Synergistic effect of Adsorbent dosage of Neem leaf powder NLP on Isotherms of lead (Pb2+) to enhance the efficient decrease of lead concentration

Ashiru Garba Abdullahi[1], Abdul'aziz Magaji[2], Abba Alhaji Bala[1], Aminu Abubakar[3]

[1]Advance Nanotechnology and Computational Physics Laboratory Department of Physics, Faculty of Physical Science, Federal University Dutse, P.M.B 7156, Ibrahim Aliyu Bye Pass, Jigawa State-Nigeria.
[2]Chemical Engineering Department, Bayero University Kano
[3]Alu College of Health Sciences and Technology Birnin Kudu

*Corresponding author: ashirugarba003@gmail.com

(Received 06 May 2025, Accepted 08 July 2025, Published 17 July 2025)

Abstract

Lead (Pb^{2+}) is one of the heavy metals that naturally occurs and is found in the earth's crust. Its widespread use has resulted in extensive environmental contamination, human exposure, and significant public health problems in many parts of the world. Many different methods were explored to remove the Pb^{2+} from the contaminated water. In this experiment, Neem leaf powder (NLP) was used as an agent for the removal of heavy metals through a process called adsorption or biosorption. It has been shown in the experiment that the NLP was a good adsorbent for the removal of Lead (Pb^{2+}). It has been observed that the increase in the dosage of the NLP also increased the % Removal of the adsorbate. The data obtained from the experiment, after kinetic models' analysis, were observed to have followed the Pseudo-second order model, and the Isotherm model analysis showed that the Langmuir mode was the best to describe the adsorption mechanism.

Keywords: Neem leaf powder NLP, Adsorbent, isotherms lead, heavy metals

1. Introduction

Lead (Pb^{2+}) is a naturally occurring toxic metal found in the earth's crust. Its widespread use has resulted in extensive environmental contamination, human exposure, and significant public health problems in many parts of the world [1][2][3][4]. Lead (Pb^{2+}) is a highly poisonous metal affecting almost every organ in the body [5]. It is toxic when consumed even in small quantities. It can't be seen, tasted, or smelled in drinking water; this makes it very easy for us to be exposed to its adverse effect [6]. Its effects can be through eating, drinking, touching, ingesting, or breathing. It is detrimental to humans because it interferes with numerous enzymes inside the cells of human organ [7]. Lead is considered one of the most toxic heavy elements for humans and is found in high concentrations in the liquid waste of industries such as metal processing, mining, battery manufacturing, paints, textiles production, fertilizers, and [8]. It causes severe health problems for human beings, such as high blood pressure, heart disease, cancer, reproductive system disorders, and skin disease [9]. Wastewater could be generated from many sources such as; industrial, agricultural, municipal, and other point and also nonpoint sources. Industrial wastewater is a major source of water pollution [10]. The water pollution caused by heavy metals from various industries poses a worldwide threat with a cumulative, chronic, and harmful effect on the environment and the health of living organisms [11]. Heavy metal is any metallic chemical element that has a relatively high density is toxic at low concentrations and causes water-borne diseases when waste containing heavy metal is put into water bodies [12]. Their persistence in nature, accumulation in the food chain, and non-biodegradable nature make them to cause serious pollution problems [13].

An outbreak of lead poisoning occurred in Zamfara State, Nigeria around March through April 2010, as a result of the processing of Lead-rich ore for the extraction of Gold. During March-April, the Ministry of Health of Zamfara State was informed by Medecins Sans Frontieres (MSF) about a gradual increase in the number of childhood deaths and illnesses in villages in the two Local Government Areas of Bukkuyum and Anka. The Nigerian Federal Ministry of Health has requested the United States Centre for Disease Control (US CDC) to deploy a response team to investigate the outbreak. Also, the Blacksmith Institute sent a team from Terra Graphics Environmental Engineering Inc. To conduct an environmental assessment. The investigation confirmed severe Lead poisoning in more than 100 children in the villages of Dareta and Yargalma [14].

The acute Lead poisoning in Zamfara State was a result of artisanal Gold mining: small-scale mining done with rudimentary tools [15]. The miners crush and grind ore to extract Gold, and in the process release dust that is highly contaminated with Lead. Children in the affected areas were exposed to this dust directly at the processing site, through contaminated water and food sources. Over 500 children have died due to the outbreak [16]. This implies that our communities need to have an extreme focus on getting rid of Lead (heavy metal) to protect our lives and health [17]. Heavy metals such as Lead ion (Pb^{2+}) are usually removed by ion exchange, coagulation, and reverse osmosis [18]. These methods are expensive and not economical. Research has been done to find low-cost materials to be used as adsorbents for the removal of heavy metals from aqueous solutions [19]. After the research, it was found that natural wastes such as orange peel, rice husk, corn stover, and neem leaf powder, can be used to serve as adsorbents for the removal of heavy metals from aqueous solutions [20][21][22]. The mechanism of the adsorption process involves the reaction between functional groups present on the adsorbent (neem leaf powder) surface and the metal ions [23]. This results in the ion exchange reaction due to the high cation exchange capacity of the adsorbent [24]. The adsorbent bears an electronegative charge and the metal is electropositive. The term 'heavy metals' is entirely applied to a group of metals with a density greater than 5g/cm^3 and atomic number above 20 and is toxic at low concentrations [25].

Herein, the research tends to explore the experimental, Neem Leaf Powder (NLP) that would be employed to serve as the adsorbent for the removal of Lead ions (Pb^{2+}) from an aqueous solution. Neem trees are among the most abundant trees in our communities; therefore, the waste of the trees (leaves) is in large quantities in the environment which can easily be harmful since it can result in polluting the environment when it is burnt (air pollution). One of the great ideas of using neem leaf powder as an adsorbent is to eliminate its adverse effect on the environmental well-being, and to make it useful in some other purposes rather than disposing it as a useless waste.

2. Material and method

A. Reagents

Lead-chloride ($PbCl_2$) was bought by Sigma Aldrich Ltd., Neem Leaf Powder (NLP), Distilled water

Equipment and Apparatus

Mechanical sieve shaker, Mechanical agitator, Weighing balance, Measuring cylinder, Conical flask, and Beaker

1) Experimental Conditions

Table 1: Experimental conditions

$PbCl_2$ concentration (mg/L)	**300**
Amount of adsorbent (g)	1
pH	6
Time interval (min)	15, 30, 45, 60, 75, 90, 105, 120
Temperature, T (K)	298
Particle size (mm)	0.25
Agitation speed (rpm)	175

2) Adsorbent Preparation

The neem leaves were collected from neem trees in Birnin Kudu local government, Jigawa State, Nigeria, and were washed with water several times to make sure the dust and impurities were removed. After the removal of the impurities and dust, the washed leaves were allowed to dry at room temperature for several hours (about 72 hours). The dried leaves were then crushed in a mortar/grinder converting the leaves into fine powder [26]. The neem leaf powder was sieved using a sieve pore size of 0.25mm to separate the smaller particles with uniform sizes. The prepared powder was then preserved in a bottle for the targeted experiment. It was used as the adsorbent [27].

3) Adsorbent Characterization

Scanning electron microscopy (SEM, JEOL JSM-35CF) of the Neem leaf powder showed that the powder was an assemblage of fine particles, that did not have a regular, fixed shape and size. The particles were of various dimensions and all of them contained a large number of steps and kinks on the external surface, with broken edges [28][29].

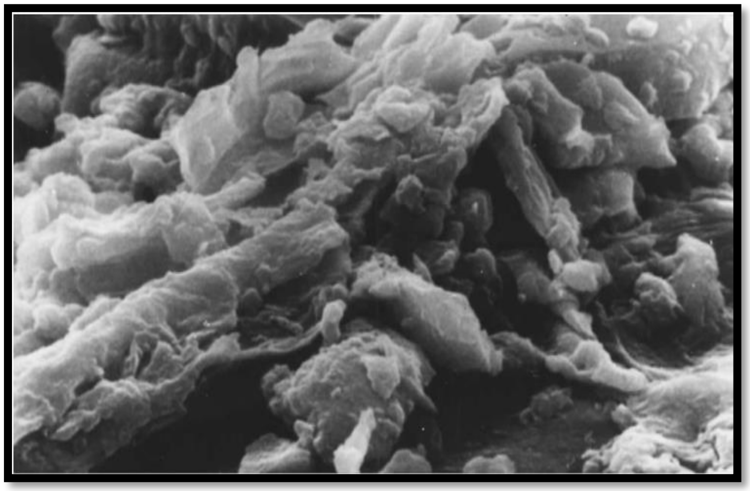

Fig 1: Schematic diagram on the surface topography of NLP using SEM

4) Solution Preparation

A solution of 300mg/L of $PbCl_2$ was prepared by dissolving 300mg of the Lead in 1 liter of distilled water and a sample of the solution was taken. 1g of NLP was weighed and mixed with the prepared solution, and another 7 different solutions were prepared using the same mass of the adsorbent [30]. The samples were agitated for 2 hours with subsequent removal of each sample after the time interval of 15 minutes. Each sample was filtered using a filter paper and the small quantity was taken (to be analyzed) [31].

3. Results and discussions

Table 2: Constant data for the calculations

Constant data	
Feed conc. (mg/L)	292.36
pH	6
Temperature (K)	298
Agitator speed (rpm)	175
Stock soln. of $PbCl_2$ (mg/L)	300
Adsorbent dosage (g)	1
Agitation time (min)	15, 30, 45, 60, 75, 90, 105, 120
Volume of the solution (L)	1

5) Percentage Removal

The percentage removal (% Removal) shows how much quantity of the adsorbate was adsorbed at a particular time in percentage. It is calculated using the relation below:

$$(\%)\ Removal = \frac{C_i - C_f}{C_i}\ x\ 100$$

Table 3: % Removal data for 1g of NLP

% Removal for 1g of NLP			
S/N	Time (min)	Effluent Concentration (mg/L)	% Removal
1	15	168.82	42.256123
2	30	62.42	78.64961
3	45	53.15	81.820358
4	60	52.2	82.1453
5	75	57.72	80.257217
6	90	57.17	80.445341
7	105	27.13	90.720345
8	120	4.1	98.597619

The data given above for the 3 different dosages are represented in a plot of graph of *% Removal vs Time,* and the results are compared. The graph is represented below:

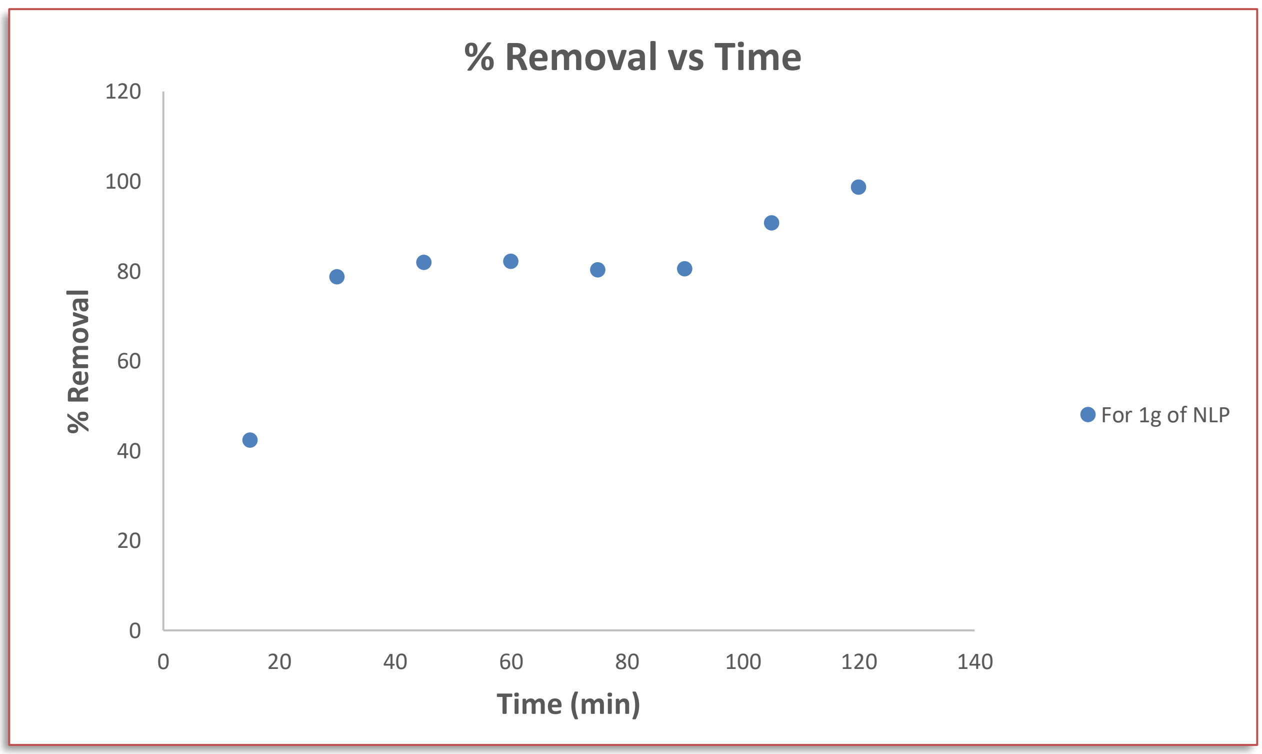

Figure 2: Comparison of %Removal for the 3 dosages.

As could be seen from the graph, the 1g dosage adsorbed less heavy metal compared to another gram dosage, which has the highest percentage removal of the adsorbate at the same time interval [32]. At the initial preceding, there's a difference in the removal efficiency between the dosages, but at exactly 60 mins. the two dosages started to adsorb the same quantity, which gave us a hint to conclude that with the increment in the dosage quantity. An equilibrium state would be attained at which no matter the dosage, there would be equal removal of the Pb by the two different dosages [33]. We can now conclude that, before that equilibrium state is attained, the %Removal increases with the increase in the adsorbent dosage [34].

6) Adsorption Capacity, q

This describes how effective is the NLP in removing the adsorbate. It compares the capacity of adsorptions of different dosages of the adsorbent. The relation is given below:

$$\boldsymbol{Adsorption\ Capacity,\ q = \frac{C_o - C_t}{m}\ x\, V}$$

Table 4: Adsorption Capacity for 1g of NLP

	Adsorption Capacity for 1g of NLP			
S/N	**Time (min)**	**Effluent (mg/L)**	**Concentration**	**Adsorption Capacity (mg/g)**
1	15	168.82		123.54
2	30	62.42		229.94
3	45	53.15		239.21
4	60	52.2		240.16
5	75	57.72		234.64
6	90	57.17		235.19
7	105	27.13		265.23
8	120	4.1		288.26

The highlighted data in the tables represent the values of optimum adsorption capacity, q_e obtained from the graph below:

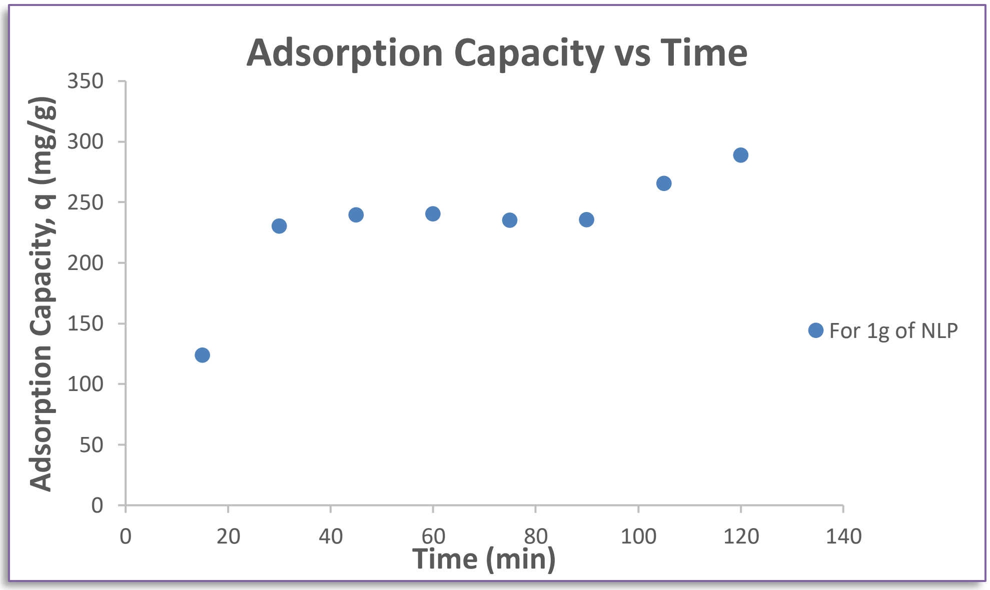

Figure 3: Comparison of adsorption capacity for the 3 dosages

The 1g of dosage also behaved totally differently from the other dosages, which means the behavior changes more between 1g and the subsequent grams of the dosage. For example in 3g and 5g, there were very minor variations in the adsorption capacities with time while for 1g, the adsorption capacity increased largely with time [35].

7) Adsorption Kinetics

a) Pseudo-first order model of Lagergren

The model is described by the following equation:

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

Table 5: Pseudo-first order data for 1g of NLP

For 1g of NLP				
S/N	t (min)	q_t (mg/g)	(q_e - q_t) (mg/g)	log(q_e - q_t) (mg/g)
1	15	123.54	141.69	2.1513392
2	30	229.94	35.29	1.547651658
3	45	239.21	26.02	1.415307292
4	60	240.16	25.07	1.399154334
5	75	234.64	30.59	1.485579477
6	90	235.19	30.04	1.477699928

The data are represented in the graphs below:

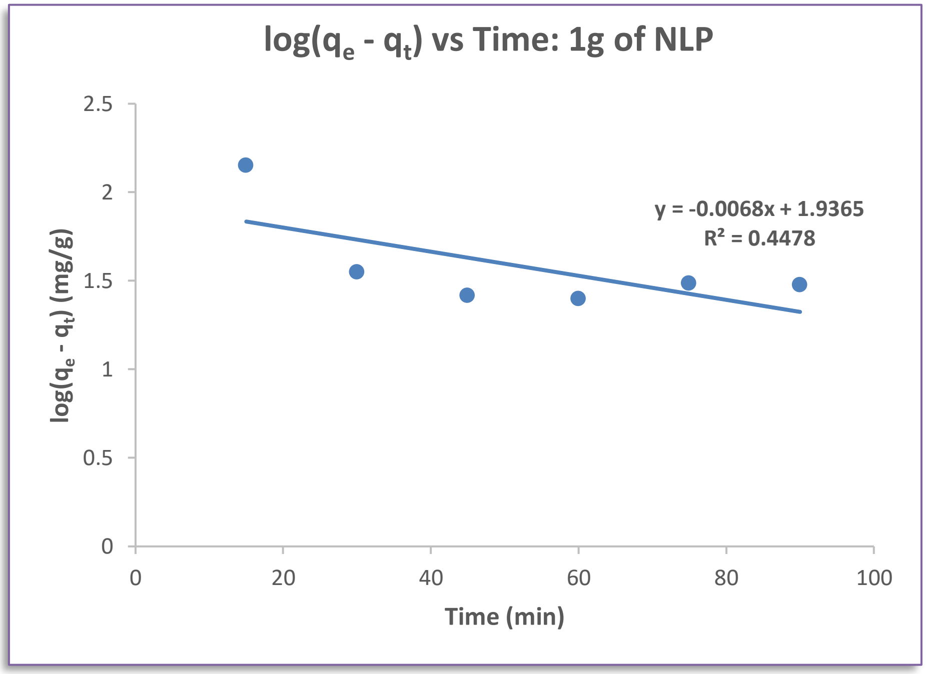

Figure 5: Pseudo-first order graph for 1g of NLP

8) Pseudo-second order model

The model is described by the following equation:

$$\frac{t}{q_t} = \frac{1}{h_o} + \left(\frac{1}{q_e}\right)t$$

Where: $h_o = k_2 q_e^2$

Table 1: Pseudo-second order data for 1g of NLP

	For 1g of NLP		
S/N	**t (min)**	**q_t (mg/g)**	**t/q_t (g.min/mg)**
1	15	123.54	0.121418164
2	30	229.94	0.130468818
3	45	239.21	0.188119226
4	60	240.16	0.249833444
5	75	234.64	0.319638595
6	90	235.19	0.382669331

The data are represented in a single graph below:

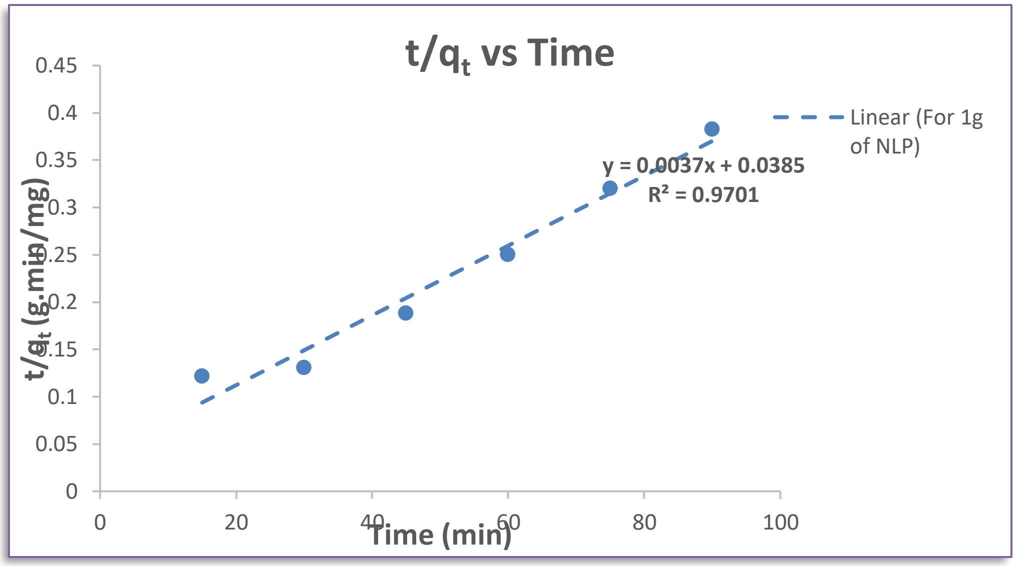

Figure 6: The Pseudo-second order plots of all the 3 dosages

Table 7: Summary of the kinetics result

						Summary of the Kinetics result				
			Pseudo-first order			Pseudo-second order				
S/N	Dosage (g)	q_e (mg/g)	k_1	R^2	q_e theo. (mg/g)	k_2	R^2	h_o exp.	h_o theo.	q_e theo. (mg/g)
1	1	265.23	0.0157	0.4478	86.397	0.00036	0.9701	25.974	25.3249	270.27

The values of q_e obtained from the adsorption capacity are compared with those obtained from the graphs of pseudo-second order, and the values were found to be close. Similarly, the values of h_o theoretical and h_o experimental were compared and the values were also found to be very close. The values of the *correlation coefficients* for the pseudo-second-order were found to be more accurate and fit, which signifies that the adsorption data has fitted and followed the Pseudo-second-order model.

9) Adsorption Isotherms

10) Langmuir model

The Langmuir isotherm model is represented by the relation:

$$\frac{C_e}{q_e} = \left(\frac{1}{Q_o}\right) C_e + \frac{1}{bQ_o}$$

Table 8: Langmuir data for 1g of NLP

For 1g of NLP				
S/N	Time (min)	C_e (mg/L)	q_e (mg/g)	C_e/q_e (g/L)
1	15	168.82	123.54	1.366520965
2	30	62.42	229.94	0.271462121
3	45	53.15	239.21	0.222189708
4	60	52.2	240.16	0.217355097
5	75	57.72	234.64	0.245993863
6	90	57.17	235.19	0.243080063
7	105	27.13	265.23	0.10228858

The data are plotted in the graphs below:

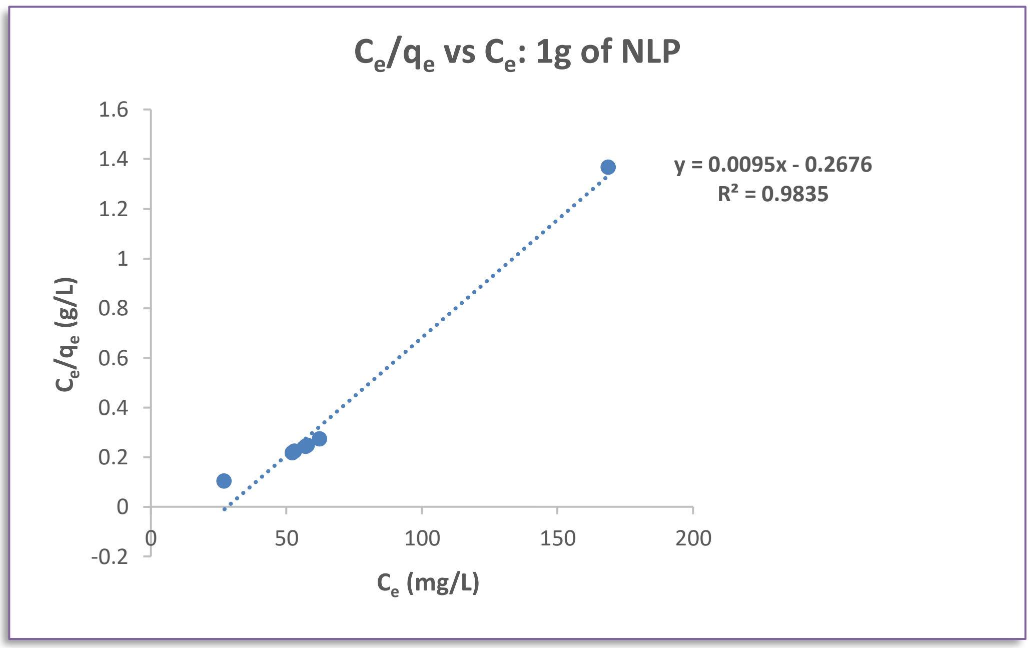

Figure 8: Langmuir graph for 1g of NLP

a) Freundlich model

The Freundlich model is represented by a linear equation below:

$$logq_e = logK_f + \frac{1}{n} logC_e$$

Table 9: Freundlich data for 1g of NLP

	For 1g of NLP				
S/N	**Time (min)**	**C_e (mg/L)**	**q_e (mg/g)**	**$logC_e$ (mg/L)**	**$logq_e$ (mg/g)**
1	15	168.82	123.54	2.227423896	2.091807597
2	30	62.42	229.94	1.795323764	2.361614527
3	45	53.15	239.21	1.725503269	2.378779331
4	60	52.2	240.16	1.717670503	2.380500675
5	75	57.72	234.64	1.761326322	2.37040205
6	90	57.17	235.19	1.757168192	2.371418852
7	105	27.13	265.23	1.433449794	2.423622645

The data are plotted in the graph below:

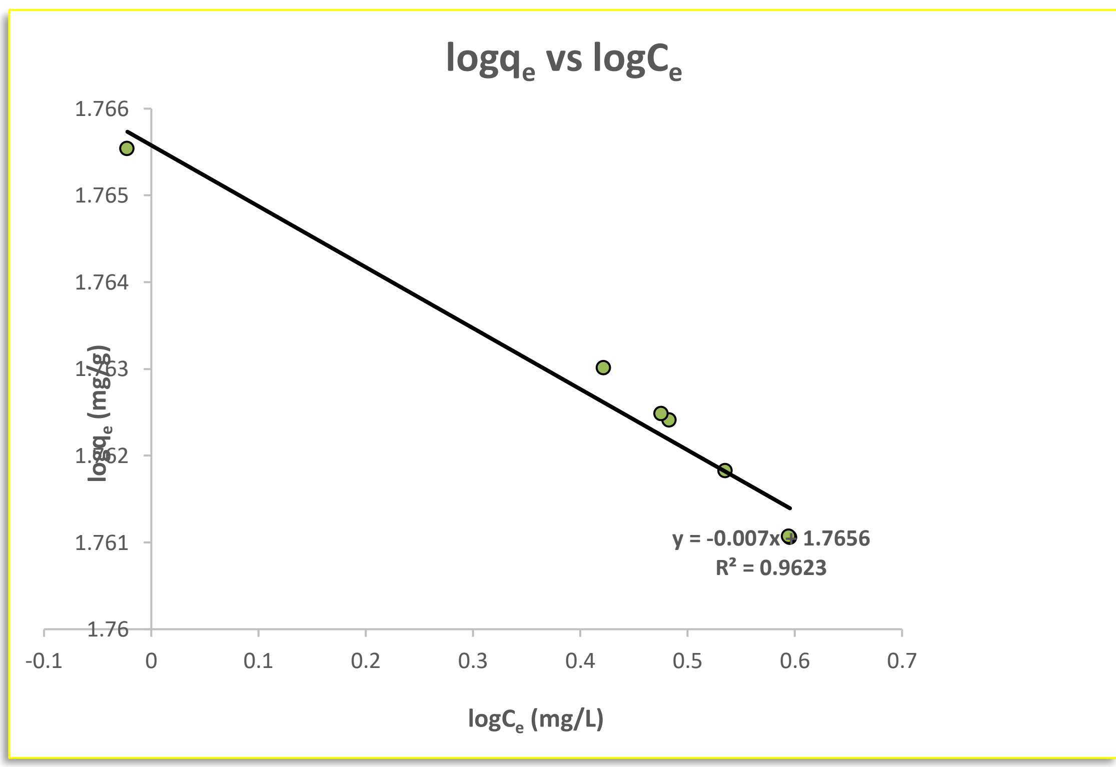

Figure 9: The Freundlich graph of the plots of all the 3 dosages

Summary of the Isotherms result

		Langmuir			Freundlich		
S/N	**Dosage (g)**	**R^2**	**b (L/mg)**	**Q_o (mg/g)**	**R^2**	**K_f (L/g)**	**n**
1	1	0.9835	-0.0355 - -	105.26	0.8724	1340.91	-2.252

Conditions of n in the Freundlich model	
If n > 1	The adsorption is chemical process
If n = 1	The adsorption is linear
If n < 1	**The adsorption is physical process**

Equilibrium parameter for Langmuir model

$$R_L = \frac{1}{1 + bC_i}$$

S/N	**Dosage (g)**	**R_L**
1	1	-0.1066 -

Conditions for R_L	
If $R_L > 1$	The adsorption is unfavorable
If $R_L = 1$	The adsorption is linear
If $R_L = 0$	The adsorption is irreversible
If $R_L < 1$	The adsorption is favorable

From the data obtained, the adsorption is best described by the Langmuir isotherm model because the values of Correlation coefficients, R^2 were found to be better than those found from the Freundlich model for the dosages. Therefore, the adsorption was *Chemisorption* (monolayer adsorption) [36]. The maximum adsorption capacities, Q_o were found to be 105.26mg/g for the dosages 1g. The Langmuir constants were found to be negatives, which indicates that the adsorbate molecules had a negative affinity to the sites of the adsorbent [37]. The Freundlich model was not suitable for the mechanism, despite its good values of R^2 because the values of heterogeinity elements, n representing the multilayer adsorption were found to be negatives. The values obtained for R_L indicated that the adsorption was favorable [38].

4. CONCLUSION

The experiment was conducted to study the effectiveness of Neem Leaf Powder in removing the Pb^{2+} from the aqueous solution. The effect of the powder dosage (adsorbent dosage) was checked and it has been confirmed that the increase in the dosage increased the amount of the heavy metal removed from the solution with time. The 1g of the adsorbent was removed apparently. From the two analyzed kinetic models, the data were found to fit the Pseudo-second order model best, therefore it is concluded that the adsorption mechanism followed the Pseudo-second order model based on the kinetics behavior. For the isotherms, two models were analyzed; Langmuir and Freundlich. It has been seen that the data were more compatible with the Langmuir model, which described the adsorption mechanism as a monolayer (chemisorption). The best R^2 values were obtained from the Langmuir model. It was depicted that the adsorbate molecules had a negative affinity to the adsorbent sites from the values obtained in the Langmuir constant, b which were found to be negatives. From the values of R_L obtained, it has been shown that the adsorption was favorable since the values were less than 1. Negative intercepts were obtained as were also obtained in the experiments conducted. The chemisorption of the adsorption mechanism means that the adsorption only occurred on a single layer of the adsorbent, and there is no interaction between the adsorbed adsorbates on different active sites.

Acknowledgment

The Tertiary Education Trust Fund (TET Fund), Nigeria, under the program of the National Research Funds (NRF)-2020 intervention [TET Fund/ES/DR&D-CE/NRF2020/SETI/77/VOL.1] provided funding for this research.

References

[1] M. L. Rahman *et al.*, "Removal of heavy metal ions from wastewater using modified cornstalk cellulose-derived poly(amidoxime) ligand," *Carbohydr. Polym. Technol. Appl.*, vol. 9, no. December 2024, p. 100633, 2025, doi: 10.1016/j.carpta.2024.100633.

[2] F. Saeed, K. Anil Reddy, and S. Sridhar, "Efficient removal of environmentally hazardous heavy metal ions from water by NH2-MIL-101-Fe and MOF-808-EDTA based polyether sulfone adsorbents," *Chem. Eng. J.*, vol. 497, no. July, p. 154688, 2024, doi: 10.1016/j.cej.2024.154688.

[3] M. H. Rahman, M. Marufuzzaman, M. A. Rahman, and M. I. H. Mondal, "Adsorption kinetics and mechanisms of nano chitosan coated cotton fiber for the removal of heavy metals from industrial effluents," *Heliyon*, vol. 11, no. 4, p. e42932, 2025, doi: 10.1016/j.heliyon.2025.e42932.

[4] S. Sheikh, O. Naghizadeh-Dehno, S. Mirkhalafi, and M. Ghashang, "Magnetic heterogenization of supramolecular carbohydrates for the efficient adsorption of heavy metals removal from wastewater," *Inorg. Chem. Commun.*, vol. 168, no. December 2023, p. 112835, 2024, doi: 10.1016/j.inoche.2024.112835.

[5] H. Huang *et al.*, "Adsorption performance of layered double hydroxides for heavy metals

removal in soil with the presence of microplastics," *J. Environ. Chem. Eng.*, vol. 10, no. 6, p. 108733, 2022, doi: 10.1016/j.jece.2022.108733.

[6] J. Feng, Y. Yu, S. Huang, N. Zhu, A. Mojiri, and D. Ge, "Tannic acid as a green chemical for the removal of various heavy metals: A critical review of recent developments," *J. Environ. Manage.*, vol. 375, no. January, p. 124390, 2025, doi: 10.1016/j.jenvman.2025.124390.

[7] W. Zou *et al.*, "High-efficiency core-shell magnetic heavy-metal absorbents derived from spent-LiFePO4 Battery," *J. Hazard. Mater.*, vol. 402, no. July 2020, p. 123583, 2021, doi: 10.1016/j.jhazmat.2020.123583.

[8] N. C. Joshi, A. Joshi, D. Mitra, P. Gururani, N. Kumar, and H. K. Joshi, "Removal of heavy metals using cellulose-based materials: A mini-review," *Environ. Nanotechnology, Monit. Manag.*, vol. 21, no. December 2023, p. 100942, 2024, doi: 10.1016/j.enmm.2024.100942.

[9] Nigist, A. H., Ali, S. R., & Zemene, W. N. (2022). Chemical Modification of Neem (Azadirachta indica) Biomass as Bioadsorbent for Removal of Pb Ion from Aqueous Waste Water. *Sage Publishing*, 2.

[10] M. García-Vargas *et al.*, "Synthesis, characterization and evaluation of cellulose-graft-poly(4-vinylpirydine), using cellulose from a new pretreatment process, for heavy metal removal from wastewater," *Int. J. Biol. Macromol.*, vol. 284, no. November 2024, 2025, doi: 10.1016/j.ijbiomac.2024.137986.

[11] M. K. Hussain *et al.*, "Unleashing the power of bio-adsorbents: Efficient heavy metal removal for sustainable water purification," *J. Water Process Eng.*, vol. 64, no. January, p. 105705, 2024, doi: 10.1016/j.jwpe.2024.105705.

[12] T. X. Thanh Le *et al.*, "A high performance of thin film composite based on dextran substrate for effective removal of heavy metal ions," *Chem. Eng. Res. Des.*, vol. 212, no. November, pp. 547–554, 2024, doi: 10.1016/j.cherd.2024.11.036.

[13] M. S. Rostami and M. M. Khodaei, "Recent advances in chitosan-based nanocomposites for adsorption and removal of heavy metal ions," *Int. J. Biol. Macromol.*, vol. 270, no. P2, p. 132386, 2024, doi: 10.1016/j.ijbiomac.2024.132386.

[14] Baldev, G. Kumar, V. Sharma, and M. Nemiwal, "Biomass-derived zirconium composite: An adsorbent for preferential removal of heavy metals and contaminants in wastewater," *J. Water Process Eng.*, vol. 69, no. December 2024, p. 106778, 2025, doi: 10.1016/j.jwpe.2024.106778.

[15] S. S. M. Hassan, M. E. A. El-Aziz, A. E. S. Fayez, A. H. Kamel, and A. M. Youssef, "Synthesis and characterization of bio-nanocomposite based on chitosan and CaCO3 nanoparticles for heavy metals removal," *Int. J. Biol. Macromol.*, vol. 255, no. September 2023, p. 128007, 2024, doi: 10.1016/j.ijbiomac.2023.128007.

[16] S. Wang, W. Song, E. Liu, P. Zhao, H. Y. Ng, and X. Wang, "Efficient, facile and recyclable coating strategy to improve heavy metals removal by UF membrane in drinking water purification," *Sep. Purif. Technol.*, vol. 363, no. P2, p. 131995, 2025, doi: 10.1016/j.seppur.2025.131995.

[17] C. Chen *et al.*, "A high absorbent PVDF composite membrane based on β-cyclodextrin and ZIF-8 for rapid removing of heavy metal ions," *Sep. Purif. Technol.*, vol. 292, no. March, p. 120993, 2022, doi: 10.1016/j.seppur.2022.120993.

[18] E. Qasemi, M. Anbia, and M. Rezaie, "Synergetic effect of heteroatoms doping and functional groups of graphene-chitosan magnetic nanocomposite on enhancement of heavy metal sorption," *React. Funct. Polym.*, vol. 214, p. 106283, 2025, doi: 10.1016/j.reactfunctpolym.2025.106283.

[19] C. He *et al.*, "Sustainable soil rehabilitation with multifunctional mandarin orange peel/tobermorite composite hydrogels: Water retention, immobilization of heavy metals, fertilizer release and bacterial community composition," *Chem. Eng. J.*, vol. 502, no. November, 2024, doi: 10.1016/j.cej.2024.158030.
[20] K. Meng *et al.*, "Advances in selective heavy metal removal from water using biochar: A comprehensive review of mechanisms and modifications," *J. Environ. Chem. Eng.*, vol. 13, no. 2, p. 116099, 2025, doi: 10.1016/j.jece.2025.116099.
[21] H. C. Lin, Y. J. Liu, and D. J. Yao, "Preparation of magnetic microalgae composites for heavy metal ions removal from water," *Heliyon*, vol. 10, no. 18, p. e37445, 2024, doi: 10.1016/j.heliyon.2024.e37445.
[22] L. Slavov *et al.*, "Leptothrix biomaterial: Investigation on a product with potential applications as a natural absorbent material for heavy metals," *Inorg. Chem. Commun.*, vol. 177, no. March, p. 114350, 2025, doi: 10.1016/j.inoche.2025.114350.
[23] A. E. Swathe Sriee and V. Shankar, "Three-dimensional bioprinted materials in alginate-hyaluronic acid complex based hydrogel based bio-ink as absorbents for heavy metal ions removal," *Carbohydr. Polym. Technol. Appl.*, vol. 8, no. October, p. 100588, 2024, doi: 10.1016/j.carpta.2024.100588.
[24] W. Ritonga *et al.*, "Research Highlights Concrete preparation using red sand adsorbed heavy metals," *South African J. Chem. Eng.*, 2025, doi: 10.1016/j.sajce.2025.03.012.
[25] J. B. M. Dassekpo *et al.*, "Waste glass as a source for green synthesis of mesoporous adsorbent for efficient removal of heavy metals," *Microporous Mesoporous Mater.*, vol. 383, no. May 2024, 2025, doi: 10.1016/j.micromeso.2024.113393.
[26] M. Qu *et al.*, "Modified water treatment residual serves as an adsorbent for the removal of heavy metals from water: A review," *J. Ind. Eng. Chem.*, no. November, 2024, doi: 10.1016/j.jiec.2024.11.048.
[27] S. H. Dhobi, D. Neupane, S. Koirala, and D. Das Mulmi, "Waste tea as absorbent for removal of heavy metal present in contaminated water," *Heliyon*, vol. 10, no. 21, p. e39519, 2024, doi: 10.1016/j.heliyon.2024.e39519.
[28] A. G. Feitosa *et al.*, "Evaluation of Pb2+ ion adsorption by roasted and grounded barley (Hordeum vulgare L.) waste," *Results Chem.*, vol. 6, no. October, 2023, doi: 10.1016/j.rechem.2023.101205.
[29] A. K. Singh, A. Hussain, M. Priyadarshi, and A. Haider, "Heavy metals removal from synthetic and industrial wastewater using synthesized zinc oxide nanoparticles," *J. Indian Chem. Soc.*, vol. 101, no. 5, p. 101145, 2024, doi: 10.1016/j.jics.2024.101145.
[30] F. H. Jaffar *et al.*, "Hydroxyapatite-based materials for adsorption, and adsorptive membrane process for heavy metal removal from wastewater: Recent progress, bottleneck and opportunities," *J. Taiwan Inst. Chem. Eng.*, vol. 164, no. February, p. 105668, 2024, doi: 10.1016/j.jtice.2024.105668.
[31] P. Singh, S. Sharma, K. Singh, P. K. Singh, F. Abdul, and N. B. Singh, "Surface modifications and its applications in water remediation," vol. 9, no. November, 2024.
[32] J. Zhou *et al.*, "Zeolite-based absorbent: Polyacrylic acid loading for enhanced ferric(III) removal from aqueous solution," *J. Environ. Chem. Eng.*, vol. 12, no. 6, p. 114317, 2024, doi: 10.1016/j.jece.2024.114317.
[33] N. A. Kazakis, "Green approaches to heavy metal removal from wastewater : Microalgae solutions in a circular economy framework," *Soc. Impacts*, vol. 5, no. January, p. 100103, 2025, doi: 10.1016/j.socimp.2025.100103.

[34] J. Cai, Y. Du, R. Zhang, Q. Tian, G. Xu, and M. Zhang, "Preparation of cement-based absorbent with coke for Cr3+ removal," *Mater. Today Commun.*, vol. 35, no. February, p. 105749, 2023, doi: 10.1016/j.mtcomm.2023.105749.

[35] F. Vahdatkhoram, A. A. Ghoreyshi, and M. J. Chaichi, "Enhancing heavy metals removal from water by thiol-incorporation of UiO-66 based metal organic framework nanosheets with L-cysteine," *Inorg. Chem. Commun.*, vol. 170, no. P2, p. 113351, 2024, doi: 10.1016/j.inoche.2024.113351.

[36] R. Lakshmana Naik, M. Rupas Kumar, and T. Bala Narsaiah, "Removal of heavy metals (Cu & Ni) from wastewater using rice husk and orange peel as adsorbents," *Mater. Today Proc.*, vol. 72, pp. 92–98, 2023, doi: 10.1016/j.matpr.2022.06.112.

[37] J. S. Park, D. W. Kim, J. B. Kwon, S. H. Park, and K. Y. Chung, "Optimal growth conditions and heavy metal removal using Coelastrella sp. CORE-3 isolated from wastewater," *J. Ind. Eng. Chem.*, vol. 140, no. May, pp. 589–598, 2024, doi: 10.1016/j.jiec.2024.07.034.

[38] B. Manimekalai and S. Subramanian, "Synthesized bioadsorbent using Aged Refuse for heavy metal removal in aqueous solution," *Desalin. Water Treat.*, vol. 320, no. July, p. 100862, 2024, doi: 10.1016/j.dwt.2024.100862.