Separation and Purification Technology 157 (2016) 141–161

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Review

Heavy metal removal from aqueous solution by advanced carbon nanotubes: Critical review of adsorption applications

Ihsanullah [a], Aamir Abbas [a], Adnan M. Al-Amer [a,*], Tahar Laoui [b,*], Mohammed J. Al-Marri [c], Mustafa S. Nasser [c,*], Majeda Khraisheh [c,d], Muataz Ali Atieh [e,f,*]

[a] Department of Chemical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[b] Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[c] Gas Processing Center, Qatar University, P.O. Box 2713, Doha, Qatar
[d] Chemical Engineering Department, Qatar University, P.O. Box 2713, Doha, Qatar
[e] Qatar Environment and Energy Research Institute (QEERI), Qatar Foundation, P.O. Box 5825, Doha, Qatar
[f] College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, P.O. Box 5825, Doha, Qatar

ARTICLE INFO

Article history:
Received 6 September 2015
Received in revised form 21 November 2015
Accepted 26 November 2015
Available online 27 November 2015

Keywords:
Carbon nanotubes
Heavy metals
Adsorption
Water treatment

ABSTRACT

The scarcity of water, especially in arid and semi-arid regions of the world is exerting great pressure on resources and establishing more need to provide good quality water for human and other consumptions. Water recovery/recycle/reuse has proven to be effective and successful in creating a new and reliable water supply. Accordingly, attention is being paid to the effective treatment of alternative sources of water (apart from fresh water) such as seawater, storm water, wastewater (e.g. treated sewage water), and industrial wastewater. In this review, the use of carbon nanotubes (CNTs), member of the fullerene structural family, is considered with special focus on the removal of heavy metals from water (lead, chromium, cadmium, arsenic, copper, zinc and nickel). A critical review into the adsorption behavior and use of the CNTs is given with attention being paid to the effects of surface modifications on the adsorption behavior and subsequent heavy metal removal. A review of the effect of a number of key variables including pH, CNTs dosage, time, ionic strength, temperature and surface charge are given. It will be demonstrated that, surface modification enhances positively the adsorption capacity of CNTs towards cadmium, chromium, lead, mercury, copper, zinc, cobalt and nickel as did the solution pH. CNTs have been proven to an excellent adsorbent for the removal of different heavy metals from water. However, most of the applications of CNTs are on lab scale in batch experiments. In spite of high costs, CNTs are expected to be a promising adsorbent in the future due to its high adsorption capacity compared to many traditional adsorbents. Researchers are also in quest of novel environment friendly techniques for the surface modification of CNTs to further improve their properties. Still, the feasibility of CNTs application in large scale treatment needs to be further studied. Effective techniques for regeneration/reuse of CNTs also need to be explored yet. One of the main hurdles that limit the applications of CNTs in large scale operation is the cost of CNTs. Future research works on developing a cost-effective way of CNT production and testing the toxicity of CNTs and CNT-related materials are recommended.

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* Corresponding authors at: Qatar Environment and Energy Research Institute (QEERI), Qatar Foundation, P.O. Box 5825, Doha, Qatar (M.A. Atieh).
E-mail addresses: alamer@kfupm.edu.sa (A.M. Al-Amer), tlaoui@Kfupm.edu.sa (T. Laoui), m.nasser@qu.edu.qa (M.S. Nasser), mhussien@qf.org.qa (M.A. Atieh).

http://dx.doi.org/10.1016/j.seppur.2015.11.039
1383-5866/

1. Introduction

Heavy metals in general have a density greater than 5 g per cubic centimeter and atomic weights between 63.5 and 200.6 [1–3]. The pollution of water due to release of heavy metals into ecosystem metals has been causing worldwide concern. The main sources of heavy metals are the wastewaters from modern chemical industries such as metal plating facilities, battery manufacturing, fertilizer, mining, paper and pesticides, metallurgical, mining, fossil fuel, tannery and production of different plastics such as polyvinyl chloride. The rapid industrialization during recent years has greatly contributed to heavy metals release into environment [4]. Heavy metals tend to accumulate in living organisms as they are not biodegradable, unlike organic contaminants. Toxic heavy metals of particular concern, in treatment of industrial wastewaters include lead, chromium, cadmium, mercury, arsenic, nickel, copper and zinc.

The toxic effects of heavy metals such as arsenic, cadmium, chromium, mercury, zinc and lead on human health have been investigated extensively. The possible symptoms of the toxic metals includes high blood pressure, speech disorders, fatigue, sleep disabilities, aggressive behavior, poor concentration, irritability, mood swings, depression, increased allergic reactions, autoimmune diseases, vascular occlusion, and memory loss [5]. Heavy metals can also disrupt the human cellular enzymes, which run on nutritional minerals such as magnesium, zinc, and selenium. Some of the toxic heavy metals that can be harmful to human body include cadmium, lead, arsenic and mercury. Though, our body needs some heavy metals such as manganese, iron, chromium, copper and zinc but still presence in large quantities of these metals may be extremely dangerous [5–7]. This paper reviews the removal of selected metal ions (lead, chromium, cadmium, arsenic, copper, zinc and nickel) from water using carbon nanotubes.

Table 1 summarizes the allowable concentrations limits for the selected heavy metals, as reported by U.S. Environmental Agency (U.S. EPA) and World Health Organization (WHO) [8,9].

Table 1
WHO and US EPA limitations of selected heavy metal in drinking water [8,9].

Contaminant	EPA limitations		WHO provisional guideline value (mg/L)
	Maximum contamination level (MCL) (mg/L)	Maximum contamination limit goal (MCLG) (mg/L)	
Lead	0.015	0	0.01
Chromium	0.1	0.1	0.05
Cadmium	0.005	0.005	0.003
Arsenic	0.010	0	0.01
Mercury	0.002	0.002	0.006
Copper	1.3	1.3	2
Zinc	5	–	3
Nickel	–	–	0.07

2. Heavy metals in water: sources of contaminations and their toxic effects

2.1. Lead

Lead is a non-biodegradable hazardous heavy metal that easily accumulates in human body. The major source of lead in human body is the drinking water, containing substantial amount of lead. Initially it can enter the body through the digestive tract and lungs and carried spread by blood throughout the body. Presence of large quantity of lead in drinking water will cause anemia, cancer, renal kidney disease, nervous system damage and mental retardation [1–5].

2.2. Chromium

Chromium is a metal found in natural deposits as ores containing other elements such as ferric chromite ($FeCr_2O_4$), crocoite ($PbCrO_4$), and chrome ochre (Cr_2O_3). Chromium is considered one of the earth crust's most abundant elements and it is estimated to be the sixth most abundant transition metal [10]. It is a well-known highly toxic metal in drinking water. Chromium naturally found in different oxidation states ranging from 2+, 3+ and 6+, with