Assessment of Adsorption Capacity of Thiol-functionalized Titanate Nanotubes for Removal of Cu(II) and Ni(II) from Aqueous Solution via Static Adsorption

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PAPER INFO

A B S T R A C T

The significance of toxic metals pollution treatment has become incrementally manifested as an important environmental issues in the recent years due to the urgent need to access healthy water and increase of the anthropogenic activities in water contamination. For efficient treatment of water contaminants, the selective and novel materials are always welcomed. In this study, the hydrothermally synthesized titanate nanotubes (TNT) were modified by the mercaptosilane modifier for the removal of Cu(II) and Ni(II) toxic contaminants. The modified TNT adsorbent (TNT/Sil) was characterized in terms of the physicochemical aspects and then, the experiments for capturing metal cations were performed in batch mode. The modified adsorbent presented more affinity for the removal of Cu(II) than Ni(II). The results demonstrated that the experimental data were highly fitted to the Freundlich isotherm model and the maximum uptake capacities for Cu(II) and Ni(II) were found to be 53.77 and 45.29 mg g^{-1}, respectively. In addition, endothermic nature of the adsorption process was predicted by the thermodynamic study as well as the pseudo-second order model that was corresponded to the kinetic data. Considering these achievements and due to the surface hydroxyl and thiol functional groups, TNT/Sil adsorbent could be effective and promising material in the purification of wastewaters, contaminated with toxic metal cations.

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NOMENCLATURE

ΔG^o	Gibbs free energy change (kJ/mol)	K_C	Thermodynamic equilibrium constant (L/g)
ΔH^o	Standard enthalpy change (kJ/mol)	q_e	Adsorption capacity at equilibrium point (mg/g)
ΔS^o	Standard entropy change (J/mol K)	q_t	Adsorption capacity at time t (mg/g)
C_e	Equilibrium concentration (mg/L)	NPs	Nanoparticles
C_0	Initial metal ion concentration (mg/L)	k_1	Pseudo-first order model rate constants (min^{-1})
k_F	Freundlich constant	TNT	Titanate nanotubes
k_L	Langmuir parameter (L mg^{-1})	TNT/Sil	Thiol-functionalized titanate nanotubes

INTRODUCTION

In the last few decades, a leaping rise in the industrialization and urbanization of worldwide coupled with the population growth have led to increased discharge of wastewater to the water streams without adequate treatment. Because of daily and enormous application of the heavy metals (e.g. Cu(II), Ni(II), Pb(II), Zn(II), Cd(II), Hg(II) and etc.) in the industrial processes, threat of heavy metal ions in the industrial effluents is a consistent concern of the environmental activists. Heavy metals are highly toxic and possess carcinogenic effects even at trace levels, they resist to the biodegradation and have propensity to accumulate in the tissue of living

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organisms. These toxic metals disrupt physiological activities of human bodies in case of entering their food chain and followed serious vital problems [1].

According to the scientific reports, water scarcity will be a major challenge toward 2025 due to the limited available healthy water resources [2]. Significant anthropogenic sources such as electroplating, specialist alloys and steels, mining, batteries, etc. generate contineously copper and nickel containing effluents [3]. Wilson's disease, acute hemolytic anemia, chronic renal disease, liver damage, etc. are some health risks which caused by Cu(II) and Ni(II) intake through the contaminated water and food. As the resources become limited more and more, treatment of these wastewaters is essential to protect the human and eco-system because of the daily utilization of these toxic metals in the industries [4, 5]. As reported by World Health Organization (WHO), the allowable limit for Cu(II) and Ni(II) contaminants in the potable water is 1.5 mg/L and less than 0.1 mg/L and in the industrial effluents is 0.05-1.5 mg/L and 2 mg/L, respectively [6]. In this matter, the removal and recovery of toxic metal ions from industrial effluents is essential; therefore various conventional and modern methods, including adsorption, precipitation, coagulation-flocculation, ion exchange, membrane filtration, electrochemical, etc. were implemented. However, all of these techniques own their remarkable excellence and drawbacks. High energy consumption, imperfect treatment, producing extra toxic wastes, low selectivity and high oparting costs and low efficiency are the challenges which constraine their applicability [4]. Undoubtedly, there is a crucial need to search more cost-effective and efficient techniques to deal with the heavy metals health hazards.

Practically, a combination of the treatment methods should be applied to acquire the desired water quality owing to the complex nature of the metallic effluents. To date, adsorption is recognized as an alternative treatment method due to the high removal efficiency, flexibility in operation, convenient recovery of the adsorbent, low costs, suitable selectivity by particular functional groups, no need to the chemical reagents and producion of high quality treated wastewater.

So far, a variety of inorganic and organic adsorbents such as carbonaceous nanomaterials, nanostructured mixed oxides or metal oxides, bioadsorbents, composite materials and polymeric sorbents have been proposed for the removal of metal impurities [4]. Nanosize metal oxides such as manganese oxides (MnO_2), silicon dioxide (SiO_2), zinc oxide (ZnO), iron oxide (Fe_3O_4), titanium oxide (TiO_2), aluminum oxide (Al_2O_3), etc. can provide high surface area and specific affinity toward the target compounds because of their different nanostructures and due to their low environmental effects and sludge production, many researches have been performed to develop adsorbents based on these materials [7]. Titanate nanostructures (e.g. nanotubes, nanosheets, nanowires,

nanorods) are such hopeful metal oxide materials which have attracted tremendous attentions in the wastewater treatment; thanks to their high specific surface area, surface rich in -OH groups, ion-exchange capability, favorable structural stability and excellent physicochemical properties [8, 9]. Many research works were devoted to the potential of the titanate nanostructures as the promising candidate for the removal of Ni(II), Cd(II), Zn(II), Pb(II), Cr(III), Hg(II) and Cu(II). These studies have focused on the adsorption behavior of titanate adsorbents and found that they present excellent removal efficiency to the metal cations [9-13].

On then other hand, the metal oxide adsorbents have high tendency to aggregation which declined their adsorption capacity. Surface modification of the adsorbents with the specific coupling agents or ligands is one method to overcome this problem. Moreover, surface functionalization can improve the adsorbents selectivity toward special metal ions. Various organic or inorganic functional groups can be grafted to the surface of the metal oxides which can be categorized into different groups such as silanes, carboxylic acids, organophosphorus and polymer/copolymers [14]. Dobrzyńska et al. [15] modified mesoporous silica with the mercapto and amino silane agents and used them for the removal of Pd(II). They found that compared to the amino silane agent, the thiol-modified silica showed great uptake and affinity to the Pd(II) in the investigated range of initial concentration and pH [15]. Zhu et al. [16] investigated four types of silane coupling agents for the surface functionalization of halloysite nanotubes/Fe_3O_4 adsorbent and applied them for the removal of Sb(V) and Cr(VI). Achieved results indicated that the modified adsorbent had higher adsorption capacity in the both single and multicomponent solutions of the toxic metal ions [16]. In another researches, ligand based functional adsorbents were synthesized for the detection and removal of Ni(II), Pb(II) and Cu(II) from wastewater; which these adsorbents containing 'S', 'O' and 'N' donor atoms to form a stable complex with the metal cations and capture them [17-19].

This study was aimed to prepare the metal oxide nanostructure modified with organosilane agent for the removal of metal ions from wastewater. The titanate nanotubes (TNTs) were synthesized hydrothermally and successfully modified with mercaptosilane agent. To the best of our knowledge, there are limited researches about the surface modification of TNTs; particularly the thiol-functionalization of their surface is not studied yet, niether in the environmental fields nor in others. This novel adsorbent was characterized by FTIR, SEM, EDS, XRD and TEM. A range of static adsorption experiments were carried out to evaluate the adsorption abilities of the mercapto-functionalized TNTs to Cu(II) and Ni(II) in the solutions. The modified TNTs have slightly more affinity to copper ions over nickel.

MATERIAL AND METHODS

NiCl$_2$.6H$_2$O and CuSO$_4$.5H$_2$O (from Aldrich) were used to prepare Ni(II) and Cu(II) stock solutions (1000 mg/L). To perform the batch adsorption experiments, working solutions were prepared by diluting the stock solutions. TiO$_2$ nanopowder (mixed of anatase and rutile crystalline phase, Evonik, Germany) and sodium hydroxide (NaOH 98 wt%, Merck) pellets were employed for the hydrothermally synthesis of TNTs. (3-mercaptopropyl) trimethoxysilane (MPTMS, HS(CH$_2$)$_3$Si(OCH$_3$)$_3$, 95 wt%, Sigma-Aldrich) was utilized as the coupling agent for the surface modification of TNTs. Deionized water (DI) was used for the preparation of all aqueous solutions. Acetone was supplied from Merck and used as the solvent.

Synthesis of titanate nanotubes
TNTs were prepared using the alkaline hydrothermal method according to the procedure of Kasuga et al. [20]. As a brief description of the synthesis method, 1 g TiO$_2$ nanopowder was added to the Teflon container with 50 ml of 10M NaOH solution and then, stirring and sonicating around 2 hours; this milky suspension was transferred to the autoclave and heated at 160 °C for 72 hours. After the hydrothermal reaction, the resulted alkaline precipitates were filtered, washed several times with DI water until the pH value of the rinsing water reached near neutral and then, were dried at 80 °C for 12 h. The as-synthesized TNTs were milled, then sieved and kept in the desiccator until usage. Durng the hydrothermal reaction, some of the Ti-O-Ti bonds of TiO$_2$ powder are broken and the compounds (i.e. [Ti(OH)$_6$]$_2$) are formed and these compounds combined together to produce a nanosheet or layered structures. Finally, the nanosheets with some Na$^+$ and H$^+$ between their layers rolled into a cylindrical shape [21].

Surface modification of TNTs
Surface modification of TNTs was performed as follows: in two separate containers, 0.2 g as-prepared TNTs in 20 mL acetone in the first one and in the second container, mercaptosilane modifier (TNT/MPTMS = 3% w/w) in 20 mL DI water were stirred. TNTs mixture was added dropwise to the modifier solution and mixed around 2 h at ambient conditions. The obtained sample was centrifuged, filtered and washed firstly with acetone and then, thoroughly rinsed with DI water to remove excessive unattached silane agent and other impurities. Afterward, the modified sample with thiol groups was dried at 60 °C for 24 h and labeled as TNT/Sil adsorbent. In the functionalization process, some of silanol groups were hydrolyzed and then condensed. Finally, these groups interacted with the surface hydroxyl groups of TNT and attached to them. A schematic of thiol functional groups grafted on the hydroxyl groups of TNTs' surface is presented in Figure 1.
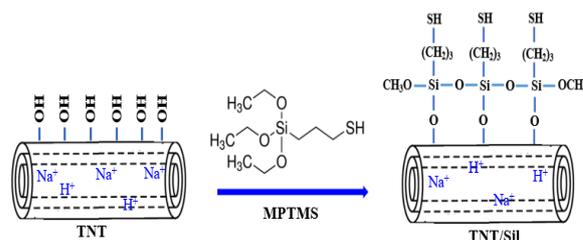

Figure 1. Schematic for the surface modification of TNT

Instruments and analyses
The determination of metal cations concentration was executed by ICP-OES (Agilent 124 Technologies 5110) measurement. Transmission Electron Microscopy (TEM) image was obtained by Hitachi 7700 and Field Emission Scanning Electron Microscopy (FESEM) (Hitachi S-4800) supplied with energy-dispersive X-ray spectroscopy (EDS) were applied to study the morphology and elemental analysis of the as-synthesized adsorbents. For determination of NPs functional groups, the FT-IR spectra of the samples was obtained using the Vertex 70 by Bruker Optics (Germany). The crystalline pattern of the TNT/Sil adsorbent were studied by X-ray diffractometer (XRD, X' Pert PRO).

Static adsorption assay
The metal ions static adsorption was studied in batch mode. All the adsorption equilibrium tests at isothermal conditions and the kinetics studies were attained for 100 mL aliquot of the metal salts working solutions by mixing them with 0.125 g of the as-synthesized adsorbent in a flask on a shaker at 170 rpm for predetermined time periods. Syringe filter of cellulose acetate membrane was utilized for filtration of the solutions in all samplings. Subsequently, the concentration of the samples was analyzed by ICP-OES. Experiments on the adsorption isotherms were carried out at various temperatures in the range of 25-45 °C and with the initial metal cation concentrations in the range of 20-150 mg/L. Moreover, to avoid the precipitation of the ions, the pH of the copper and nickel solutions were adjusted around 5 and 6.5, respectively. The adsorption kinetic tests were lasted for 75 min and the samples were withdrawn at the determined time intervals. The achieved experimental data in batch mode were used to calculate the amount of adsorbed metal ions (q$_e$) according to the Equation (1):

$$\text{Uptake capacity,} \quad q_e = \frac{C_0 - C_e}{m} V \qquad (1)$$

where, q_e (mg g^{-1}) is the amount of adsorbed Cu(II) and Ni(II) per unit mass of TNT/Sil at the equilibrium, m (g) is the weight of TNT/Sil; V (L) is the volume of metal ion solution sample; C_0 and C_e are the initial and equilibrium copper and nickel concentration (mg L^{-1}), respectively.

RESULTS AND DISCUSSION

From the XRD pattern that is depicted in Figure 2, the peaks at $2\theta = 10°, 25°, 30°, 34°, 36°, 40°, 48°, 53°$ and $61°$ are attributed to the crystalline phase of the sodium titanate compounds that is consistent with the reported values in literature [22]. As can be observed from the crystal structure, a series of six-coordinate monomers (TiO_6 octahedra) were connected to form a layered structure where Na^+ and H^+ are situated between the layers [21].

The FT-IR spectra of TNT/Sil adsorbent is presenetd in Figure 3 as well as MPTMS spectra as the reference to validate the weak peak of thiol group [23, 24]. The wavenumbers of the characteristic peaks of the related functional groups were summarized in Table 1. As thiol group's peak was naturally weak, this peak was not observed in TNT/Sil NPs spectra but the existence of Si-O-Ti and CH_2 groups confirmed the successful modification of the TNT sample [25, 26].

According to the morphological characterization test results as are illustrated in Figures 4(a, b), the hydrothermal and severe alkaline conditions changed the form of TiO_2 precursor to tubular/rod structure. This tubular structure of TNT/Sil with uniform diameter along

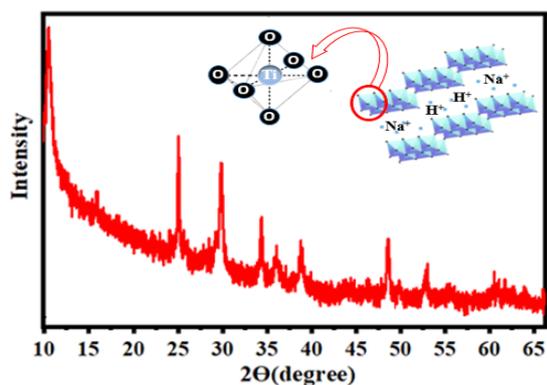the length provide high surface area for uptake of the metal contaminants. The EDS analysis was carried out to certify the presence of S, C, Si, Ti, O and Na as major elements of TNT/Sil adsorbent [21, 27].

Uptake of copper and nickel ions on TNT/Sil adsorbent
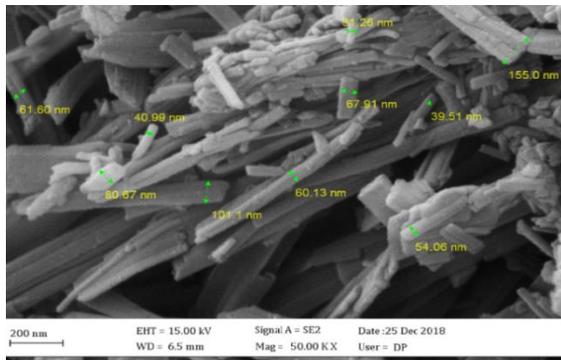
Isotherm study
Adsorption isotherms provides data about the distribution of metal ions at adsorbent/adsorbate system at equilibrium point and the calculation of uptake capacity. Figures 5(a) and 5(b) represent nonlinear Freundlich and Langmuir adsorption isotherm models which were fitted to the experimental data of Cu(II) and Ni(II) uptake on TNT/Sil at different temperatures (298-318 K). Moreover, the Langmuir model describes monolayer adsorption on homogeneous surface of adsorbent while the Freundlich model is based on multi-layer adsorption on heterogeneous adsorbent and in spite of the Langmuir model, the energy level of the adsorption spots is not identical [28, 29]. The applied isotherm models' parameters are summarized in Table 2. The correlation coefficient (R^2) suggested that the experimental data of the metal ions uptake can be properly fitted by the Freundlich model ($R^2 > 0.99$). According to Table 2, the values of R_L for both metal ions at all operating temperatures lie at $0<R_L<1$ which indicates favorable adsorption of metal ions on TNT/Sil. Furthermore, according to the Freundlich model the values of $n>1$ confirm favorable adsorption of studied metal ions. The maximum adsorption capacities of TNT/Sil for copper ions at T = 298, 308 and 318 K were 53.77, 54.02 and 56.34 mg g^{-1}, respectively which were more than the values for Ni(II) at the same conditions. The oxygen and

Figure 2. XRD pattern of the functionalized TNT

Figure 3. FTIR spectra of TNT/Sil NPs and MPTMS modifier

Table 1. FT-IR absorption peaks of MPTMS modifier and TNT/Sil adsorbent

Sample	Description of vibration	Wavenumber (Cm^{-1})
TNT/Sil	-OH stretching vibration of silanol group	3440-3740
	-OH stretching vibration of water molecule	1640-1690
	aliphatic C-H stretching vibration	2852-2922
	Si-O-Ti and Si-O-Si stretching vibration	900-1100
MPTMS	Thiol group	2564
	stretching vibration of C-H	2839-2940
	bending vibration of CH_2	1455
	stretching vibration of Si-O-Si and Si-O	800-1075

Table 2. Isotherm parameters for copper and nickel uptake on TNT/Sil adsorbent

Isotherm model	Metal ion	Isotherm parameters	Temperature (K)		
			298	308	318
Langmuir [29]: $q_e = \dfrac{q_{max}\,k_L\,C_e}{1+k_L\,C_e}$ q_{max}: the maximum uptake capacity $(mg\,g^{-1})$ k_L: energy of uptake $(L\,mg^{-1})$ $R_L = \dfrac{1}{1+k_L\,C_0}$ C_0: the initial concentration $(mg\,L^{-1})$ R_L: separation factor	Cu(II)	q_{max}	53.77	54.02	56.34
		k_L	0.22	0.38	0.57
		R_L	0.029	0.017	0.011
		R^2	0.85	0.86	0.87
	Ni(II)	q_{max}	45.29	46.17	44.29
		k_L	0.09	0.11	0.24
		R_L	0.06	0.05	0.02
		R^2	0.99	0.98	0.97
Freundlich [28]: $q_e = k_F\,C_e^{\frac{1}{n}}$ k_F: Freundlich adsorption capacity $(L\,g^{-1})$ n: intensity of the adsorption	Cu(II)	K_F	29.07	30.67	35.53
		n	7.65	7.65	9.18
		R^2	0.99	0.99	0.99
	Ni(II)	K_F	9.45	10.89	13.76
		n	2.97	3.14	3.65
		R^2	0.99	0.99	0.99

(a)

(b)

Figure 4. FE-SEM micrograph of the as-prepared TNT/Sil (a) TEM image of TNT/Sil with the embedded EDS spectrum in it

sulphur atoms in hydroxyl and thiol functional groups on the surface of TNT/Sil NPs are considered electron donor atoms and target metal cations are electron acceptor species which possess high selectivity to interact with these groups.
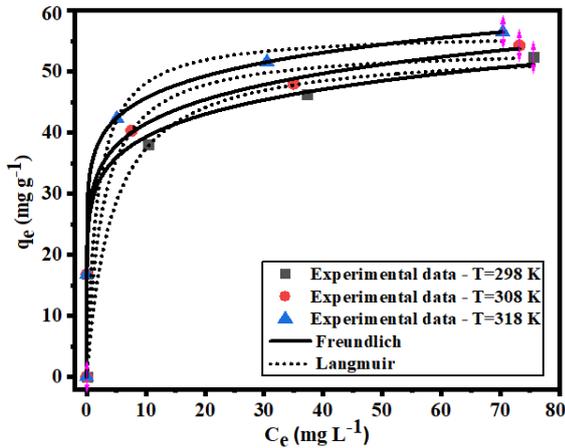
Kinetic study

The kinetic study assists to determine the rate limiting step of the adsorption process. The slow steps of adsorption process which involve film diffusion, pore diffusion and intraparticle diffusion are determinative for the prediction of predominant adsorption mechanism. Two conventional non-linear kinetic models including pseudo-first order and pseudo-second-order were applied to kinetic data which are expressed in Equations (2) and (3):

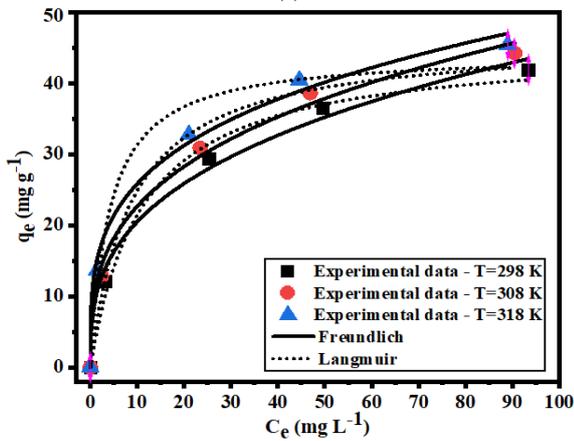Pseudo-first order [30]: $\quad q_t = q_e\,(1 - e^{-k_1 t})$ (2)

Pseudo-second-order [31]: $\quad q_t = \dfrac{t\,q_e^2\,k_2}{1+t\,q_e\,k_2}$ (3)

where q_t and q_e $(mg\,g^{-1})$ refer to the uptake capacities at time t and at equilibrium point, k_1 (min^{-1}) and k_2 $(g\,mg^{-1}\,min^{-1})$ are the constants for first and second order kinetic models, respectively.

As is depicted in Figure 6, the kinetic data were fitted with these models at different metal ions concentrations (20-150 mg L-1) and at T = 298 K. The TNT/Sil NPs become saturated by both metal cations after 15 min of
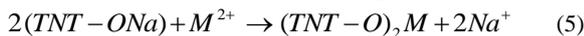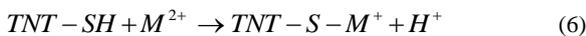
Figure 5. Adsorption isotherms of copper (a) and nickel (b) on TNT/Sil adsorbent at various temperatures

Figure 6. Adsorption kinetics of Cu(II) (a) and Ni(II) (b) on TNT/Sil adsorbent

beginning the adsorption process (see Figure 6). According to R^2 values, the experimental data of both metal cations were fitted well to pseudo second order model and the predicted uptake capacities of this model are closer to the experimental kinetic data (see Table 3). It is predicted that the adsorption of metal cations on TNT/Sil NPs can be related to the ion-exchange with H$^+$/Na$^+$ cations situated between the layers of TNTs and/or the complex formation of surface thiol or hydroxyl groups with the metal ions as following:
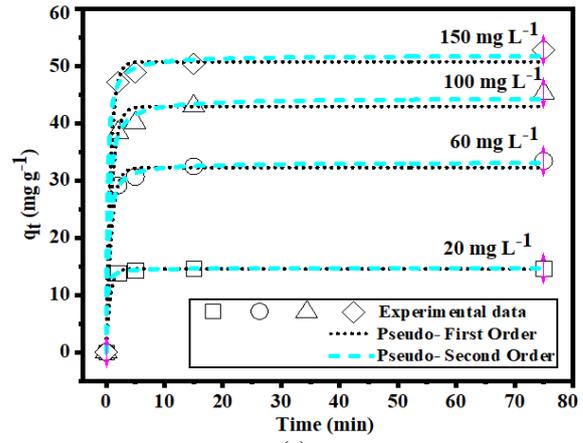
Ion exchange [32]:

$$2(TNT-OH) + M^{2+} \rightarrow (TNT-O)_2 M + 2H^+ \qquad (4)$$

$$2(TNT-ONa) + M^{2+} \rightarrow (TNT-O)_2 M + 2Na^+ \qquad (5)$$

Surface complexation [33]:

$$TNT-SH + M^{2+} \rightarrow TNT-S-M^+ + H^+ \qquad (6)$$

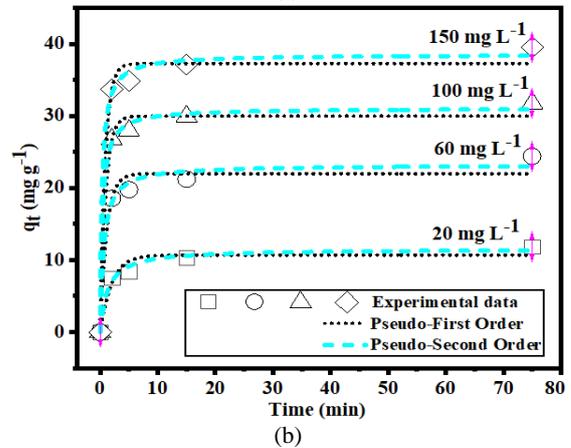**Thermodynamic study**

The effect of temperature on the adsorption process and its spontaneity status can be evaluated by thermodynamic parameters including Gibbs free energy change (ΔG^0), entropy change (ΔS^0) and enthalpy change (ΔH^0) according to the Equations (7) and (8) [34]:

$$\Delta G^0 = -RT\ LnK_c \qquad (7)$$

$$LnK_c = -\frac{\Delta H^0}{RT} + \frac{\Delta S^0}{R} \qquad (8)$$

where K_c and R (8.314 J/mol K) correspond to the thermodynamic equilibrium constant and universal gas constant, respectively and T is the metal cations solution temperature (K). As listed in Table 4, the positive values of enthalpy change indicated endothermic nature of the adsorption process and therefore, higher temperatures facilitate the adsorption of metal ions on TNT/Sil adsorbent [35, 36]. The negative values of Gibbs free energy change implied that the metal cations uptake performed spontaneously, moreover the quantity of -ΔG^0 increased at higher temperature which demonstrate the degree of spontaneity of process enhances at higher temperatures. The positive values of $\Delta S°$ further suggest increased randomness at the interface of TNT/Sil adsorbent and metal cation solution.

Table 3. Kinetic parameters for the uptake of copper and nickel on TNT/Sil adsorbent

Metal ion	C_0 (mg L^{-1})	$q_{e, exp}$ (mg g^{-1})	Pseudo-first order model			Pseudo-second order model		
			k_1 (min^{-1})	$q_{e, cal}$ (mg g^{-1})	R^2	k_2 (g mg^{-1} min^{-1})	$q_{e, cal}$ (mg g^{-1})	R^2
Cu(II)	20	16.79	1.5	14.5	0.99	0.54	14.70	0.99
	60	38.08	1.14	32.25	0.99	0.099	33.17	0.99
	100	46.24	1.09	42.93	0.99	0.063	44.42	0.99
	150	52.32	1.31	50.74	0.99	0.088	51.86	0.99
Ni(II)	20	12.16	0.49	10.69	0.95	0.066	11.52	0.98
	60	29.44	0.88	21.97	0.97	0.072	23.18	0.98
	100	36.56	1.08	29.96	0.99	0.087	31.05	0.99
	150	41.92	1.14	37.27	0.99	0.078	38.52	0.99

Table 4. Thermodynamic parameters for Cu(II) and Ni(II) uptake onto the TNT adsorbent

Metal ion	$-\Delta G^{\circ}$ (kJ mol^{-1})			ΔH° (kJ mol^{-1})	ΔS° (J mol^{-1} K^{-1})
	298 K	308 K	318 K		
Cu^{2+}	3.77	4.84	6.18	32.216	120.56
Ni^{2+}	0.938	1.282	1.769	11.42	41.39

CONCLUSION

In the present study, the organic moiety (i.e. thiol) of the mercaptosilane modifier were anchored to the surface of the hydrothermally synthesized TNT NPs and this material was assessed as the adsorbent for the removal of Cu and Ni from synthetic wastewater. The physicochemical properties of the modified TNT were investigated through some analyses such as FESEM, EDS, FTIR, XRD and TEM. The kinetic and isotherm results demonstrated that experimental data are highly corresponded to the pseudo-second order and Freundlich model, respectively. In addition, the thermodynamic study indicated endothermic nature of the adsorption process. The TNT/Sil adsorbent have high tendency for adsorption of copper ions than nickel and the maximum uptake for these two cations was 53.77 and 45.29 mg g^{-1}, respectively.

ACKNOWLEDGEMENT

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Persian Abstract

چکیده

در سال های اخیر، اهمیت تصفیه آلودگی فلزات سنگین از جریان های آبی به دلیل نیاز به منابع آب سالم با توجه به محدودیت این منابع، پیامدهای زیست محیطی این آلاینده‌ها، افزایش فعالیت‌های صنعتی بشر با توجه به استفاده روزانه از این فلزات در فناوری‌های مدرن و اثرات سمی و سرطان‌زای این آلودگی ها بیش از پیش به یک نگرانی جدی برای فعالان محیط‌زیست تبدیل شده است. استفاده از مواد گزینش پذیر و کارآمد جهت تصفیه کامل و موثر این آلاینده‌های فلزی همواره مورد استقبال پژوهشگران عرصه محیط‌زیست بوده است. در این پژوهش، سطح نانولوله‌های اکسید تیتانیوم که با روش هیدروترمال سنتز شدند، توسط گروه های تیول اصلاح گردید و جهت حذف آلودگی‌های فلزات سنگین (II)Cu و (II)Ni از پساب سنتزی استفاده شد. خواص فیزیکی و شیمیایی نانوجاذب ساخته شده توسط آنالیزهای مختلف ارزیابی شد و توانایی جذب آن برای آلاینده‌های فلزی در فرآیند جذب ایستا مطالعه گردید. نتایج نشان داد که جاذب تهیه شده میل ترکیبی بیشتری نسبت به یون‌های مس دارد. همچنین داده‌های آزمایشگاهی تطابق‌پذیری بیشتری با مدل هم‌دمای فرندلیچ داشتند و حداکثر ظرفیت جذب برای یون‌های مس و نیکل به ترتیب $53/77$ mg g^{-1} و $45/29$ mg g^{-1} بود. به علاوه، طبیعت گرماگیر فرآیند جذب توسط مطالعه ترمودینامیکی تایید شد و نیز داده‌های سینتیکی با مدل شبه درجه دو برازش بهتری داشتند. با توجه به یافته‌های جذب، جاذب تهیه شده با حضور گروه‌های عاملی هیدروکسیل و تیول بر روی آن می‌تواند گزینه مناسب و کارآمدی جهت پالایش پساب حاوی یون‌های فلزات سنگین باشد.