

Research Article

Adsorption of Chromium Ions from Aqueous Solutions by Synthesized Nanoparticles

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In the present manuscript, an attempt has been made to remove chromium metal ions from synthetic effluent using adsorption process. The synthesized titanium dioxide nanoparticles were used as adsorbents. Adsorption studies were performed in batch process. Various characterization of synthesized nanoparticles such as XRD analysis, optical properties of nanoparticles using UV-visible absorption spectroscopy, concentration of chemical bonds, and atomic arrangement using (FTIR) have been performed and analyzed. The dependency of adsorption percentage of metal ions and equilibrium amount of metal adsorbed with respect to pH, adsorbent dosage, initial concentration, and temperature are studied. Mechanisms of metal ion adsorption process explained by various adsorption isotherms and adsorption kinetic models. The criteria for statistical significance of correlation coefficient (R^2) for fitting the experimental data to the various isotherms were tested and analyzed. The experimental results reveal that synthesized titanium dioxide nanoparticles could be used as adsorbents in order to remove chromium ions present in industrial wastewater.

1. Introduction

Heavy metals may defined as metal with a density greater than 4 gm/cm³ or metals with a high atomic weight or metals commonly used in industry and toxic to man and other organisms. These include arsenic (As), silver (Ag), chromium (Cr), mercury (Hg), and platinum group of metal [1]. The various anthropogenic activities that introduce the heavy metals in the environment are mining of ores, municipal waste, burning,

and agricultural activities [2, 3]. The released toxic metals are having more dangerous to concentrate in ecosystems and habitats. The source of heavy metals is mostly by industrials, i.e., metallurgical industries, electroplating industries, metal finishing industries, tanneries, chemical manufacturing industries, and battery manufacturing industries [4, 5].

The presence of lead and chromium compounds causes more toxic to the environment. Various processes of sources of chromium and lead metals are mining, tanning, cement, textile and dyeing, electroplating industries, steel, photographic material, and paints. Heavy metals removed from wastewater using various technologies like ion exchange process, flocculation, precipitation process, membrane filtration, RO, and phytoremediation are the conventional methods, and the merits and demerits of each method have extensively reviewed [6, 7]. The conventional process has demerits such as increasing the disposal problems due to the large amount sludge production, and treated wastewater is contaminated and very difficult to treat the toxic industrial wastewater because of high biological demand, total solids, and huge amount of weakly biodegradable and toxic matters. The literature reveals that adsorption process gives more efficiency, low cost, and user-friendly [8].

In recent research, [8] states that environmental related problems are reduced by using nanotechnology principles, and it has emerging and promising techniques for eliminating pollutants from industrial effluent. Nanomaterial preparation in nanoscale is the basic in the nanotechnology method. Nanoscale materials have distinctive characteristics, on account of their tiny size, and they possess high surface area. These characteristics improve the surface assimilation capability of the nanoparticles [9]. Due to their large area of surface, nanoparticles contain bigger interaction with chemical species [10, 11]. The current paper concentrates on synthesis of titanium oxide nanoparticles and the removal of chromium ions from synthetic wastewater using synthesized titanium oxide nanoparticles. Adsorption studies were performed in batch process. The pH was varied from 2 to 12 and for the different adsorbent dosage (0.2 to 1 gm/100 ml), the experiment was carried out. The removal of chromium was examined by changing the initial concentration between 50 ppm and 150 ppm. The procedure was repeated for 40°C and 50°C.

2. Materials and Methods

2.1. Synthesis of Nanoparticles. Titanium dioxide (TiO_2) nanoparticles have prepared by using chemical precipitation method and mechanical grinding [12]. Titanium chloride was mixed with 10% sulfuric acid placed in an ice-water bath with constant stirring, because it produce dense fumes of titanium oxysulfate, then temperature was maintained at 60°C, for 1 hour, and the addition of ammonia forms sudden precipitate. Whatman filter paper was used for filtering the precipitate. Precipitate was heated at 500°C in a muffle furnace. Finally, product was recovered as TiO₂ particles. It has been treated in a ball mill at 100 rpm for more than 4 hours, in order to avoid the contamination. Balls and container should be treated with deionized water.

2.2. Characterization of Nanoparticles

2.2.1. XRD Results. The XRD analysis can be used to find peak intensity and full width [13]. The XRD results pointed out the presence of nanoscale particles in the synthesized materials. By using Debye-Scherrer formula, diameter of synthesized nanoparticle was obtained. Figure 1 and Table 1 show the results of XRD analysis in detailed.



50

Position (* 2θ) (Copper (ca))

60

70

80

FIGURE 1: XRD results for TiO₂.

40

2.2.2. UV Results. The nanoparticles size considered being a very important part in changing the whole properties of materials, and hence determination of size of semiconducting nanoparticles becomes very important to investigate the material properties. To examine the optical properties of nanoparticles, UV-visible absorption spectroscopy is used. For TiO₂ band, emissions were observed at different wavelengths such as 403, 421, 425, 441, 446, 460, 466, 484, and 528 nm. The experimental observation reveals that in the absorption spectrum of Fe₂O₃, the absorption maximum (at 550 nm) progressively reduced upon UV irradiation, with no change of maximum peak of absorption [14].

2.2.3. FTIR Results. In Fourier transform infrared spectroscopy, intensity frequency is measured using intensity-time output subjected to a Fourier transform, and it converts to an infrared spectrum. Concentration of chemical bonds and atomic arrangement presence can be identified by using FTIR, where transmission percentage and wave number are the output. The absorption band signals analyzed from 400 to 1000 cm⁻¹ correspond to Ti–O–Ti vibration. Figure 2 shows the FTIR results of nanoparticles. The band with respect to Fe-O stretched manner of Fe₂O₃ is seen at 576 cm⁻¹ [15].

3. Results

Counts

0

20

30

3.1. Adsorption Studies

3.1.1. General Procedure. Adsorption studies were performed in batch process. Synthetic solution was prepared in order to optimize various parameters. The diluted solution was prepared from concentrated stock solution using distilled water with different concentrations from 50 to 150 ppm. The experimental study was performed with 100 ppm solution. The pH was varied from 2 to 12. For the different adsorbent dosages (0.2 to 1 gm/100 ml), the experiment was carried out. The removal of chromium was examined by changing the initial concentration between 50 ppm and 150 ppm. The same process was repeated for 40°C and 50°C [16].

The % adsorption of metal ions was calculated by eq. (1).

%Adsorption =
$$((C_0 - Cr)/(C_0)) \times 10$$
, (1)

TABLE 1: XRD results for TiO_2 .

Φ (°2Th)	φ/2	FWHM (°2Th)	FWHM (3.14/180)	λ (Å)	Size (Å)	Nanometer (nm)
10.072	5.036	0.098	0.0017	1.54	2651.24	265.12
13.468	6.7341	0.147	0.0025	1.54	624.66	62.46
27.057	13.528	0.393	0.0068	1.54	368.89	36.88
27.643	13.821	0.147	0.0025	1.54	1811.80	181.18
23.157	11.578	0.147	0.0025	1.54	1021.03	102.10
Average						129.55



FIGURE 2: FTIR Result for TiO₂.

where C_0 is concentration of Cr ions (ppm) at initial, and Cr is metal ion residual concentration in the filtrate after shaking for a definite time period (mg/l).

The metal uptake at a particular time q_t was determined by the following equation.

$$q_t = [(C0 - Cr)/m] * V.$$
 (2)

Equilibrium amount of metal adsorbed, q_e , was found by

$$q_e = [(C0 - Ce)/m * V,$$
 (3)

where *m* and *V* represent adsorbent mass and volume of sample, respectively. C_e is the Cr concentration at equilibrium.

3.2. Chromium Removal Using Titanium Dioxide

3.2.1. Influence of pH. Chromium removed using titanium dioxide as an adsorbent from 2 to 12 was studied for analyzing the influence of pH. The change of pH affects the adsorptive process through dissociation of functional groups on the adsorbent surface active sites. The highest chromium removed level was observed on lower pH 6 and further increasing pH, there will be no change in the removal of chromium. Figure 3 shows influencing of the pH factor of Cr removal percentage [17].

3.2.2. Influence of Adsorbent Dosage. Adsorption experiment was carried out at varying adsorbent dose (0.2-1 gm/100 ml)



FIGURE 3: Influence of pH on % of chromium removal.

while pH (6) was kept constant for Cr. The increase in adsorbent dosage leads to an increase of metal removal that was observed and was shown in Figure 4. As there is more surface area for the adsorption process, the more metal ions get adsorbed onto the surface of the titanium dioxide [18].

3.2.3. Influence of Initial Concentration. At room temperature, the effect of initial Cr ion concentration of effluent on Cr removal has been evaluated using titanium dioxide by keeping the optimized value unchanged. These optimized values are maintained constant for the further studies. Initial concentration was increased while rate of adsorption increases. But after the process reached equilibrium, i.e., after 75 min, there was no increase in the metal removal. At 100 ppm, the removal attained equilibrium. Figure 5 shows that the removal of metal ions on titanium dioxide powder depends on initial concentration, the boundary layer increases diffusion of Cr ions resulted maximum sorption by TiO₂ [18, 19].

3.2.4. Influence of Temperature. Batch studies were conducted at the optimal conditions and different temperatures. The temperature varied from 30°C to 50°C by keeping all the optimized parameters unchanged. The adsorption of Cr on TiO_2 was noted by varying temperature. Figure 6 shows that there is no appreciable increase in percentage removal with increasing temperature [19].

3.3. *Kinetics Studies on Adsorption*. In this study, adsorption mechanism examined using the rate data was analyzed using



FIGURE 4: Influence of adsorbent dosage on removal of Cr.





FIGURE 5: Influence of initial concentration on Cr removal.

FIGURE 6: Influence of temperature on Cr removal.

the suitable kinetic model. The adsorption dynamics illustrated by metal ion rate uptake on stability time and adsorbents were controlled by rate. Different kinetic models were examined using experimental data (different initial concentration and temperatures). The adsorption dynamics of the metal ions on nanoadsorbent were checked with the different models as described below [20].

3.3.1. Kinetic Studies

(1) Pseudo 1^{st} Order. The kinetics of adsorption may be explained by a pseudo 1^{st} order equation as mentioned below (eq. (4)).

$$\log (q_e - q_t) = \log q_e - (k_1 t)/2.303, \tag{4}$$

where q_e and q_t are adsorbed metal ions (mg/g) at equilibrium and time, and k_1 is the rate constant (min⁻¹).

The plot of $(\log (q_e - q_t) \text{ vs. } t)$ and the suitability of equation imply 1^{st} order process. The experiments were conducted at various temperatures with different concentrations. Using eq. (4), the theoretical q_e values of Cr removal have been calculated, and the results revealed that this adsorption system is pseudo first-order.

(2) Pseudo 2^{nd} Order. The linearized pseudo 2^{nd} order is mentioned in eq. (5).

$$\frac{t}{qt} = \frac{1}{k_2}q_e^2 + \frac{1}{qt} * t,$$
 (5)

where k_2 is the rate constant (g/mg.min), and k_2 and q_e can be found that a good agreement with experimental data and confirm with 2nd order kinetics for different temperatures and initial concentrations. For second order kinetics, obtained regression coefficients are in the range of acceptable value, and it is found that this model suits for adsorption of Cr ions [21, 22].



FIGURE 7: Determination of constants using the fractional power model.

(3) Fractional Power Model. The linear fractional power function equation is given by eq. (6).

$$\ln q_t = \ln k + \mu \ln t. \tag{6}$$

The values of μ and k can be found using the above linear relationship. For different temperatures and concentrations, the model was checked to fit. Figure 7 indicates that the power function model described the time-dependent. The kinetic of Cr ion adsorption can be satisfactory described by the power function model. Power model describes rates of adsorption. However, the regression coefficient R^2 was very high for a Cr ion which indicates that power function is the best model to correlate kinetic data [23].

(4) *Intraparticle Diffusion*. It is represented by the following eq. (7).

$$q_t = \text{klntt}_{1/2},\tag{7}$$

where k is the rate constant (mg/g.min).

Adsorption mechanism is difficult but in the initial stage, intraparticle diffusion is important. In this case, linear portions observed at different temperatures and concentrations were shown in Figure 8. When intraparticle diffusion occurs, the slopes of these linear portions can be distinct by adsorption rate and rate parameter in this area. At first, minimum time period, it was assumed that ions transferred through nanoadsorbent to external surface. Behind surface saturation, until equilibrium was reached, ions are entered through intraparticle diffusion to nanoadsorbent, pore, and interior surface diffusion, and it is by second straight. This model well suits for Cr removal [24]. (5) Elovich Equation. It is mentioned by eq. (8) that

$$q_t = \frac{1}{\beta} * \ln (\alpha \beta) + \frac{1}{\beta} * \ln t, \qquad (8)$$

where α is the primary sorption rate (mg/g.min), and β is the surface area coverage (g/mg).

Elovich equation explains about chemical adsorption on heterogeneous adsorbents, but for adsorbate-adsorbent interaction, this equation does not recommend any specific mechanism. The experiment was conducted for various temperatures, and different concentrations were shown that this kinetic data not fit Cr removal process, because of the low regression coefficient value [25]. Table 2 represents the consolidated values of various parameters of the different models at various temperatures.

3.4. Adsorption Isotherm. Equilibrium isotherm was represented by a sorption isotherm and characterized by some of the constants. The adsorbent sorption was established when the sorbate concentration in the bulk solution was in dynamic balance at sorbent interface. The statistical significance of the correlation coefficient (R^2) was the criteria by which the fitting of the data to the various isotherms was tested and tabulated in Table 3. In order to measure the nanoadsorbent affinity for the metal examined, i.e., Cr, the following isotherm models were used [25].

3.4.1. Isotherm Studies on Cr Using Tio₂

(1) Langmuir Adsorption Isotherm. At a constant temperature, adsorbent surface was represented by Langmuir adsorption isotherm. It is represented by (9).

$$\frac{C_e}{q_e} = \left[\frac{1}{Kd}qm\right] + \left[\frac{1}{qm}\right]C_e,\tag{9}$$

where q_e is the Cr adsorbed level (mg/g), C_e is the aqueous phase metal concentration (mg/l), K_d is the sorption equilibrium constant, and q_m is the monolayer capacity(mg/g).

For different temperatures and different concentrations, the equation is checked to fit the Cr removal using titanium dioxide. The value of q_m and K attained from linear graph [25].

(2) *Freundlich Isotherm*. The important assumption of Freundlich isotherm is adsorption on heterogeneous surface by multilayer adsorption. The linear form of the equation is

$$\log q_e = \log k_f + \frac{1}{n \log Ce}.$$
 (10)

The nomenclature is as follows: q_e is the adsorption capacity, C_e is the final concentration, and n is the empirical constant.



FIGURE 8: Determination of constants using intraparticle diffusion.

TABLE 2:	Cr removal	for diffe	rent concenti	ations and	temperatures.
INDEL 2.	Of removal	ioi anic	rent concent	attonio ana	temperatures.

			Concentration			Temperature	
Models	Parameters	50 ppm	100 ppm	150 ppm	30°C	40°C	50°C
	R^2	0.85	0.96	0.97	0.97	0.95	0.95
Decudo first order	Κ	0.02	0.026	0.02	0.03	0.03	0.04
r seudo mist order	Q_e	1.61	1.85	1.89	1.91	2.07	2.09
					0.99	0.98	0.99
	R^2	0.86	0.99				
Pseudo second order	Κ	0.02	0.016	0.01	0.03	0.02	0.02
	Q_e	3.51	0.43	0.37	0.44	0.46	0.42
	R^2	0.99	0.95	0.99	0.95	0.93	0.95
Fractional power	Κ	0.86	0.46	0.86	0.46	0.49	0.45
	N	0.94	1.85	2.11	1.85	1.71	1.74
Internetial differences	R^2	0.72	0.85	0.94	0.85	0.81	0.83
Intraparticle diffusion	Κ	0.46	0.33	0.46	0.33	0.34	0.32
Elovich	R^2	0.55	0.97	0.98	0.97	0.96	0.96

TABLE 3: Constants of isotherm and kinetics studies for TiO_2 .

			Concentration			Temperature		
Models	Parameters	50 ppm	100 ppm	150 ppm	30°C	40°C	50°C	
	R^2	0.9563	0.0566	0.9663	1	0.9162	0.9993	
Freundlich isotherm	K_f	0.3752	3.7858	50.72	0.0217	0.0313	0.0214	
	Ν	5.4905	4.7058	292.63	0.0054	0.1223	0.028	
Langmuir isotherm	R^2	0.9999	1	0.9999	0.8782	0.8687	0.8733	
	R^2	0.9673	0.9291	0.9426	0.9909	0.9895	0.9894	
Temkin isotherm	а	52.57	72.922	140.92	96.505	92.575	98.766	
	b	12.807	12.044	24.11	31.258	30.405	31.867	

From the experimental data, various temperatures and concentrations, the plots $\ln q_e$ vs. $\ln C_e$ and Freundlich coefficients n and K_f are obtained. From the data, it was observed that this adsorption process has not followed Freundlich isotherm [24].

(3) *Temkin Isotherm*. It assumed that due to interactions between adsorbent and adsorbate, adsorption heat of molecules in the adsorbed layer diminishes.

It is given by eq. (11).

$$X = a + b \ln C, \tag{11}$$

where *C* is the concentration of adsorbate (mg/l), *X* is the metal adsorbed (mg/g), and *a* and *b* are constants.

For different temperatures and concentrations, the given equation was checked for the fitness [26].

(4) Isotherm Study Table.

4. Conclusion

The experimental results indicated that heavy metals can be removed by nanomaterials as adsorbents with low concentration and adsorption capability. Mechanisms of adsorption process enlightened by various adsorption isotherms and adsorption kinetic models. The influence of various important variables on heavy metal removal was examined. The development of nanotechnology reduces the exploitation of resourceful adsorption materials. In future, a nanomaterial application in heavy metal removal in wastewater treatment is practically vivid.

Data Availability

The underlying data supporting the results of this study were included in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

- H. Sunil, H. N. Pradeep, and K. S. Mahesh, "Removal of chromium metal ions from waste water using alternatives ad sorbents-a comparative study," *International Journal of Scientific and Research Publications*, vol. 4, pp. 104–119, 2014.
- [2] W. Salah Abdel, M. Abdel Monem, S. Mohameed, and M. A. Mohamed, "Adsorption studies on the removal of hexavalent chromium- contaminated wastewater using activated carbon and bentonite," *Asian Journal of Chemistry*, vol. 25, pp. 95– 105, 2012.
- [3] K. Senthilkumar, V. Sivakumar, and P. Akilamudhan, "Experimental studies on disposal of various industrial solid wastes," *Modern Applied Science*, vol. 2, no. 6, pp. 128–132, 2009.
- [4] M. N. Rashed, "Lead removal from contaminated water using mineral adsorbents," *Environmentalist*, vol. 21, no. 3, pp. 187– 195, 2001.

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- [5] N. D. Kandpal and N. Sah, "Co-precipitation method of synthesis and characterization of iron oxide nanoparticles," *J. Sci. Ind. Res.(India)*, vol. 73, pp. 87–90, 2014.
- [6] K. Senthilkumar, V. Chitradevi, S. Mothil, and M. N. Kumar, "Adsorption studies on treatment of textile wastewater using low cost adsorbent, desalination," *Water Treat.*, vol. 123, pp. 90–100, 2018.
- [7] A. K. Gupta and M. Gupta, "Synthesis and surface engineering of iron oxide nanoparticles for biomedical applications," *Biomaterials*, vol. 26, no. 18, pp. 3995–4021, 2005.
- [8] S. Recillas and A. Garcia, "Use of CeO₂, TiO₂ and Fe₃O₄ nanoparticles for the removal of lead from water: Toxicity of nanoparticles and derived compounds," *Desalination*, vol. 277, no. 1-3, pp. 213–220, 2011.
- [9] S. A. Majid, "Green synthesis of iron oxide nanorods from deciduous Omani mango tree leaves for heavy oil viscosity treatment," *Arabian Journal of Chemistry*, vol. 12, no. 8, pp. 4084–4090, 2019.
- [10] R. K. Ganapathi and C. H. Ashok, "Green synthesis of titanium dioxide nanoparticles using aloe vera extract," *Int. J. Adv. Res. Phy. Sci.*, vol. 2, pp. 28–34, 2015.
- [11] V. K. Gupta, R. Chandra, I. Tyagi, and M. Verma, "Removal of hexavalent chromium ions using CuO nanoparticles for water purification applications," *Journal of Colloid and Interface Science*, vol. 478, pp. 54–62, 2016.
- [12] S. Gupta, A. Yadav, and N. Verma, "Simultaneous Cr(VI) reduction and bioelectricity generation using microbial fuel cell based on alumina-nickel nanoparticles-dispersed carbon nanofiber electrode," *Chemical Engineering Journal*, vol. 307, pp. 729–738, 2017.
- [13] H. Wang, X. Yuan, Y. Wu et al., "Facile synthesis of polypyrrole decorated reduced graphene oxide- Fe₃O₄ magnetic composites and its application for the Cr(VI) removal," *Chemical Engineering Journal*, vol. 262, pp. 597–606, 2015.
- [14] J. Yu, C. Jiang, Q. Guan et al., "Enhanced removal of Cr(VI) from aqueous solution by supported ZnO nanoparticles on biochar derived from waste water hyacinth," *Chemosphere*, vol. 195, pp. 632–640, 2018.
- [15] S. S. Poguberović, D. M. Krčmar, S. P. Maletić et al., "Removal of As(III) and Cr(VI) from aqueous solutions using "green" zero-valent iron nanoparticles produced by oak, mulberry and cherry leaf extracts," *Ecological Engineering*, vol. 90, pp. 42–49, 2016.
- [16] A. Masud, Y. Cui, D. John, and A. N. Aich, "Shape matters: Cr (VI) removal using iron nanoparticle impregnated 1-D vs 2-D carbon nanohybrids prepared by ultrasonic spray pyrolysis," *Journal of Nanoparticle Research*, vol. 20, no. 3, pp. 64–75, 2018.
- [17] R. Fu, X. Zhang, Z. Xu, X. Guo, D. Bi, and W. Zhang, "Fast and highly efficient removal of chromium (VI) using humussupported nanoscale zero-valent iron: influencing factors, kinetics and mechanism," *Separation and Purification Technology*, vol. 174, pp. 362–371, 2017.
- [18] M. Fazlzadeh, R. Khosravi, and A. Zarei, "Green synthesis of zinc oxide nanoparticles using _Peganum harmala_ seed extract, and loaded on _Peganum harmala_ seed powdered activated carbon as new adsorbent for removal of Cr(VI) from aqueous solution," *Ecological Engineering*, vol. 103, pp. 180– 190, 2017.
- [19] M. Fazlzadeh, K. Rahmani, A. Zarei, H. Abdoallahzadeh, F. Nasiri, and R. Khosravi, "A novel green synthesis of zero

valent iron nanoparticles (NZVI) using three plant extracts and their efficient application for removal of Cr(VI) from aqueous solutions," *Advanced Powder Technology*, vol. 28, no. 1, pp. 122–130, 2017.

- [20] J. B. Dima, C. Sequeiros, and N. E. Zaritzky, "Hexavalent chromium removal in contaminated water using reticulated chitosan micro/nanoparticles from seafood processing wastes," *Chemosphere*, vol. 141, pp. 100–111, 2015.
- [21] V. N. Bhusari, D. Rashmi, R. Sadhana, and B. Amit, "Comparative study of removal of hexavalent chromium from water using metal oxide nanoparticles," *Adv. Nanopart.*, vol. 5, no. 1, pp. 67–74, 2016.
- [22] A. Dargahi, H. Golestanifar, P. Darvishi, and A. Karam, "An investigation and comparison of removing heavy metals (lead and chromium) from aqueous solutions using magnesium oxide nanoparticles," *Polish Journal of Environmental Studies*, vol. 25, no. 2, pp. 557–562, 2016.
- [23] S. Rajput, U. Charles, and J. D. Mohan, "Magnetic magnetite (Fe₃O₄) nanoparticle synthesis and applications for lead (Pb²⁺) and chromium (Cr⁶⁺) removal from water," *Journal of Colloid and Interface Science*, vol. 468, pp. 334–346, 2016.
- [24] L. Wenhui, L. Jinhua, S. Yanqing, Z. Xinshen, J. You, and L. Chen, "One-pot synthesis of magnetic iron oxide nanoparticle-multiwalled carbon nanotube composites for enhanced removal of Cr(VI) from aqueous solution," *Journal* of Colloid and Interface Science, vol. 505, pp. 1134–1146, 2017.
- [25] N. Zahra, "Lead removal from water by low cost adsorbents: a review," Pakistan Journal of Analytical & Environmental Chemistry, vol. 13, pp. 1–8, 2012.
- [26] S. Li, W. Wang, F. Liang, and W. Zhang, "Heavy metal removal using nanoscale zero-valent iron (nZVI): theory and application," *Journal of Hazardous Materials*, vol. 322, pp. 163–171, 2017.