium data were best described by the Freundlich isotherm model, indicating a multilayer adsorption mechanism on a heterogeneous surface. Kinetic analysis suggested that the adsorption process predominantly follows a chemisorption mechanism. The removal of ampicillin is likely governed by multiple interaction pathways, including surface complexion, electrostatic attraction, and hydrogen bonding. Thermodynamic evaluation further confirmed that the adsorption process is spontaneous and thermodynamically favorable. Additionally, the for copper oxide and iron oxide nanoparticles demonstrated satisfactory regeneration performance, maintaining good adsorption efficiency for up to three successive cycles.

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