

INVESTIGATION OF CACTUS ASH ADSORPTION ISOTHERMS FOR MAXIMUM ADSORPTION OF HEAVY METAL IONS FROM WATER

Patrick, D.O.* , Bathon, F., Chiroma, T.M. and Kefas, H.M.

Department of Chemical Engineering, Modibbo Adama University, Yola, Nigeria

*Corresponding email: dopatrick@mau.edu.ng

ABSTRACT

The natural setting of our ecosystem has long been contaminated by industrialization and modern technology, hence the need for mitigation. This study aims at investigating cactus ash adsorption isotherms models for heavy metal adsorption from water. Batch experiment was conducted using Cactus ash as adsorbent for the study at pH ranges of 2 to 11 and temperature ranging from 25°C to 60°C. Langmuir isotherm model was suitable for adsorption of Cr onto Cactus ash residue. The process was monolayer adsorption. The correlation of the experimental results fits with the Freundlich isotherm model for Ni and Cr both with R^2 values of 0.9801. It is also confirmed to be favorable for n values <1 , which indicates a chemical process. The Langmuir, Freundlich, Temkin, Halsey and Harkin & Jura isotherm models were used for the description of the adsorption equilibrium of the heavy metal ions onto cactus ash residue. For Ni and Cr, the data were in good agreement with the Langmuir isotherm, but Cr fitted better to Halsey and Freundlich as their R^2 values are 0.9412, 0.991 and 0.9801, respectively. The Isotherm that fitted best for Pb is Temkin, also, Temkin, Freundlich, and Halsey equally fits Ni, while the Freundlich and Halsey isotherm fitted best to Cd. The isotherms give an understanding of the mechanism of the adsorption of the metals by the adsorbent, hence giving metals the it can be effectively used to adsorb.

Keywords: Isotherms, Heavy metals, adsorption, cactus

1 INTRODUCTION

One of the major challenges bedeviling our modern society is environmental pollution [1]. More than 10 million sites spanning more than 20 million hectares of land throughout the world are classified as soil polluted, with $>50\%$ of them contaminated with hazardous heavy metals (HHMs) and/or metalloids [2]. In recent times, studies confirm that management of waste and quality of water is two of the important propositions in human life and the accretion of technologies in urbanization and industrialization is a major factor leading to the increase in percentage accumulation of waste all around the world, releasing heavy metal in the water streams which are regarded as an output from varieties of activities such as industrial, waste disposal, agricultural and others. Accumulation of heavy metal in wastewater streams acts against human bodies and cause to death [3]. With a population of 182 million, Nigeria is considered the most populous country in Africa, however increase in population and industrialization consequently poses major environmental population. The people suffer environmental pollution from high levels of heavy metal accumulation in the environment and in food crops [4]. Petroleum, Pharmaceutical, plastics and textile industries situated near from river banks are the greatest threats to water quality due to effluents discharged into them [5]. The use of polluted water either for irrigation of plants, consumption or for recreational purposes causes a great threat to human health. The impact of water pollution is recently becoming a major challenge in developing countries due to increase in population, poverty and lack of access to safe drinking water, sanitation and hygiene [6]. According to [7], the problem with most

developing countries, especially Nigeria, is inefficient discharge of man-made wastes, especially those generated by industries into surrounding rivers, which end up being the major recipient of these wastes. Urban and Rural areas in Nigeria, experience water pollution from agricultural activities and increased concentration of soil particles washed into water bodies by erosion. Numerous techniques have been utilized for the removal of heavy metals from solution, which include reverse osmosis, ion exchange, precipitation, phyto-extraction, ultra-filtration and adsorption. However, most of these processes are expensive, complicated, ineffective at low metal concentrations and inapplicable to a wide range of pollutants [8]. Of the all the methods used in water treatment, adsorption stands as the best and cheapest. Adsorption a surface phenomenon, differs from absorption process where a fluid (the absorbate) permeates or is dissolved by a liquid or solid absorbent [9]. Applicability of different adsorbents for treatment of waste water is limited as they are usually prepared from non-renewable materials and are also found to be expensive. In recent years, different types of biomaterials have been applied for removal of dyes and heavy metals from waste water due to their low cost and enhanced adsorption potential [10]. Several recent publications utilized different inexpensive and locally abundantly available adsorbents like barley straw, waste tea leaves, sago waste, peanut hulls, hazel nut shell, saw dust, neem bark, chitin beads, thermally treated rice husk ash, waste banana, orange peels, cocoa shells, tree fern coffee residue, rice husk, olive stone waste, orange peel, grape stalk, Tea waste, bagasse fly, rice husk etc. [11]. The efficiency of various plant residues as adsorbent has been tried with exception of Cactus plant, hence the objective of this study to study the adsorption isotherms of heavy metal removal using Cactus ash as adsorbent. Some of the advantages of using plant wastes for wastewater treatment include simple technique, requires little processing, good adsorption capacity, selective adsorption of heavy metal ions, low cost, free availability and easy regeneration. Adsorption isotherms are major design requirements for any adsorption system. Isotherm expresses the relation between the quantities of adsorbate (mg) removed from the liquid phase by a unit mass of adsorbent (g) at the constant temperature. Adsorption isotherms give qualitative information about the nature of the solute–surface interaction as well as the specific relation between the concentration of adsorbate and its degree of accumulation onto the surface at a specified temperature [12]. For instances, the most commonly used isotherm models for heavy metal adsorption are the Langmuir, Freundlich, and Temkin isotherms [13]. [14] WHO studied the adsorption of heavy metal ions using zeolite materials of municipal solid waste incineration fly ash modified by microwave-assisted hydrothermal treatment reported that the adsorption isotherms of heavy metal cations in mixed solution could be described by Langmuir isotherm equations, with a high correlation coefficient value. An adsorption isotherm is a curve relating the equilibrium concentration of a solute on the surface of an adsorbent, q , to the concentration of the solute in the liquid, C_e , with which it is in contact. The Langmuir isotherm model deals with a monolayer maximum adsorption capacity of the adsorbent. This means that each site can take in only one molecule and it assumes constant adsorption energy for all the active binding sites present on the adsorbent. In addition, the adsorbed molecules cannot move across the surface or react with neighboring molecules [15]. The Langmuir model describes the monolayer adsorption. It assumes a uniform energy of adsorption, a single (homogenous) layer of adsorbed solute at a constant temperature [16]. The isotherm is valid for monolayer adsorption on a surface containing a finite number of identical sites. The model assumes uniform adsorption on the surface and no transmigration in the plane of the surface [17]. The linear form of Langmuir equation is given as.

$$\frac{C_e}{q_e} = \frac{1}{q_m k_l} + \frac{C_e}{q_m} \quad (1)$$

Where q_e (mg/g) is the amount of heavy metal adsorbed at equilibrium, q_m (mg/g) is the amount of heavy metal adsorbed when saturation is attained, C_e is the equilibrium heavy metal concentration (mg/l) and k_l is Lagmuir constant related to the binding strength of heavy metal onto the adsorbent. The Freundlich model is an empirical equation that is very useful in describing the distribution of solute between solid and aqueous phases at a point of saturation. The basic assumption of this model is that there is an exponential variation in site energies of adsorbent and also the fall in heat of adsorption is logarithmic [18]. The linearized form of Freundlich equation is expressed as.

$$\text{Log}q_e = \text{Log}K_f + \frac{1}{n}\text{Log}C_e \quad (2)$$

where $q_e = K_f C_e^{\frac{1}{n}}$. A plot of $\log q_e$ against $\log C_e$ gives a straight line which can be used to determine K_f and n . Where slope = $\frac{1}{n}$ and intercept = K_f . Where K_f is the Freundlich constant that represents adsorption capacity and n is the strength of adsorption (is the Freundlich exponent for adsorption intensity). The significance of n is as follows: $n=1$ (linear); $n<1$ (chemical process); $n>1$ (physical process) [18]. The Harkins and Jura adsorption isotherm model accounts for multilayer adsorption and can be explained by the existence of a heterogeneous pore distribution [19]. The Harkins and Jura equation can be expressed as:

$$\frac{1}{q_e^2} = \frac{B}{A} - \text{Log} \frac{C_e}{A} \quad (3)$$

Where B and A are the isotherm constants and can be obtained from the intercept and slope of the plot of $1/q_e^2$ versus $\log C_e$ respectively. The Halsey adsorption isotherm model is suitable for multilayer adsorption at a relatively large distance from the surface and the fitting of the experimental data to this equation attest to the heteroporous nature of the adsorbent. The Halsey adsorption isotherm model can be expressed as [20].

$$\ln q_e = \ln \frac{k}{nH} - \frac{\ln\left(\frac{1}{C_e}\right)}{nH} \quad (4)$$

Where nH and K are Halsey isotherm constants and can be obtained from the slope and intercept of the plot of $\ln q_e$ against $\ln(1/C_e)$. Temkin isotherm is one of the earliest reported isotherms and assumes the heat of adsorption decreases linearly with increasing coverage due to the interactions between adsorbate and adsorbent. The Temkin isotherm has been generally applied in the form as shown in equation 5 [21]. Temkin isotherm model assumes that the fall in the heat of adsorption is linear rather than logarithmic as stated in Freundlich expression [22]. The heat of adsorption of all molecules in the layer would decrease linearly with coverage owing to the adsorbent/adsorbate interactions [23]. The linearized form of Temkin equation is expressed as:

$$q_e = B \ln KT + B \ln C_e \quad (5)$$

Where KT (mol/l) is the equilibrium binding constant corresponding to maximum binding energy, B is the constant related to the heat of adsorption and the differential surface capacity for the adsorbate sorption per unit binding energy. If the constant B is less than 8kJ/mol, it indicates a weak interaction between the adsorbate and adsorbent hence such adsorption can be expressed as physical adsorption [24]. This study focused on evaluation of cactus ash adsorption isotherms models for heavy metal adsorption from water. Adsorption of various metal from heavy metals were fitted to several isotherm models to ascertain the mechanism behind their adsorption from water.

2 METHODOLOGY

2.1 Sample Collection and Pretreatment

The cactus plant was collected at Girei, Adamawa State, washed and identified by plant botanist in the Department of Botany, Modibbo Adama University, Yola.

2.2 Preparation of Cactus Ash Residue

The clean plant sample was cut into strips of 1 to 2cm, dried in an oven at 60° C for 24 hours. Ash was obtained as dry plant material was heated in a furnace at 600°C with excess air for 24 hours. Ash residue was prepared by dissolving the ash in distilled water to remove the soluble alkali, filtered, washed with distilled water and dried in an oven at 100°C.

2.3 Preparation of Metal Ion Solutions

Analytical grade compound containing metal element were obtained from a Biochemistry laboratory, Gombe State University. A stock solution of metal ion of concentration 1000 mg/L was prepared by using

molar mass of compound containing metal element divide by the atomic mass of the corresponding metal element by dissolving the required gram of the chemical in 1 L of distilled water. An experimental metal ion solution of desired concentration was obtained by appropriate dilution of the stock solution.

2.4 Adsorption Isotherm Model

Equilibrium sorption isotherms express the surface properties and affinity of the adsorbent. Data used for describing the isotherm was obtained by fixing the mass of adsorbent, temperature, volume and pH of adsorbent, the experiment is similar to those for batch adsorption. In this study, the isotherms were investigated using models namely: Langmuir, Freundlich, Temkin, Halsey, Harkin and Jura isotherms as stated in Equation 1, 2, 3, 4 and 5, respectively.

2.5 Batch Adsorption Experiments/ Parameters

Batch tests were carried out in 120 ml plastic bottles to check the influence of various parameters such as pH, adsorbent concentration (dose), contact time and temperature. The experiments were carried out at the same shaking speed. For each experimental run, 50 ml aqueous solution of known concentrations of Cr, Ni, Pb and Cd ions were put in 120 ml plastic bottles that contained known amount of cactus ash residue a combusted product. These bottles were shaken at a constant shaking rate of 150 rpm and at room temperature and filtered. At the end of each experiment, plastic bottles were removed from the shaker and solutions separated from the adsorbents by filtration through filter paper. The concentrations of Cr, Ni, Pb and Cd ions in the filtrates obtained were measured using flame atomic absorption spectrophotometer. The amounts of Cr, Ni, Pb and Cd adsorbed per unit mass was calculated using Equations 6. The pH of the medium was adjusted using HCl and NaOH solution [24].

$$q_e = \frac{(c_o - c_e)}{m} V \quad (6)$$

Where, q_e = Amount of sorbate adsorbed per unit mass of adsorbent at equilibrium, C_o = Initial concentration of sorbate, C_e = Concentration of sorbate at equilibrium, m = mass of the adsorbent (g), V = volume of solution.

$$R = \frac{(c_o - c_e)}{c_o} 100 \quad (7)$$

Where R = percentage removal.

3 RESULTS AND DISCUSSION

3.1 Equilibrium Isotherm Models

The adsorption isotherm indicates how the adsorption molecules distribute between the liquid phase and the solid phase when the adsorption process reaches an equilibrium state. Various sorption isotherm models are used for fitting data in order to examine the relationship between sorption and aqueous concentration at equilibrium. In this study, the relationship between metal adsorption capacity and metal ion concentration at equilibrium has been described by Langmuir, Temkin, Halsey, Harkins Jura and Freundlich models. Langmuir and Freundlich adsorption isotherms are the widely used isotherms. The analysis of the adsorption data by fitting them to different isotherm models is an important step to find the suitable model that can be used for design purpose. The adsorption isotherms and their parameters of Cr, Ni, Pb and Cd are shown in Table 1, Figure 1. All model parameters were evaluated by linearizing, the use of Microsoft Excel and manual calculations.

Table 1. Equilibrium Isotherms Parameters for Cr, Ni, Pb and Cd Removal

Model	Parameter	Cr	Ni	Pb	Cd
Langmuir	q_m (mg/g)	1.3463	1.9179	1.067	0.957
	K_L (L/mg)	0.945	0.588	0.376	0.4946
	R_L	0.0104	0.0167	0.0259	0.01981
	R^2	0.854	0.765	0.753	0.851
Freundlich	$K_f \left[\left(\frac{\text{mg}}{\text{g}} \right) \left(\frac{\text{L}}{\text{mg/L}} \right) \right]^{1/n}$	0.8460	4.8506	1.5151	1.8032
	N	3.9904	0.8883	0.6369	0.6144
	R^2	0.9801	0.9801	0.9439	0.9815
	R^2	0.9272	0.9833	0.9699	0.917
Temkin	K_T (mol/L)	1.3414408	5.5911	6.4653	17.611
	B (kJ/mol)	18.607	17.049319	2.074	1.299166
	R^2	0.9272	0.9833	0.9699	0.917
Halsey	nH	0.2528	0.88825	0.63698	0.61440
	K	1.1759	33.700	1.65829	2.38832
	R^2	0.991	0.9801	0.9439	0.9815
Harkins & Jura	A	17.57	4.9407	5.5897	8.27129
	B	-10.50967	1	-3.0318	-4.9718
	R^2	0.8642	0.7595	0.7137	0.8926

The best fitting order of these models is conformed to be also Freundlich>Temkin>Harkins & Jura>Langmuir: for Cr, Temkin>Freundlich>Halsey>Langmuir>Harkins and Jura: for Ni, Temkin>Freundlich>Halsey>Langmuir>Harkins & Jura: for Pb and Freundlich>Halsey>Temkin> Harkins & Jura>Langmuir: for Cd. Langmuir isotherm model fitted the results quite well for removal of Cr>Cd>Ni>Pb by Cactus ash suggesting that: the surface of the sorbent is homogenous, all sites are energetically equivalent and each binding site accepts only one metal ion molecule, the adsorbed molecules are organized as a monolayer and no interaction between adsorbed molecules. The maximum monolayer adsorption capacity (Q_{max}) were Ni>Cr>Pb>Cd. These suggest that Langmuir Isotherm model was more suitable for Ni onto cactus ash residue. The process was therefore monolayer adsorption. And the maximum adsorption capacity for Ni ion was 1.91 mg/g with Langmuir constant (K_L) value of 0.588 L/mg suggested that adsorption of Ni ion onto cactus ash residue is more favorable. Table 1 also showed that the correlation of the experimental results was obtained fitted with the Freundlich isotherm model with Ni and Cr with R^2 of 0.9801 both, and it also confirmed favorable from n values <1 which indicates a chemical process. Table 1 and Figure 2 also showed that the best correlation of the experimental results was obtained with the Temkin isotherm model with for the removal of Ni; the Temkin isotherm equation explicitly takes into the account of adsorbent-adsorbate interactions by ignoring the extremely low and large value of concentrations. It assumes that the heat of adsorption of all the molecules in layer decreases linearly rather than logarithmic with coverage due to adsorbent-adsorbate interactions the constant B is greater than 8kJ/mol, it indicates a strong interaction between the adsorbate and adsorbent hence such adsorption can be expressed as physical adsorption. The Harkin and Jura Isotherm did not provide a good fit to the experimental data. The Harkin and Jura constants, A, B and the correlation coefficients R^2 for Cr, Ni, Pb and Cd are given in Table 1. The plot of $1/q_e^2$ against $\log C_e$ Figure 2 was also nonlinear with low R^2 suggesting that it was not appropriate for describing the adsorption of such metals onto cactus ash residue. The Halsey adsorption isotherm model is suitable for multilayer adsorption at a relatively large distance from the surface and the fitting of the experimental data to this equation attest to the heterosporous nature of the adsorbent [29]. The Halsey isotherm model fitted well to Cr, Ni, Pb, and Cd as there R^2 values are 0.991, 0.9801, 0.9439 and 0.9815 respectively.

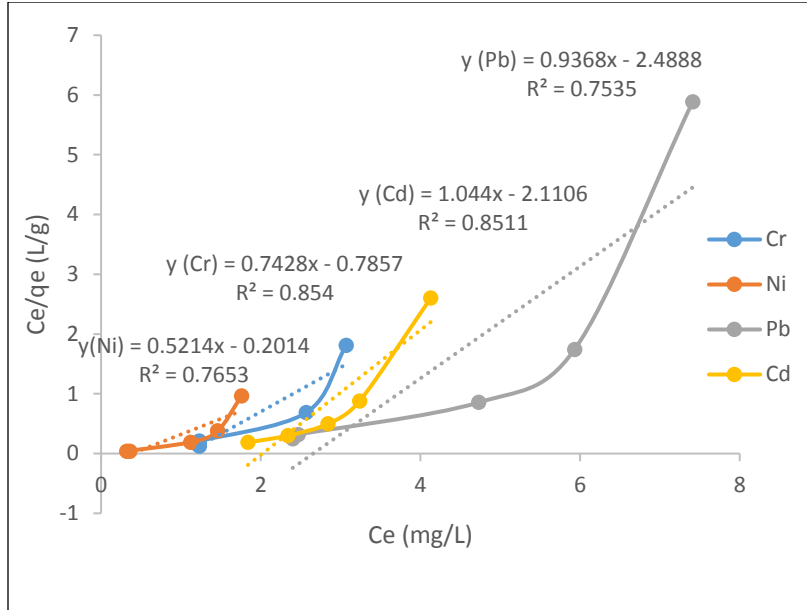


Figure 1. Langmuir Isotherm Model for Cr, Ni, Pb and Cd Removal

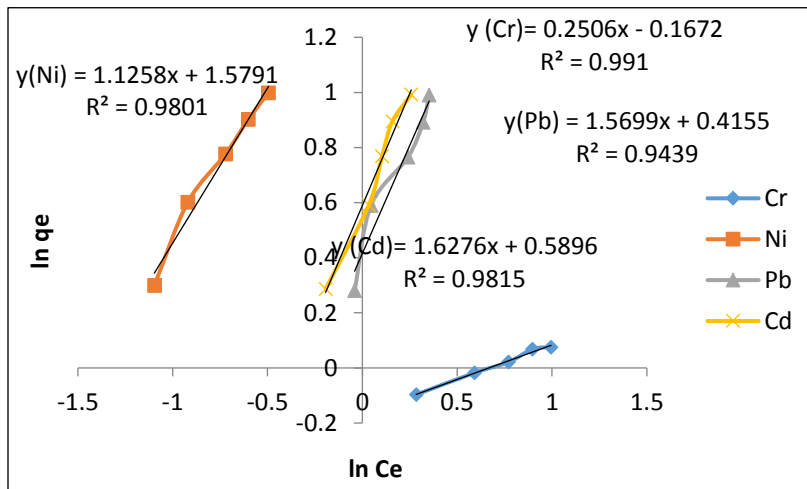


Figure 2. Freundlich Isotherm Model for Cr, Ni, Pb and Cd Removal

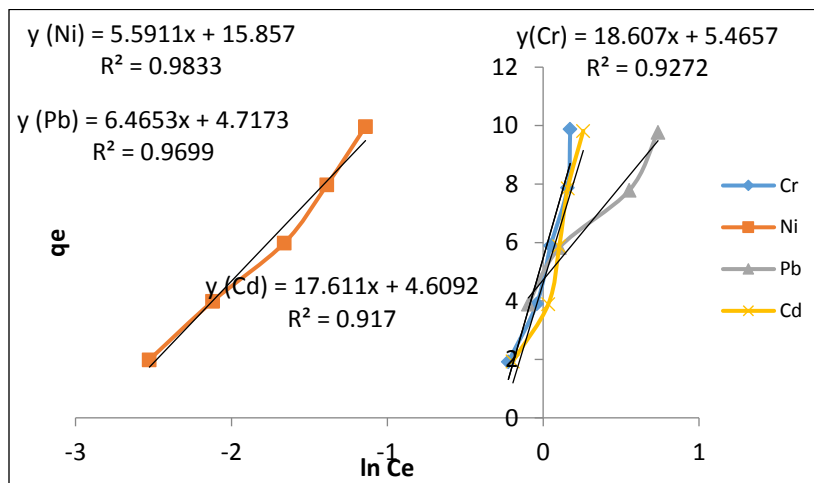


Figure 3. Temkin Isotherm Model for Cr, Ni, Pb and Cd Removal

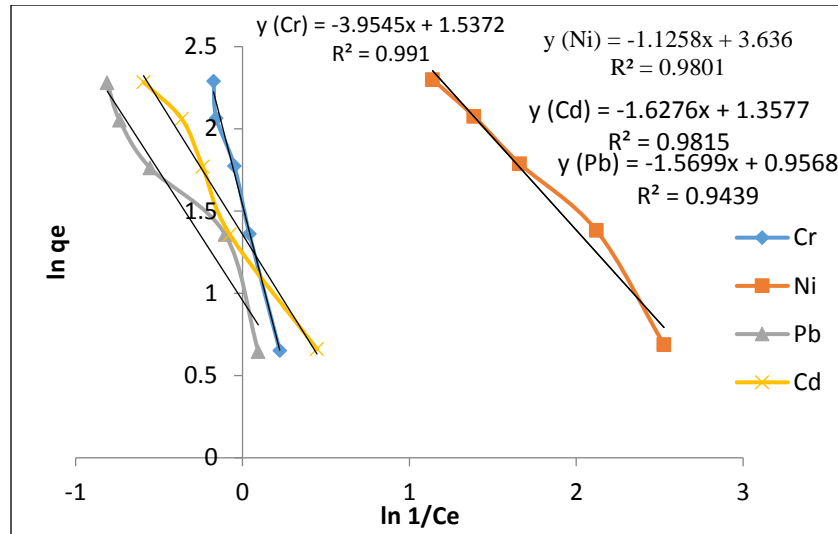


Figure 4. Halsey Isotherm Model for Cr, Ni, Pb and Cd Removal

4 CONCLUSIONS

The Langmuir, Freundlich, Temkin, Halsey and Harkin and Jura adsorption isotherm models were used for the description of the adsorption equilibrium of Cr, Ni, Pb and Cd ions onto cactus ash residue. The data were in good agreement with the Langmuir isotherm for Ni and Cr, but Cr fitted better to Halsey and Freundlich with higher R^2 values of 0.991 and 0.9801, respectively. The Isotherm that fitted best for Pb is Temkin. Temkin, Freundlich, and Halsey equally fits Ni, while the Freundlich and Halsey isotherm fitted best to Cd.

REFERENCES

1. Fang, Z., Zhu, H., Preston, C., Rzaev, Z.M.O., Ligrani, P.M. and Collopy, H. (2022). Natural filtration unit for removal of heavy metals from water. *In Natural filtration unit for removal of heavy metals from water, UK*, pp. 1-9. doi: 10.1088/1757-899X/888/1/012034.
2. Karaouzas, I., Kapetanaki, N., Mentzafou, A., Kanellopoulos, T.D. and Skoulikidis, N. (2021). Heavy metal contamination status in Greek surface waters: A review with application and evaluation of pollution indices. *Chemosphere*, vol. 263, pp. 1-15. doi: 10.1016/j.chemosphere.2020.128192.
3. Raji, Z., Karim, A., Karam, A. and Khalloufi, S. (2023). Adsorption of Heavy Metals: Mechanisms, Kinetics, and Applications of Various Adsorbents in Wastewater Remediation-A Review. *Waste*, vol. 1, no. 3, pp. 775-805. doi: 10.3390/waste1030046.
4. Amari, A., Alalwan, B., Eldirderi, M.M. and Mnif, W. (2020). Cactus material-based adsorbents for the removal of heavy metals and dyes : a review Cactus material-based adsorbents for the removal of heavy metals and dyes : a review. *Mater. Res. Express*, vol. 7, pp. 1-14.
5. Bekewei, R.A. and Bariweni, P.A. (2021). Physico-chemical characteristics and heavy metals in wastewater from paint industries in Yenagoa Metropolis , Bayelsa State , Nigeria. *Int. J. Res. Environ Stu*, vol. 8, pp. 48-54.
6. Akalezi, C.O., Maduabuchi, A.C., Enenebeaku, C.K. and Oguzie, E.E. (2020). Experimental and DFT evaluation of adsorption and inhibitive properties of Moringa oliefera extract on mild steel corrosion in acidic media. *Arab. J. Chem.*, vol. 13, no. 12, pp. 9270-9282. doi: 10.1016/j.arabjc.2020.11.010.
7. Zhu, Y., Fan, W., Zhou, T. and Li, X. (2019). Removal of chelated heavy metals from aqueous solution: A review of current methods and mechanisms. *Sci. Total Environ.*, vol. 678, no. 37, pp.

- 253-266. doi: 10.1016/j.scitotenv.2019.04.416.
8. Türkmen, D., Bakhshpour, M., Akgönüllü, S., Aşır, S. and Denizli, A. (2022). Heavy Metal Ions Removal From Wastewater Using Cryogels: A Review. *Front. Sustain.*, vol. 3, pp. 1-17. doi: 10.3389/frsus.2022.765592.
 9. Benalia, M.C., Youcef, L., Bouaziz, M.G., Achour, S. and Menasra, H. (2022). Removal of Heavy Metals from Industrial Wastewater by Chemical Precipitation: Mechanisms and Sludge Characterization. *Arab. J. Sci. Eng.*, vol. 47, no. 5, pp. 5587-5599. doi: 10.1007/s13369-021-05525-7.
 10. Znad, H., Awual, M.R. and Martini, S. (2022). The Utilization of Algae and Seaweed Biomass for Bioremediation of Heavy Metal-Contaminated Wastewater. *Molecules*, vol. 27, no. 4, pp. 1-21. doi: 10.3390/molecules27041275.
 11. Kocaoba, S. (2022). Determination of some heavy metals from aqueous solutions using modified Amberlite XAD-4 resin by selective solid-phase extraction. *J. Anal. Sci. Technol.*, vol. 13, no. 1, pp. 1-10. doi: 10.1186/s40543-022-00324-7.
 12. Yin, X., Ke, T., Zhu, H., Xu, P. and Wang, H. (2023). Efficient Removal of Heavy Metals from Aqueous Solution Using Licorice Residue-Based Hydrogel Adsorbent. *Gels*, vol. 9, no. 7, pp. 1-21. doi: 10.3390/gels9070559.
 13. Al-Zboon, K.K. (2023). Single and Ternary Removal of Heavy Metals from Aqueous Solution Using Fe₃O₄ Magnetic Nano-particles. *Jordan J. Civ. Eng.*, vol. 17, no. 2, pp. 335-350. doi: 10.14525/JJCE.v17i2.13.
 14. Abdalla, M.S. (2022). Adsorption Properties of Magnetite Nanoparticles for the Removal of Heavy Metals From Aqueous Solution. *Egypt. J. Appl. Sci.*, vol. 37, no. 5, pp. 11-29. doi: 10.21608/ejas.2022.261097.
 15. Singh, E., Kumar, A., Mishra, R., You, S., Singh, L., Kumar, S. and Kumar, R. (2021). Pyrolysis of waste biomass and plastics for production of biochar and its use for removal of heavy metals from aqueous solution. *Bioresour. Technol.*, vol. 320, pp. 1-27. doi: 10.1016/j.biortech.2020.124278.
 16. Imran-Shaukat, M., Rosli, N.R.B., Wahi, R., Abdullah, S.M.A.A. and Ngaini, Z. (2021). Chemically modified coconut shell biochar for removal of heavy metals from aqueous solution. *Defect Diffus. Forum*, vol. 411, pp. 79-91. doi: 10.4028/www.scientific.net/DDF.411.79.
 17. Xiao, F., Cheng, J., Cao, W., Yang, C., Chen, J. and Luo, Z. (2019). Removal of heavy metals from aqueous solution using chitosan-combined magnetic biochars. *J. Colloid Interface Sci.*, vol. 540, pp. 579-584. doi: 10.1016/j.jcis.2019.01.068.
 18. Dim, P.E. and Termtanun, M. (2021). Treated clay mineral as adsorbent for the removal of heavy metals from aqueous solution. *Appl. Sci. Eng. Prog.*, vol. 14, no. 3, pp. 511-524. doi: 10.14416/j.asep.2021.04.002.
 19. Erdogan, F.O. (2018). Freundlich, Langmuir, Temkin, DR and Harkins-Jura isotherm studies on the adsorption of CO₂ on various porous adsorbents. *Int. J. Chem. React. Eng.*, vol. 17, no. 5, pp. 1-11.
 20. Amari, A., Alalwan, B., Eldirderi, M.M. and Mnif, W. (2020). Cactus material-based adsorbents for the removal of heavy metals and dyes : a review Cactus material-based adsorbents for the removal of heavy metals and dyes : a review. *J. Inst. Phys. Mater. Res. Express*, vol. 7, pp. 1-13. doi: <https://doi.org/10.1088/2053-1591/ab5f32>.
 21. Qasem, N.A.A., Mohammed, R.H. and Lawal, D.U. (2021). Author Correction: Removal of heavy metal ions from wastewater: a comprehensive and critical review (npj Clean Water. *npj Clean Water*, vol. 4, no. 1, pp. 1-11. doi: 10.1038/s41545-021-00144-z.

22. Oh, H., Lee, J.H. and Patel, R. (2019). Removal of Heavy Metal Ions from Wastewater by Polyacrylonitrile based Fibers: A Review. *Membr. J.*, vol. 29, no. 3, pp. 123-129. doi: 10.14579/membrane_journal.2019.29.3.123.
23. Sen, T.K. (2023). Agricultural Solid Wastes Based Adsorbent Materials in the Remediation of Heavy Metal Ions from Water and Wastewater by Adsorption: A Review. *Molecules*, vol. 28, no. 14, pp. 1-22. doi: 10.3390/molecules28145575.
24. Ranaweera, K.H., Grainger, M.N.C., French, A.D. and Mucalo, M.R. (2023). Construction and demolition waste repurposed for heavy metal ion removal from wastewater: a review of current approaches. *Int. J. Environ. Sci. Technol.*, vol. 20, no. 8, pp. 9393-9422. doi: 10.1007/s13762-023-05029-x.
25. Kausar, A., Iqbal, M., Javed, A., Aftab, K., Bhatti, H. N. and Nouren, S. (2018). Dyes adsorption using clay and modified clay: A review. *J. Mol. Liq.*, vol. 256, pp. 395-407. doi: 10.1016/j.molliq.2018.02.034.