

Nanoporous carbon synthesized from grass for removal and recovery of hexavalent chromium

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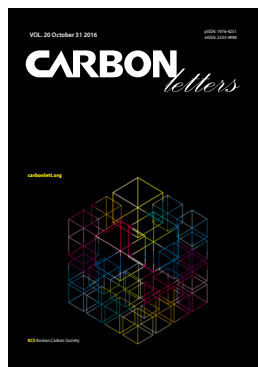
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Abstract

Nanoporous carbon structures were synthesized by pyrolysis of grass as carbon precursor. The synthesized carbon has high surface area and pore volume. The carbon products were acid functionalized and characterized by Fourier transform infrared spectroscopy, X-ray diffraction, Brunauer–Emmett–Teller, transmission electron microscopy, and Energy Dispersive X-ray microanalysis. Acid functionalized nanoporous carbon was explored for use in removal of toxic Cr(VI) ions from aqueous media. An adsorption study was done as a function of initial concentration, pH, contact time, temperature, and interfering ions. The experimental equilibrium data fits well to Langmuir isotherm model with maximum monolayer adsorption capacity of 35.335 mg/g. The results indicated that removal obeys a pseudo-second-order kinetic model, and that equilibrium was reached in 10 min. A desorption study was done using NaOH. The results of the present study imply that acid functionalized nanoporous carbon synthesized from grass is an efficient, renewable, cost-effective adsorbent material for removal of hexavalent chromium due to its faster removal rate and reusability.

Key words: porous carbon, Brunauer–Emmett–Teller, surface area, adsorption

1. Introduction

Pollution of water by heavy metal ions has become a worldwide problem. Industries related to metallurgy, chemicals, textiles, tanning, and mining are the main sources of contamination of water by Cr(VI). Hexavalent chromium is listed not only in the 2011 CERCLA Priority List of Hazardous Substances (US Environmental Protection Agency [EPA]) but also in the European Union Restriction of Hazardous Substances Directive [1,2] among the topmost contaminants. The permissible limit for Cr(VI) in industrial wastewaters is 0.1 mg/L, and 0.05 mg/L in drinking water (EPA 1990). Hexavalent chromium compounds are already proven to be genotoxic carcinogens via inhalation. Concentrations above the 0.05-mg/L limit in drinking water of Cr(VI) can be carcinogenic. Cr(VI) causes liver and kidney damage, producing lung tumors, severe diarrhea, allergic dermatitis, skin irritation, internal hemorrhages, and respiratory problems [3]. Hence, Cr(VI) should be removed from water. There are many methods developed for removal of heavy metals from water, such as electrolysis, chemical precipitation, oxidation-reduction, solvent extraction and ion-exchange. However, a better method for removal of metal ions from aqueous medium is by adsorption on a suitable sorbents. However, many adsorbents have poor removal efficiency and slow rates of adsorption [4-8]. Carbon nanomaterials in various forms are also being widely studied due to their high surface area, thermal stability, porosity and good mechanical strength for removal of heavy metal ions. The raw materials for synthesis of carbon based materials are generally obtained using fossil fuel, but a better alternative is to synthesize carbon from inedible biomass. Biomass precursors are renewable and cost effective [9-11].

In the present study, cost-effective nanoporous carbon (NPC) material was synthesized

by pyrolysis of yard-grass clippings using FeCl_3 as catalyst. Grasses serve as a rich source of carbon and their inherent porous structure also helps in imparting a useful porous morphology to the carbon products. Many methods have been used for the synthesis of porous carbon materials, but a simple, economical method is needed. Use of the inorganic catalyst FeCl_3 reduces the time and temperature; therefore the cost as well, of the synthesis. During pyrolysis metallic particles are produced due to carbothermal reduction of FeCl_3 salts. These particles help in formation of porous nanostructured carbon materials [12]. After removing Fe, the NPC was acid functionalized to introduce active oxygen containing groups on the surface. The acid functionalized nanoporous carbon (Af-NPC) was then studied for use as an adsorbent for removing hexavalent chromium from aqueous media.

2. Experimental

2.1. Synthesis of Af-NPC

Yard-grass-waste clippings were used as carbon precursor for synthesis of NPC due to availability and cost effectiveness. Grass was powdered and dried at 95°C for 6 h. After drying it was soaked in $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ solution in acetone; then air dried at room temperature. The treated mixture was then pyrolyzed under nitrogen gas in a tube furnace. The process was carried out in nitrogen flowing at 30 cc/min. The temperature was maintained at 800°C for 2 h. The obtained carbon products were immersed and sonicated in aqua regia ($\text{HNO}_3:\text{H}_2\text{SO}_4 = 1:3$) for 2 h and kept overnight for functionalization of the carbon surfaces with different functional groups. Treatment with acid also removes catalyst from NPC. After acid treatment and purification, the carbon products were washed several times with double-distilled water to remove acid and dried at 100°C .

Iodine numbers were determined for all products according to the procedure established by the American Society for Testing and Materials (ASTM 2006), to get an idea about the surface area. It is known that the value of the iodine number is close to the surface area of a sample determined by N_2 adsorption [13].

2.2. Structural and physicochemical characterization of NPC

Elemental analysis of the grass was done by EA-3000 Euro Vector, Italy. X-ray diffraction (XRD) patterns were collected on a Rigaku D/MAX 2500 diffractometer (Tokyo, Japan) with Cu K alpha radiation ($\lambda = 1.5418 \text{ \AA}$) using a generator voltage of 40 kV and generator current of 250 mA. The scan speed and step were $5^\circ/\text{min}$ and 0.02° , respectively. In order to find surface area and pore size, N_2 sorption/desorption isotherms were performed at -195.69°C on a Micromeritics ASAP 2020 V3.00 H volumetric adsorption system (Norcross, GA, USA). Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were carried out using a JSM-7600F field emission electron microscope operated at 15 kV. Transmission electron microscopy (TEM) was performed using a Philips CM 200 transmission

electron microscope with acceleration voltage of 200 kV. FTIR (FTIR) was carried out using a FTIR 300E spectrometer (Jasco, Easton, MD, USA).

2.3. Adsorption of Cr(VI) on synthesized NPC

NPC and Af-NPC were tested separately for removal of Cr(VI) in the pH range of 2–12. A solution of 10 ppm Cr(VI) solution was mixed with 0.5 g L^{-1} of NPC and Af-NPC for about 1 h at 150 r/min. The pH of the reaction mixture was adjusted with aqueous solution of 0.1 N HCl and 0.1 N NaOH. All samples were filtered through $0.45\text{-}\mu\text{m}$ syringe filters. The initial and residual concentrations of metal ions were measured by inductively coupled plasma-atomic emission spectrometer (ICP-AES, ARCOS from M/s; Spectro, Kleve, Germany). Af-NPC was found to be a good adsorbent for Cr(VI) removal, as compared to only NPC; hence, further study was carried out using Af-NPC.

To investigate the effect of the initial ion concentration, 20 mL of Cr(VI) at various concentrations (1, 2, 3, 5, 10, 15, 20, and 25 ppm) were mixed with 10 mg of Af-NPC for an adsorption period of 1 h at pH 2.5. These mixtures were kept at room temperature with continuous shaking at 150 r/min. All samples were filtered and analyzed by ICP-AES. In order to study adsorption kinetics, batch adsorption experiments were carried out by mixing 10 mg of Af-NPC with 20 mL of 1, 5, and 10 ppm metal ion solutions. All the samples were stirred at 150 r/min for predetermined time intervals (5, 10, 15, 20, 30, 60, 120 min) at room temperature and pH 2.5. The effect of different ionic concentrations on removal of Cr(VI) was studied in the presence of ions like chloride and sulfate with concentration ranging between 0.02 and 0.1 M while keeping other parameters constant. The adsorption was also studied at different temperatures (30°C , 40°C , and 50°C) with initial Cr(VI) concentration of 20 ppm.

In order to assess the recycling capacity of adsorbent, desorption studies were performed using NaOH. The adsorbent was treated with 5 ppm Cr(VI) solution and later desorbed by NaOH. In the desorption process, the effect of NaOH concentration was studied by mixing 35 mg of used Af-NPC into 10 mL of 0.05 M, 0.1 M, and 0.2 M NaOH separately. The solutions were sonicated and filtered through $0.2 \mu\text{m}$ membrane filter papers. The adsorbents were thoroughly washed with double distilled water several times; then reused for adsorption in succeeding cycles at pH 2.5.

2.4. Data analysis

All the adsorption experiments were performed in triplicate and the average values were reported. The removal efficiency (%) and metal adsorption capacity q_e (mg/g) were calculated using the following equations.

$$\%R = \frac{C_0 - C_e}{C_0} \times 100$$

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

Where C_0 and C_e are the initial and final equilibrium concentrations of metal ions (mg/L) in aqueous solution, V is the total volume of solution (L) and M is the adsorbent mass (g).

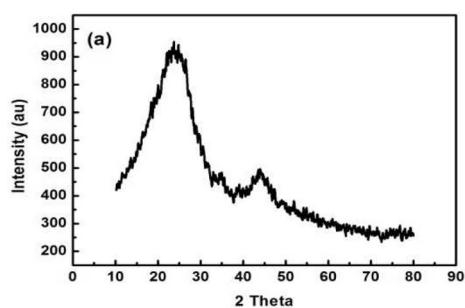
3. Results and Discussion

3.1. Characterization of Af-NPC

The elemental composition of the grass precursor is shown in Table 1. The carbon content of the grass was found to be 40.031% by wt. Fig. 1a shows the XRD pattern of the Af-NPC sample. The broad diffraction peaks indicate that the products were poorly crystallized. Two diffraction peaks at 2θ values of 24.5° and 43° corresponds to (002) and (101)

Table 1. Elemental analysis of grass

Elements	C	H	N	S	O (Estimated by difference)
Content wt%	40.031	9.037	0.921	Nil	45.911



diffractions of graphitic carbon. XRD results suggest the presence of amorphous graphitic carbon in the synthesized carbon products.

Nitrogen adsorption–desorption isotherms of the Af-NPC products are also presented in Fig. 1. The physicochemical parameters such as Brunauer–Emmett–Teller surface area, average pore diameter and pore volume obtained from the isotherm are summarized in Table 2. All these Af-NPC products showed type IV adsorption–desorption isotherm according to the International Union of Pure and Applied

Table 2. Porosity characteristics of Af-NPC

Sample	BET surface area (cm^2/g)	Average pore volume (cm^3/g)	Average pore diameter (nm)
Af-NPC	1013.71	0.697	2.7

Af-NPC, acid functionalized nanoporous carbon; BET, Brunauer–Emmett–Teller.

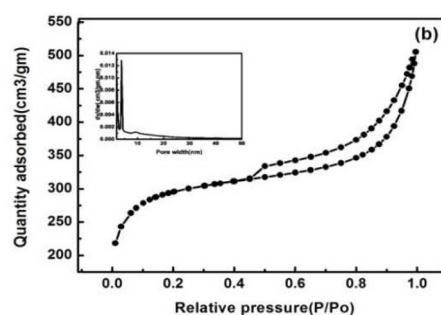


Fig. 1. (a) X-ray diffraction patterns and (b) N_2 adsorption-desorption isotherm and pore size distribution curve in inset of acid functionalized nanoporous carbon.

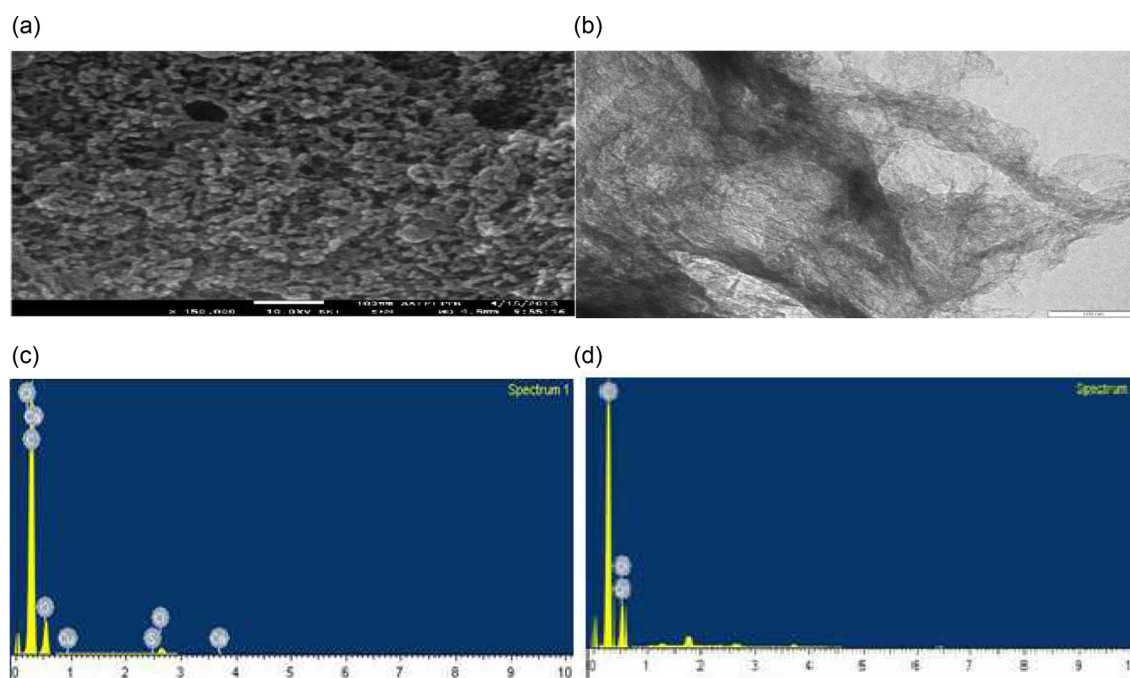


Fig. 2. (a) Scanning electron microscopy and (b) transmission electron microscopy micrographs of acid functionalized nanoporous carbon (Af-NPC) (c, d) energy dispersive spectroscopy of Af-NPC before and after adsorption of Cr(VI), respectively.

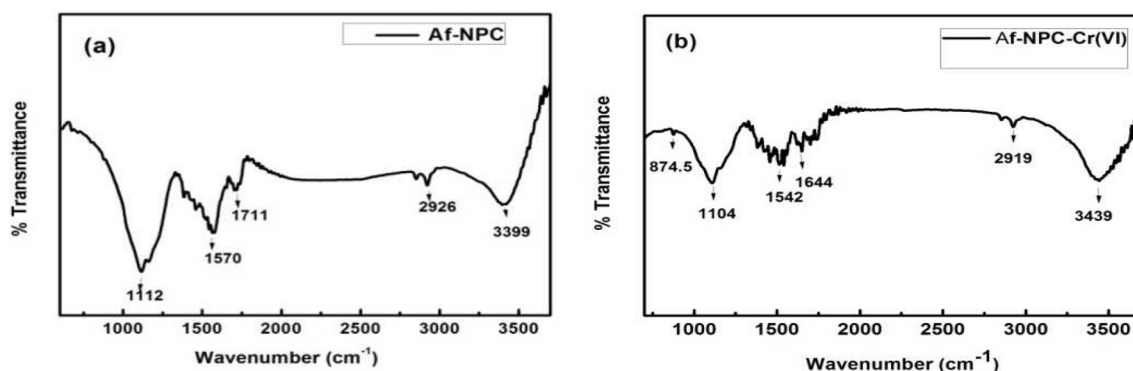


Fig. 3. Fourier transform infrared spectroscopy spectrum of (a) acid functionalized nanoporous carbon (Af-NPC) (before) and (b) Af-NPC-Cr(VI) (after adsorption).

Chemistry (IUPAC) classification [14]. This kind of shape is characteristic of mesoporous material [15]. Af-NPC shows an H3-type hysteresis loop, which shows mesoporous materials with plate-like particles and slit-shaped pores [16]. Hence, grass was found to be a good precursor for synthesis of NPC with high surface area of about 1013.71 cm²/g and average pore diameter of 2.7 nm.

SEM and TEM micrographs, and EDS elemental mapping, of Af-NPC are depicted in Fig. 2. The SEM micrograph of Af-NPC indicates the presence of beaded structures of average size 12 nm on the surface. EDS of Af-NPC indicated the presence of Cr(VI) after adsorption.

FTIR analysis of the carbon products was carried out in order to analyze surface characteristics of Af-NPC and to gain insight into the mechanism of adsorption of Cr(VI). FTIR spectra of Af-NPC (Fig. 3) shows shifts in vibrational frequencies of different oxygen-containing functional groups after adsorption of Cr(VI). A broad peak corresponding to OH stretching shifted from 3399 to 3439 cm⁻¹, which could be assigned to a phenolic group. This indicates interaction of OH groups with HCrO₄⁻. The peak at 1711 cm⁻¹ is attributed to -C=O stretching vibrations of carboxyl groups, which has shifted to 1644 cm⁻¹. There is a slight decrease in the frequency of a peak from 1112 to 1104 cm⁻¹, corresponding to -C-O stretching vibrations. The peak at 1570 cm⁻¹ in Af-NPC corresponds to the C=C stretching vibration of the graphitic carbon skeleton, which shifted to 1542 cm⁻¹. The vibrational mode appearing at 874 cm⁻¹ is due to the Cr-O bond of hexavalent chromium after adsorption [17]. The peak due to aliphatic C-H str. has shifted slightly from 2926 to 2919 cm⁻¹, which might be due to changes in the proximal electronic atmosphere after adsorption of Cr(VI).

3.2. Mechanism of adsorption of Cr(VI)

No major shifts were seen in the FTIR spectra after adsorption of Cr(VI), suggesting that the bonding of Cr(VI) is weak on the surface of Af-NPC. Moreover, greater adsorption of Cr(VI) was found in acidic medium. Because HCrO₄⁻ is the major species of Cr(VI) between pH 2 and 6.5, the probable mechanism of adsorption would be first attachment of H⁺ ions on oxygen containing active groups (-C=O, -O-H) of carbon surface through hydrogen bonding (protonation) fol-

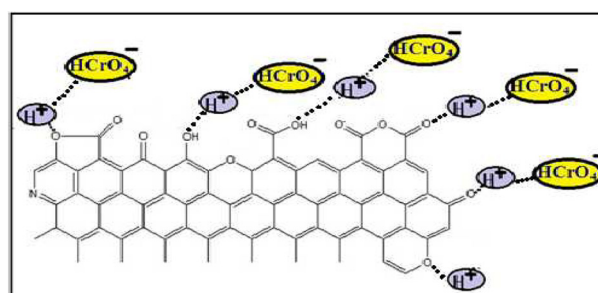


Fig. 4. Schematic representations of possible mechanisms for adsorption of Cr(VI) by acid functionalized nanoporous carbon.

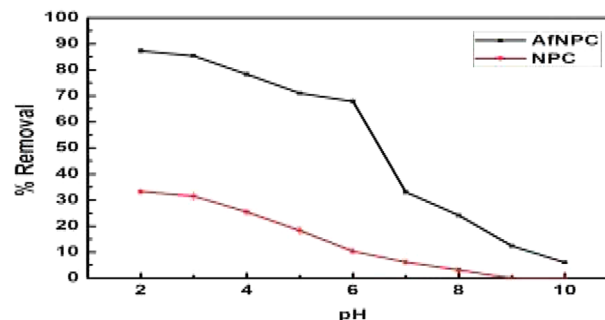


Fig. 5. Percent removal efficiency of NPC and acid functionalized nanoporous carbon (Af-NPC) for Cr(VI) at different pH.

lowed by adsorption of HCrO₄⁻ ions by electrostatic force of attraction on adsorbed H⁺ ions forming an electrical double layer. Hence, we can conclude from the findings of FTIR that the electrostatic forces of attraction dictate the mechanism of adsorption. Fig. 4 depicts the probable mechanism of adsorption of Cr(VI).

3.3. Adsorption studies of Cr(VI)

3.3.1. Adsorption of arsenic on NPC and Af-NPC at various Ph

The percentage removal efficiency of Cr(VI) by Af-NPC was greater than only NPC (Fig. 5). Percentage removal of Cr(VI) was 87% for Af-NPC and 33% for NPC, with an initial con-

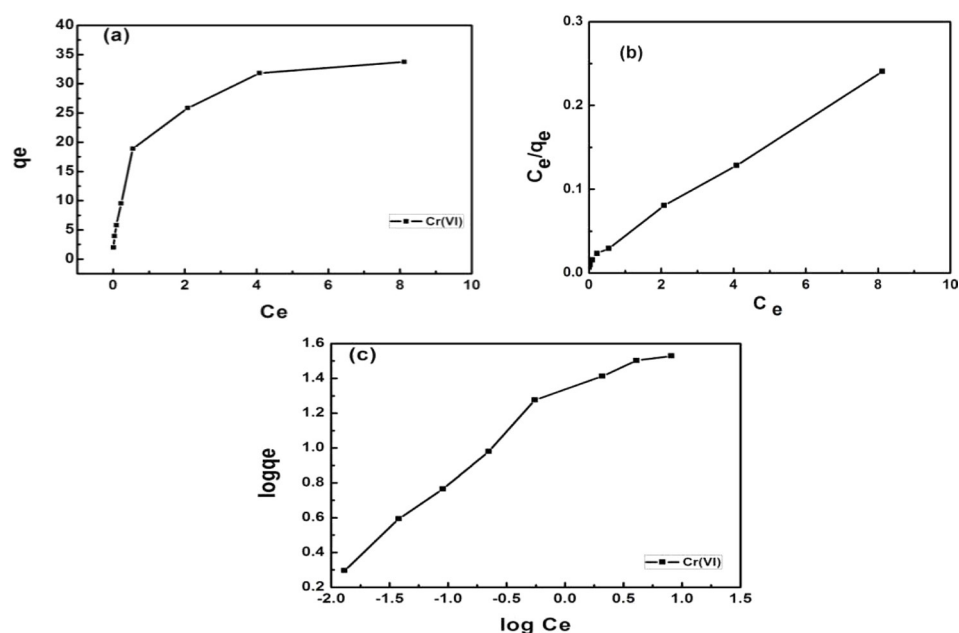


Fig. 6. (a) Adsorption isotherm of Cr(VI), (b) Langmuir, and (c) Freundlich isotherm of Cr(VI) on the surface of acid functionalized nanoporous carbon (initial concentration 1–25 ppm).

Table 3. Adsorption isotherm parameters for Cr(VI) on Af-NPC

Langmuir			Freundlich			
q_m (mg g ⁻¹)	K_L (L/mg)	R^2	R_L	K_F (mg g ⁻¹)	n	R^2
35.335	2.1939	0.9965	0.00113	1.237	2.211	0.966

Af-NPC, acid functionalized nanoporous carbon.

centration of 10 ppm. Acid functionalization increased adsorption of Cr(VI) due to formation of active sites in terms of different oxygen containing functional groups on the surface of Af-NPC. Removal of hexavalent Cr(VI) decreased as the pH increased and the maximum removal was observed at pH <4. At pH <6.5 more H⁺ ions were present on the surface of adsorbent and Cr(VI) existed as oxyanion (HCrO₄⁻); hence, the percentage removal of Cr(VI) was more due to electrostatic forces of attraction. For pH >6.5 chromium existed as CrO₄²⁻ but at the same time OH⁻ ions also increased in solution. The affinity of OH⁻ with carbon is better than CrO₄²⁻, hence the adsorption of Cr(VI) declined due to competition with OH⁻ ions for adsorption sites in alkaline medium.

3.3.2. Effect of initial Cr(VI) concentration and adsorption isotherms

Adsorption isotherms provide information about adsorption capacity and interaction of adsorbate molecules with adsorbent. It also helps in designing a proper adsorption system. In the present study, Langmuir and Freundlich models were tested for adsorption. Langmuir isotherms are applicable to homogeneous surfaces, which have equal adsorption affinity sites; while the Freundlich model assumes heterogeneous adsorption sites. The linear form of Langmuir isotherms is described by eq 1 [18].

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

where K_L and q_m are the Langmuir adsorption constant and maximum monolayer adsorption capacity (mg/g), respectively. K_L represents affinity between solute and adsorbent. The other parameters are the same as mentioned before.

The linearized form of the Freundlich isotherm is given by eq 2 [19].

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (2)$$

where the Freundlich constants K_F and n are measures of adsorption capacity and adsorption intensity, respectively. The bond energy increases proportionally with surface density because n is >1. Fig. 6 shows isotherm plots and Table 3 gives different parameters calculated from the two isotherms.

A high correlation factor (0.996) indicates that the Langmuir adsorption isotherm fits the data well, which is attributed to monolayer adsorption of Cr(VI). The maximum adsorption capacity by the Langmuir model was found to be 35.335 mg/g. The Freundlich constant n was >2 (i.e., 2.211), which indicates that adsorption of hexavalent chromium is a favorable process on the surface of Af-NPC. The separation factor R_L was 0.00113, which also confirms that adsorption

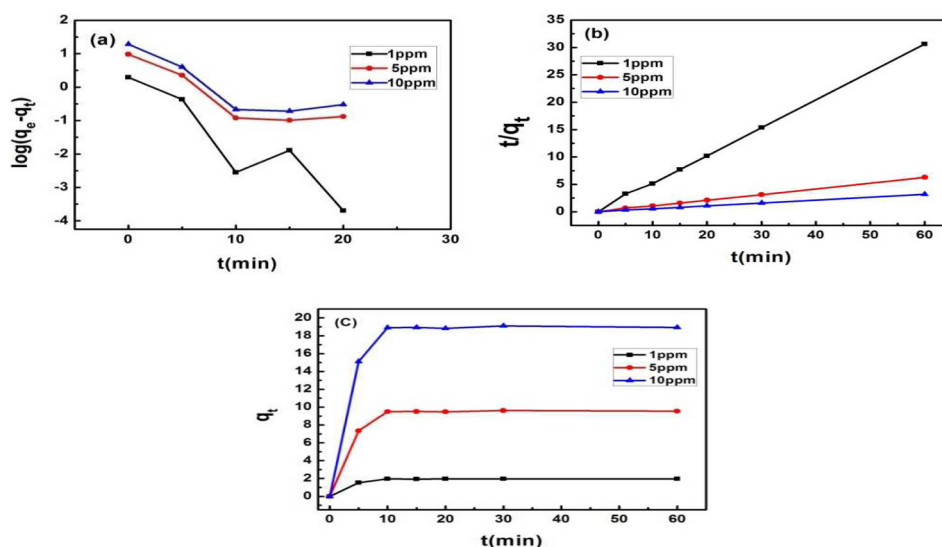


Fig. 7. (a) Pseudo first order kinetics model and (b) Pseudo-second-order kinetics model of Cr(VI) adsorption on acid functionalized nanoporous carbon (Af-NPC), (c) time profile of Cr(VI) adsorption on Af-NPC for different metal ion concentrations.

Table 4. Pseudo first and second order rate parameters of Cr(VI) adsorption on Af-NPC

C ₀ (mg/L)	Pseudo-first-order rate parameters			Pseudo-second-order rate parameters			
	q _e (mg/g)	K ₁ (min ⁻¹)	R ²	q _e (mg/g)	K ₂ (g/mg min)	H (mg/g min)	R ²
1 ppm	0.4452	2.22 × 10 ⁻¹	0.506	1.977	1.256	4.911	0.9994
5 ppm	0.0568	6.31 × 10 ⁻²	0.4385	9.65	0.2369	22.07	0.9993
10 ppm	0.302	5.36 × 10 ⁻²	0.346	19.08	0.155	56.497	0.9995

Af-NPC, acid functionalized nanoporous carbon.

Table 5. Comparison of adsorption capacity of acid functionalized nanoporous carbon with other adsorbents for Cr(VI) removal

Adsorbents	q _m (mg/g)	Optimum pH	Equilibrium time (min)	Reference
Feroxyhyte-coated maghemite NPs	25.8	2.5	-	[21]
AC/CNT	9	2	60	[22]
Mixed magnetite and maghemite	2.4	2	60	[23]
Fertilizer industry waste	15.24	2.5	70	[24]
Oxidized multi-walled carbon nanotubes	3.044	2.88	In hours	[25]
Polymeric Fe/Zr pillared montmorillonite	22.35	3	120	[26]
Acid functionalized nanoporous carbon	35.335	2.5	10	This work

NPs, nanoparticles; AC/CNT, carbon nanotubes coated on activated carbon.

was favorable and that Af-NPC is a good adsorbent. At lower initial concentration (<1 ppm) no residual Cr(VI) was detected. The Af-NPC could be an efficient adsorbent for removal of hexavalent chromium due to its good affinity, low cost, and high adsorption capacity.

3.3.3. Sorption kinetic studies

Sorption kinetic studies were conducted with Af-NPC in batch

mode. Fig. 7 depicts the kinetics of Cr(VI) onto Af-NPC at various time intervals. Analysis of sorption kinetics was carried out by Lagergren pseudo first-order model and Ho's pseudo-second-order reaction rate model [20]. Mathematical representations of these models are given in eqs 3 and 4, respectively.

Lagergren pseudo-first-order equation:

$$\frac{dq_t}{dt} = k_1(q_e - q_t) \quad (3)$$

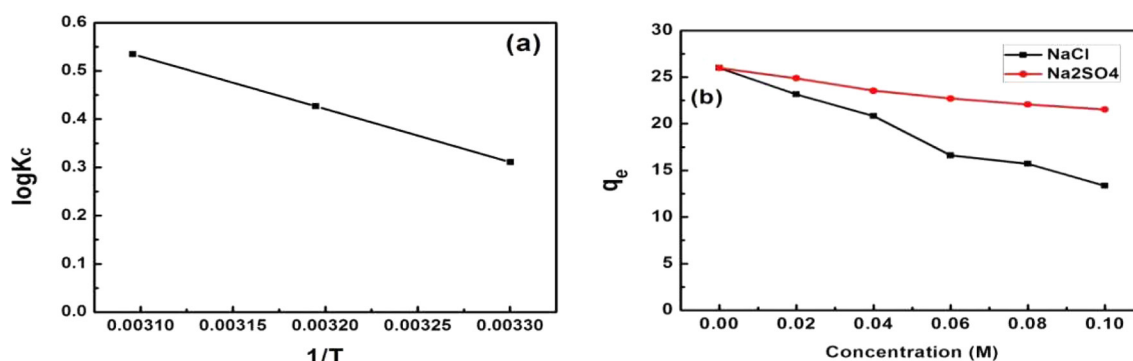


Fig. 8. (a) Effect of temperature on adsorption of Cr(VI) ($C_0 = 25$ ppm), (b) effect of interfering ions on adsorption ($C_0 = 15$ ppm).

Ho's pseudo-second-order equation:

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \quad (4)$$

where q_t is amount of adsorbate sorbed on the surface at any time t , k_1 is the first order rate constant of sorption (min^{-1}), k_2 is the second-order rate constant of sorption ($\text{g mg}^{-1} \text{min}^{-1}$), and t is the time (min). Pseudo second and first order rate parameters are summarized in Table 4.

The adsorption of Cr(VI) on Af-NPC follows second order kinetics because the correlation coefficient is higher than first order kinetics and the adsorption equilibrium was reached within 10 min. Within the initial 5 min, 75% of the Cr(VI) was removed. The faster removal rate of Cr(VI) by Af-NPC might be attributed to the high surface area of Af-NPC because this provides more active sites for adsorption, and to the presence of mesoporosity, which increases the rate of diffusion of Cr(V) ions inside the pores. Table 5 shows the comparison of Af-NPC with the other adsorbents from the literature, with respect to equilibrium time and adsorption capacity. Af-NPC has better adsorption capacity and faster removal rate than the other adsorbents mentioned.

3.3.4. Effect of temperature

The effect of temperature on the adsorption capacity of Af-NPC for Cr(VI) was studied by varying the temperature while keeping other parameters fixed. Thermodynamic adsorption parameters such as change in enthalpy (ΔH^0) and entropy (ΔS^0) were calculated from the Van't Hoff equation (eq 5).

$$\ln Kc = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \quad (5)$$

$$\Delta G = \Delta H - T\Delta S \quad (6)$$

Table 6. Thermodynamic parameters for adsorption of Cr(VI) on acid functionalized nanoporous carbon

Temperature (K)	ΔG^0 (kJ/mol)	ΔH^0 (kJ/mol)	ΔS^0 (kJ/mol·K)
303	-0.586		
313	-0.906	9.11	0.0326
323	-1.226		

where Kc is the equilibrium constant. Here, ΔH^0 and ΔS^0 were obtained from the slope and intercept of the Arrhenius plot of $\log Kc$ versus $1/T$ (Fig. 8a), and the ΔG^0 values (kJ/mol) were calculated from eq 6. Table 6 shows the calculated values of the thermodynamic parameters for the adsorption of Cr(VI) on Af-NPC.

The positive value of the change in enthalpy confirms that the adsorption process is endothermic. The positive entropy of the adsorption process indicates that Af-NPC has affinity towards Cr(VI) and that the negative free energy values indicate that the process is spontaneous in nature. The value of ΔG^0 decreases with temperature, which implies that the reaction is promoted by higher temperature.

3.3.5. Effect of interfering ions

Normally, industrial and ground waters contain a variety of salts, the concentration of which might affect removal of Cr(VI). Fig. 8b shows the effect of salt concentration on removal of Cr(VI). As the salt concentration increases from 0 to 0.1 M, the adsorption capacity of Af-NPC declines from 26 to 13.36 mg/g in the presence of NaCl, and 21.54 mg/g in the presence of Na₂SO₄, with initial concentration of 15 ppm. The presence of Cl⁻ and SO₄²⁻ ions decreases the adsorption capacity of Af-NPC for Cr(VI) due to competition between HCrO₄⁻ and other negatively charged ions (Cl⁻ and SO₄²⁻) for active sites. Cl⁻ ions reduce the adsorption capacity of Af-NPC more than sulfate ions do. This could be due to greater affinity and diffusion of Cl⁻ ions on Af-NPC, than HCrO₄⁻.

3.3.6. Sorbent regeneration

Regeneration of an adsorbent is an important aspect of reducing the overall cost of the process. NaOH was used to desorb Cr(VI) from Af-NPC. To test the reusability of the regenerated adsorbent, the same sorbent was subjected to three consecutive cycles of adsorption-desorption. By increasing the strength of NaOH from 0.05 to 0.2 M it was possible to concentrate Cr(VI) up to 30 ppm in a small volume of eluent. Desorption was achieved in 10 min. The ratio of volume of initially treated solution to the volume of NaOH solution used for desorption was '7.' The results of these studies showed that Af-NPC has good re-use potential. The adsorption capacity declines only by 3% up to the third cycle of adsorption (Fig. 9). From these results, it seems that Af-NPC could continue to be used as an effective

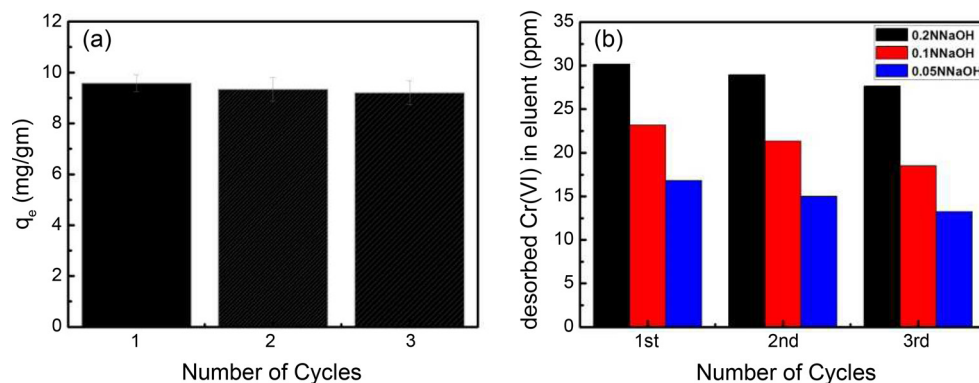


Fig. 9. (a) Removal efficiency of acid functionalized nanoporous carbon for hexavalent Cr(VI) during three different adsorption cycles, (b) effect of NaOH concentration on desorption of Cr(VI).

alternative sorbent for Cr(VI) removal after regeneration with NaOH.

4. Conclusions

Acid functionalization increased the removal efficiency of Cr(VI) by NPC. The Langmuir adsorption model results fit well the adsorption data with maximum adsorption capacity of 35.335 mg/gm. The adsorption equilibrium was reached in 10 min. The large surface area and mesoporous nature of Af-NPC contribute to fast removal of Cr(VI) from aqueous media. The main forces of interaction of Cr(VI) with Af-NPC seem to be electrostatic. The high adsorption capacity and fast adsorption and desorption rates prove that the synthesized Af-NPC has the potential to be used as a cost effective, eco-friendly adsorbent for removal of hexavalent chromium from aqueous media.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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