The Adsorptive Power of Nylon–Gelatin–Hematite Composite: Study on NaCl Solution Adsorption Through Equilibrium, Kinetic, and Thermodynamic Approach

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Abstract. The development of composite adsorbent materials is a promising strategy for saline water treatment. In this study, a nylon–gelatin–hematite composite with a porous structure was investigated for NaCl ion removal. The porous matrix and functional groups on the polymer and hematite surfaces facilitated Na^+ and Cl^- adsorption through electrostatic interactions and surface adsorption mechanisms. Adsorption performance was evaluated using a batch method with variations in adsorbent dosage, contact time, and temperature. Functional groups were confirmed by Fourier-transform infrared (FTIR) spectroscopy. Adsorption performance was evaluated through measurements of salinity, total dissolved solids, and electrical conductivity. The adsorption behavior was examined through equilibrium, kinetic, and thermodynamic analyses to elucidate the underlying mechanism and efficiency. The FTIR spectra confirmed characteristic vibrations of nylon, gelatin, and hematite, indicating the successful formation of the composite. Equilibrium data fitted well with the Freundlich isotherm models ($R^2 > 0.99$) at dosage variation, suggesting favorable multilayer adsorption on heterogeneous surfaces. The maximum adsorption capacity q_{max} reached 1.626 mg/g. Kinetic studies revealed that the adsorption process followed a pseudo-first-order model, indicating a dominant physisorption mechanism. Negative Gibbs free energy values (ΔG = -1.905 to -2.139 kJ/mol) confirmed the spontaneous adsorption process.

1 Introduction

Water remains a vital necessity for sustaining life. Global water demand is projected to reach 6.9 trillion cubic meters by 2030. However, water scarcity and increasing salinity are causing serious global problems due to high levels of industrialization and seawater intrusion [1, 2]. Among the various methods to address the problem of high salinity in water, Reverse Osmosis (RO) has been practiced on a large scale due to its high level of separation efficiency [3]. Although RO is very effective in providing clean water on a large scale, this technology still requires high pressures of 10–100 bar, high power consumption, and a high potential for membrane fouling. Therefore, this technology often uses chemical cleaning agents. Adsorption is a promising alternative approach due to its ease of operation, efficiency, and environmental friendliness in removing dissolved salts [4-6].

In recent years, gelatin–iron oxide nanocomposites, especially gelatin–hematite (α-Fe_2O_3), have gained attention as adsorbents due to the cumulative interaction of biopolymer functional groups ($-NH_2$,$-COOH$) and metal oxide surfaces [7, 8] and observed that gelatin-conjugated hematite nanoparticles had a high adsorption capacity of

169.49 mg g^{-1} Pb(II) with a removal efficiency of over 90%. The gelatin and α-Fe_2O_3 composite could adsorb Pb^{2+} with a high capacity of 800 mg/g and a removal efficiency of 82% based on pseudo-first-order kinetics [4]. Gelatin-Pluronic F127-hematite patterned flakes demonstrated adsorption activity towards ibuprofen, with an adsorption capacity of 25.5-55 mg g^{-1} and a removal efficiency of 22%. These studies validate that gelatin has a high adsorption capacity; however, mechanical instability and particle aggregation remain limitations of gelatin-based composites in aqueous conditions.

Nylon has been incorporated as a structural reinforcement polymer within the gelatin–hematite composite framework to overcome these challenges. The presence of nylon provides a robust and flexible matrix that enhances the adsorbent's mechanical integrity, stability, and reusability. Moreover, its fibrous morphology facilitates improved ion diffusion and transport throughout the adsorbent structure [6, 9]. Additionally, nylon minimizes hema-tite particle aggregation and stabilizes gelatin under aqueous conditions, thereby enhancing adsorption capacity and operational durability. According to Hamad [9], nylon-based materials exhibit significant adsorption performance, achieving up to an 86% removal of Congo red dye with a 300 mg/L capacity. Similarly, a nylon–Fe_3O_4 composite has demonstrated efficient Cu^{2+} ion removal, with a removal efficiency of 94.67% and an adsorption capacity of 11.57 mg/g. Nylon–gelatin–hematite composites represent a promising class of low-cost adsorbent materials for desalination applications. The interconnectedness of the components provides advantageous physicochemical characteristics, while the nylon matrix offers an inherently porous structure capable of accommodating small molecules. Moreover, the potential to utilize nylon derived from waste further enhances the economic feasibility and sustainability of this composite.

This study serves as a preliminary investigation of the membrane system aimed at gaining a fundamental understanding of the adsorption mechanisms involved in membrane-based processes. Specifically, the research focuses on the adsorption behavior of a nylon–gelatin–hematite composite for sodium chloride (NaCl) removal. The adsorption performance was systematically evaluated using equilibrium, kinetic, and thermodynamic analyses to clarify the controlling mechanisms, adsorption efficiency, and associated energy characteristics. The findings offer new insights into the development of composite adsorbent systems for saline water treatment, demonstrating enhanced ion removal capability, improved stability, and greater sustainability of the gelatin–hematite composite.

2 Method

2.1 Material and instrumentation

The materials used in this research include nylon yarn, hematite, gelatin, 37% hydrochloric acid (HCl) (Merck), glutaraldehyde, demineralized water, and sodium chloride (NaCl) (Central Drug House Ltd.). The instruments used in this research were Fourier-transform Infrared (FTIR) spectroscopy, utilizing a Varian spectrometer, to determine the functional groups of hematite and composites. Water tester meter (EZ-9909) to determine the total dissolved solids (TDS), electrical conductivity (EC), and salinity of samples.

2.2 Method

2.2.1 Preparation and characterization of nylon-gelatine-hematite composite

The nylon solution was prepared by dissolving 3 g of nylon yarn in 15% hydrochloric acid (HCl). Subsequently, 1 g of gelatin and 10–50 mg of hematite was added to the nylon solution. The mixture was heated at 50°C for 30 minutes under continuous stirring to ensure homogeneity. The homogeneous mixture was then cast onto a glass plate to form a thin film and left to stand for several minutes before being immersed in a 1% glutaraldehyde solution within a coagulant bath for cross-linking. After coagulation, the composite film was carefully removed, washed, and dried at room temperature. The composite film was characterized by FTIR using the wavenumber 400 – 4000 cm^{-1}.

2.2.2 *Adsorption of nylon-gelatine-hematite composite to saline water*

The prepared composite film measuring 7x7 cm with thicknes range 0.125-0.2 mm which was cut into small pieces with weight of adsorbent range 10-50 mg according the variation of the dosage of adsorbent used. The composite samples were tested as adsorbents for a 3500ppm saline (NaCl) solution. Adsorption experiments were conducted under varying contact times (1–24 h) and temperatures (60–100 °C) to investigate the effects of time and thermal conditions on adsorption performance. The adsorption data were fitted into the adsorption isotherm model, as shown in Tables 1 and 4, to determine the nature of the adsorption phenomenon and find the adsorption capacity of the adsorbent. The removal rate is calculated according to the formula [6] :

$$\%R = \frac{Co-Ct}{Co} \text{ x } 100 \tag{1}$$

C_o is the initial concentration of the solution, and C_t is the concentration after Adsorption of the solution.
The adsorption capacity (mg/g) is calculated according to the equation:

$$Qe = \frac{(Co-Ct)V}{m} \tag{2}$$

The Langmuir and the Freundlich isotherms evaluate the equilibrium adsorption as described by the following equations (3-4). The kinetics of the reaction were evaluated by applying pseudo-zero-order, pseudo-first-order, and pseudo-second-order models, as described by the following [5, 6, 10, 11]:

$$\frac{1}{qe} = \frac{1}{Kl \, x \, qmax} + \frac{1}{qmax} \text{ x } \frac{1}{Ce} \tag{3}$$

$$\ln qe = \ln Kf + \frac{1}{n} \ln Ce \tag{4}$$

$$\ln (qe - qt) = \ln qe - k_1 t \tag{5}$$

$$\frac{t}{q_t} = \frac{1}{k_2(q_e)^2} - \frac{1}{q_e} t \tag{6}$$

3 Result and Discussion

3.1 Characterization of nylon-gelatine-hematite composite

The structural characteristics of the nylon–gelatin–hematite composite were examined using Fourier Transform Infrared (FTIR) spectroscopy, and the corresponding spectrum is presented in Fig. 1. The FTIR bands observed at 3294, 2932, 1637, 1540, 1461, and 1263 cm^{-1} are attributed to N–H stretching, C–H stretching, and the amide I (C=O stretching), amide II (N–H bending), and amide III (C–N stretching) vibrations of the amide groups derived mainly from nylon [12]. Similar absorption bands at 1637 cm^{-1} amide I (C=O stretching), 1540 cm^{-1} (amide II), and 1263 cm^{-1} (C–O stretching) are also characteristic of gelatin [4, 13]. In addition, a distinct absorption band around 576-520 cm^{-1} corresponds to the Fe–O stretching vibration of hematite [14], confirming the incorporation of iron oxide within the composite matrix. No significant difference or noticeable shift in the absorption bands was observed among the three composite variations. This indicates that the small amount of hematite incorporated into the polymer matrix was insufficient to alter the characteristic absorption intensity of nylon or gelatin. Based on characterization, FTIR interpreted that the interaction between the polar groups of gelatin/nylon and the hematite surface is reflected in the stable position in the composite network, supporting the interpretation that hematite particles are not only physically embedded, but also associated through weak electrostatic or coordinative interactions, as shown in Fig. 2.

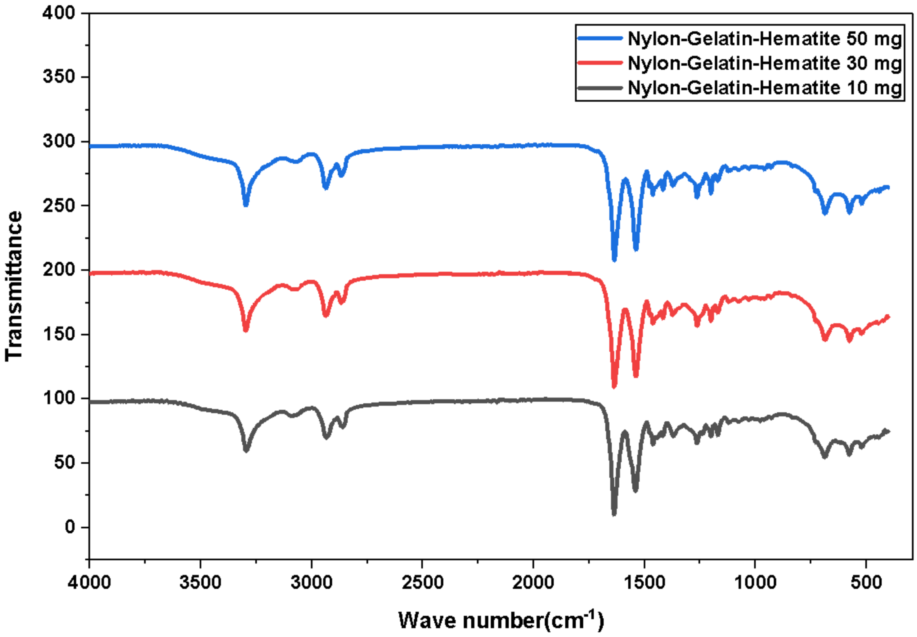


Fig 1. The Infrared Spectra FTIR of nylon-gelatin-hematite composite with variation of hematite composition.

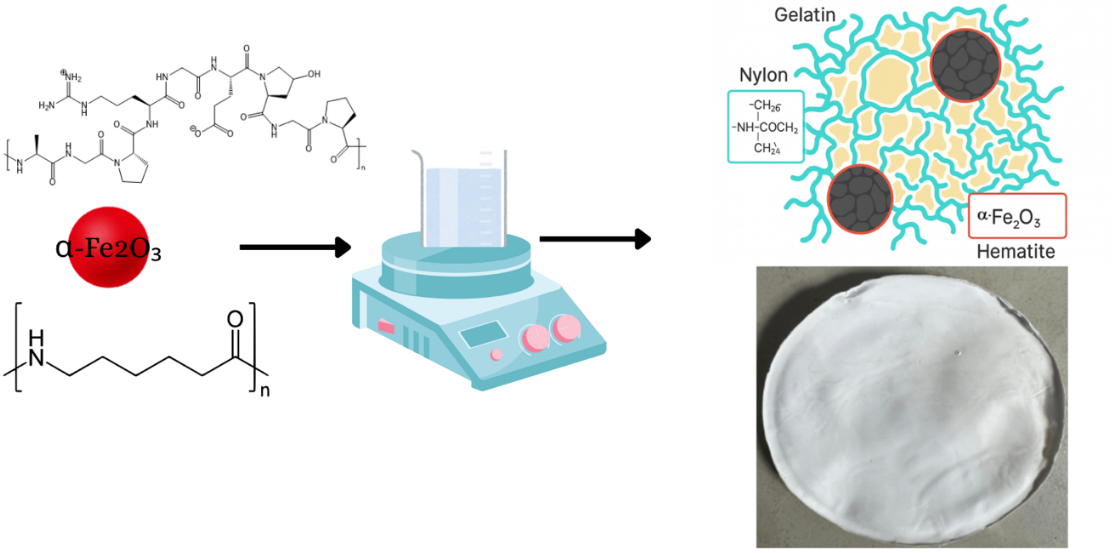


Fig 2. Schematic representation of the fabrication process nylon-gelatin-hematite composite

3.2 Effect of Adsorbent Dosage on Saline Solution

The effect of adsorbent dosage on NaCl removal was evaluated using 10, 30, and 50 mg of nylon–gelatin–hematite composite at a fixed concentration of 3500 ppm and a contact time of 1.5 hours. Figure 3 shows that the percentage of electrical conductivity removal increased, but total dissolved solids and salinity decreased with increasing adsorbent mass. The removal efficiency of electrical conductivity increased from 3.9% to 6.4%, but the percentage of total dissolved solids removal decreased from 3.1% to 2.1%, and salinity decreased from 3.5% to 2.1% with increasing dosage from 10 to 50 mg. The increase in adsorption performance on electroconductivity values is due to the increasing number of active surface sites, so that more Na^+ and Cl^- ions can be adsorbed on the adsorbent surface through electrostatic interactions or ion exchange. However, the decrease in the percentage of TDS and salinity removal is due to the remaining adsorbent mass without full interaction due to the limited availability of more ions and the increase in the higher surface area of the adsorbent [5].

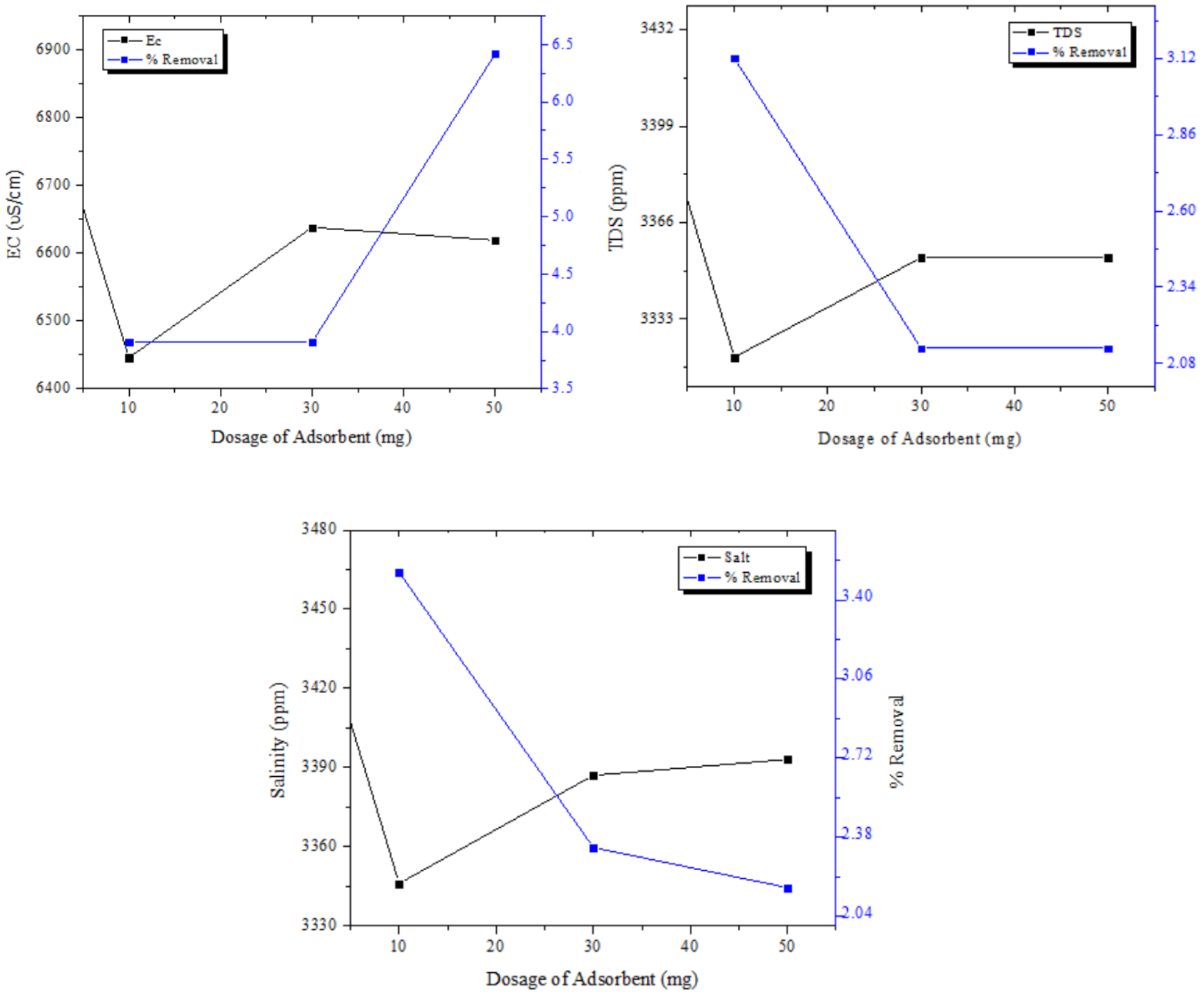


Fig 3. The Effect of the dosage of nylon-gelatin-hematite on NaCl Solution

The Salinity and TDS removal decreased when the dosage increases. At a dosage of 50 mg, the adsorption capacity tends to decrease (Fig. 3), indicating that particle agglomeration may occur at higher dosages, which reduces the effective surface area and leads to the overlap of adsorption sites. This phenomenon is consistent with observations reported for iron oxide–polymer composites by [6, 9], where excessive adsorbent loading diminished active site accessibility due to interparticle interactions.

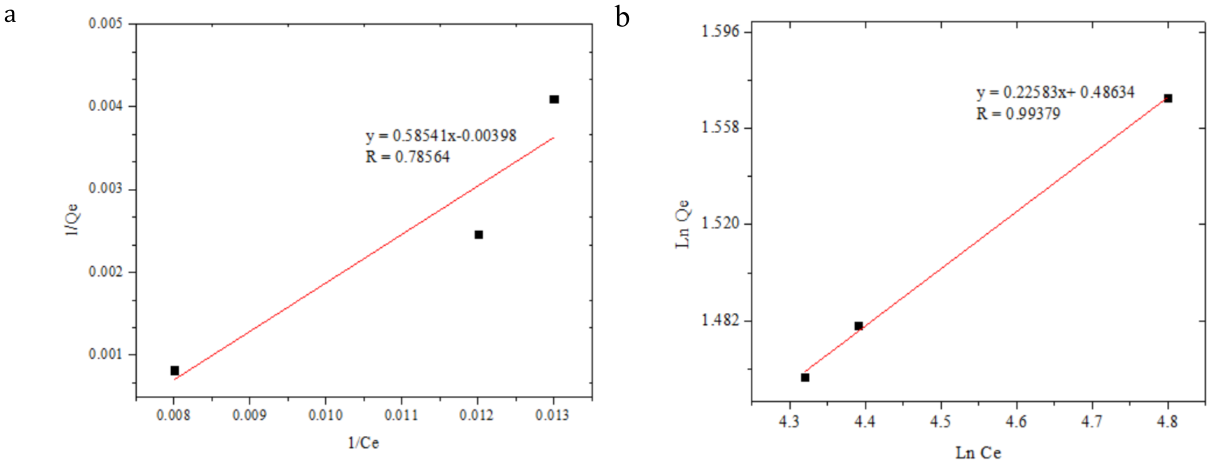


Fig 4. Linear isotherm of saline solution adsorption based on composite nylon-gelatin-hematite from data on salinity

Table 1. Isothermal adsorption-desorption model fitting parameters

Adsorption Model			
Langmuir		**Freundlich**	
q_{max} (mg/g)	1.708	**K_F** (mg/g)(L/mg)$^{1/n}$	1.626
R	0.78564	**R**	0.99379

Based on Figure 4, the equilibrium interaction between NaCl ions and the composite surface follows the Freundlich adsorption isotherm, with a correlation coefficient (R^2) of approximately 0.99, and based on the Langmuir adsorption isotherm, a maximum absorption capacity of 1.708 mg/g, as shown in Table 1. This result suggests that the adsorption process occurs through multilayer adsorption mechanisms on the heterogeneous surface of the composite. The Adsorption of NaCl onto the nylon–gelatin–hematite composite involves a combination of physical interactions. Electrostatic attraction occurs between Na^+ and Cl^- ions and the polar functional groups (–OH, –NH, and –COOH) in gelatin and nylon, initiating Adsorption. Subsequently, partial ion exchange occurs between Na^+ ions and the Fe–OH sites on the hematite surface. Another possible mechanism for reducing salinity is the interaction between amino functional groups and Na^+ ions through Lewis acid–base interactions, suggesting that nitrogen-containing groups play a crucial role in enhancing adsorption performance [7].

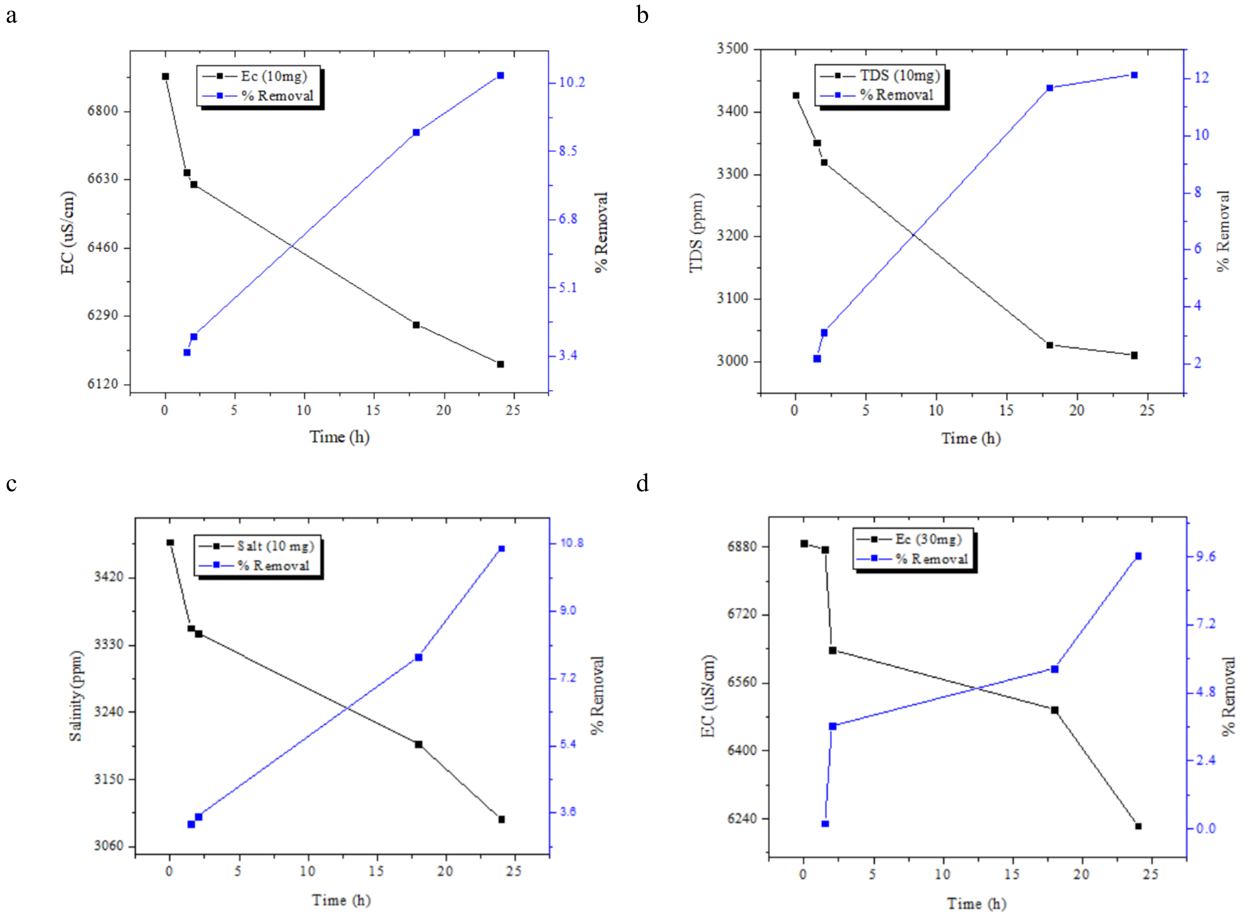
Table 2. A comparison of q_{max} of the prepared composite with other previously reported

Reported adsorbent	**Molecul adsorbate**	**Q_{max} (mg/g)**	**References**
Gelatin - α-Fe_2O_3 composite	Pb (II) solution	800	(4)
Nylon fiber waste (porous nylon sheet)	Congo red	188	(9)
Gelatin-conjugated hematite (α-Fe_2O_3) nanoparticles	Pb(II) solution	169.49	(7)
Modified gelatin / montmorillonite nanocomposite (gelatin-based)	Malachite Green (MG)	950.5	(10)
Gelatin-Pluronic F127-hexagonal hematite	Ibuprofen	55	(8)
Nylon@Fe_3O_4	Copper ion	11.57	(6)
Nylon-gelatin-hematite	NaCl Solution	1.626	This work

3.3 Effect of Time on Saline Solution Adsorption

The adsorption behavior of NaCl on nylon–gelatin–hematite composites was investigated at various contact times, ranging from 1 to 24 hours. As illustrated in Figure 5, the adsorption rate increased sharply during the initial stage (first two hours), with a removal efficiency of approximately 3%. Subsequently, the adsorption rate gradually increased at a low rate. It reached equilibrium after 24 hours, achieving removal efficiencies of approximately 10% for electrical conductivity (EC), 13% for total dissolved solids (TDS), and 13% for salinity. The initial rapid adsorption can be attributed to the many vacant active sites on the composite surface, which allow Na^+ and Cl^- ions to be readily adsorbed through electrostatic attraction and ion exchange processes. As adsorption progresses, these sites become occupied, leading to a slower diffusion-controlled phase where intraparticle diffusion governs ion transport to the interior of the adsorbent pores [9].

This kinetic profile, characterized by an initial adsorption followed by a slower intraparticle diffusion stage, is typical of heterogeneous polymer–oxide composites. The equilibrium time of 24 hours observed in this study aligns with reports on similar materials, such as gelatin–hematite hydrogels [7] and gelatin–αFe_2O_3 composites [10], confirming that the overall adsorption process is primarily governed by electrostatic interaction and ion-exchange between Na^+/Cl^- ions and the surface functional groups (–OH, –COOH, and –NH). These results support the mixed physisorption mechanism previously identified through isotherm.



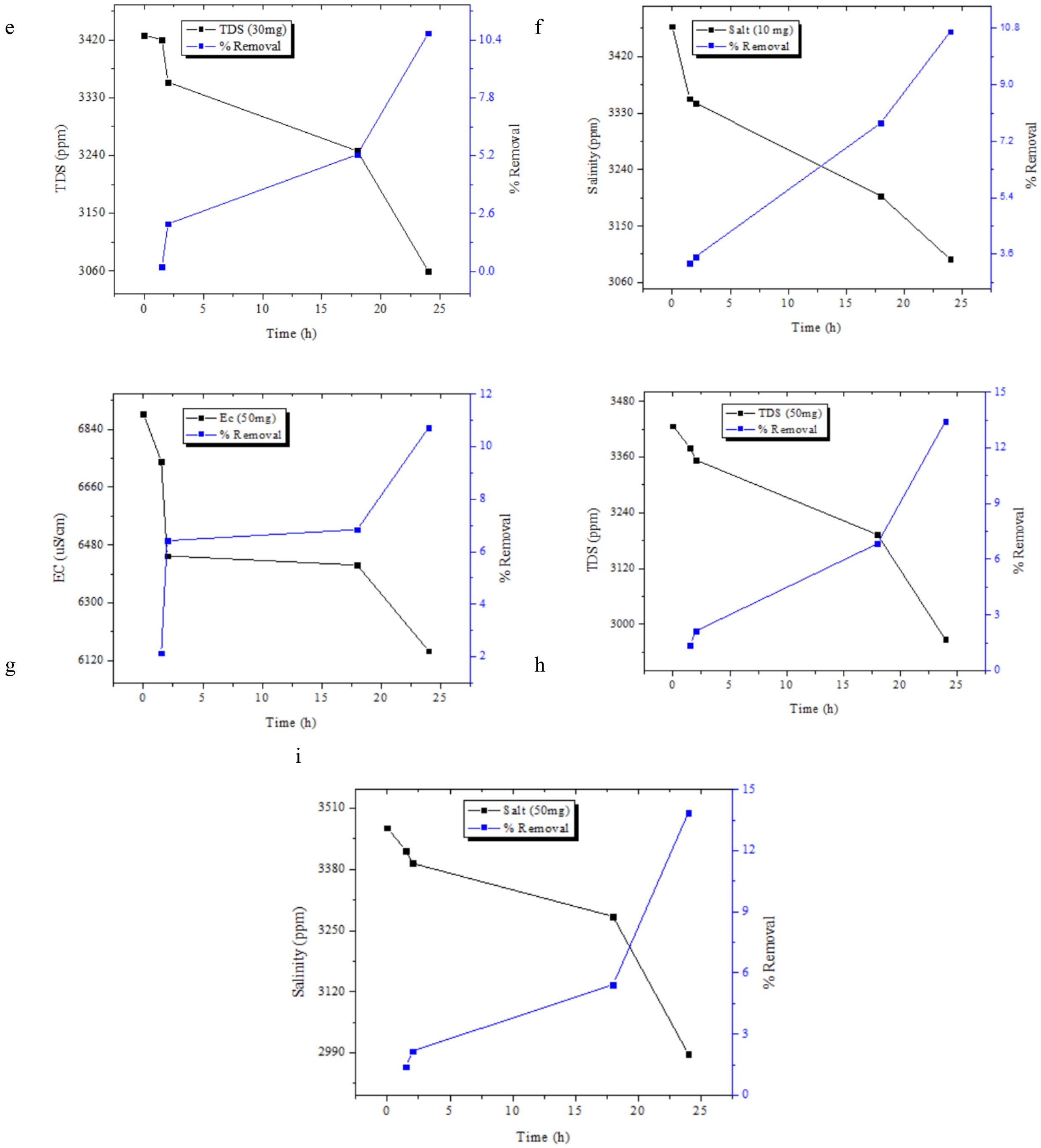


Fig 5. The Effect of dosage of nylon-gelatin-hematite on NaCl Solution

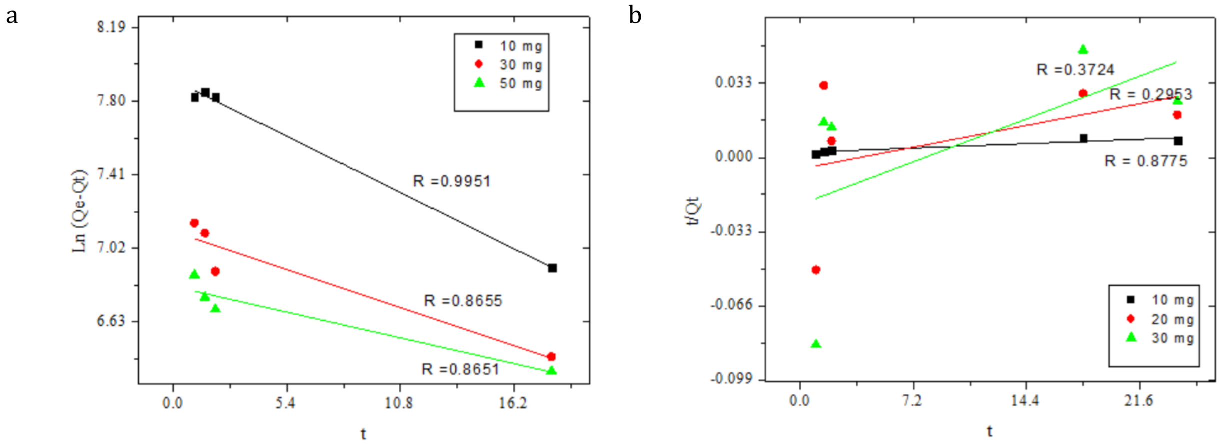


Fig 6. Linear isotherm of saline solution adsorption based on composite nylon-gelatin-hematite at 100 °C (from data salinity) a) Pseudo-first-order b) Pseudo-second-order

Table 3. Kinetic parameters for the pseudo-first and second order

Kinetic Model	Parameter	Dosage (10 mg)	Dosage (30 mg)	Dosage (50 mg)
Pseudo-first-order	R^2	0.9951	0.8656	0.8651
Pseudo-second-order	R^2	0.8775	0.2953	0.3724

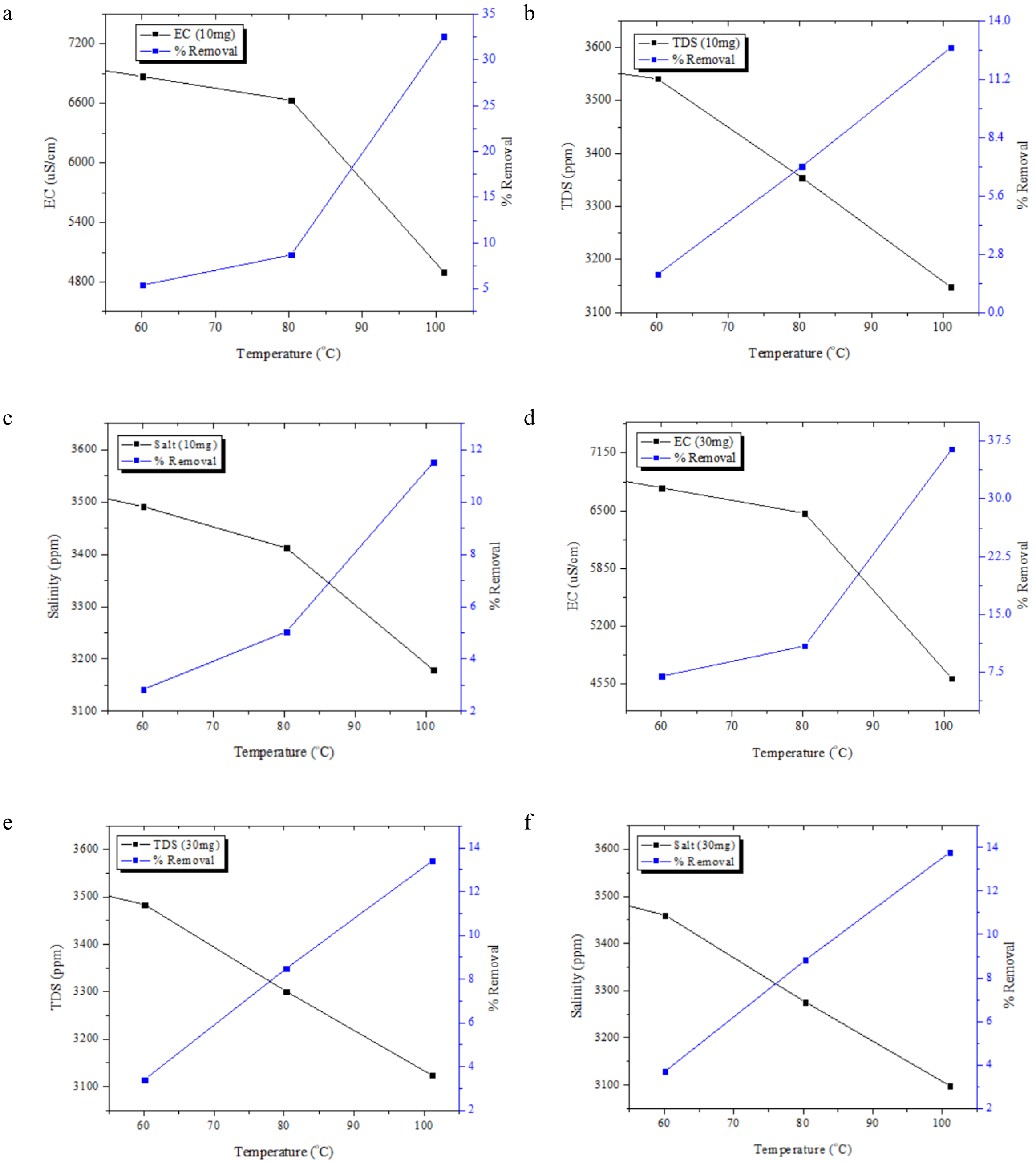
The adsorption kinetics of NaCl onto the nylon–gelatin–hematite composite were evaluated using the pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models, and the corresponding parameters are presented in Table 3. The pseudo-first-order model exhibits consistently higher correlation coefficients (R^2 = 0.86–0.99) compared to the pseudo-second-order model, indicating that the adsorption process is better described by the PFO kinetics. This finding suggests that the adsorption of Na^+ and Cl^- ions is predominantly governed by physical interactions, such as electrostatic attraction and surface diffusion, rather than by chemisorption. The dominance of the PFO model implies that the rate-limiting step is associated with mass transfer and ion diffusion to the available surface sites of the composite adsorbent.

At an adsorbent dosage of 10 mg, the pseudo-second-order model shows a moderate linear correlation (R^2 = 0.87) with a relatively low rate constant, indicating a slow adsorption rate. This behavior can be attributed to the limited number of accessible active sites and the low probability of effective ion–surface interactions during the initial adsorption stage. As the adsorbent dosage increases to 30 mg and 50 mg, a pronounced decrease in the correlation coefficient (R^2), reaching 0.2953, is observed along with fluctuations in the k_2 values. This trend can be explained by particle aggregation and surface overlapping at higher adsorbent concentrations, which reduce the effective surface area and hinder ion diffusion toward active sites. Consequently, the applicability of the pseudo-second-order model becomes less significant at higher dosages, further confirming that chemisorption is not the dominant mechanism governing NaCl adsorption under the studied conditions [5].

3.4 Effect of Temperature on Saline Solution Adsorption

Temperature variation experiments were conducted at 60°C, 80°C, and 100°C to evaluate the thermodynamic properties of NaCl adsorption. Figure 7 shows that the higher the adsorption temperature, the greater the decrease in electrical conductivity, TDS, and salinity, with a sharp decrease observed at 100°C. This is likely due to increased entropy at the molecular interface, as evidenced by the low value of Gibbs delta, especially at 100°C. The frequent decrease in conductivity, TDS, and salinity values with increasing temperature indicates that the adsorption process is endothermic.

The adsorption capacity increases with increasing temperature, indicating that the process is endothermic. Thermodynamic parameters were determined from equilibrium data and summarized in Table 5. The Gibbs free energy change (ΔG) values were -1.905, -2.019, and -2.139 kJ mol^{-1} for temperatures of 60, 80, and 100 ºC, respectively. Negative ΔG values indicate spontaneous Adsorption, while their magnitude increases with increasing temperature, indicating increased feasibility at higher thermal energies.



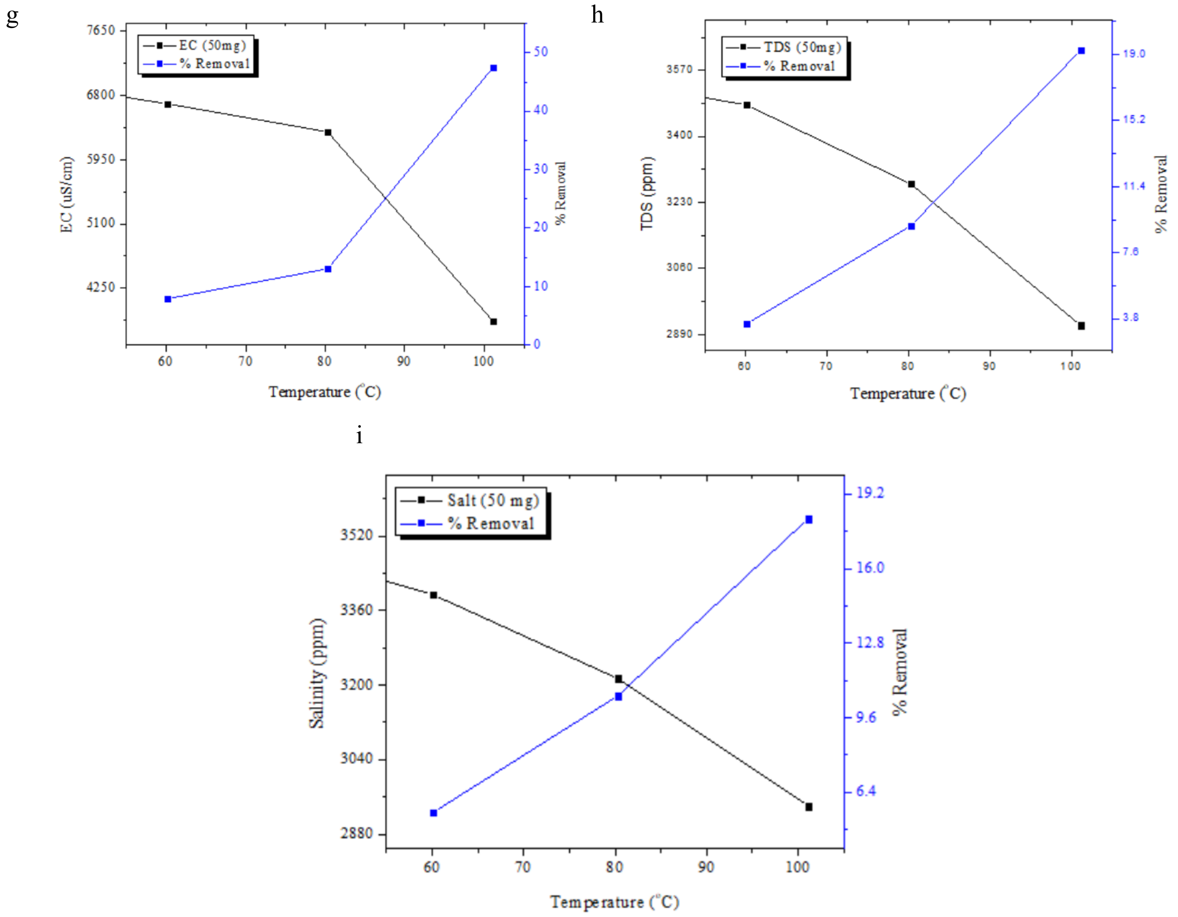


Fig 7. The Effect of temperature on NaCl solution by nylon-gelatin-hematite composite

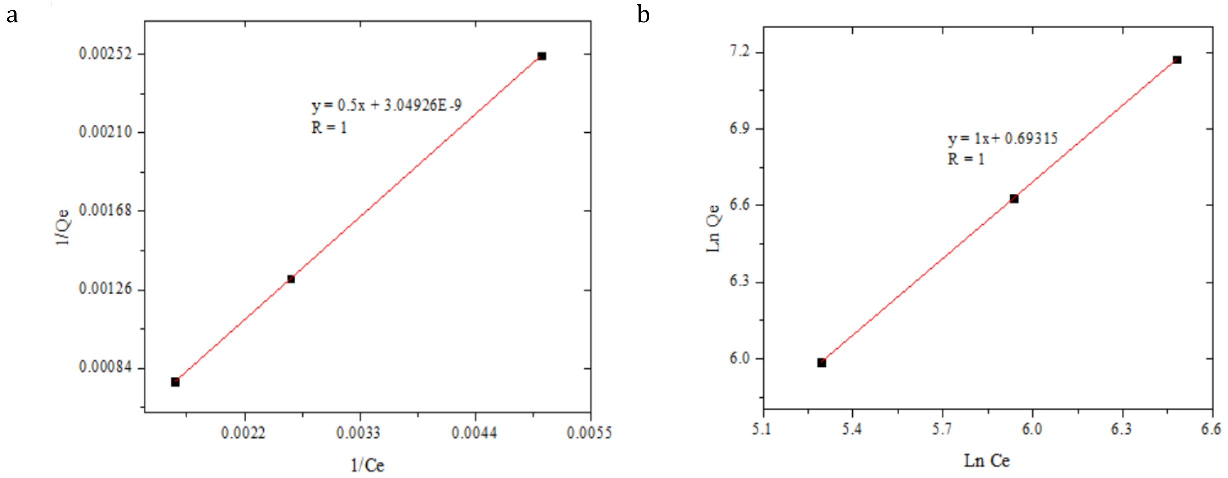


Fig 8. Linear isotherm of saline solution adsorption based on composite nylon-gelatin-hematite at 100 °C (from data salinity)

Table 4. Isothermal adsorption-desorption model fitting parameters

Adsorption Model			
Langmuir		**Freundlich**	
q_{max}	2	**1/n**	1
K_L(L/mg)	1.64E+08	**K_F(mg/g)(L/mg)$^{1/n}$**	1.99
R^2	1	**R^2**	1

Table 5. Thermodynamic parameters for NaCl solution removal on nylon-gelatin-hematite at various temperatures

ΔG (kJ/mol)		
T = 60 ºC	T = 80 ºC	T = 100 ºC
-1.905	-2.019	-2.139

The negative ΔG values indicate spontaneous Adsorption, while the increasing magnitude with temperature suggests enhanced feasibility at higher thermal energy. Similar thermodynamic trends have been reported for Na^+ and Cl^- Adsorption on biopolymer–iron oxide composites. This behavior suggests that the adsorption mechanism involves electrostatic attraction and diffusion-assisted ion penetration into the composite matrix.

4 Conclusion

The nylon–gelatin–hematite composite demonstrated relatively good adsorption performance for removing NaCl from saline solutions. The adsorption data fit well with the Freundlich isotherm models, indicating multilayer and heterogeneous adsorption behavior. Kinetic analysis revealed that the process followed a pseudo-first-order model with an R^2 value of 0.99, confirming physisorption as the dominant mechanism. Thermodynamic results revealed negative ΔG values, ranging from -1.905 to -2.139 kJ/mol, indicating spontaneous Adsorption. Increasing temperature and adsorbent dosage enhanced the adsorption capacity. Overall, the synergistic combination of nylon, gelatin, and hematite significantly improved surface activity and ion-binding affinity, making this composite a promising material for efficient saline water treatment.

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