



Effect of fullerol nanoparticles on the transport and release of copper ions in saturated porous media

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Abstract

While the application and discharge of carbon nanomaterials (CNMs) increased rapidly, the research on the environmental safety of CNMs is also increasing. The high dispersity and mobility of modified CNMs in environmental media may have impacts on the environmental behavior of heavy metals. This work mainly studied the effect of fullerol nanoparticles ($C_{60}(OH)_n$) on Cu^{2+} transport, sorption, and release in water-saturated porous media. The results showed that due to the strong adsorption capacity of $C_{60}(OH)_n$ for Cu^{2+} , the transport of Cu^{2+} could be facilitated. However, with the pre-existence of $C_{60}(OH)_n$ in porous media, the transport of Cu^{2+} was also slightly enhanced. In addition, when loaded into the pre-contaminated porous medium, the $C_{60}(OH)_n$ also enhanced the release of retained Cu^{2+} , which implies a high environmental risk of $C_{60}(OH)_n$.

Keywords Environmental behavior · Copper ions · Fullerol nanoparticles · Facilitate

Introduction

Carbon nanomaterials (CNMs) take up a unique position in nanoscience and technology. Because of their excellent properties such as high chemical stability, mechanical strength, specific surface area, and electrical conductivity, CNMs have been applied in multiple areas (Choi et al. 2010; Eissa et al. 2017; Jariwala et al. 2013; Hou et al. 2016; Kato et al. 2010; Liu et al. 2009). The big amount of production and utilization of CNMs will inevitably give rise to the release of them into the environment, resulting in potential risks to human health and the ecological environment (Hou et al. 2017; Pérez et al. 2009; Selck et al. 2016; Wang et al. 2010).

Most kinds of CNMs show low stability and mobility in aqueous environment because of their high hydrophobicity. Therefore, in practical applications, to prepare uniform and well-dispersed CNMs, popular surface modification techniques have been widely applied (Zhu et al. 2003). For example, carbon nanotubes could be modified with various functional groups on their surfaces via covalent or non-covalent methods (Bolong et al. 2009; Bougeard et al. 2010; Chowdhury et al. 2011; Tian et al. 2013) to improve their hydrophilicity and dispersity in aqueous media (Ahmed et al. 2012; Saleh et al. 2008; Treviñocordero et al. 2013).

Numerous studies have shown that modified CNMs had high stability and mobility, and particularly, the surface modification could considerably enhance the adsorption ability (Rao et al. 2007). In an aquatic environment, the presence of colloidal modified CNMs might increase the risk of colloid-facilitated transport of adsorbed environmental pollutants (Vendelboe et al. 2012). For example, Johnson et al. (2009) have shown that nanoparticles have a strong adsorption capacity for soil organic matters and can promote their mobility in porous media. Zhang et al. (2011) reported that fullerene nanoparticles could significantly enhance the transport and mobility of organic contaminants polychlorinated biphenyl (PCB) and phenanthrene.

Furthermore, heavy metals, as a group of the typical environment contaminants, could also interact with CNMs in an aqueous environment (Li et al. 2013; Rao et al. 2007; Yuan

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and Peng 2017). Studies proved that CNMs had strong adsorption ability for heavy metals, and the mechanism was mainly the electrostatics attraction, complexation between heavy metal ions and the surface functional groups of CNMs, and the sorption-precipitation (Gupta and Saleh 2013). Yuan and Peng (2017) found that in the saturated aqueous environment, $C_{60}(OH)_n$ facilitated Cu^{2+} transport mainly by decreasing the retention factor of Cu^{2+} on porous media, and pH and $C_{60}(OH)_n$ concentration had significant effects on it. Moreover, Newman et al. (1993) found that the association with mobile colloids could facilitate the transport of metals through soil-packed columns, and alterations in eluent chemistry had apparent influence on it, such as pH and ionic strength. Most natural organic matters were found to significantly increase the metal transport by complexation in aqueous system (Schmitt et al. 2003). Bradford and Kim (2010) reported that the transport of Cu^{2+} was dramatically enhanced by adsorption on clay colloidal particles that were released following cation exchange and ionic strength reduction in porous media.

However, to date, the research on the influence of CNMs on the transport and release of heavy metals in environmental media is still limited. In this study, fullerol nanoparticles and Cu^{2+} were respectively selected as representative materials of CNMs and heavy metals; co-transport experiments of Cu^{2+} and fullerols in water-saturated porous media were conducted to investigate the environmental risks of the fullerols. However, in some cases, the existing order of fullerols and Cu^{2+} in the environmental media was different; therefore, the transport experiments of Cu^{2+} in fullerol-existed porous media and the release experiments of Cu^{2+} under the effect of fullerols in pre-contaminated porous media were conducted respectively to further clarify the environmental risks of fullerols.

Methods

Materials and characterization

Solid fullerols was purchased from Nanjing XFNANO Materials Tech Co. Ltd. (Nanjing, China). It was claimed to have 18 to 28 hydroxy functional groups by the producer. The fullerol dispersion utilized in this research was prepared by simply weighing a predetermined amount of solid fullerols and adding into a certain amount of DI water. Other chemicals of guaranteed reagent (GR) grade, including copper nitrate, nitric acid, sodium hydroxide, and sodium chloride, were provided by Sinopharm Chemical Reagent Co. Ltd. Quartz sand was bought from Beijing Shuangxiangda Instrument Sales Department. The average particle size of the quartz sand was measured by a Laser Diffraction Particle Size Analyzer (Mastersizer 2000, Malvern Instruments, Ltd. UK) to be 523 μm .

The UV-visible Spectrophotometer (DR5000, Hach Company, USA) was used to determine the concentration of fullerol dispersion. The measurement was conducted at 342 nm with 10-mm quartz cells, where a good correlation between the absorbance and the fullerol concentration was observed. The particle morphology of fullerol dispersion was observed by TEM (H-7500, Hitachi Ltd. Japan). The data used in each figure were taken from the average of three replicate experiments, and the standard deviation of each group of data was within $\pm 5\%$.

Copper transport experiments

Batch column experiments were employed to study the co-transport of fullerol nanoparticles and Cu^{2+} . The experimental setup is shown in Fig. 1. Polymethyl methacrylate (PMMA) columns with a height of 12 cm and the inner diameter of 3 cm were employed in the column experiments. Cleaned dry quartz sand was used as the porous media for convenient operation, and it was dry-packed into the column at several times. For each time, 1–2-cm height of sand was packed with slight patting on the column side face. After that, the porosity of the packed column was measured to be 0.38 ± 0.01 . For each column, DI water was input upward for at least 24 h at a relatively fast groundwater flow velocity of 60 ± 0.5 cm/h by a peristaltic pump to avoid bubbles and stabilize the flow velocity. Then a certain amount of influent solution was loaded into the column upward.

Two different influent solutions were used in the experiment of Cu^{2+} transport with fullerol nanoparticles. One was pure Cu^{2+} solution with a concentration measured to be 10.01 mg/L, and another was mixed Cu^{2+} solution and fullerol dispersion where the Cu^{2+} concentration was 9.89 mg/L and the fullerols concentration was 100 mg/L. The concentration of Cu^{2+} and fullerol

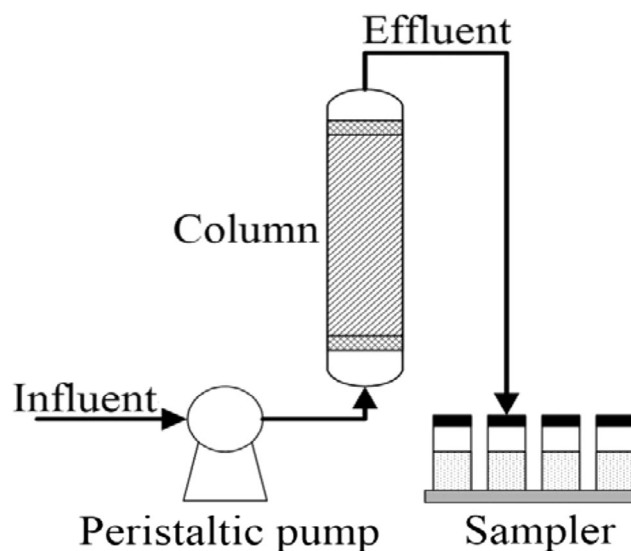


Fig. 1 The apparatus of the column experiments

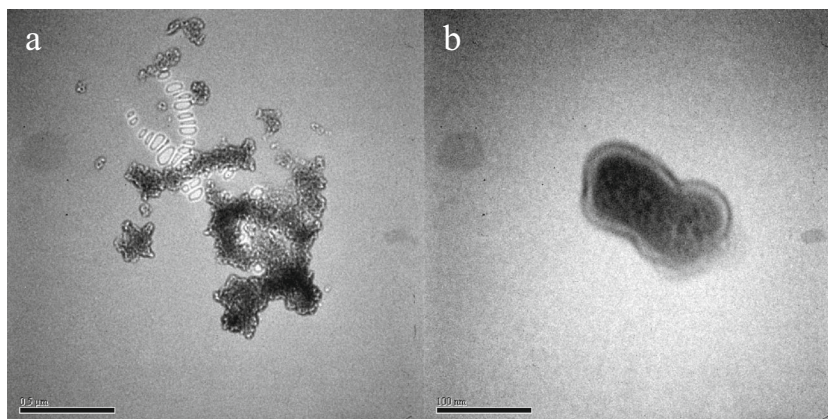
was selected based on a typical contaminative concentration. Before being input into the column, the mixed solution was stirred at 25 °C, 170 rpm for at least 24 h for complete adsorption. After the column was flushed by DI water, the influent was input upward and the effluent was sampled at a fixed interval by a fraction collector (SBS-100, Shanghai Qing Pu-Hu xi Instruments Factory, China). The Cu^{2+} concentration of samples was analyzed by an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (ICPE-9800, Shimadzu Corporation, Japan).

The column setup was the same as mentioned above when studying Cu^{2+} transport in fullerol-existed porous media. After the flow velocity was stable, 100 mg/L fullerol dispersion or DI water was loaded upward into the column at the same velocity for about 3.5 h. Effluent samples of fullerol dispersion were collected to calculate the fullerol retention rate. After that, 10.01 mg/L (C_0) of Cu^{2+} solution was input as influent, and the effluent samples were collected at a fixed interval. Cu^{2+} and fullerol concentration were measured by the methods mentioned above.

Copper release experiments

The Cu^{2+} release from the pre-contaminated porous media was investigated by column experiments. The column setup was the same as mentioned above and the porosity was measured to be about 0.39. Firstly, the column was flushed with DI water at about an average flow velocity of 12 cm/h for at least 24 h. After flushing the column, 10.01 mg/L Cu^{2+} solution was loaded upward into the column at the same velocity for about 16 h to make sure that the media were completely contaminated. Measurement of the effluent showed that no Cu^{2+} was detected in the effluent, which means that the Cu^{2+} was most retained in the column and the porous media had already been contaminated. Then 100 mg/L fullerol dispersion or DI water was loaded into the column upward to flush the column for about 20 h. Effluent samples were collected to plot the release curve.

Fig. 2 TEM images of fullerol nanoparticles. **a** $\times 60,000$; **b** $\times 300,000$



Adsorption isotherm

The adsorption isotherms of Cu^{2+} on fullerols and porous media (quartz sand) were studied. Firstly, a certain amount of Cu^{2+} solutions was added into a series of 50-mL centrifuge tubes containing 50 mg/L $\text{C}_{60}(\text{OH})_n$ dispersion. The tubes were shaken at 25 °C, 170 rpm for 24 h and then sampled with an injector. To remove $\text{C}_{60}(\text{OH})_n$ completely, samples were filtered using a 3 KD Millipore Ultrafiltration Device centrifuged at 10,000 rpm for 20 min. Then the Cu^{2+} concentration was analyzed to obtain the adsorption isotherm of Cu^{2+} on fullerols. Secondly, a certain amount of Cu^{2+} solutions was added into a series of 50-mL centrifuge tube and then 5 g cleaned and dried quartz sand was added into the tubes. The tubes were shaken at 25 °C, 170 rpm for 24 h and then sampled with an injector. The sample was filtrated using a 0.22- μm PES filter to completely remove quartz sand, and then the Cu^{2+} concentration was analyzed to obtain the adsorption isotherms of Cu^{2+} on quartz sand.

Results and discussion

Morphological properties of fullerol nanoparticles

Fullerol nanoparticles used in this study are a derivative of fullerene C_{60} . Fullerols have the same basic structure as fullerenes, which in this case are the closed carbon cages formed by 12 pentagons and 20 hexagons (Li et al. 1993). However, compared to the highly hydrophobic fullerene particles, fullerols are partly hydrophilic because of its abundant hydroxy groups on the surface of the carbon structure, which makes fullerol easily to disperse in an aqueous environment and to form very fine particles.

The morphology of fullerols in an aqueous environment was observed using TEM and the image is given in Fig. 2. When dispersed into water, fullerols will form nano-size particles whose diameters are about 90–150 nm, and these nanoparticles may gather to form bigger aggregates with diameters of hundreds of nanometers. The good dispersity in water as

well as the nano-scale particles formed by fullerols indicates that fullerol nanoparticles may have high possibility to interact with copper ions in water solutions when existing at the same time.

Transport of copper ions with fullerol nanoparticles

The effect of fullerol nanoparticles on Cu^{2+} transport is shown in Fig. 3. Obviously, the existence of fullerol nanoparticles enhanced the transport behavior of Cu^{2+} in saturated porous media. Without fullerol nanoparticles in the influent solution, the breakthrough of Cu^{2+} started at 9 PV, and the C/C_0 value reached 0.48 at 14 PV. However, when transported with fullerol nanoparticles, Cu^{2+} was detected in the effluent at 2 PV, and then the breakthrough curve experienced a quick increase from 2 PV to 4 PV and after 14 PV, the C/C_0 value reached 0.79. The transport of Cu^{2+} with fullerol nanoparticles showed similar breakthrough pattern as fullerols transport which was studied in previous research (Yuan and Peng 2017), which the C/C_0 value reached over 0.8 within 10 PV, and from 2 PV to 4 PV, the fullerols breakthrough curve rapidly increased. Considering the high dispersity and mobility of fullerol nanoparticles, it is reasonable that fullerols can enhance the mobility of Cu^{2+} when transported together in porous media. However, this phenomenon also indicates that when released into the environment, fullerol nanoparticles may interact with the heavy metal ions and further enhance their aqueous mobility, which could be harmful to the environment.

Transport of copper ions in fullerol-existed porous media

Given that in the realistic aqueous environment, there is usually not enough time for the nanoparticles to adsorb heavy

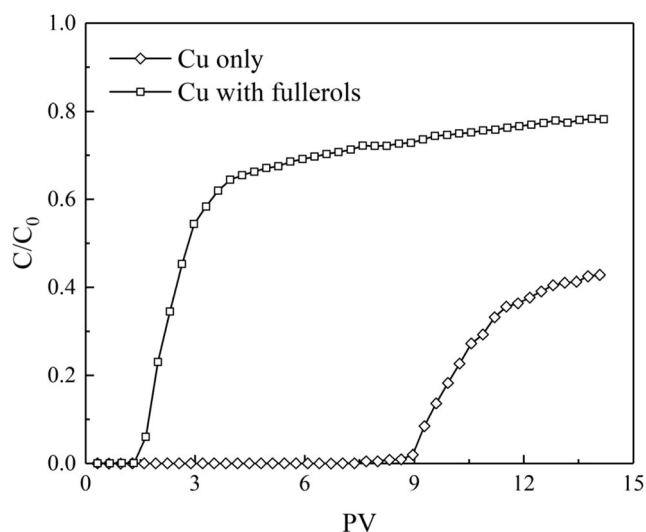


Fig. 3 Transport of Cu^{2+} with fullerol nanoparticles

metal ions until reaching to the adsorption equilibrium, the experiment of Cu^{2+} transport in fullerol-existed porous media was also conducted.

Figure 4 shows the influent and effluent concentration curves of fullerol nanoparticles. By integrating the two curves, the retention rate of fullerol nanoparticles in the porous media was calculated to be 15.24%. At the same time, since the average flow velocity applied in this experiment is relatively high (60 cm/h), the time for Cu^{2+} to react with fullerol nanoparticles is really limited.

Figure 5 shows the comparison of breakthrough curves of Cu^{2+} in the porous media with and without fullerol nanoparticles, which reflects the effect of the pre-existence of fullerol nanoparticles on Cu^{2+} transport through the porous media. It is surprisingly found that the pre-existence of fullerol nanoparticles could slightly enhance the transport of Cu^{2+} since breakthrough starts at around 2 pore volumes earlier, and the final C/C_0 value (at about 14 pore volumes) reached 0.73, which is higher than that without fullerol pre-existence (0.48). This is contrary to the hypothesis that the retained fullerol nanoparticles in porous media would adsorb Cu^{2+} and thus resulted in a higher retention of Cu^{2+} in porous media. In fact, results in accordance with this hypothesis have been found in other studies. A study found that under relatively high ion strength, the average percent elution of gold nanospheres is lower for the coated sand by pluronic acid modified single-walled carbon nanotubes, but this effect is very small at low ion strength (Afrooz et al. 2016). Besides, it was reported that graphene oxide (GO) enabled the sand column to increase the metal removal efficiency of Cu and Pb, and higher GO amount led to a higher removal efficiency (Ding et al. 2014). However, in this study, the presence of fullerol nanoparticles in the column did not improve the deposition of Cu^{2+} but enhanced its transport instead. This may indicate that although fullerol

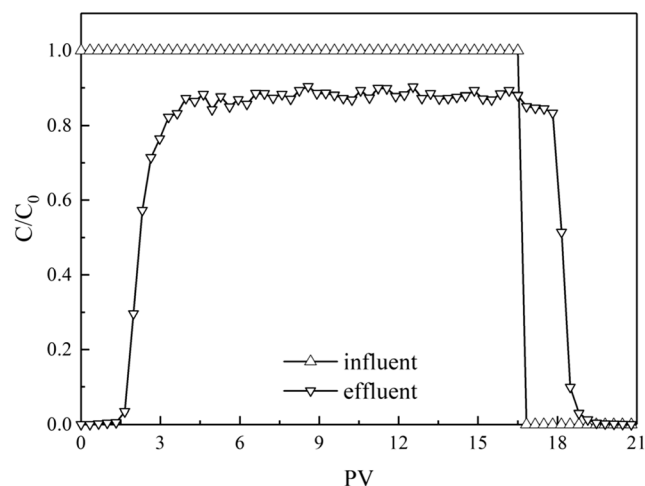


Fig. 4 The influent and effluent concentration curves of fullerol nanoparticles

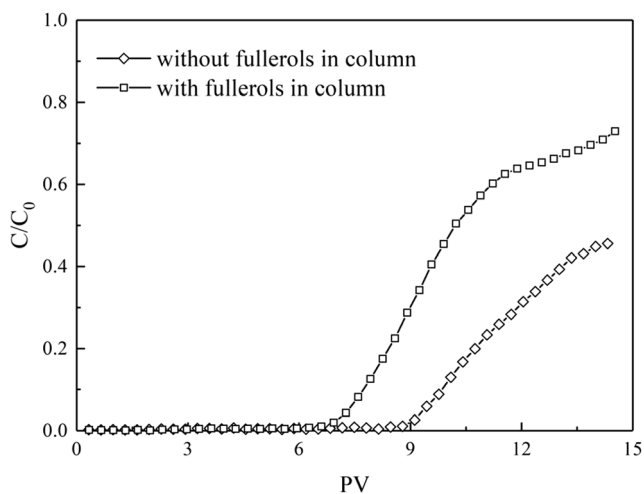


Fig. 5 Transport of Cu^{2+} with and without fullerols pre-existed in columns

nanoparticles partly retained in the column, they did not closely combine with the quartz sand surface. Therefore, when Cu^{2+} solution was loaded into the column, the retained fullerol nanoparticles may be released from the column and at the same time, carrying some Cu^{2+} to transport. Besides, based on some similar study results (Han et al. 2013; Li et al. 2013; Wu et al. 2016, 2017; Yang et al. 2012), the competition for deposition site on the quartz sand surface by Cu^{2+} and fullerol nanoparticles could be another important reason result in the enhanced transport of Cu^{2+} . However, these hypotheses need further experiments to verify.

Release of copper ions in pre-contaminated porous media

To further determine the environmental risk of fullerol nanoparticles, the impact of fullerol nanoparticles on Cu^{2+} release from the porous media was studied by comparing the Cu^{2+} release rate from columns flushed by fullerol dispersion and by DI water. Figure 6 gives the release curves of Cu^{2+} from the pre-contaminated porous media with and without fullerol nanoparticles; the inset figure in Fig. 6 is the magnification of the release curve of Cu^{2+} from 0 PV to 10 PV when the column was flushed by DI water.

When the influent was fullerol dispersion, the presence of Cu^{2+} was detected in the samples from 2 pore volumes, and the highest Cu^{2+} concentration measured was 10.5 mg/L whereas the concentration of Cu^{2+} solution used to contaminate the column was only 10.01 mg/L. By integrating the release curve, the total Cu^{2+} release rate was up to 73.8% when flushed by fullerol nanoparticles. However, when the influent was DI water, only a few Cu^{2+} were detected at around 3 pore volumes, and the release rate of Cu^{2+} was only 0.4%. The results imply that fullerol nanoparticles could significantly enhance the release of Cu^{2+} from the contaminated porous media and further promote its

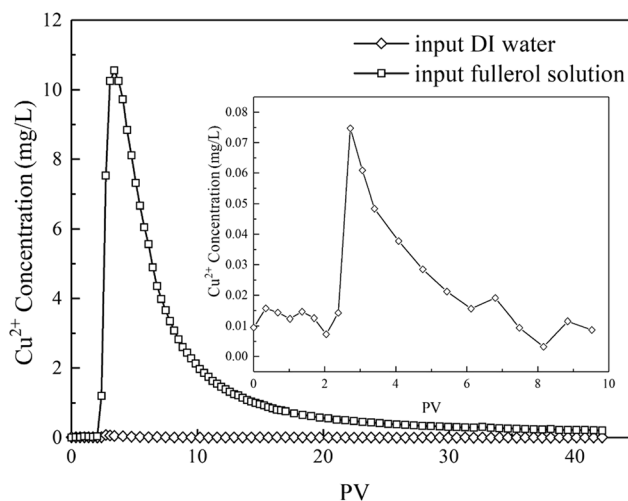


Fig. 6 Effect of fullerol nanoparticles on the release of Cu^{2+} from pre-contaminated porous media

transport, which was mainly achieved in two steps. Firstly, due to the strong adsorption capacity of fullerol nanoparticles for copper ions, when fullerol dispersion was loaded in, the most copper ions retained in the column were released. Secondly, because fullerol nanoparticles have a very high transport ability in porous media, it could carry the released copper ion transport. Therefore, fullerol nanoparticles should be regarded as having environmental risks.

Adsorption isotherms

Figure 7 shows the adsorption isotherm of Cu^{2+} on fullerol nanoparticles. The maximum adsorption capability is almost up to 200 mg/g, which shows that the fullerol nanoparticles have a very high adsorption ability on Cu^{2+} . Figure 8 shows the adsorption isotherm of Cu^{2+} on quartz sand. The maximum adsorption capability is only 0.0911 mg/g. These results indicate that Cu^{2+} is more easily to be adsorbed by fullerol

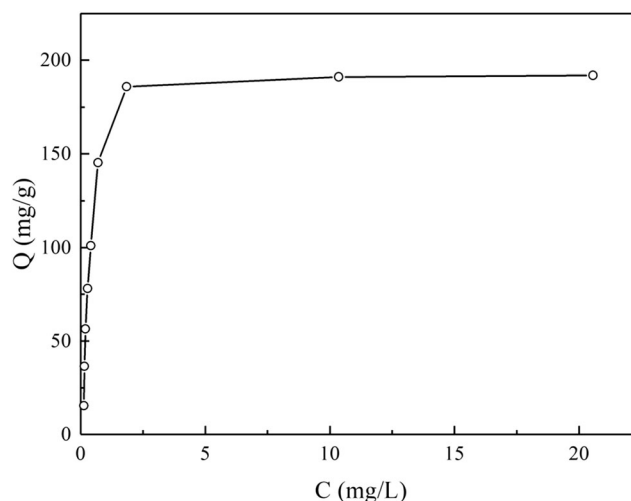


Fig. 7 Adsorption isotherm of copper ions on fullerols

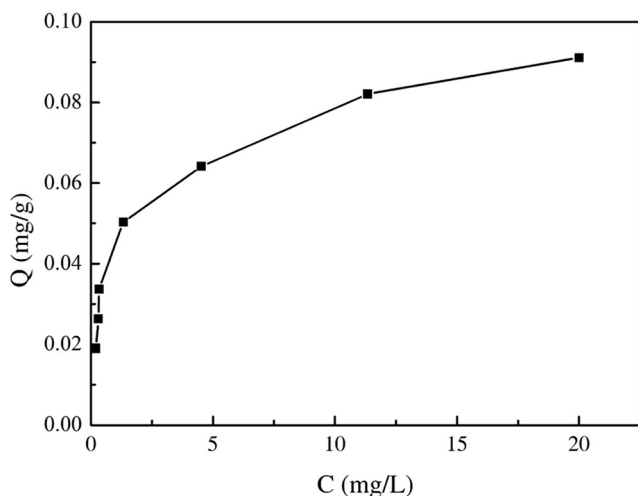


Fig. 8 Adsorption isotherm of copper ion on quartz sand

nanoparticles other than by the porous media. Thus, the existence of fullerols can have significant influence on Cu^{2+} transport and release due to the adsorption effect.

Conclusions

In this study, based on the high dispersity and mobility of fullerol nanoparticles in water-saturated porous media and the strong adsorption behavior for Cu^{2+} , the effect of fullerol nanoparticles on the transport and release of Cu^{2+} was studied in saturated aquatic environment. The following can be concluded.

- (1) Fullerol nanoparticles can facilitate the transport of Cu^{2+} in saturated porous media.
- (2) With the pre-existence of fullerol nanoparticles in saturated porous media, the transport of Cu^{2+} is slightly increased, which may be because the release of retained fullerols when Cu^{2+} solution is loaded into the column and the competition for deposition site on the quartz sand surface between fullerols with Cu^{2+} .
- (3) When loaded into the pre-contaminated porous media, the fullerol nanoparticles can increase the release of retained Cu^{2+} .

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References

Afroz AR, Das D, Murphy CJ, Vikesland P, Saleh NB (2016) Co-transport of gold nanospheres with single-walled carbon nanotubes in saturated porous media. *Water Res* 99:7–15

- Ahmed F, Santos CM, Vergara RA, Tria MC, Advincula R, Rodrigues DF (2012) Antimicrobial applications of electroactive PVK-SWNT nanocomposites. *Environ Sci Technol* 46(3):1804–1810
- Bolong N, Ismail AF, Salim MR, Matsuura T (2009) A review of the effects of emerging contaminants in wastewater and options for their removal. *Desalination* 239(1):229–246
- Bougard CM, Goslan EH, Jefferson B, Parsons SA (2010) Comparison of the disinfection by-product formation potential of treated waters exposed to chlorine and monochloramine. *Water Res* 44(3):729–740
- Bradford SA, Kim H (2010) Implications of cation exchange on clay release and colloid-facilitated transport in porous media. *J Environ Qual* 39(6):2040–2046
- Choi W, Lahiri I, Seelaboyina R, Kang YS (2010) Synthesis of graphene and its applications: a review. *Crit Rev Solid State* 35(1):52–71
- Chowdhury S, Rodriguez MJ, Sadiq R (2011) Disinfection byproducts in Canadian provinces: associated cancer risks and medical expenses. *J Hazard Mater* 187(1):574–584
- Ding Z, Hu X, Morales VL, Gao B (2014) Filtration and transport of heavy metals in graphene oxide enabled sand columns. *Chem Eng J* 257(8):248–252
- Eissa S, Alshehri N, Rahman AMA, Dasouki M, Salah KMA, Zourob M (2017) Electrochemical immunosensors for the detection of survival motor neuron (SMN) protein using different carbon nanomaterials-modified electrodes. *Biosens Bioelectron* 101:282–289
- Gupta VK, Saleh TA (2013) Sorption of pollutants by porous carbon, carbon nanotubes and fullerene - an overview. *Environ Sci Pollut Res* 20(5):2828–2843
- Han P, Shen X-F, Yang H-Y, Kim H, Tong M-P (2013) Influence of nutrient conditions on the transport of bacteria in saturated porous media. *Colloid Surf B* 102:752–758
- Hou J, Wang X, Hayat T (2016) Ecotoxicological effects and mechanism of CuO nanoparticles to individual organisms. *Environ Pollut* 221:209–217
- Hou J, Zhou Y, Wang C, Li S, Wang X (2017) Toxic effects and molecular mechanism of different types of silver nanoparticles to the aquatic crustacean daphnia magna. *Environ Sci Technol* 51(21):12868–12878
- Jariwala D, Sangwan VK, Lauhon LJ, Marks TJ, Hersam MC (2013) ChemInform abstract: carbon nanomaterials for electronics, optoelectronics, photovoltaics, and sensing. *Chem Soc Rev* 42(7):2824–2860
- Johnson RL, Johnson GO, Nurmi JT, Tratnyek PG (2009) Natural organic matter enhanced mobility of nano zerovalent iron. *Environ Sci Technol* 43(14):5455–5460
- Kato S, Taira H, Aoshima H, Saitoh Y, Miwa N (2010) Clinical evaluation of fullerene-C60 dissolved in squalane for anti-wrinkle cosmetics. *J Nanosci Nanotechnol* 10(10):6769–6774
- Li J, Takeuchi A, Ozawa M, Li X, Saigo K, Kitazawa K (1993) C₆₀ fullerol formation catalysed by quaternary ammonium hydroxides. *J Chem Soc Chem Commun* 23(23):1784–1785
- Li C, Tong M-P, Ma H-Y, Kim H (2013) Cotransport of titanium dioxide and fullerene nanoparticles in saturated porous media. *Environ Sci Technol* 47(11):5703–5710
- Liu Z, Tabakman S, Welsher K, Dai H (2009) Carbon nanotubes in biology and medicine: in vitro and in vivo detection, imaging and drug delivery. *Nano Res* 2:85–120
- Newman ME, Elzerman AW, Looney BB (1993) Facilitated transport of selected metals in aquifer material packed columns. *J Contam Hydrol* 14(3–4):233–246
- Pérez S, Farré ML, Barceló D (2009) Analysis, behavior and ecotoxicity of carbon-based nanomaterials in the aquatic environment. *Trends Anal Chem* 28(6):820–832
- Rao GP, Lu C, Su F (2007) Sorption of divalent metal ions from aqueous solution by carbon nanotubes: a review. *Sep Purif Technol* 58(1):224–231

- Saleh NB, Pfefferle LD, Elimelech M (2008) Aggregation kinetics of multiwalled carbon nanotubes in aquatic systems: measurements and environmental implications. *Environ Sci Technol* 42(21):7963–7969
- Schmitt D, Saravia F, Frimmel FH, Schuellser W (2003) NOM-facilitated transport of metal ions in aquifers: importance of complex-dissociation kinetics and colloid formation. *Water Res* 37(15):3541–3550
- Selck H, Handy RD, Fernandes TF, Klaine SJ, Petersen EJ (2016) Nanomaterials in the aquatic environment: an European Union–United States perspective on the status of ecotoxicity testing, research priorities, and challenges ahead. *Environ Toxicol Chem* 35(5):1055–1067
- Tian C, Liu R, Liu H, Qu J (2013) Disinfection by-products formation and precursors transformation during chlorination and chloramination of highly-polluted source water: significance of ammonia. *Water Res* 47(15):5901–5910
- Treviñocordero H, Juárezaguilar LG, Mendozacastillo DI, Hernándezmontoya V, Bonillapetriciolet A, Montesmorán MA (2013) Synthesis and adsorption properties of activated carbons from biomass of *Prunus domestica* and *Jacaranda mimosifolia* for the removal of heavy metals and dyes from water. *Ind Crop Prod* 42(1):315–323
- Vendelboe AL, Moldrup P, Schjønning P, Oyedele DJ, Jin Y, Scow KM (2012) Colloid release from soil aggregates: application of laser diffraction. *Vadose Zone J* 11(1):120–128
- Wang Y-G, Li Y-S, Kim H, Walker SL, Abriola LM, Pennell KD (2010) Transport and retention of fullerene nanoparticles in natural soils. *J Environ Qual* 39(6):1925–1933
- Wu D, Tong M-P, Kim H (2016) Influence of perfluorooctanoic acid on the transport and deposition behaviors of bacteria in quartz sand. *Environ Sci Technol* 50(5):2381–2388
- Wu D, He L, Sun R, Tong M-P, Kim H (2017) Influence of bisphenol a on the transport and deposition behaviors of bacteria in quartz sand. *Water Res* 121:1–10
- Yang H-Y, Kim H, Tong M-P (2012) Influence of humic acid on the transport behavior of bacteria in quartz sand. *Colloid Surf B* 91:122–129
- Yuan Y, Peng X-J (2017) Fullerol-facilitated transport of copper ions in water-saturated porous media: influencing factors and mechanism. *J Hazard Mater* 340:96–103
- Zhang L, Wang L, Zhang P, Kan AT, Chen W, Tomson MB (2011) Facilitated transport of 2,2',5,5'-polychlorinated biphenyl and phenanthrene by fullerene nanoparticles through Sandy soil columns. *Environ Sci Technol* 45(4):1341–1348
- Zhu J, Yudasaka M, Zhang M-F, Kasuya D, Iijima S (2003) A surface modification approach to the patterned assembly of single-walled carbon nanomaterials. *Nano Lett* 3:1239–1243

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