

Research Article

Removal and Adsorption of *p*-Nitrophenol from Aqueous Solutions Using Carbon Nanotubes and Their Composites

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Received 9 April 2014; Revised 1 June 2014; Accepted 11 June 2014; Published 2 July 2014

Academic Editor: Shadi A. Dayeh

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In an attempt to explore the possibility of using carbon nanotubes (CNTs) as efficient adsorbents for removal of pollutants from the contaminated water, the adsorption of *p*-nitrophenol (PNP) on raw multiwalled carbon nanotubes (r.MWNTs) with different outer diameters, various functionalized multiwalled carbon nanotubes (*f*-MWNTs), raw single-walled carbon nanotubes (r.SWNTs) and oxidized single-walled carbon nanotubes (ox-SWNTs) has been investigated. The ox-SWNTs showed better adsorption ability for PNP with different concentrations, while lower uptake capacity was found for all of the r.MWNTs and *f*-MWNTs. The removal efficiency of PNP by ox-SWNTs was around 98%, indicating that ox-SWNTs possess a great potential application prospect for removing PNP from aqueous solutions.

1. Introduction

Because of an accumulated interaction with blood, nitrophenols can potentially cause cyanosis, confusion, and unconsciousness [1]. Exposure to nitrophenol could also cause skin and eye burns. However, many untreated industrial effluents, such as pesticides, pharmaceuticals, wood preservatives, and petrochemicals industries, are discharged into the environment. To remove nitrophenol from contaminated water, various techniques such as membrane filtration [2], degradation [3, 4], adsorption [2, 5], and chemical reduction [6–8] have been reported. Taking advantage of high efficiency, simplicity, and low costs, adsorption is usually considered a most widely applicable technology for the removal of pollutants from aqueous solution. However, the adsorption performance of an adsorbent is highly dependent on its chemical composition and physicochemical characteristics such as shape, size, and dispersion of particles. To obtain novel absorbent materials with effective adsorption as well as lower costs, continuous research and development activities focus on design and preparation of different structured porous [9, 10]

and nanostructured materials [5, 11] with high surface area and strong adsorption affinity.

Due to the unique physicochemical and electrical properties, carbon nanotubes (CNTs) have been widely used in the field of electronics [12–14], conducting materials [15, 16], hydrogen storage [17, 18], chemical sensors [19–21] as well as drug carriers [22, 23], and so forth. Because of their high surface area and large micropore volume, CNTs are also considered as extremely good adsorbents [24]. To remove various different organic compounds from water with higher efficiency, CNTs have found their widespread applications in the adsorption [25–30]. Because NP pollutants are major byproducts formed in industrial processes, thus the potential industrial applications of CNTs as filter materials in water purification are highly appreciated. The adsorption of 4-chloro-2-nitrophenol (4C2NP) from aqueous solution was reported, and a maximum adsorption capacity of 1.44 and 4.42 mg · g⁻¹ for SWNTs and MWNTs was obtained, respectively [31]. Copper and silver nanoparticles were immobilized on CNTs and embedded in water-insoluble cyclodextrin polyurethane polymers, which had a maximum adsorption of

TABLE 1: The raw CNTs used in the experiments.

Type of CNTs	Main range of diameter	Length	Purity	Ash	Specific surface area	Amorphous carbon
Aligned MWNTs	10–30 nm	5–15 μm	$\geq 95\%$	≤ 0.2 wt%	160–200 m^2/g	$< 3\%$
L.MWNTs-10	< 10 nm	5–15 μm	$\geq 95\%$	≤ 0.2 wt%	250–500 m^2/g	$< 3\%$
S.MWNTs-10	< 10 nm	1–2 μm	$\geq 95\%$	≤ 0.2 wt%	250–500 m^2/g	$< 3\%$
S.MWNTs-1030	10–30 nm	1–2 μm	$\geq 95\%$	≤ 0.2 wt%	100–160 m^2/g	$< 3\%$
S.MWNTs-2040	20–40 nm	1–2 μm	$\geq 95\%$	≤ 0.2 wt%	70–150 m^2/g	$< 3\%$
S.MWNTs-4060	40–60 nm	1–2 μm	$\geq 95\%$	≤ 0.2 wt%	60–120 m^2/g	$< 3\%$
S.MWNTs-60100	60–100 nm	1–2 μm	$\geq 95\%$	≤ 0.2 wt%	40–70 m^2/g	$< 3\%$
R.SWNTs	< 2 nm	5–15 μm	$\geq 95\%$	≤ 0.2 wt%	500–700 m^2/g	$< 5\%$

Notes: the acronym “L” is “long” and “S” is “short.” Therefore, the acronyms “L.MWNTs” and “S.MWNTs” are defined as long MWNTs and short MWNTs, respectively.

55% of *para*-nitrophenol (PNP) [32]. Adsorption of PNP in aqueous solution from petrochemical wastewater by single-walled CNTs (SWNTs) and oxidized SWNTs (ox-SWNTs) was reported by Moradi et al., and these reports indicated that CNTs can be used as potential adsorbents for the treatment of wastewater containing nitrophenol.

CNTs with different diameters would have different specific surface, which would affect their adsorptive properties. However, to the best of our knowledge, the effects of different outer diameters of CNTs on adsorption of organic contaminants were not investigated up to now. To clarify the outer diameters of CNTs on their adsorption capacity, PNP was selected as the sorption test molecule. And raw multiwalled carbon nanotubes (MWNTs) of different outer diameters, various functionalized MWNTs (*f*-MWNTs), and oxidized SWNTs (ox-SWNTs) were used as adsorbents to investigate CNTs adsorption properties. The obtained results could offer some new insights into the relationship between the microstructures and adsorption properties of CNTs.

2. Experimental and Methods

2.1. Materials. The raw SWNTs (r.SWNTs) with external diameters of < 2 nm used in this study were supplied by Nanjing Jcnano technology Co., LTD. The raw MWNTs (r.MWNTs) with external diameters of < 10 nm, 10–20 nm, 10–30 nm, 20–40 nm, 40–60 nm, and 60–100 nm were bought from Shenzhen Nanotech Port Co., Ltd. As shown in Table 1, the specific surface area of CNTs was estimated by Brunauer-Emmett-Teller (BET) method according to the data provided by the vendors. Various *f*-MWNTs were prepared and fully characterized by our group according to the literature methods. Other conventional reagents were of analytical grade and were used without further purification. The deionized water used in all experiments was prepared in a three-stage Millipore Milli-Q plus 185-purification system and had a resistivity higher than 18.2 M Ω .

2.2. Functionalization of CNTs. Oxidized MWNTs (ox-MWNTs) were prepared by refluxing 100 mg of S.MWNTs-2040 in 25 mL concentrated nitric acid (HNO₃) for 24 hrs [33, 34]. Brominated MWNTs (S.MWNT-Br) were obtained by heating r-S.MWNTs-2040 with liquid bromine at 55°C for 10

days [35–38]. Chitosan (CS) grafted MWNTs (S.MWNT-CS) were prepared by treating the ox-MWNTs with CS through a microwave-assisted reaction [39, 40]. The dihalocarbene functionalized MWNTs (S.MWNTs-2040-CCl₂, S.MWNTs-2040-CBr₂, and S.MWNTs-2040-Cl₂) were prepared by reaction of raw S.MWNTs-2040 with sodium hydroxide (NaOH) with chloroform, or bromoform, or iodoform, respectively [41–43]. And poly(ethylene glycol) (*M_w* = 400; PEG400) grafted MWNTs (S.MWNT-PEG400) were obtained by firstly acyl chlorination of ox-MWNTs with thionyl chloride (SOCl₂), followed by an esterification reaction with PEG400 [44–46]. All of the abovementioned functionalized CNTs were purified and fully characterized as demonstrated in the previous work [35–46].

Oxidized SWNTs (ox-SWNTs) were prepared by treating SWNTs (200 mg) with HNO₃/H₂SO₄ (volume ratio is 3:1, 60 mL) at 60°C for 6 hours [46, 47]. The mixture was then diluted with deionized water and filtered, and the residue was washed with large amount of deionized water until pH value of the filtrate was close to neutral. The residue was collected and dried under vacuum at 80°C for 48 hrs to obtain ox-SWNTs (187 mg).

2.3. Characterization. The microscopic morphologies of raw MWNTs (r.MWNTs), functionalized MWNTs (*f*-MWNTs), raw SWNTs (r.SWNTs), and ox-SWNTs were characterized using high-resolution transmission electron microscopy (HRTEM). Drops of raw CNTs or CNT composites ethanol suspensions were delivered onto the copper grid and dried in air. Afterwards, the HRTEM images were acquired on a JEOL JEM-1230 microscope using an accelerating voltage of 100 kV.

2.4. Adsorption of PNP on the CNTs. Parallel series of batch adsorption tests were carried out as follows. In 25.00 mL Falcon centrifuge tubes, 0.0050 mg of various CNTs were introduced into 10.00 mL of solutions which contain a specific amount of PNP, respectively. The tubes were sonicated in water bath under a constant temperature for 30 min and then shaken for 0.5~6.0 h at 200 rpm on a horizontal shaker at room temperature. After shaking, the mixture was filtered using 0.45 μm polycarbonate membranes, and the obtained filtrates were also labelled as Aligned MWNTs

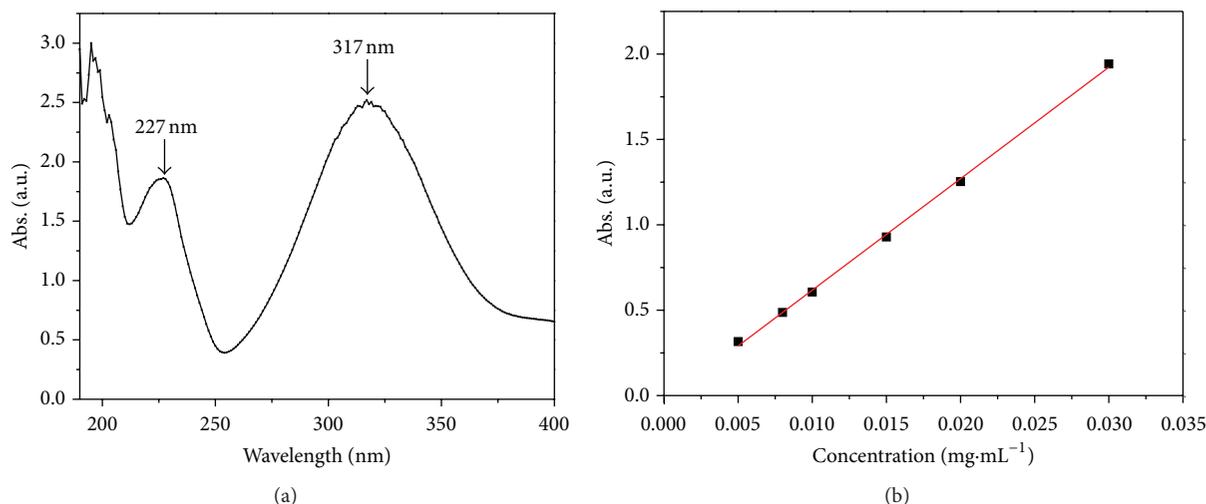


FIGURE 1: Uv-vis spectrophotometry curves of PNP: (a) scanning curve and (b) standard curve.

(A.MWNTs), L.MWNTs-10, S.MWNTs-10, S.MWNTs-1030, S.MWNTs-2040, S.MWNTs-4060, S.MWNTs-60100, S.MWNTs-2040-Br, S.MWNTs-2040-CS, ox-MWNTs, ox-SWNTs, MWNTs-2040-PEG400, S.MWNTs-2040-CCl₂, S.MWNTs-2040-CBr₂, S.MWNTs-2040-Cl₂, and r.SWNTs, respectively. The PNP concentration was determined by UV-Vis spectrophotometry at a wavelength of 317 nm (Figure 1(a)). The amount of the adsorbed PNP on to abovementioned CNTs was calculated with

$$q_e = \frac{(C_0 - C_e) \times V}{m}, \quad (1)$$

where q_e is PNP adsorbed amount on the CNTs (mg·g⁻¹); C_0 and C_e are the initial and equilibrium concentrations of the PNP (mg·mL⁻¹), respectively; V is the solution volume (mL); m is the CNTs' dosage (g).

And the percentage removal (%R) of PNP was calculated with

$$\%R = \frac{C_0 - C_e}{C_0} \times 100, \quad (2)$$

where C_0 and C_e are the initial and equilibrium concentrations of the PNP (mg·mL⁻¹), respectively.

2.5. Quantitative Analysis. We collected the absorption at different concentration of PNP and drew a diagram (Figure 1(b)), which was then linearly fitted to gain the linear equation (3). The linearity of the calibration curve was rather good after correction, with a correlation coefficient (R) of 0.99874 and R^2 of 0.99698:

$$Y = -0.03277 + 61.62929 * X, \quad (3)$$

where X is the concentration of the PNP (mg·mL⁻¹) and Y is the absorbance (a.u.).

3. Results and Discussions

3.1. Characterization of CNTs. All of the abovementioned functionalized CNTs were prepared using the same methods as demonstrated in the previous work by our group [33–37, 39–43]. Herein, only the morphologies/features and defects of CNT samples before and after functionalization were analyzed. HRTEM with very high spatial resolution was applied to characterize their microstructures. As shown in Figures 2(b)–2(c), the diameters of CS or PEG400 modified MWNTs were enlarged a little (around 5–13 nm) due to the entangled polymers such as CS or PEG (marked by the arrows). Simultaneously, dihalocarbene modified MWNTs (including S.MWNTs-2040-CCl₂, S.MWNTs-2040-CBr₂, and S.MWNTs-2040-Cl₂) (Figures 2(d)–2(f)) and brominated MWNTs (S.MWNTs-2040-Br) (Figure 2(g)) largely preserve their morphologies/features in contrast with pristine MWNTs (S.MWNTs-2040) (Figure 2(a)). However, due to the formation of cyclopropane derivatives on the CNTs' surface, the aromatic properties would be weakened a lot (Figure 3) [48–50]. And the introduction of -Br to CNTs would also weaken their aromatic properties [35, 37]. As for oxidized MWNTs (ox-MWNTs) (Figure 2(h)), CNTs would be broken under severe oxidation conditions by concentrated nitric acid [51]. Therefore, the ends of the tubes are opened, and thus the surface area of CNTs would be enlarged as a result.

As shown in Figure 4, high-resolution TEM images of SWNT samples also clearly indicate that the defects of ox-SWNTs (Figure 4(b)) have emerged due to the severe oxidation for SWNTs (Figure 4(a)), which provides new sites for further modification of CNTs or adsorption of adsorbates (marked by the arrows).

3.2. Effect of Kinds of CNTs on Removal of PNP. To evaluate the specific surface area of CNTs on removal of PNP, r.SWNTs and seven kinds of MWNTs including A.MWNTs,

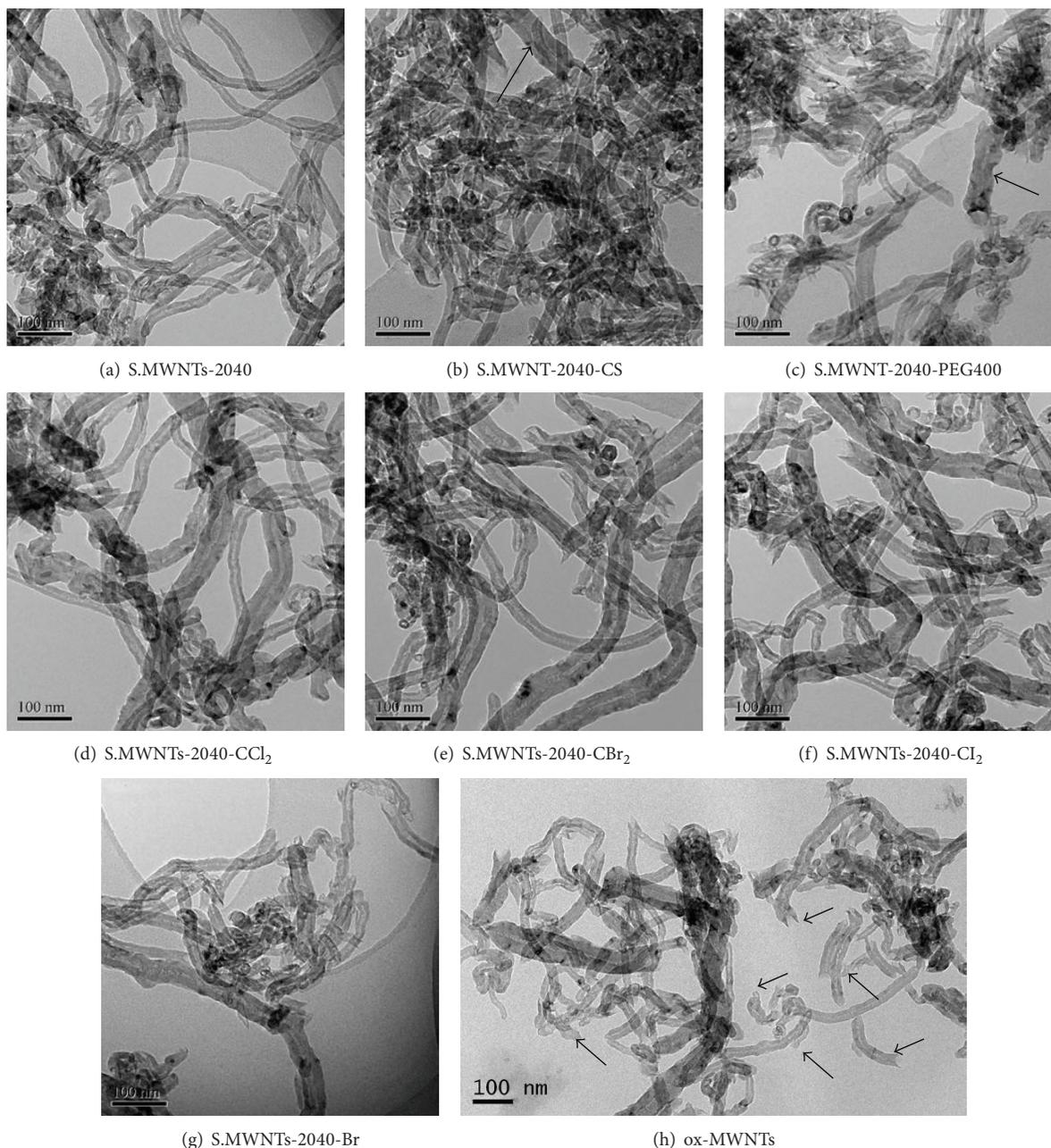


FIGURE 2: TEM images of MWNT samples: (a) S.MWNTs-2040; (b) S.MWNT-2040-CS; (c) S.MWNT-2040-PEG400; (d) S.MWNTs-2040-CCl₂; (e) S.MWNTs-2040-CBr₂; (f) S.MWNTs-2040-Cl₂; (g) S.MWNT-2040-Br; (h) ox-MWNTs.

L.MWNTs-10, S.MWNTs-10, S.MWNTs-1030, S.MWNTs-2040, S.MWNTs-4060, and S.MWNTs-60100 were used as adsorbents. As shown in Figure 5(b), the percentage removal increased from 7.5% to around 80% when the diameters of MWNTs decrease from 60–100 nm to less than 10 nm. Obviously, the specific surface area of CNTs decreases along with the increased diameters (Table 1); thus their enhanced adsorption capacities might be based on the more possible surface sites for adsorption. When r.SWNTs with diameters of less than 2 nm were utilized, higher removal efficiency of over than 84% could be obtained (Figure 5(a)).

In order to investigate the grafted organic ligands on the adsorption capacity of CNTs, ox-SWNTs and the S.MWNTs-2040 composites prepared by functionalizing S.MWNTs-2040 with -Br, -CS, -COOH, PEG400, -CCl₂, -CBr₂, and -Cl₂ (S.MWNTs-2040-Br, S.MWNTs-2040-CS, ox-MWNTs, S.MWNTs-2040-PEG400, S.MWNTs-2040-CCl₂, S.MWNTs-2040-CBr₂, and S.MWNTs-2040-Cl₂) were used to remove PNP. As shown in Figure 5, the removal efficiency was decreased by the S.MWNTs-2040 composites abovementioned in contrast with S.MWNTs-2040, indicating that functionalization is not an efficient

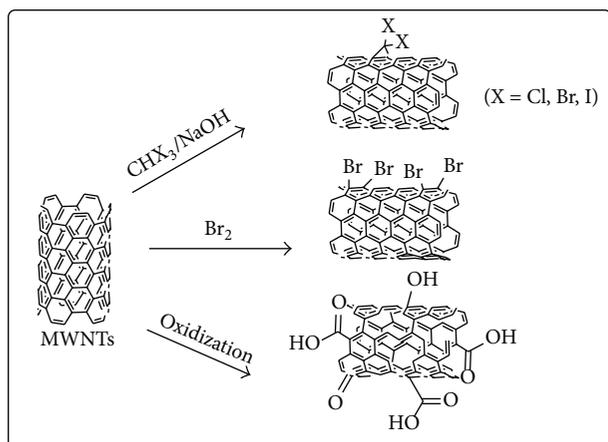


FIGURE 3: Scheme of functionalization of CNTs by attachment of $-CX_2$ ($X = Cl, Br, I$) or $-Br$, and oxidation of CNTs.

way to enhance CNTs' removal capacity. As a matter of fact, the removal efficiency of *f*-MWNTs was decreased. Of all the possible reasons, the interaction between the adsorbates (PNP) and the adsorbents (*f*-MWNTs) would play vital roles. Firstly, it is well-known that CNTs would be coated with polymers during surface modification of CNTs with polymers [34–37] (Figures 2(b) and 2(c)); thus the effective adsorption sites for forming π - π interaction forces between the adsorbates (PNP) and the adsorbents (CNTs) would be decreased. Secondly, functionalization of S.MWNTs-2040 by grafting $-CCl_2$, $-CBr_2$, Cl_2 , or $-Br$ would damage their aromatic properties (Figure 3) by opening the double $C=C$ bonds, and therefore the π - π interaction forces between PNP and *f*-MWNTs would also be decreased.

Based on the reasons aforementioned, the oxidized CNTs, including ox-MWNTs and ox-SWNTs, would provide additional intermolecular forces such as hydrogen-bonding between PNP and CNTs due to the introduced hydroxyl, carbonyl, and carboxyl groups. In fact, the results indicated that the removal efficiency for PNP was increased by ox-MWNTs (19.5%) and ox-SWNTs (94.5%) in contrast with r.MWNTs (17.5%) and r.SWNTs (84.0%), respectively. Undoubtedly, the available sites on the adsorbents are the limiting factor for PNP adsorption and removal [52, 53].

3.3. Removal of PNP Using ox-SWNTs

3.3.1. Effect of Initial PNP Concentration. To overcome all mass transfer resistance of the molecules between the aqueous phases (including PNP and H_2O , especially adsorbate PNP) and the solid phase (adsorbent: SWNT-COOH), the initial concentration of PNP could provide an important driving force. Using ox-SWNTs as adsorbent, the effect of PNP concentrations (variation from 0.0050 to 0.0300 $mg \cdot mL^{-1}$) on the adsorption was monitored. Increasing the initial concentrations led to an increase in the PNP percentage removal in the range of 0.005 to 0.0100 $mg \cdot mL^{-1}$. However, increasing the initial concentration would lead to a decrease in the PNP percentage removal in the range of 0.0100 to 0.0300 $mg \cdot mL^{-1}$

TABLE 2: Effect of agitation time on removal of PNP.

Agitation time/min	$C_e/mg \cdot mL^{-1}$	Percentage removal
30	0.0001630	98.37%
90	0.0002810	97.19%
240	0.0002810	97.19%
360	0.0002980	97.02%

although the actual amount of PNP adsorbed per unit mass of adsorbents was increased (Figure 6). Therefore, the initial concentration of PNP provides an important driving force to overcome its mass transfer resistance between the aqueous and the solid phases. At an optimal initial concentration of 0.0100 $mg \cdot mL^{-1}$, the max PNP percentage removal was 97.9%.

3.3.2. Effect of Agitation Time. When the initial PNP concentration (C_0) is 0.01000 $mg \cdot mL^{-1}$, the effects of agitation time on the sorption of PNP at room temperature are shown in Table 2. It can be seen from Table 2 that the amount of adsorbed PNP was almost the same when the agitation time was increased from 30 to 360 min. The adsorption rate is very fast because PNP might be mainly adsorbed on the exterior surface of SWNT-COOH. The percentage removal of PNP was close to 100%.

In a usual adsorption process, initially adsorbate molecules diffuse from boundary layer film onto the adsorbent surface due to the boundary layer effects, and then they will diffuse into the porous structure of the adsorbent. However, the latter phenomenon will take a relatively longer contact time. As we can see from Table 2, the adsorption equilibrium was achieved after only 30 min. Therefore, the adsorption of PNP from its aqueous solution was a surface adsorption process. The PNP molecules would be mainly adsorbed by the external surface of ox-SWNTs, and scarcely any diffusion into the pores of CNTs would happen due to the very small holes of CNTs and the induced steric hindrance.

3.3.3. Effect of Solution Temperature. By using 0.0100 $mg \cdot mL^{-1}$ PNP as adsorption solution and 5.000 mg ox-SWNTs as adsorbents, when the adsorption was operated at 20, 25, 30, 35, or 40°C, the percentage removal of PNP was obtained. As shown in Figure 7, one can see that the percentage removal of PNP decreased from 98.0% to 92.1% when the temperature increased from 20°C to 40°C. Therefore the adsorption process is exothermic.

3.3.4. The Maxim Adsorption Capacity. By using 500.0 mL of 0.0100 $mg \cdot mL^{-1}$ PNP as adsorption solution, 5.000 mg ox-SWNTs as adsorbents, and then the solution was left standing for 24 h, the solution concentration of PNP was decreased to 0.00794 $mg \cdot mL^{-1}$ after adsorption, indicating a maxim adsorption capacity of 206 $mg \cdot g^{-1}$ for adsorption of PNP onto ox-SWNTs. The high adsorption capacity for PNP by ox-SWNTs could be ascribed to its high specific surface area, opened tubular ends, and introduced hydroxyl, carbonyl, and carboxyl groups.

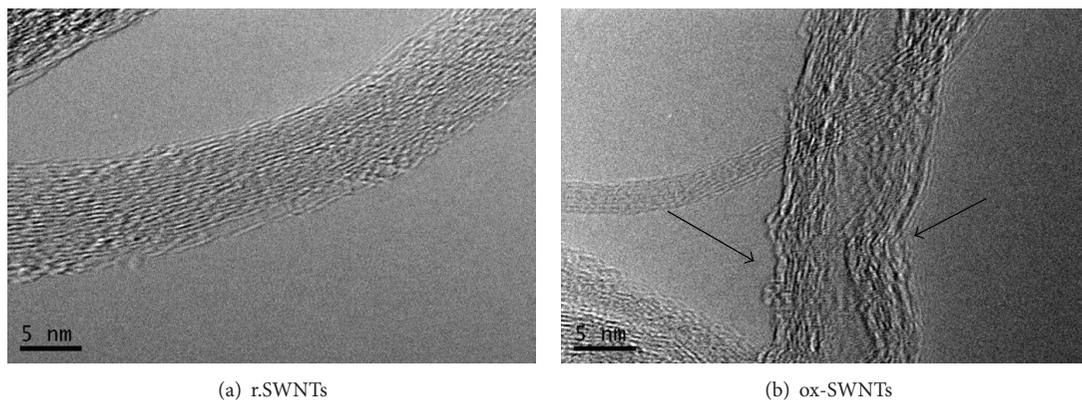


FIGURE 4: High-resolution TEM images of SWNT samples: (a) r.SWNTs and (b) ox-SWNTs.

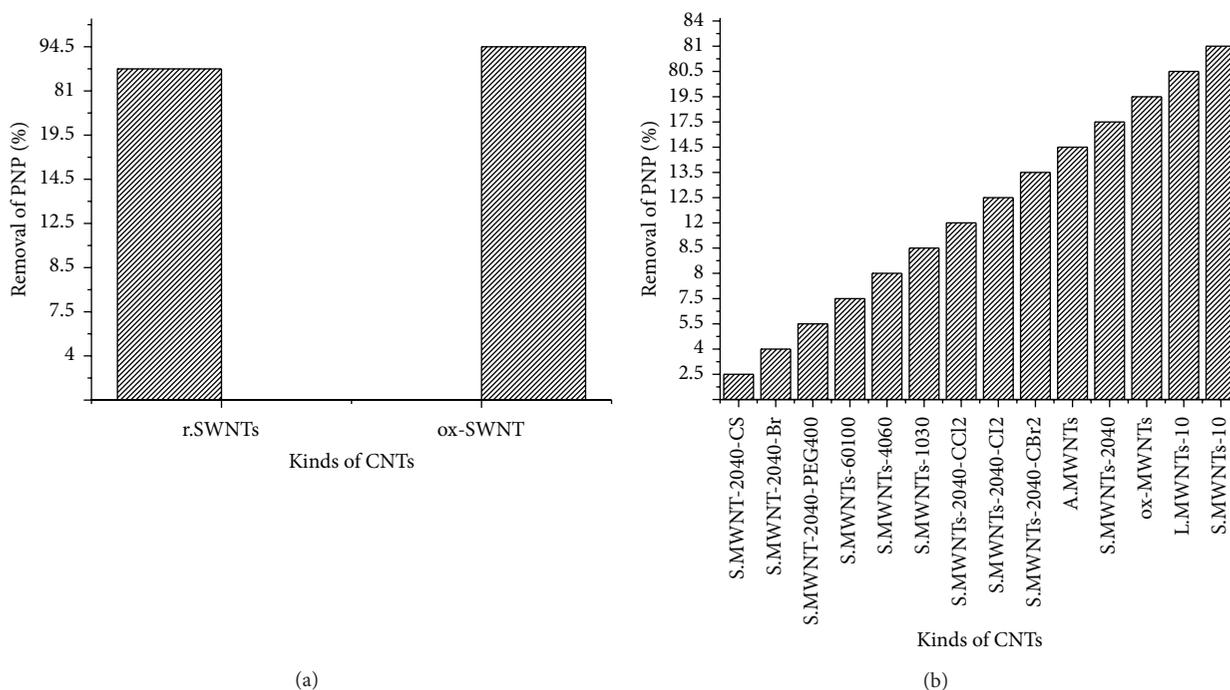


FIGURE 5: Effect of kinds of CNTs on removal of PNP ($C_0 = 0.020 \text{ mg}\cdot\text{mL}^{-1}$): (a) r.SWNTs and ox-SWNTs; (b) various MWNTs and their composites.

3.3.5. Desorption Ability. To analyze the desorption capacity of PNP from ox-SWNTs, the ox-SWNT samples obtained from the maxim adsorption capacity test were then dispersed in 50 mL ethyl acetate and oscillate for 24 h at room temperature. The solution concentration of PNP was increased to 0.00646 mg/mL after desorption, indicating that about 31.4% desorption amount could be achieved.

4. Conclusions

Our results highlight the significance of CNTs' surface area for contaminant adsorption and the associated influence of grafted molecules on adsorption. From the experimental results, covalent functionalization of CNTs by attachment of polar molecules or groups would weaken their aromatic

properties and decrease their surface area, and therefore their adsorption capacity would decrease. However, oxidation could open CNTs and introduce hydroxyl group, carbonyl group, and carbonyl group; thus their adsorption capacity would increase due to CNTs' magnified surface area and emerging hydrogen bonds between oxidized CNTs and adsorbates. The adsorption process for removing PNP is exothermic due to the decreased removal efficiency along with increased temperature.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

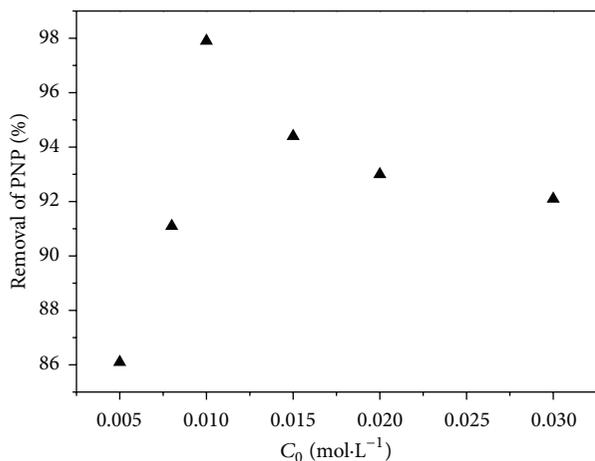


FIGURE 6: Effect of initial concentration on removal of PNP.

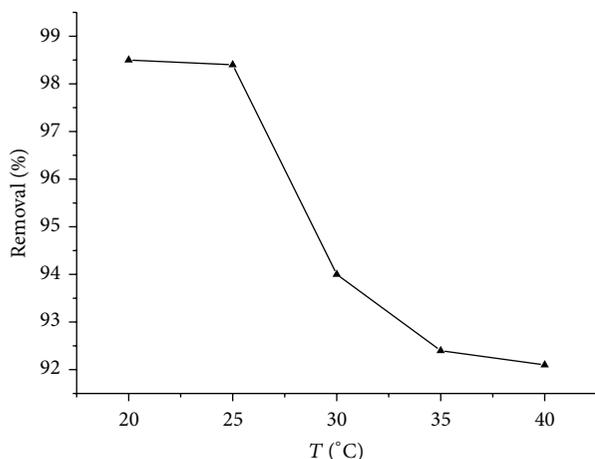


FIGURE 7: Effect of solution temperature on removal of PNP.

Acknowledgments

The financial supports from the National Natural Science Foundation of China (no. 21201181), the Research Fund for the Doctoral Program of Higher Education of China (no. 20110162120070), China Postdoctoral Science Foundation (no. 2013M542107), Postdoctoral Daily Fund of Hunan Province, and the Open Fund of Key Laboratory of Resources Chemistry of Nonferrous Metals, Ministry of Education (no. 2012-KF-04) are greatly appreciated.

References

- [1] W. H. Hallenbeck and K. M. Cunningham-Burns, *Pesticides and Human Health*, Springer, New York, NY, USA, 1985.
- [2] I. Ivančev-Tumbas, R. Hobby, B. Kuchle, S. Panglisch, and R. Gimbel, "p-Nitrophenol removal by combination of powdered activated carbon adsorption and ultrafiltration - comparison of different operational modes," *Water Research*, vol. 42, no. 15, pp. 4117–4124, 2008.
- [3] M. L. Chen, J. S. Bae, H. S. Yoon, C. S. Lim, and W. C. Oh, "The photodegradation effect of organic dye for metal oxide (Cr_2O_3 , MgO and V_2O_5) treated CNT/ TiO_2 composites," *Bulletin of the Korean Chemical Society*, vol. 32, no. 3, pp. 815–820, 2011.
- [4] P. Xiong, Y. Fu, L. Wang, and X. Wang, "Multi-walled carbon nanotubes supported nickel ferrite: A magnetically recyclable photocatalyst with high photocatalytic activity on degradation of phenols," *Chemical Engineering Journal*, vol. 195–196, pp. 149–157, 2012.
- [5] A. Mehrizad, K. Zare, H. Aghaie, and S. Dastmalchi, "Removal of 4-chloro-2-nitrophenol occurring in drug and pesticide waste by adsorption onto nano-titanium dioxide," *International Journal of Environmental Science and Technology*, vol. 9, no. 2, pp. 355–360, 2012.
- [6] L. H. Qiu, Y. J. Peng, B. Q. Liu, B. C. Lin, M. J. Malik, and F. Yan, "Polypyrrole nanotube-supported gold nanoparticles: an efficient electrocatalyst for oxygen reduction and catalytic reduction of 4-nitrophenol," *Applied Catalysis A: General*, vol. 413–414, pp. 230–237, 2012.
- [7] R. Jin, Y. Xing, X. Yu et al., "Facile synthesis of well-dispersed silver nanoparticles on hierarchical flower-like $\text{Ni}_3\text{Si}_2\text{O}_5(\text{OH})_4$ with a high catalytic activity towards 4-nitrophenol reduction," *Chemistry*, vol. 7, no. 12, pp. 2955–2961, 2012.
- [8] C. M. Fan, L. F. Zhang, S. S. Wang, D. H. Wang, L. Q. Lu, and A. W. Xu, "Novel CeO_2 yolk-shell structures loaded with tiny Au nanoparticles for superior catalytic reduction of p-nitrophenol," *Nanoscale*, vol. 4, no. 21, pp. 6835–6840, 2012.
- [9] J. Zhou, Z. Zhang, B. Cheng, and J. Yu, "Glycine-assisted hydrothermal synthesis and adsorption properties of crosslinked porous $\alpha\text{-Fe}_2\text{O}_3$ nanomaterials for p-nitrophenol," *Chemical Engineering Journal*, vol. 211–212, pp. 153–160, 2012.
- [10] A. E. Ofomaja, "Kinetics and pseudo-isotherm studies of 4-nitrophenol adsorption onto mansonia wood sawdust," *Industrial Crops and Products*, vol. 33, no. 2, pp. 418–428, 2011.
- [11] H. S. Wahab, "Molecular modeling of the adsorption and initial photocatalytic oxidation step for para-nitrophenol on nano-sized TiO_2 surface," *Surface Science*, vol. 606, no. 5–6, pp. 624–633, 2012.
- [12] K. D. M. Rao, B. Radha, K. C. Smith, T. S. Fisher, and G. U. Kulkarni, "Solution-processed soldering of carbon nanotubes for flexible electronics," *Nanotechnology*, vol. 24, no. 7, Article ID 075301, 2013.
- [13] Q. Cao, S. Han, G. S. Tulevski, Y. Zhu, D. D. Lu, and W. Haensch, "Arrays of single-walled carbon nanotubes with full surface coverage for high-performance electronics," *Nature Nanotechnology*, vol. 8, no. 3, pp. 180–186, 2013.
- [14] H. Zhang, B. Wu, W. Hu, and Y. Liu, "Separation and/or selective enrichment of single-walled carbon nanotubes based on their electronic properties," *Chemical Society Reviews*, vol. 40, no. 3, pp. 1324–1336, 2011.
- [15] J. Pu, S. Wan, Z. Lu et al., "Controlled water adhesion and electrowetting of conducting hydrophobic graphene/carbon nanotubes composite films on engineering materials," *Journal of Materials Chemistry A*, vol. 1, no. 4, pp. 1254–1260, 2013.
- [16] A. Aldabahi, J. Chu, P. Feng, and M. I. H. Panhuis, "Conducting composite materials from the biopolymer kappa-carrageenan and carbon nanotubes," *Beilstein Journal of Nanotechnology*, vol. 3, no. 1, pp. 415–427, 2012.
- [17] Z. Liu, Q. Xue, C. Ling, Z. Yan, and J. Zheng, "Hydrogen storage and release by bending carbon nanotubes," *Computational Materials Science*, vol. 68, pp. 121–126, 2013.
- [18] P. Dibandjo, C. Zlotea, R. Gadiou et al., "Hydrogen storage in hybrid nanostructured carbon/palladium materials: influence

- of particle size and surface chemistry," *International Journal of Hydrogen Energy*, vol. 38, no. 2, pp. 952–965, 2013.
- [19] H. H. Choi, J. Lee, K. Dong, B. Ju, and W. Lee, "Gas Sensing performance of composite materials using conducting polymer/single-walled carbon nanotubes," *Macromolecular Research*, vol. 20, no. 2, pp. 143–146, 2012.
- [20] P. Teerapanich, M. T. Z. Myint, C. M. Joseph, G. L. Hornyak, and J. Dutta, "Development and improvement of carbon nanotube-based ammonia gas sensors using ink-jet printed interdigitated electrodes," *IEEE Transactions on Nanotechnology*, vol. 12, no. 2, pp. 255–262, 2013.
- [21] A. Abdellah, A. Abdelhalim, M. Horn, G. Scarpa, and P. Lugli, "Scalable spray deposition process for high-performance carbon nanotube gas sensors," *IEEE Transactions on Nanotechnology*, vol. 12, no. 2, pp. 174–181, 2013.
- [22] S. Prakash, M. Malhotra, W. Shao, C. Tomaro-Duchesneau, and S. Abbasi, "Polymeric nanohybrids and functionalized carbon nanotubes as drug delivery carriers for cancer therapy," *Advanced Drug Delivery Reviews*, vol. 63, no. 14–15, pp. 1340–1351, 2011.
- [23] U. Arsawang, O. Saengsawang, T. Rungrotmongkol et al., "How do carbon nanotubes serve as carriers for gemcitabine transport in a drug delivery system?" *Journal of Molecular Graphics and Modelling*, vol. 29, no. 5, pp. 591–596, 2011.
- [24] R. Q. Long and R. T. Yang, "Carbon nanotubes as superior sorbent for dioxin removal," *Journal of the American Chemical Society*, vol. 123, no. 9, pp. 2058–2059, 2001.
- [25] J. G. Yu, X. H. Zhao, H. Yang et al., "Aqueous adsorption and removal of organic contaminants by carbon nanotubes," *Science of the Total Environment*, vol. 482–483, pp. 241–251, 2014.
- [26] M. Sakuma, S. Hori, T. Hayashida, S. Mayama, and K. Umemura, "A new method for removing dispersed carbon nanotubes from aqueous solution by nanoporous biosilica (frustule)," *Journal of Porous Materials*, vol. 20, no. 4, pp. 961–966, 2013.
- [27] K. L. Salipira, B. B. Mamba, R. W. Krause, T. J. Malefetse, and S. H. Durbach, "Carbon nanotubes and cyclodextrin polymers for removing organic pollutants from water," *Environmental Chemistry Letters*, vol. 5, no. 1, pp. 13–17, 2007.
- [28] W. S. Huang, C. H. Yang, and S. H. Zhang, "Simultaneous determination of 2-nitrophenol and 4-nitrophenol based on the multi-wall carbon nanotubes nafion-modified electrode," *Analytical and Bioanalytical Chemistry*, vol. 375, no. 5, pp. 703–707, 2003.
- [29] J. Zheng, J. Hu, and F. Du, "Modification of carbon nanotubes with sodium p-aminobenzenesulfonate and its effect on Cu^{2+} adsorption," *New Carbon Materials*, vol. 28, no. 1, pp. 14–19, 2013.
- [30] Y. Zhou, B. Wen, Z. Pei et al., "Coadsorption of copper and perfluorooctane sulfonate onto multi-walled carbon nanotubes," *Chemical Engineering Journal*, vol. 203, pp. 148–157, 2012.
- [31] A. Mehrizad, M. Aghaie, P. Gharbani, S. Dastmalchi, M. Monajjemi, and K. Zare, "Comparison of 4-chloro-2-nitrophenol adsorption on single-walled and multi-walled carbon nanotubes," *Iranian Journal of Environmental Health Science & Engineering*, vol. 9, no. 1, article 5, 2012.
- [32] L. P. Lukhele, R. W. M. Krause, Z. P. Nhlabatsi, B. B. Mamba, and M. N. B. Momba, "Copper and silver impregnated carbon nanotubes incorporated into cyclodextrin polyurethanes for the removal of bacterial and organic pollutants in water," *Desalination and Water Treatment*, vol. 27, no. 1–3, pp. 299–307, 2011.
- [33] J. Yu, K. Huang, Q. Yang, and Y. Liu, "Solubilizing polycarbonate-modified single-walled carbon nanotubes by simultaneously attaching octadecylamine," *Physica E: Low-Dimensional Systems and Nanostructures*, vol. 41, no. 5, pp. 771–774, 2009.
- [34] J. Yu, K. Huang, S. Liu, and J. Tang, "Preparation and characterization of soluble methyl- β -cyclodextrin functionalized single-walled carbon nanotubes," *Physica E: Low-Dimensional Systems and Nanostructures*, vol. 40, no. 3, pp. 689–692, 2008.
- [35] J. Yu, D. Huang, K. Huang, and Y. Hong, "Cross-linking of multi-walled carbon nanotubes with polyethylene glycol," *Polymer: Plastics Technology and Engineering*, vol. 50, no. 3, pp. 328–331, 2011.
- [36] J. Yu, D. Huang, K. Huang, and Y. Hong, "Preparation of hydroxypropyl- β -cyclodextrin cross-linked multi-walled carbon nanotubes and their application in enantioseparation of clenbuterol," *Chinese Journal of Chemistry*, vol. 29, no. 5, pp. 893–897, 2011.
- [37] J. G. Yu, K. L. Huang, S. Q. Liu, J. C. Tang, and L. Q. Chen, "Modification of brominated multiple-walled carbon nanotubes with octadecanol through nucleophilic substitution," *Chinese Journal of Inorganic Chemistry*, vol. 24, no. 2, pp. 293–297, 2008.
- [38] Y. K. Chen, M. L. H. Green, J. L. Griffin, J. Hammer, R. M. Logo, and S. C. Tsang, "Purification and opening of carbon nanotubes via bromination," *Advanced Materials*, vol. 8, no. 12, pp. 1012–1015, 1996.
- [39] J. Tang, K. Huang, J. Yu, and S. Liu, "Mechanical property and pH sensitivity of chitosan-carbon nanotube/chitosan semi-interpenetrating hydrogel," *Acta Chimica Sinica*, vol. 66, no. 5, pp. 541–544, 2008.
- [40] J. Yu, K. Huang, J. Tang, Q. Yang, and D. Huang, "Rapid microwave synthesis of chitosan modified carbon nanotube composites," *International Journal of Biological Macromolecules*, vol. 44, no. 4, pp. 316–319, 2009.
- [41] J. Yu, K. Huang, Y. Hong, and D. Huang, "Preparation and characterization of dichlorocarbene modified multiple-walled carbon nanotubes," *Chemical Research in Chinese Universities*, vol. 23, no. 5, pp. 505–507, 2007.
- [42] J. G. Yu, K. L. Huang, and J. C. Tang, "Chemical attachment of dibromocarbene to carbon nanotubes," *Physica E: Low-Dimensional Systems & Nanostructures*, vol. 41, no. 2, pp. 181–184, 2008.
- [43] J. Yu, X. Jiang, D. Zeng, X. Chen, F. Jiao, and Z. Peng, "Preparation and characterization of diiodocarbene functionalized multi-walled carbon nanotubes," *Current Nanoscience*, vol. 9, no. 1, pp. 89–92, 2013.
- [44] W. Huang, S. Fernando, L. F. Allard, and Y. Sun, "Solubilization of single-walled carbon nanotubes with diamine-terminated oligomeric poly(ethylene glycol) in different functionalization reactions," *Nano Letters*, vol. 3, no. 4, pp. 565–568, 2003.
- [45] M. Shim, N. W. S. Kam, R. J. Chen, Y. Li, and H. Dai, "Functionalization of carbon nanotubes for biocompatibility and biomolecular recognition," *Nano Letters*, vol. 2, no. 4, pp. 285–288, 2002.
- [46] V. Datsyuk, M. Kalyva, K. Papagelis et al., "Chemical oxidation of multiwalled carbon nanotubes," *Carbon*, vol. 46, no. 6, pp. 833–840, 2008.
- [47] B. K. Price, J. R. Lomeda, and J. M. Tour, "Aggressively oxidized ultra-short single-walled carbon nanotubes having oxidized sidewalls," *Chemistry of Materials*, vol. 21, no. 17, pp. 3917–3923, 2009.

- [48] J. G. Yu, K. L. Huang, Y. Homg, and D. S. Huang, "Preparation and characterization of dichlorocarbene modified multiple-walled carbon nanotubes," *Chemical Research in Chinese Universities*, vol. 23, no. 5, pp. 505–507, 2007.
- [49] J. G. Yu, K. L. Huang, and J. C. Tang, "Chemical attachment of dibromocarbene to carbon nanotubes," *Physica E: Low-Dimensional Systems and Nanostructures*, vol. 41, no. 2, pp. 181–184, 2008.
- [50] J. G. Yu, X. Y. Jiang, D. M. Zeng, X. Q. Chen, F. P. Jiao, and Z. G. Peng, "Preparation and characterization of diiodocarbene functionalized multi-walled carbon nanotubes," *Current Nanoscience*, vol. 9, no. 1, pp. 89–92, 2013.
- [51] J. Chen, M. A. Hamon, H. Hu et al., "Solution properties of single-walled carbon nanotubes," *Science*, vol. 282, pp. 95–98, 1998.
- [52] W. B. Yang, Y. P. Lu, F. F. Zheng, X. X. Xue, N. Li, and D. M. Liu, "Adsorption behavior and mechanisms of norfloxacin onto porous resins and carbon nanotube," *Chemical Engineering Journal*, vol. 179, pp. 112–118, 2012.
- [53] F. Yu, Y. Wu, X. Li, and J. Ma, "Kinetic and thermodynamic studies of toluene, ethylbenzene, and m -xylene adsorption from aqueous solutions onto KOH-activated multiwalled carbon nanotubes," *Journal of Agricultural and Food Chemistry*, vol. 60, no. 50, pp. 12245–12253, 2012.



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