



Modelling the Sorption Behaviour of Heavy Elements on Soil

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DOI:10.21608/AJSWS.2024.327476.1020



Article Information

Received: November 3rd 2024

Revised: November 18, 2024

Accepted: November 25, 2024

Published: January 1st 2025

ABSTRACT: A laboratory experiment was conducted to examine, compare and evaluate the sorption of heavy metals (nickel and lead) on sorbent materials (sandy and sandy loam soils). The sorption data were fitted with some sorption isotherm models using the software IsoFit such as Linear, Freundlich, and proposed new model. Measured and simulated data were compared statistically to evaluate model reliability. It noticed that the sorption of Ni and Pb was more pronounced in sandy loam soil than in sandy soil and the sorption percentage was decreased by increasing the initial concentration. The results showed that the average values of sorption percentages of sandy and sandy loam soils were 80.39 and 87.69% and 87.23 and 93.89% for Ni and Pb, respectively. Also, the experimental data was analyzed to examine the adsorption isotherm models. The distribution coefficients (K_d) obtained from the linear sorption isotherm model were 98.772 and 168.524 L/kg (as Ni and Pb) for sandy soil and 161.606 and 388.391 L/kg (as Ni and Pb) for sandy loam soil. Metals can be arranged according to their K_d values, i.e. their affinities for the soil, in the following relative sequence: Pb > Ni. This general sequence tends to vary slightly for different soil types. The obtained results are promising and useful in industrial wastewater infiltration into the soil profile and groundwater. In conclusion, understanding the sorption dynamics of heavy metals in soil systems is essential for managing contaminated sites and protecting environmental health. This research recommends future studies to verify the competitive mechanism of heavy metals sorption correlated to the soil characteristic parameters.

Keywords: heavy metals sorption, IsoFit software, Adsorption; sorption isotherm models

INTRODUCTION

Soil plays an essential role in the human ecological system and is a crucial natural resource for human existence. The rapid pace of urbanization and the industrial revolution in recent years have resulted in increased energy consumption and significant environmental pollution challenges. Among the various forms of pollution, heavy metal contamination stands out as one of the most pressing environmental concerns. Research conducted by Yang et al. (2021) identifies arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn) as the primary heavy metal pollutants affecting the environment.

Because heavy metals are poisonous, persistent, and may bioaccumulate, they constitute a significant risk to the ecosystem and may have detrimental effects on the environment. Various sources contribute to the introduction of heavy metals into agricultural soils, including the use of fertilizers, the discharge of wastewater, the application of sewage sludge, inadequate soil enhancement practices, mining activities, and the application of fertilizers. As a result, these metals are absorbed by crops, subsequently

entering the human food chain and potentially affecting human health.

Heavy metals represent a significant category of hazardous contaminants frequently found in both municipal and industrial wastewater (Demirbas, 2008). As noted by Kadirvelu et al. (2001), these metals originate from various human activities associated with multiple industries, including mining, electroplating, dyeing, electrochemical metal processing, and battery manufacturing. Due to their inherent stability, heavy metals are resistant to degradation or removal (Shi et al., 2009; Vinodh et al., 2011). The accumulation of these metals and their residues is a direct consequence of inadequately treated wastewater being discharged into the environment. Numerous studies have indicated that heavy metals can be detected in various environmental matrices, including soil (Yaylali-Abanuz, 2011; Wei and Yang, 2010), vegetation (Meena et al., 2005), sediments (Guzel et al., 2008), and airborne dust (Wei and Yang, 2010).

Wastewater released into the soil can either infiltrate the ground and contaminate groundwater or travel over the surface to lower-lying areas. Research has demonstrated that soils possess the capacity to remove heavy metals effectively (Chaari et al., 2011; Abat et

al., 2012). Composed of naturally occurring minerals, soils play a crucial role in the treatment of wastewater by acting as a filter that captures metals before they can reach groundwater or disperse into adjacent regions or waterways. The primary mechanism influencing the behaviour of heavy metals within the soil matrix is the process of adsorption, wherein metals transition from their liquid state to a solid state within the soil (Srivastava et al., 2005).

Although this research only examined a small number of soils, several studies on the behaviours of heavy metals absorbed by soils have been carried out. Furthermore, the simulation of real conditions upon wastewater release into the soil was not very thorough.

Most heavy metals found in soil have integrated into the soil matrix. These adsorbed metals can migrate to deeper soil layers and groundwater, or they may desorb into the soil solution, subsequently being taken up by plants in a dissolved state. The movement of heavy metals within the soil environment can be quantified through a distribution coefficient, defined as the ratio of the concentration of the metal in

the solid phase to that in the liquid phase when equilibrium is achieved (Anderson et al., 1988). The calculation of distribution coefficients can be performed by analyzing the slopes of adsorption isotherms.

This research investigates the absorption characteristics of different soil types concerning prevalent heavy metals, specifically lead (Pb) and nickel (Ni). The methodology employed involved batch sorption experiments to elucidate the sorption behaviour and properties, which were further analyzed through the application of several isotherm models.

2. Materials and Methods

1. Soil sampling

Sandy and sandy loam soil samples were collected from surface layer (0–30 cm depth) of the farmed area at Rashid City and Bousilly region, Beheira Governorate, Egypt. The air-dried soil samples were filtered using a 2.0 mm sieve and stored for analysis. Physical and chemical properties of the soil samples were determined according to the methods described by Carter and Gregorich (2008) and depicted in Table (1).

Table (1). Some physical and chemical analyses of soil samples

Parameters	Site 1	Site 2
Particle-size distribution		
Sand, %	95.52	76.72
Silt, %	0.00	16
Clay, %	4.48	7.28
Textural class	Sandy	Sandy loam
Saturation percentage, %	30.0	52.5
Soil bulk density, Mg/m ³	1.30	1.55
Chemical properties		
pH	8.00	7.99
EC, dS/m	0.27	2.40
OM, %	0.29	2.30
CaCO ₃ , %	0.52	1.07
Soluble cations, meq/l		
Ca	2.40	1.80
Mg	5.60	2.70
Na	0.86	13.80
K	0.19	1.50
Soluble Anions. meq/l		
HCO ₃	1.00	1.00
Cl	1.00	12.40
SO ₄	0.21	0.50
Available nutrients, mg/kg		
N	17.81	14.80
P	17.40	28.00
K	300.00	500.00
Available Heavy metals, mg/kg		
Ni	0.0488	0.1225
Pb	0.3418	0.5323

2. The batch sorption of heavy metals:

The Ni²⁺ and Pb²⁺ stock solutions at 1000 mg/l were prepared using the analytical Following this, dilutions of Ni²⁺ (0.0 to 8.0 mg/l) and Pb²⁺ (0.0 to 8.0 mg/l) were done by appropriately diluting the stock solution by distilled water. Three repetitions of each experiment were used, and the experiments were carried out in a 100 ml flask with 50 ml of a heavy metal solution at varying concentrations and 2.0 g of sandy or sandy loam soil. The mixture was agitated for an hour at 200 rpm in a rotary shaker before being filtered through Whatman filter paper (No. 1). The residual concentration of heavy metals (filtrate) kept for analysis. The heavy metals in filtrate were measured using ICP-MS (Ivajlo et al., 2008). Soil models were used to fit the sorption data. Once equilibrium was reached, the sorbents' capacities were computed. Using the following formula, the adsorbed metal for each sample was determined based on a mass balance of the metal ion (Vijayaraghavan et al., 2006):

$$q_e = \frac{(C_0 - C_e) \times V}{m}$$

Where (1)

q_e = amount of sorbate at equilibrium, mg kg⁻¹ (adsorption capacity),

V = the volume of the solution (L),

m = the mass of the soil (g),

C_0 = the initial concentration of metal (mg L⁻¹), and

C_e = Equilibrium concentration of sorbate in solution, mg L⁻¹

The following formula was used to calculate the adsorbed percentage of heavy metals in the solution (Sethuraman and Balasubramanian, 2010):

$$\text{sorbed}(\%) = \frac{(C_0 - C_e)}{C_0} \times 100 \quad (2)$$

3. Mathematical modelling of the sorption process

Using the program IsoFit, the sorption data were fitted to a few sorption isotherms models to examine and contrast the sorption of heavy metals on sorbent materials (Matott, 2004; Matott and Rabideau, 2008). The potential of an adsorbent to remove a contaminant down to water resources has been predicted using isotherm sorption models. The amount of pollutant adsorbed and the amount still in the solution will balance out once a mass of adsorbent and a waste stream come into contact for a long enough periods. The relationship between the solute's equilibrium concentration (C_e) and adsorption capacity (q_e) can be expressed mathematically as an adsorption isotherm. It is crucial to model adsorption isotherm data to forecast or compare adsorption performances. The sorption data should be modelled using one-, two-, three-, or four-parameter isotherm models (Table 2).

Table (2). Isotherm sorption models used in the

present study	
Sorption	Equation
Linear or Henry isotherm Xue et al. (2001)	$q_e = K_d \times C_e$ (3)
Freundlich isotherm Freundlich (1906) and Jain et al. (2003)	$q_e = K_f \times C_e^{1/n}$ (4)
New model (GK)	$q_e = \frac{(K_{GK1} * C_e)}{(1 + K_{GK2} * C_e)} * (1 + EXP(-K_{GK3} * C_e))$
K_{GK1} = GK isotherm constant, K_{GK2} = GK isotherm constant K_{GK3} = GK isotherm constant, K_F = Freundlich isotherm constant, L g ⁻¹ K_d = Distribution coefficient, L kg ⁻¹	

4. Performance evaluation of sorption models

To assess the dependability of the model, statistical comparisons were made between simulated and measured data (AgriMetSoft, 2018). The coefficient of determination (R^2), the root mean square error (RMSE), the normalized root mean square error (NRMSE) (Jacovides and Kontoyiannis, 1995), and the index of Willmott (d) (Willmott, 1982&1985) were used to determine the degree of agreement between the predicted and measured values.

Statistical parameters expressed in Equations (6 to 11) were:

5- Statistical parameters

5.1. The Average Absolute Error (AAE)

Absolute percentage error between simulated and observed values may be calculated using the following equation (Loague and Green, 1991):

$$AAE = \frac{\sum_{i=1}^n |O_i - S_i|}{n} \quad (6)$$

5.2. Root Mean Square Error (RMSE)

Root means square error (RMSE) is calculated as follows (Loague and Green, 1991):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (S_i - O_i)^2}{n}} \quad (7)$$

If RMSE is close to zero, the model performance can be described as acceptable.

5.3. Coefficient of Determination (R^2)

$$R^2 = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - O_{av})^2} \quad (8)$$

A value between 0 and 1 that indicates how well a statistical model predicts a result is called the coefficient of determination (R^2).

5.4. Index of agreement (d)

The index of agreement (d) was calculated using the **Willmott et al. (2012)** equation:

$$d = 1 - \frac{\sum_{i=1}^n (S_i - O_i)^2}{\sum_{i=1}^n (|S_i - O_{av}| + |O_i - O_{av}|)^2} \quad (9)$$

The agreement (d) value index varies between 0 and +1 (**Andarzian et al., 2011; Valbuena et al., 2019**). According to d values, the closer to one indicates that estimated and observed values are identical.

5.5. Correlation coefficient (r)

The correlation coefficient is an indication of the degree of closeness between observed and simulated values. The observed and simulated values are correlated better when the correlation coefficient approaches 1.0. If observed and anticipated values are totally independent, i.e., uncorrelated, then r will be zero. The correlation coefficient was estimated by the following equation:

$$r = \frac{\sum_{i=1}^n (O - O_{av})(S - S_{av})}{\sqrt{\sum_{i=1}^n (O - O_{av})^2 \sum_{i=1}^n (S - S_{av})^2}} \quad (10)$$

Where

n = the number of observations,

1/n = exponent in Freundlich isotherm

O_i = the observed value

O_{av} = the mean of the observed value.

q_t = amount of sorbate sorbed at time t, mg kg⁻¹

S_i = the simulated value

S_{av} = the mean of the simulated value

5.6. Normalized Root Mean Square Error

The normalized root means square error (NRMSE) (**Jacovides and Kontoyiannis, 1995**) is calculated as follows:

$$\text{NRMSE}(\%) = \frac{\text{RMSE}}{O_{av}} \times 100$$

(11) If NRMSE is less than 10%, model simulation can be considered perfect (between 10 and 20%; acceptable, 20 and 30%; fair, greater than 30%; poor) (**Valbuena et al., 2019**).

6. Soil characteristics analysis:

The soil samples were air-dried, passed through a 2 mm sieve and analyzed. Some physical and chemical

properties of the collected soil samples were determined according to the recommended procedures as follows:

6.1. Physical properties of soils

The bulk density of each soil sample was measured according to the weight of the soil and the volume of the packed column. Particle-size distribution was determined by the hydrometer method (**Carter and Gregorich, 2008**). The saturation percentage (K_s) was determined according to the constant head method (**Klute and Dirksen, 1986**).

6.2. Chemical properties of soils

Total carbonates were estimated volumetrically using a calcimeter and calculated as calcium carbonate percentages according to **Richards (1954)**. The modified Walkley-Blacks titration method determined organic carbon (OC) (**Carter and Gregorich, 2008**). The organic matter content (OM) was calculated using the suitable constant ($OM = 1.724 \times OC$). Electrical conductivity (EC) of soil: water extract, 1:2 (w/v), soluble cations and anions were measured and determined using methods according to **Jackson (1973)**. The concentration of available heavy metals in soil samples was determined by extraction with DTPA extractant (**Lindsay and Norvell, 1978**).

7. Statistical analysis:

All obtained data of the present study were, statistically, analyzed according to the design used by the **Statistix (2024)** computer software program and were tested by analysis of variance. The revised least significant difference test at 0.05 level of probability was used to compare the differences among the means of the various parameter combinations as illustrated by Gomez and Gomez (1984).

Tables (3 and 4) show the equilibrium sorption of Ni and Pb ions in two different soil samples. The equilibrium concentration ranged from 0.370 to 1.645 mg/l (as Ni) and 0.207 to 1.052 mg/l (as Pb) for sandy soil and between 0.218 to 1.089 mg/l (as Ni) and 0.124 to 0.48 mg/l (as pb) for sandy loam soil. The sorption capacity ranged between 40.75 and 158.88 mg/kg (as Ni) and between 44.83 and 173.70 mg/kg (as Pb) for sandy soil. For sandy loam soil, the sorption capacity ranged between 44.55 and 172.78 mg/kg (as Ni) and between 46.90 and 188.00 mg/kg (as Pb).

The average sorption percentage was 80.39 and 87.69% for Ni and Pb, respectively for sandy soil. For sandy loam soil, it was 87.23% and 93.89% for Ni and Pb, respectively.

Table (3). Equilibrium sorption of heavy metals on the sandy soil

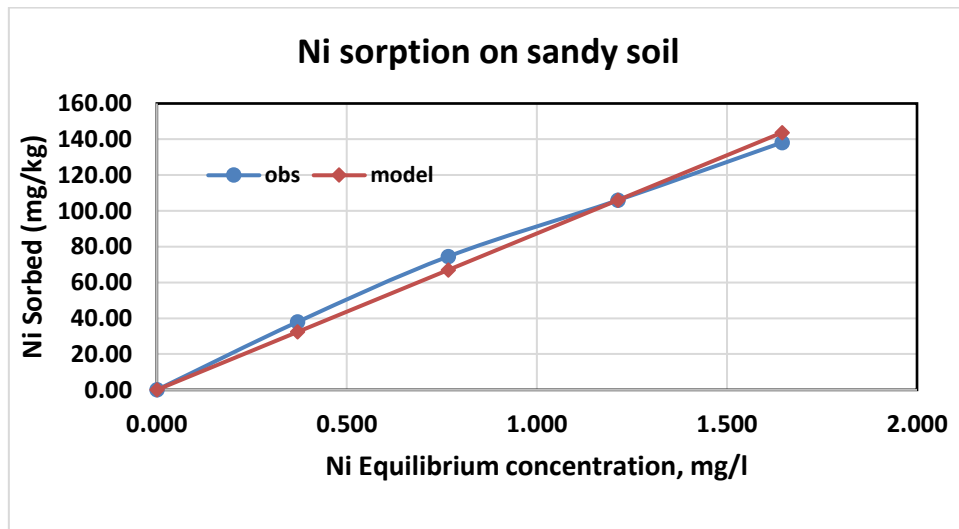
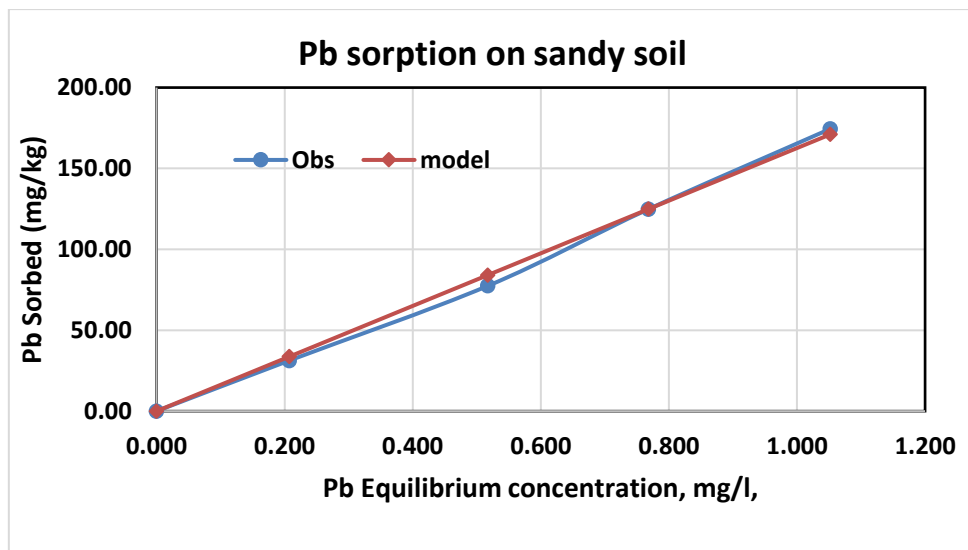
Ni ²⁺				Pb ²⁺			
C ₀ mg/l	C _e mg/l	q _e mg/kg	% Adsorbed	C ₀ mg/l	C _e mg/l	q _e mg/kg	% Adsorbed
0.000	0.000	0.00	0.00	0.000	0.000	0.00	0.00
2.000	0.370	40.75	81.50	2.000	0.207	44.83	89.65
4.000	0.767	80.83	80.83	4.000	0.517	87.08	87.08
6.000	1.213	119.68	79.78	6.000	0.768	130.80	87.20
8.000	1.645	158.88	79.44	8.000	1.052	173.70	86.85
Average			80.39	Average			87.69

Table (4). Equilibrium sorption of heavy metals on the sandy loam soil

Ni^{2+}				Pb^{2+}			
C_0 mg/l	C_e mg/l	q_e mg/kg	% Adsorbed	C_0 mg/l	C_e mg/l	q_e mg/kg	% Adsorbed
0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00
2.000	0.218	44.55	89.10	2.000	0.124	46.900	93.80
4.000	0.527	86.83	86.83	4.000	0.248	93.800	93.80
6.000	0.804	129.90	86.60	6.000	0.363	140.925	93.95
8.000	1.089	172.78	86.39	8.000	0.480	188.000	94.00
Average			87.23	Average			93.89

Tables (3 and 4) and Figures (1 through 4) show the equilibrium isotherms for each heavy metal (Ni^{+2} , Pb^{+2}) onto sandy and sandy loam soils. The findings demonstrated that both soils absorbed the initial concentration of the heavy metal ions from the aqueous solution to a degree of approximately 80.39 and 87.69% (Ni and Pb) for sandy soil and approximately 87.23 and

93.89% (Ni and Pb) for sandy loam soil because of sandy loam soil has more fine particles that can adsorb heavy metals than sandy soil, there is greater sorption of heavy metals in sandy loam soil than in sandy soil. Tables (3 and 4) show a decrease in the sorption percentage or removal efficiency with an increase in the starting concentration.

**Figure (1). Linear sorption isotherm of Ni on sandy soil****Figure (2). Linear sorption isotherm of Pb on sandy soil**

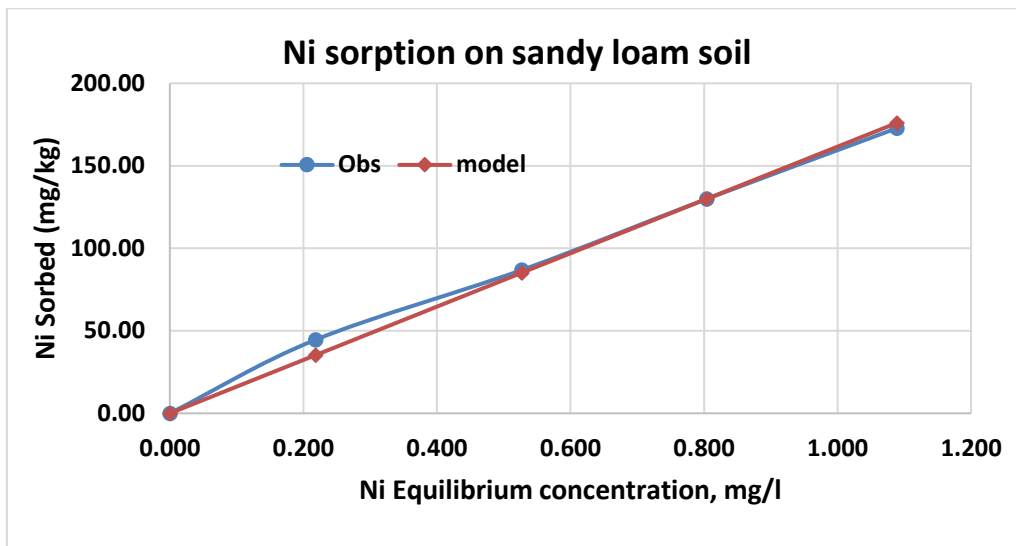


Figure (3). Linear sorption isotherm of Ni on sandy loam soil

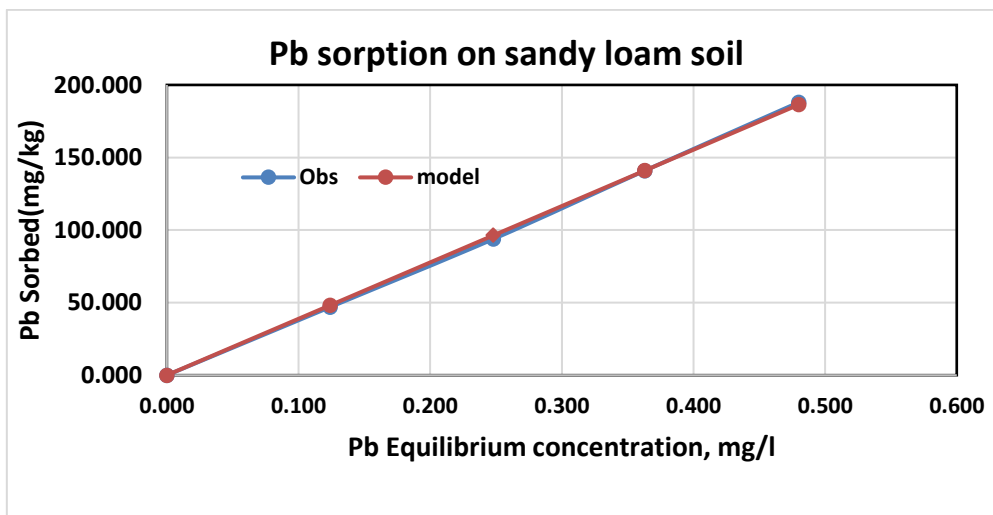


Figure (4). Linear sorption isotherm of Pb on sandy loam soil

An essential factor influencing adsorption is the initial concentration of heavy metal ions, as the capacity of the adsorbent to capture these ions is limited to a specific quantity. Data presented in Tables (5 and 6) illustrate a decline in the percentage of ions adsorbed as the initial concentration rises. Conversely, Tables (3 and 4) reveal that with an increase in the starting ion concentration within the test solution, the actual quantity of ions adsorbed per unit mass of the adsorbent correspondingly increased.

The high proportion of surface-active sites relative to the total metal ions present in the solution facilitates the interaction of all metal ions with the soil at low concentrations, leading to their rapid extraction from the solution. As the initial concentration of metal ions increased, there was a corresponding decline in the percentage of ions that were adsorbed, as evidenced by the data presented in Tables (5 and 6). Nevertheless, these tables also reveal that the actual quantity of ions adsorbed per unit mass of the adsorbent increased with higher initial concentrations of ions in the test solution.

All metal ions engage with soil at low concentrations, leading to their swift removal from the solution due to the significant ratio of surface-active sites relative to the total metal ions present. Conversely, at elevated concentrations, there is an increased adsorption of metal ions per unit weight of the adsorbent, denoted as q_e . The maximum adsorption capacity of the adsorbent was assessed by utilizing higher concentrations of metal ions, as demonstrated in the studies by **Karthikeyan et al. (2004)** and **Mohanty et al. (2005)**.

The adsorption isotherm serves as a fundamental tool for elucidating the mechanisms underlying the adsorption of cations onto the surface of adsorbents, with equilibrium studies playing a vital role in assessing the adsorbent's capacity. In the present investigation, various isotherm models, such as linear, Freundlich, Langmuir, Langmuir–Freundlich, Generalized Langmuir–Freundlich, along with two novel models, were employed to analyze the experimental data, thereby facilitating a comprehensive examination of the adsorption isotherm, as detailed in Tables (7 and 8).

In this work, adsorption isotherm models were investigated through the analysis of experimental data. According to **Abdulrasaq and Basiru (2010)**, The sorption process is often described using adsorption isotherms like Langmuir and Freundlich models (**Ali et al., 2023**). These models provide information about the sorption capacity and affinity.

In sandy soils, the coarser texture and reduced surface area contribute to less efficient sorption processes. This type of soil is particularly susceptible to leaching, resulting in the potential loss of both nutrients and contaminants instead of their retention (**Ali et al., 2023**). Conversely, sandy loam soils, characterized by a mixture of finer particles and organic matter, enable more intricate interactions such as ion exchange and surface adsorption, which improve the retention of heavy metals. Additionally, the structural properties of this soil type enhance water retention, thereby

increasing the duration of contact between metal ions and soil particles (**Ali et al., 2023**).

Sandy soil exhibits a distribution coefficient (K_d) of 98.772 L/kg for nickel (Ni) and 168.524 L/kg for lead (Pb), suggesting a relatively weaker interaction with heavy metals in comparison to sandy loam soil. In contrast, sandy loam soil demonstrates a greater affinity for heavy metals, as evidenced by its K_d values of 161.605 L/kg for Ni and 388.391 L/kg for Pb, which indicate a robust interaction with metal ions.

Sandy loam soil exhibits superior sorption capacity for heavy metals compared to sandy soil, primarily attributable to its finer texture, increased surface area, and enhanced retention mechanisms. These characteristics render sandy loam soil more efficient for use in strategies designed to alleviate heavy metal pollution in environmental contexts.

Table (5). Sorption isotherm parameters of models for heavy metals sorption on sandy soil

model	Parameters	Ni	Pb
linear	K_d	98.772	168.524
	R^2	0.9973	0.9955
Freundlich	K_f	101.291	165.170
	$1/n$	1.109	0.909
	R^2	0.9999	0.9994
	K_{GK1}	112.883	190.577
New model GK	K_{GK2}	0.106	0.151
	K_{GK3}	100.000	107.088
	R^2	0.9998	0.9974

Table (6). Sorption isotherm parameters of models for heavy metals sorption on sandy loam soil

model	Parameters	Ni	Pb
linear	K_d	161.606	388.391
	R^2	0.9960	0.9996
Freundlich	K_f	159.398	402.331
	$1/n$	1.125	0.963
	R^2	0.9989	0.9999
	K_{GK1}	183.893	388.879
New model GK	K_{GK2}	0.154	0.092
	K_{GK3}	100.000	27.000
	R^2	0.9981	0.9997

Tables(5and6) provide the sorption isotherm parameters for each model. The findings showed that all evaluated models adequately described the sorption data in cases where the (R^2) was more than 0.99. For both soils, the sorption capacity was in the following order: Pb>Ni. Additionally, the sorption percentages of the used soils were 80.39 and 87.69% (as Ni) for sandy soil, respectively, while sandy loam soil was 87.23 and 93.89% (as Pb). By contrast to sandy soil, the results showed that sandy loam soil had a higher affinity for the sorption of heavy metals (Ni^{2+} and Pb^{2+}). According to **Lehmann (2006)**, sandy loam soil has a large surface area and a negative surface charge density. These characteristics help the soil become more stable and boost its ability to hold nutrients. The sorption of heavy metals on soil was better described by the new model (GK), which showed to be more stable and accurate.

The distribution coefficients, K_d (Figure 5) for sandy and sandy loam soils were 98.772 and 168.524 L/kg (as Ni) in sandy soil and 161.606 and 388.391 L/kg (as Pb) for sandy loam soil based on the linear sorption isotherm. Metals can be ordered in the following relative sequence: Pb>Ni based on their K_d values or soil affinities. Figure (5) illustrates how this broad process tends to change slightly for various soil types. The sorption mechanism was ion exchange for all metals investigated. Sandy loam soil has a high affinity for heavy metal sorption due to its high surface area and negative surface charge density (**Ali et al., 2023**). In general, sandy loam soil exhibited higher sorption capacities for heavy metals compared to sandy soil, with Pb having the greatest affinity for both soil types. The sorption mechanism was primarily ion exchange.

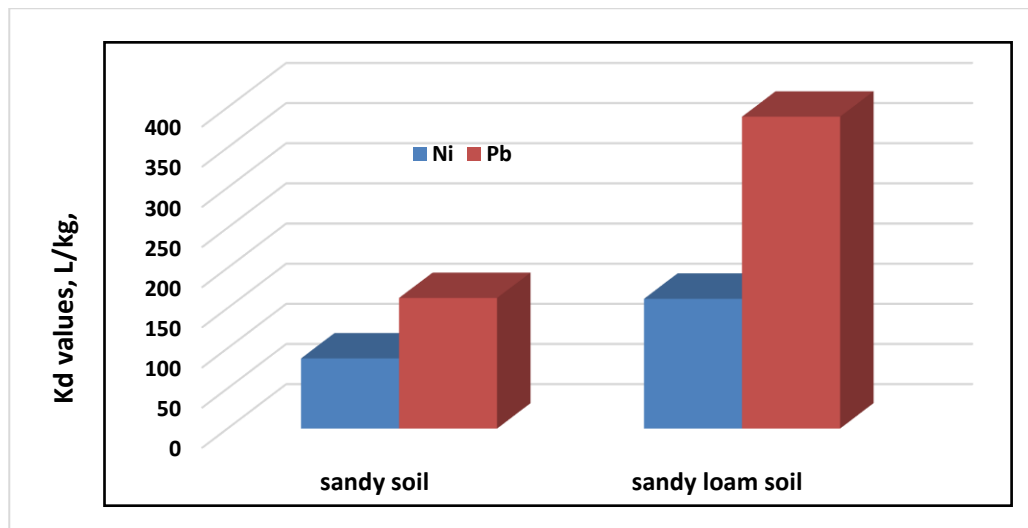


Figure (5). Affinities of heavy metals for two types of soil

The Pb>Ni was the observed heavy metal sequence in the recent investigation. This broad sequence seems to be compatible with electronegativity sequences Pb (2.33)>Ni (1.91) or with ionic radii Pb (202 pm)> Cd (158 pm). The current results corroborate the findings of **Abd-Elfattah and Wada (1981)**, who reported that the majority of the observed sequences do not exhibit any correlation with the electronegativity sequence, which is Pb (1.8) = Ni (1.8), or with the sequence of ionic radii, which is Pb (1.20) > Ni (0.69) Å°.

A distribution coefficient, which is the ratio of metal concentration in the solid phase to that in the liquid phase at equilibrium, can be used to characterize the mobility of heavy metals in soil (**Anderson et al., 1988, Khater, 2007**). The adsorption isotherms' slopes can be used to calculate distribution coefficients.

The degree to which the metal may be absorbed by plant roots and how far it can go through the soil profile are both greatly influenced by the sorption (bioavailability). Among the metals that have been the subject of recent research, those with tiny distribution coefficient values—like Co—are the most mobile (**Wang & Lei, 2018**). The degree of precision

obtained from adsorption operations is highly dependent on the success of adsorption isotherm modelling and interpretation.

Linear regression has been used widely to evaluate performance and goodness of fit because of its wide applicability to a wide range of adsorption data. However, a lot of researchers have also employed nonlinear regression analysis a lot to close the gap between experimental and anticipated data. Because of this, it's critical to understand the significance of both linear and nonlinear regression analysis in various adsorption systems.

2. Performance evaluation of sorption models

Tables (7 and 8) illustrate the goodness of fit statistical description. We may infer that all of the isotherm models that were employed in this study provide an acceptable explanation of how heavy metals sorb. The Linear, Freundlich and the novel model (GK) were more appropriate than the other isotherm models. Also, The Freundlich isotherm is the more efficient model to express the sorption of Ni and Pb on studied sandy and sandy loam soil used in the present study.

Table (7). The goodness of fit techniques for Ni-tested sorption isotherm models of sandy soil

Model	AAE	RMSE	NRMSE	d
Linear Isotherm	2.6046	3.3637	4.2031	0.9966
Freundlich Isotherm	0.5638	0.6957	0.8694	0.9998
GK Isotherm	0.7495	0.9252	1.1561	0.9999

Table (8). The goodness of fit techniques for Pb-tested sorption isotherm models of sandy loam soil

Model	AAE	RMSE	NRMSE	d
Linear Isotherm	2.9946	4.7671	5.4618	0.9945
Freundlich Isotherm	1.5071	1.7567	2.1532	0.9994
GK Isotherm	2.3849	3.5332	4.0481	0.9989

Adsorption is one technique that has been used to describe the transport of pollutants in an aqueous medium and the subsequent creation of containment measures (**Ayawei et al., 2005; Shooto et al., 2016**).

The primary mechanisms involved in the sorption process include ion exchange, adsorption onto mineral surfaces, and precipitation. The specific mechanism can depend on the type of soil and the

concentration of heavy metals present (Dube et al., 2001; Sangiumsak and Punrattanasin, 2014).

The retention of heavy metals in soil significantly influences both their movement and their availability to flora and microorganisms. When metals are tightly adhered to soil particles, the likelihood of their leaching into groundwater or absorption by plants diminishes, which in turn mitigates their ecological hazards. Nevertheless, shifts in environmental factors, including heightened precipitation or modifications in land utilization, can disturb these balances, resulting in increased leaching of pollutants (Liu et al., 2022).

Understanding adsorption equilibrium is crucial for comprehending the dynamics of the adsorption process. The findings from this study on the adsorption rates of nickel (Ni) and lead (Pb) across various soil types indicate that the equilibrium state was achieved as predicted by the proposed models. The linear, Freundlich, and new isotherm models effectively characterize the adsorption isotherms observed. Among the soil types examined, sandy loam exhibited the highest adsorption capacity, while sandy soil demonstrated the lowest. Furthermore, the adsorption potential across nearly all soil types was determined to follow the order of Pb greater than Ni, highlighting that the adsorption capacity is significantly influenced by the specific surface area and charge characteristics of the soil.

The investigation into the sorption of heavy metals from industrial wastewater in two distinct soil types yielded several significant findings. It was established that various factors influence the sorption process of heavy metals within soils, such as pH levels, organic content, mineral composition, soil texture, and the specific metal ions being analyzed. As highlighted by Ali et al. (2023), the research underscored the necessity of creating precise mathematical models to forecast the sorption behaviour of heavy metals in soils, as these models are instrumental in the effective management of contaminated soils and in mitigating potential negative environmental consequences.

This research has demonstrated that the levels of heavy metals present in soil significantly influence their sorption capacity, revealing that greater sorption capacities are observed at reduced concentrations. Investigations into the impact of soil temperature and moisture on the sorption process indicate that soils characterized by low temperatures and high moisture content exhibit an enhanced ability to adsorb heavy metals. The implications of these findings are valuable for developing effective strategies aimed at the remediation of contaminated soils by removing heavy metals.

In order to mitigate the environmental impact of heavy metals, forthcoming investigations in this field ought to emphasize the utilization of advanced techniques, including nanotechnology, to create efficient sorbents for heavy metals. Additionally, there is a pressing need to develop more predictive models capable of anticipating the behavior and final distribution of heavy metals across different soil types and environmental conditions. This area of research has provided valuable insights into the sorption processes of

heavy metals in soils, taking into consideration all relevant factors and parameters. Furthermore, it may stimulate the innovation of novel and more effective remediation strategies to tackle challenges associated with wastewater treatment.

The findings presented are highly relevant to the infiltration of industrial wastewater into soil profiles and groundwater systems. Research into the sorption behaviour of heavy metals in soil has utilized various sorption isotherm models, indicating that monolayer adsorption is the dominant mechanism in these soils. Furthermore, it was observed that sandy loam soil exhibits a greater sorption capacity compared to sandy soil. Additionally, this study suggests that further investigations are necessary to explore the competitive mechanisms of heavy metal sorption about the specific characteristics of the soil.

In summary, comprehending the sorption dynamics of heavy metals within soil systems is crucial for the management of contaminated sites and the safeguarding of environmental health. Continuous research efforts are required to enhance predictive models and to formulate effective remediation strategies that are specifically designed for various soil types and contamination contexts.

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الملخص العربي

نمذجة سلوك ادمصاص العناصر الثقيلة على التربة

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أجريت تجارب معملية لفحص ومقارنة وتقييم سلوك ادمصاص المعادن الثقيلة (النيكل والرصاص) على المواد المدمصة (تربة رملية و رملية لومية). تم تجهيز بيانات الادمصاص لادخالها في نماذج معادلات الادمصاص باستخدام برامج IsoFit مثل Linear و Freundlich والنموذج الجديد المقترح. تمت مقارنة البيانات المقاسة والمحاكاة إحصائياً لتقييم موثوقية النموذج. لوحظ أن ادمصاص النيكل والرصاص كان أكثر وضوحاً في التربة الرملية اللومية عنه في التربة الرملية كما انخفضت نسبة الادمصاص بزيادة التركيز الأولي. أظهرت النتائج أن متوسط قيم نسب الادمصاص للتربة الرملية و الرملية اللومية كانت 80.39 و 87.69% و 87.23 و 93.89% للنيكل والرصاص على التوالي. تم تحليل البيانات التجريبية لفحص نماذج معادلة الادمصاص. كانت معاملات التوزيع (Kd) التي تم الحصول عليها من نموذج معادلة الامتصاص الخطي هي 98.772 و 168.524 لتر / كجم (النيكل والرصاص) للتربة الرملية و 161.606 و 388.391 لتر / كجم (النيكل والرصاص) للتربة الطميية الرملية. يمكن ترتيب المعادن وفقاً لقيم Kd الخاصة بها بالتسلسل النسبي التالي: $Pb > Ni$. يميل هذا التسلسل العام إلى التباين قليلاً لأنواع التربة المختلفة. النتائج الحالية مفيدة جداً في رشح مياه الصرف الصناعي الى قطاع التربة والمياه الجوفية. في الختام يمكن القول بأن فهم ديناميكيات ادمصاص المعادن الثقيلة في أنظمة التربة أمرًا ضروريًا لإدارة المواقع الملوثة وحماية الصحة البيئية. توصي الدراسة الحالية بإجراء دراسات مستقبلية للتحقق من الآلية التنافسية لامتصاص المعادن الثقيلة المرتبطة بمعلمات خصائص التربة.