Environ Sci Pollut Res (2016) 23:5056–5076
DOI 10.1007/s11356-015-5880-x

REVIEW ARTICLE

Removal of mercury by adsorption: a review

Jin-Gang Yu[1] · **Bao-Yu Yue**[1] · **Xiong-Wei Wu**[2] · **Qi Liu**[1] · **Fei-Peng Jiao**[1] ·
Xin-Yu Jiang[1] · **Xiao-Qing Chen**[1,3]

Received: 12 August 2015 / Accepted: 24 November 2015 / Published online: 1 December 2015

Abstract Due to natural and production activities, mercury contamination has become one of the major environmental problems over the world. Mercury contamination is a serious threat to human health. Among the existing technologies available for mercury pollution control, the adsorption process can get excellent separation effects and has been further studied. This review is attempted to cover a wide range of adsorbents that were developed for the removal of mercury from the year 2011. Various adsorbents, including the latest adsorbents, are presented along with highlighting and discussing the key advancements on their preparation, modification technologies, and strategies. By comparing their adsorption capacities, it is evident from the literature survey that some adsorbents have shown excellent potential for the removal of mercury. However, there is still a need to develop novel, efficient adsorbents with low cost, high stability, and easy production and manufacture for practical utility.

Keywords Adsorption · Adsorbents · Mercury · Removal · Properties

Introduction

Mercury (Hg) is a naturally occurring element. It is widely used in electricity generation and industrial production such as chlor-alkali, plastics, metallurgy, and electronics. The two main oxidation states of Hg are +1 [Hg(I)] and +2 [Hg(II)] (Pervukhina et al. 1999). Mercury sulfide (HgS) is clinical used in Chinese and Indian traditional drugs, such as cinnabar and "Rasasindura," which might have little or no therapeutic effects because it may not react with any cell receptors due to its insolubility in aqueous solution (Kamath et al. 2012). Mercury chloride ($HgCl_2$) was widely used in producing polyvinyl chloride. A higher oxidation state for Hg is +4 [Hg(IV)], which has been detected only under exceptional conditions, e.g., Hg(IV) fluoride (HgF_4) (Wang et al. 2007). Another highly toxic form of Hg(II), methylmercury [MeHg, $(CH_3Hg^+)X^-$], is a bioaccumulative environmental toxicant which can be enriched in fish, shellfish, and animals that eat fish (Choi et al. 2008).

Due to its volatility, persistence, and bioaccumulation, Hg has been considered as one of the most toxic metals which can affect the health of human beings. Long-term exposure to large amounts of Hg would harm the human brain, heart, kidneys, lungs, and even the immune system (Hsiao et al. 2011). Exposure to Hg in the womb or fed with seafood containing MeHg may harm the developing nervous system of unborn babies and young children and reduce their IQs (Yau et al. 2014). Elemental (metallic) Hg [Hg^0] adsorbed through the lungs can cause health effects such as tremors, muscle atrophy, headaches, and so on when it is breathed as a vapor. However, the amount of Hg discharged into the environment is increasing continuously. Carbonaceous fuel combustion such as coal-fired plants and incinerators has contributed a lot of the current global Hg emissions. Up to now, Hg can be found in water, rocks, and soil. Additionally, trace amounts of

Responsible editor: Philippe Garrigues

✉ Jin-Gang Yu
yujg@csu.edu.cn

[1] College of Chemistry and Chemical Engineering, Central South University, Changsha, Hunan 410083, China

[2] College of Science, Hunan Agricultural University, Changsha, Hunan 410128, China

[3] Collaborative Innovation Center of Resource-Conserving and Environment-Friendly Society and Ecological Civilization, Changsha, Hunan 410083, China

Hg can even be found in the air (Heaven et al. 2000; Xue et al. 2013). High Hg concentrations in the range of Hg-associated neurochemical effects have been found in the brain tissue of Arctic toothed whales (Kamath et al. 2012).

The adverse effects from food and water mercury contamination are difficult to measure. However, over 100,000 kg of Hg was generated by human activities and discharged into the environment annually. Most of the Hg in both gaseous and liquid forms is from the coal-fired power industry (Singh et al. 2011). and Hg^0 removal from flue gas has a tremendous effect on human daily life (Zheng et al. 2012). Hg^0, $HgCl_2$, which is also called Hg(II), and MeHg have already made their way into the overall environment (Henneberry et al. 2011) and have brought great harm to the environment and human health.

Due to its bioaccumulative properties and potential risk to human health, the Hg-containing wastewater and flue gas have attracted a great global concern. Therefore, efficient methods must be developed to remove them from the environment (Liu et al. 2014d). Adsorption separation is one of the most facile, convenient, and practical technologies among the existing Hg control technologies. In the past 4 years, we have seen significant progress of Hg removal in adsorptive separation technology and materials science. The latest developed adsorbents for Hg removal are reviewed in detail in this paper.

Adsorbent development

Carbon-based adsorbents

Activated carbons (ACs)

Due to its very big internal surface (between 500 and 1500 $m^2\ g^{-1}$), AC is produced as an ideal adsorbent for removal of contaminants. AC has also been used for Hg removal for years by the researchers. Both the pore structure and chemical property of AC would affect its adsorption properties (Asasian et al. 2012; Lu et al. 2014; Zabihi et al. 2011). and the chemical modification seems to be one of the most efficient ways to improve its adsorption efficiencies (Asasian and Kaghazchi 2013a; Kim et al. 2011; Wahby et al. 2011). For example, incorporation of sulfur group to an adsorbent could improve its Hg adsorption capacities (Asasian and Kaghazchi 2013b; Hsi and Chen 2012; Morris et al. 2012). Derived from the pyrolysis, activation, and sulfurization of waste tires, the prepared AC possessed an adsorptive capacity of 5.236 $\mu g\ g^{-1}$ for vapor-phase $HgCl_2$ (Ie et al. 2012). If ACs were impregnated with several sulfur species such as elemental sulfur (S^0), aqueous-phase sodium sulfide (Na_2S), or hydrogen sulfide (H_2S), various sulfur forms such as sulfide, sulfoxide, elemental sulfur, sulfone, thiophene, and sulfate would be introduced (Ie et al. 2013). In comparison with the unmodified ACs, these sulfur-impregnated ACs exhibited higher Hg adsorption capacities (Feng et al. 2006a, b; Li et al. 2013c). Besides the sulfurization methods mentioned above, treatment of ACs by aqueous solutions of Na_2S and H_2SO_4 is also feasible (Abdelouahab-Reddam et al. 2014). Also, the newly emerged interactions between the introduced -S- group and Hg(II) are considered to favor the high adsorption efficiencies of modified ACs (Fig. 1).

The physical properties of the adsorbents such as specific surface area, pore volume, pore size, and pore number could affect their adsorption capacities. However, sulfurization of AC will reduce the number of micropores, which would restrain its adsorption capacity. To retain the porous structure of AC after modification, simultaneous sulfurization/activation of ACs was developed, and the modified ACs showed an increased Hg(II) adsorption of 1637 $m^2\ g^{-1}$ due to the higher specific surface area (ShamsiJazeyi and Kaghazchi 2014).

Besides the sulfur-containing functional groups, the introduction of other functional groups such as $-NH_2$, $-NHCOCH_3$, -Br, -Cl, -I, -C=N, -OH, and so on onto the surface of ACs is also responsible for Hg(II) adsorption (Hsi et al. 2013; Reddy et al. 2014). Various impregnating substances such as NaI, $CuCl_2$, $CuBr_2$, and $FeCl_3$ were applied to graft halogen functional groups onto the adsorbents (Zhang et al. 2012b). The Hg(II) removal efficiencies increased in the order of AC<Cl-impregnated AC<Br-impregnated AC<I-impregnated AC, indicating that the electron-donating ability of the introduced functional groups may help increase the adsorption capacities of the adsorbents (De et al. 2013).

It is really easy to collect magnetic materials by providing a magnetic environment, and magnetic AC (MAC) has found its application prospect in the adsorption field (Faulconer et al. 2012). However, as-prepared MAC is limited in practical use for removal of Hg(II) due to its poor gradient magnetic separation properties (Okamoto et al. 2011). The introduction of functional groups onto MAC was carried out, and the adsorption capacities of two kinds of modified MACs, oxidized MAC (ox-MAC) and thiol radical decorated MAC (SH-MAC), were improved (Miura and Tachibana 2014).

The resource consumption for production of ACs is huge, and the production may produce waste containing pollution to the environment at the same time. The synthesis of ACs from biomass materials through more straightforward, more

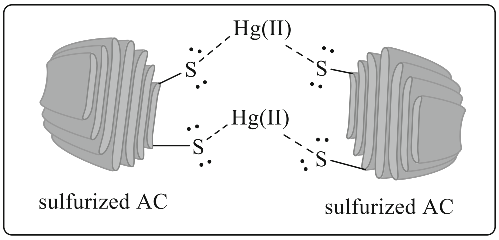

Fig. 1 The possible interactions between sulfurized AC and Hg(II)

economically viable, and greener approach is expected. Coconut shell was used to produce AC (Hu et al. 2014). and the adsorption capacity could also be improved by impregnating it with sulfur (Hsi et al. 2014).

Activated carbon fibers (ACFs)

Due to their larger surface area and lighter than that of ACs, ACFs are considered as efficient and alternative adsorbents for removal of pollution or contaminants to achieve environmental remediation. However, the comprehensive research on ACFs in removing Hg was less. Recently, dimethylsulfoxide (DMSO), disodium tetrasulfide (Na_2S_4), sodium hydrosulfide (NaSH), and sulfur vapor were used as sulfur sources to modify ACFs, and the prepared sulfur-impregnated ACFs (ACFs-SH) showed higher Hg adsorption capacities than that of pristine ACFs, demonstrating once again that sulfur impregnation is beneficial to increasing the Hg removal capacity of the adsorbents (Yao et al. 2014b).

Mesoporous carbons (MCs)

Due to its porous structure and high specific surface area, MC has been widely applied in adsorption and removal of metal ions from aqueous solutions. To maintain the high surface area and mesoporous structure of hexagonal ordered mesoporous carbon (OMC) CMK-3 and introduce functional groups, 2-amino-5-mercapto-1,3,4-thiadiazole (AMT) groups were used as the modification material, and the prepared AMT-OCMK-3 showed high adsorption capacity of 450.45 mg g^{-1} for Hg(II) (Anbia and Dehghan 2014).

The utilization of zinc oxide (ZnO) or copper (Cu) nanoparticles as efficient adsorbents for the removal of metal ions is considered viable. The diffusion or accumulation of metal ions onto the surface of ZnO or Cu nanoparticles has made important contributions to the adsorption. The ZnO-modified CMK-3 was found to adsorb Hg(II) with high removal efficiency (Zolfaghari et al. 2011). Taking advantage of the chemical affinity between Cu particles and Hg, Cu-coated porous carbon (Cu/PC) was developed for removal of Hg^0, and the surface oxidation level of Cu particles and total Cu content could affect the Hg^0 removal efficiencies (Kim et al. 2012).

Carbon nanotubes (CNTs)

Due to the large particle size of the conventional adsorbents, the massive mass transport resistance reduces their adsorption capacities. To overcome this limitation, the use of nanoscale materials as adsorbents has attracted considerable attention in recent years (Habuda-Stanic and Nujic 2015; Yao et al. 2014a). Owing to their extremely small size and large specific surface area, nanoscale adsorbents have shown many unusual physical and chemical properties. The unique properties include huge specific surface area, strong adsorption ability, high stability, and high mechanical strength. Due to these outstanding characteristics, various carbon-based nanoparticles (CBNPs) including CNTs and graphene have been used for the removal and adsorption of heavy metal ions (Yu et al. 2014c, 2015).

The introduction of functional groups onto CNTs could enhance their adsorption capacities (Yu et al. 2014b). For example, chitosan (CTS)-functionalized CNT beads, including oxidized multiwalled CNT (ox-MWCNT)-impregnated CTS beads, MWCNT-impregnated CTS beads, and single-walled CNT-impregnated CTS beads, all exhibited higher adsorption capacity toward Hg(II) than that of pristine CNTs (Shawky et al. 2012). Amino- and thiol-functionalized MWCNTs exhibited high adsorption capability for Hg(II) due to the introduction of the electron-donating groups (Hadavifar et al. 2014; Shadbad et al. 2011). and thiol-containing SWCNT (SWCNT-SH) showed threefold higher adsorption capacity than that of pristine SWCNT and fourfold higher adsorption capacity than that of AC (Bandaru et al. 2013).

Graphene and graphene oxide (GO)

As a new member of carbon-based nanomaterials, GO has attracted great attention in the adsorption field due to its huge specific surface area and the plentiful surface oxygen functional groups (Yu et al. 2015). To improve its adsorption performance, the introduction of CTS onto GO was carried out, and the CTS-nanofilled GO (GO/CTS) showed a high maximum adsorption capacity of 381 mg g^{-1} than that (187 mg g^{-1}) of the as-prepared GO (Kyzas et al. 2014). Sulfur/reduced graphene oxide (SRGO) nanohybrid also demonstrated a fast and efficient Hg(II) removal and excellent reusability (Thakur et al. 2013).

Because of the low production cost, abundant functional groups, diverse shapes and structures, strong adsorption ability, and easy processability, conducting polymers have a wide range of attractive applications in adsorption. The integration of conducting polymers with graphene might be an effective way for developing novel adsorbents. Combined with the advantages of both polyaniline (PANI) and reduced graphene oxide (RGO), the built PANI-RGO composites showed a tremendous adsorption capacity of 1000 mg g^{-1} for Hg(II), which was much higher than that (515.46 mg g^{-1}) of PANI (Li et al. 2013b).

Magnetic materials

Iron oxides

Iron oxides, such as maghemite and magnetite, possess some good characteristics such as low toxicity and price, high specific surface area, being magnetic, and easy modification of surface. Taking advantage of the high affinity of the sulfur-containing functional groups for Hg(II), the dithiocarbamate group-modified iron magnetite particles were developed as a new adsorbent for removal of Hg(II) (Figueira et al. 2011).

The assembly of multifunctional materials has attracted increasing interest in recent years, and the sterically stabilized core-shell nanoparticles could offer some significant advantages for adsorption due to the extended hydrophilic shells. Using superparamagnetic Fe_3O_4 as the core and hydrophilic silica molecular sieve as the shell, the core-shell structured Fe_3O_4@SiO_2 nanocomposites exhibited high selectivity toward Hg(II) (Jing-po et al. 2014; Tavares et al. 2013) and so did the thiol group-modified Fe_3O_4@SiO_2 (Fe_3O_4@SiO_2-SH) nanoparticles (Hakami et al. 2012; Zhang et al. 2013). pyrene-modified Fe_3O_4@SiO_2 nanoparticles (Li et al. 2012a). and mercapto group-modified core-shell structured nanomagnetic Fe_3O_4 polymers (SH-Fe_3O_4-NMPs) (Pan et al. 2012a, b).

Although the modification often benefits the adsorption, multifunctionalization is sometimes redundant and absolutely useless due to the reduced specific surface area caused by the grafted components. For example, CTS-crosslinked magnetic Fe_3O_4 (CTS-Fe_3O_4) nanoparticles possessed higher adsorption capacity for Hg(II) than that of the raw nanoparticles (Katok et al. 2013) and so did 2-mercaptobenzothiazole-modified magnetic Fe_3O_4 (2-MBTZ-Fe_3O_4) (Parham et al. 2012). However, the adsorption capacity of phenylthiourea (PTU) resin-modified CTS-Fe_3O_4 (CTS-Fe_3O_4-PTU) is greatly decreased (Monier and Abdel-Latif 2012).

To obtain magnetic adsorbents with high efficiency, special efforts were devoted to constructing doped materials. Recently, $Zn_{0.46}Fe_{2.54}O_4$, a novel Zn-doped biomagnetite nanostructured material, was developed. For its easy operation in aqueous separation process, the 3-mercaptopropyl trimethoxysilane (MPTMS)-modified $Zn_{0.46}Fe_{2.54}O_4$ has prospects for Hg(II) removal in real applications due to its high adsorption capacity of 416 mg g^{-1} for Hg(II) (He et al. 2012).

Cobalt ferrite

Cobalt ferrite ($CoFe_2O_4$), another kind of magnetic material, can be facilely recovered and reused. Taking advantage of the excellent characteristics of $CoFe_2O_4$ and RGO, magnetic cobalt ferrite ($CoFe_2O_4$-RGO) nanocomposite was developed. Also, the high adsorption capacity of 157.9 mg g^{-1} makes it more attractive than other magnetic adsorbents (Zhang et al. 2014b).

Nonmetal and other metal adsorbents

Metals and metal oxides

Due to its structural and electronic properties, gold (Au) is in favor of Hg adsorption (Lim et al. 2012). Colloidal gold nanoparticles (Au NPs) have been employed for the rapid removal of Hg(II) from aqueous solutions (Ojea-Jimenez et al. 2012). However, the high price of Au-related materials limits their potential practical applications. Therefore, adding other cheap materials to Au adsorbents might be a good choice. For example, aluminum oxide (Al_2O_3)-mixed Au NPs exhibited relatively low price besides its high removal efficiency (Lo et al. 2012).

Cheap adsorbents have gotten more and more attention in recent years. Due to the excellent hydrothermal and mechanical stability, copper oxide (CuO), copper chloride ($CuCl_2$), and carrier (such as neutral Al_2O_3, artificial zeolite, and AC)-impregnated $CuCl_2$ were used as adsorbents for the removal of Hg^0 (Du et al. 2014). Hierarchical mesoporous CuO nanoflakes (HCMP-CuO-NFs) showed an enormous adsorption capacity of 1767.97 mg g^{-1} for Hg(II) due to their very huge specific surface area (9.72 m^2 g) and total pore volume (mesopores with pore sizes of 9.35 nm; 0.023 cm^3 g) (Kumar et al. 2014).

Material nanocrystallization is also beneficial in the increase in the adsorbents' specific surface areas and adsorption capacities. For example, zinc oxide (ZnO) nanoparticles were used for Hg(II) removal with a maximum adsorption capacity of 714 mg g^{-1} (Sheela et al. 2012). TiO_2 nanocrystals could be employed as efficient adsorbents for both Hg^0 (Tsai et al. 2011) and Hg(II) removal (Dou and Chen 2011; Ghasemi et al. 2012).

Mixed metal oxides, metal-impregnated oxides, and metal salts

Besides specific surface area and particle size, the affinity of an adsorbent for a solute is also crucial. A synergistic adsorption effect would be formed by constructing mixing metal oxides, metal-impregnated oxides, and metal salts, which provides a new way for making novel adsorbents. An environmentally benign chemical, potassium ferrate (K_2FeO_4), has given a convincing result in removing heavy metals from water and wastewater through oxidation and coagulation. The mixing of sodium chlorite ($NaClO_2$) and K_2FeO_4 solution would increase its removal efficiency for Hg^0 (Zhang et al. 2014c). Hydrotalcite-type compounds/layered double hydroxides and their chemically modified derivatives such as $(Mg_{3-x}, M_x)AlCO_3$ (M = Cu or Zn) were developed for Hg removal under medium high temperature conditions, providing an access to design novel high efficient adsorbents (Yu et al. 2014a).

A hybrid of different materials can help to improve their adsorption performance. For example, Hg adsorption on pure SnO_2 particles could be negligible, and Hg adsorption on MnO_x would also decrease significantly with an increase of the contact temperature. A newly developed binary metal oxide, Sn-Mn oxide, showed high Hg adsorption capacity at not only low temperature but also high temperature (Xie et al. 2014). A novel Ce-Ti adsorbent, CeO_2 supported on TiO_2, also exhibited higher Hg^0 removal efficiency than that of sulfur-impregnated AC (Hou et al. 2014; Zhou et al. 2013a). By incorporation of Ce-Mn into Ti-pillared-clay (Ti-PILC), the prepared Ce-Mn/Ti-PILC was an excellent Hg^0 adsorbent (He et al. 2014). Despite the lower specific surface areas and total pore volumes after metal loading, the Hg^0 adsorption capacities of Cu/AC or Ni/AC hybrid materials were also higher than those of the as-prepared material, and the high activity of nickel was thought to be beneficial in Hg^0 adsorption (Bae et al. 2014).

Nonmetals, nonmetal oxides, and salts

Due to its excellent thermal and mechanical stability, silica gel is always used as a supporter material for chelating adsorbents. By introducing organic moieties which own some active donor atoms or groups such as O, N, and S onto the skeleton of silica gel, the modified solid silica gel would possess many extraordinary adsorption properties for Hg. For example, sulfur-functionalized silica materials exhibited higher adsorption capacity for Hg(II) than that of pristine silica without sulfur groups (Arsuaga et al. 2014; Saman et al. 2014). Using bis(triethoxysilylpropyl) tetrasulfide (BTESPT) and MPTMS as sulfur ligands, the sulfur-functionalized silica gels (BTESPT-SGs and MPTMS-SGs) showed increased adsorption capacities (Johari et al. 2014a, b). Therefore, it is worthwhile to construct a chelating matrix by introduction of multifunctional organic molecules onto the adsorbents. 4-Amino-5-methyl-1,2,4-triazole-3(4H)-thion-modified silica aerogel exhibited a maximum adsorption capacity of 142.85 mg g^{-1}, which was eight times more than that (17.24 mg g^{-1}) of silica aerogel (Tadayon et al. 2013). Also, 1-(pyridin-3-yl) imine-modified silica gel also exhibited high adsorption capacities due to the bidentate ligand of N atoms (Fig. 2) (Toubi et al. 2013). A novel chelating resin silica gel supported by aminophosphonic acids also possessed high adsorption capacity (Wang et al. 2012) and so did the vinyl imidazole (VIM)-modified silica (Sun et al. 2013). Thiol, amino, and amide groups could be simultaneously introduced onto silica by reacting SBA-15 with L-cysteine (L-cys), and the L-cys-SBA-15 nanocomposite (Fig. 3) showed higher Hg adsorption capacity and faster adsorption rate (Li et al. 2014). In addition, polymer grafting modification, hybrid processing, and nanocrystallization are all beneficial to improving the adsorption capacities of the silica-based adsorbents (Perez-Quintanilla and Sierra 2014). For example, poly(aniline-co-o-aminophenol) (PAOA)/mesoporous silica SBA-15 (PAOA/SBA-15) exhibited a maximum adsorption capacity of over 400 mg g^{-1} toward Hg(II) (Tang et al. 2011).

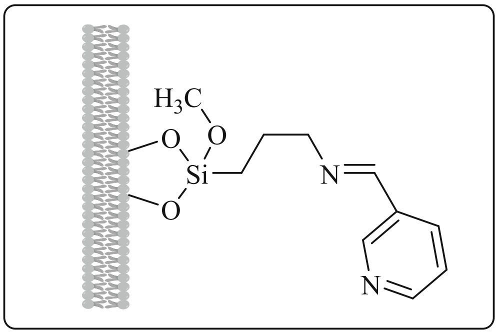

Fig. 2 The schematic drawing of 1-(pyridin-3-yl) imine-modified silica gel

Due to its tunable mesopore sizes and high surface area, a mesoporous molecular sieve was used as a promising adsorbent. Mesoporous silica (MS) is an ideal adsorbent for Hg removal because of its high surface area and biocompatibility. Owing to its hierarchical structure and hexagonal arrangement of one-dimensional mesopores, Mobil composition of matter No. 41 (MCM-41), a mesoporous or nanoporous silica, has been widely used in Hg(II) removal (Aboufazeli et al. 2013). Its adsorption capability could also be improved by $ZnCl_2$ modification ($ZnCl_2$-MCM-41) (Raji and Pakizeh 2013. 2014). The chelation between the -Cl groups of $ZnCl_2$-MCM-41 and Hg(II) species (Fig. 4) might make great contributions toward adsorption (Raji and Pakizeh 2014).

Besides affecting the adsorption efficiency, surface modification also affects the selectivity of the adsorbents. MPTMS, 3-aminopropyl-trimethoxysilane (APTES), and n-(2-aminoethyl)-3-aminopropyl-trimethoxysilane (AEAPTMS)-modified diatom silica microparticles exhibited higher maximum adsorption capacities of 185.2, 131.7, and 169.5 mg g^{-1}, respectively (Yu et al. 2012a). Amidoxime (AO) group-modified silica gel showed selective adsorption ability for Hg(II) (Chen et al. 2012). Also, 1-(3-carboxyphenyl)-2-thiourea (CPTU)-modified mesoporous silica showed both high efficiency and excellent selectivity for Hg(II) (Zhang et al. 2012c). Recently, a regenerable and highly selective core-shell structure composite, thymine (T) and T-rich DNA-functionalized magnetic mesoporous silica (Fe_3O_4@nSiO_2@mSiO_2-T-TRDNA), was developed for the simultaneous detection and removal of Hg(II) (He et al.

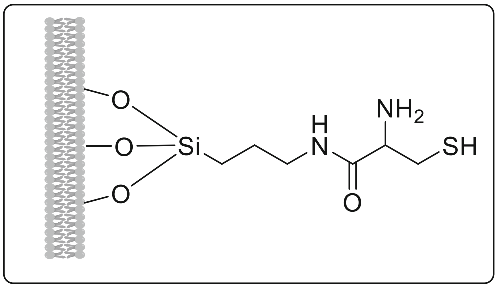

Fig. 3 The schematic drawing of L-cysteine-functionalized mesoporous silica

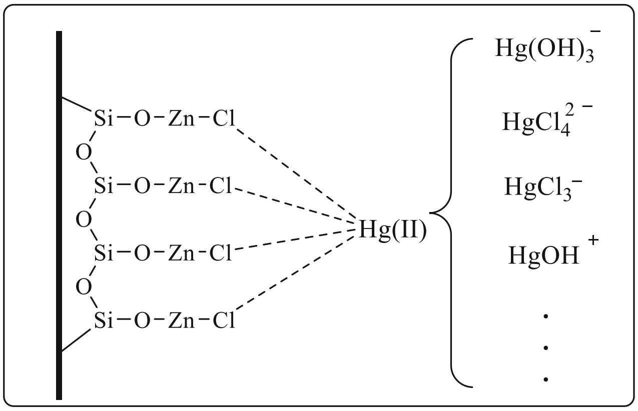

Fig. 4 Proposed interactions between Hg(II) species and $ZnCl_2$-MCM-41

2013). Through forming ion-pair interactions with Hg(II), quaternary ammonium-functionalized magnetic mesoporous silica exhibited fast Hg(II) removal rate (Liu and Du 2011). Such a rapid demercuration with high Hg(II) removal efficiency provided some new ideas for constructing hybrid nanostructures for efficient Hg removal.

Polymers

Conventional polymers

Polymeric materials have been used as one of the most promising and effective adsorbents for the removal of toxic metals from wastewater, and their application in Hg removal is becoming increasingly important. Polyacrylonitrile (PAN) is an important polymer in the adsorption field. However, PAN fibers exhibited low adsorption capacity for the removal of heavy metals, including Hg(II) and Hg^0. A new chelating resin, PAN-2-aminothiazole (PAN-AT), possessed higher adsorption capability for Hg(II) (Xiong et al. 2013) and so did hydroxylamine hydrochloride ($NH_2OH·HCl$, AO·HCl)-modified PAN (Zong et al. 2012). Recently, a copolymer prepared from bromoacetyl bromide ($BrCOCH_2Br$)-modified corn starch (CS-Br), PAN, and AO (AO PAN-CS-Br) exhibited an enormous maximum adsorption capacity of 826.43 mg g^{-1} for Hg(II) (Xu et al. 2014). Owing to the unlimited efforts made by the researchers, PAN-based resins have already shown great potential in Hg adsorption and removal technologies.

Due to its plenty of imine and amine groups that can chelate cationic metal ions, PANI was widely used as an efficient adsorbent for adsorption and removal of heavy metals. Humic acid (HA)-grafted PANI (HA-PANI) showed a high adsorption capacity for Hg(II) (Li et al. 2011a). and the introduction of HA changed the morphology of PANI and prevented its aggregation; therefore, the adsorption properties of modified PANI were improved.

Diethylenetriamine-bridged polysilsesquioxanes (DETA-b-PMPSQs) showed higher adsorption capacity for Hg(II) than as-prepared PMPSQs, indicating once again that electron donor atoms are beneficial for Hg(II) adsorption (Sun et al. 2014a). In addition, selective adsorption could be realized by grafting special functional groups onto polymer adsorbents. For example, thiol-functionalized PMPSQs (PMPSQs-SH) could selectively adsorb Hg(II) from binary ion systems in the presence of some coexistent ions such as Mn(II), Cu(II), Pb(II), Co(II), and Ni(II) (Niu et al. 2014) and so did 3-amino-5-methylisoxazole (AMI)-modified chloromethylated polystyrene (PS) beads (Xiong et al. 2012) and 2-pyridinethiol-grafted PS (Tan et al. 2012). Modification of chelating PS-ethylene diamine tetraacetic acid (EDTA) resins using metal (Fe, Al, and Zr) oxides could increase the adsorption efficiencies, accelerate the adsorption rate, and improve the adsorption selectivity toward Hg(II) (Li et al. 2012b). Moreover, PS-AMI also exhibited high maximum adsorption capacity for Hg(II) at 298 K. A novel chelating resin, which was based on chloromethylated copolymer of styrene-divinylbenzene (CMPS) with dicyandiamide (DCDA), exhibited an enormous adsorption capacity of up to 1077 mg g^{-1} due to its cyanoguanidine moiety (Ma et al. 2011). A higher maximum adsorption capacity of 1163.8 mg g^{-1} was obtained by bis-8-oxyquinoline-terminated open-chain crown ether-modified PS (Sun et al. 2012).

One of the most common synthetic polymers, poly(ethylene terephthalate) (PET), does not have adsorption ability toward anions or cations. However, a newly developed thiosemicarbazide-modified PET could remove Hg(II) from water quickly and efficiently, indicating that certain desirable properties could be introduced to PET by further functionalization (Monier and Abdel-Latif 2013).

A novel photo-crosslinkable nanofiber, uracil-functionalized poly[1-(4-vinylbenzyl uracil)] (PVBU), was converted into a covalent network nanofiber by exposure to UV light. This PVBU nanofiber could selectively remove Hg(II) with a high maximum adsorption capacity (Wang et al. 2013b). Due to the introduced amine functional groups, acrylic acid copolymerized polypropylene fiber, a newly developed chelating fiber, showed an astounding high adsorption capacity of 1144.86 mg g^{-1} for Hg(II) (Ma et al. 2012).

Selectivity is always a challenge in adsorption technologies. 4-Vinyl pyridine-modified poly(ethylene terephthalate) (4-VP-PET) fiber exhibited high adsorption selectivity for Hg(II) (Bozkaya et al. 2012). Due to the adsorption for selectivity of bentonite (BT) toward Hg(II), CTS-poly(vinyl alcohol)/BT (CTS-PVA/BT) nanocomposites possessed excellent adsorption selectivity for Hg(II) (Wang et al. 2014c). Selective adsorption of Hg(II) could also be carried out by hydrolyzed acrylamide (AAm)-grafted polyethylene terephthalate (PET) (AAm-PET) films (Rahman et al. 2014). three-dimensional structured CTS-PVA hydrogel (Wang et al. 2013a). thymine

(T)-grafted PVA-polyethyleneimine (PEI) (T-g-PVA-PEI) nanofibers (Huang et al. 2014). and sulfonated crosslinked PEI CPEI (SCPEI) (Saad et al. 2012).

Dendrimers

Hyperbranched polymers, named dendrimers, have received significant attention for Hg removal due to their terminal surface functional groups and specific structures in contrast with the conventional linear polymers. Poly(amidoamine) (PAMAM) dendrimers, a family of highly branched well-defined polymers, have been widely used in sewage treatment (Sun et al. 2011a, 2014b). Due to their unique topological structures and their surface amino groups which are especially apt to bind metal ions, chitosan (CTS)-functionalized PAMAM dendrimers of generation 1.0, 2.0, and 3.0 showed high maximum adsorption capacities of 398.41, 259.07, and 259.07 mg g^{-1} for Hg(II) at 35 °C, respectively (Ma et al. 2009).

Biomass materials

The removal of heavy metals by natural adsorbents, especially biomass materials, has become a hot area of research for several years. To develop efficient adsorbents with low cost, strong affinity, and high adsorption capacity and are ecofriendly, biomass materials such as bamboo strips (Siddiqui et al. 2011). starch (Huang et al. 2011). rambai tree leaves (Sen et al. 2011). cellulose (Zhou et al. 2013b). Lemna (Li et al. 2011b). lignin (Lv et al. 2012). kenaf fibers (Macias-Garcia et al. 2012), bamboo charcoal (Tan et al. 2012). guar gum (GG), cork stoppers (CSTs) (Lopes et al. 2014). CTS, lignocellulosic fiber (LCF) (Johari et al. 2014c). and polysaccharide were used. Other agricultural by-products such as almond shell (Khaloo et al. 2012). mandarin peel (Husein 2013). buckwheat hulls (Wang et al. 2013c). wheat straw (Zhang et al. 2014a). barley husk (Naser-Azizi et al. 2013), rice husk ash (RHA) (Ghorbani et al. 2011). banana stem (BS) (Mullassery et al. 2014). rice husk (Rocha et al. 2013, 2014b). mulberry twig chars (Shu et al. 2013). Sargassum muticum algal (Carro et al. 2013). adulsa leaves (ALP) (Aslam et al. 2013). and rice straw (Song et al. 2013) are all good choices. For example, rice husks were extremely efficient in the removal of Hg(II) with lower concentrations (less than 500 μg L^{-1}) from river water (Rocha et al. 2014a, b). and potassium permanganate ($KMnO_4$)-modified calcium (CaO)/rice husk could effectively remove Hg^0 (Zhao et al. 2012).

Being associated with ion-dipole interactions which are stronger than hydrogen bonding, the hydroxyl, carboxyl, and methoxyl groups presented in alkali lignin (AL) are very important functional groups (Lopes et al. 2014). Therefore, lignin has been widely used as a promising material for adsorption and removal of Hg(II). The mercapto-functionalized alkali lignin (AL-SH) showed more excellent affinity and higher adsorption capability for Hg(II) than that of AL (Zhou et al. 2014).

Besides improving their stability, chemical modification is also beneficial to increase the removal efficiency of biomass-based adsorbents due to the introduced additional useful functional groups (Kushwaha and Sudhakar 2011; Thakur et al. 2014). Amine and thiol moieties cellulose (Donia et al. 2014). mercapto-grafted rice straw (RS-GM) (Song et al. 2013). glycidyl methacrylate (GMA) and diethylenetriamine-modified cellulose (Donia et al. 2013). and formaldehyde polymerized BS (FPBS) (Mullassery et al. 2014) all exhibited higher maximum adsorption capacity for Hg(II) than that of the pristine adsorbents.

Recycled solid waste materials

Due to their porous structure and large specific surface area, recent researches have shown that some recycled solid waste materials such as sawdust (SD) (Hashem et al. 2011). fly ash (Liu et al. 2013; Song et al. 2014). sewage sludge (Liu et al. 2014a). mussel shell ash (Seco-Reigosa et al. 2013), lignite semi-coke (SC) (Zhang et al. 2012a). malt spent rootlets (MSR) (Anagnostopoulos et al. 2012). and even animal mature (Zhang et al. 2014b) can be used in sewage treatment, especially in heavy metal adsorption and removal. In general, the major influence factors for the Hg adsorption capability of fly ash are its average pore size, followed by its surface area. The application of solid waste materials in the area of Hg(II) adsorption could not only fulfill the production of novel adsorbents but could also realize the use of waste and save useful natural resources.

Halogen functional groups have a special and strong affinity for Hg. By halogenation of fly ashes with different agents such as calcium chloride ($CaCl_2$), HBr, and calcium bromide ($CaBr_2$) and HBr, the treated fly ash showed greater Hg adsorption efficiency 6.7 times than that of unmodified fly ash (Song et al. 2014). Specially, selective adsorption of Hg^0, particulate Hg (p-Hg), and Hg(II) with higher efficiency was realized by hydrogen bromide (HBr)-functionalized fly ash (Song et al. 2014; Zhong et al. 2014). In addition, the incompletely burned carbon (UBC) present in fly ash is also an important factor for Hg removal due to its huge specific surface area which is similar to that of graphene (Xu et al. 2013). The predicated high adsorption energy for Hg on the simulated UBC surface is close to 289 kJ/mol, and the adsorption might occur as a chemical process (Li and Maroto-Valer 2012).

Although untreated synthetic zeolite (Na-X and Na-P1) derived from coal fly ash had negligible Hg adsorption capacity, its adsorption capacity for Hg^0 could be markedly improved after impregnation with silver (Wdowin et al. 2014) or zeolite A precursors (Liu et al. 2013). A waste mixture containing shell ash, sewage sludge, and wood ash exhibited higher adsorption capacity than that of any single one, indicating that the mixture could be employed as a cheap and efficient adsorbent (Pena-Rodriguez et al. 2013; Seco-Reigosa et al. 2013).

Bacterial species

Due to the presence of various organic and inorganic complexing ligands on the surface, cells may bind with Hg species to realize adsorption. The adsorption of Hg(II), HgCl(OH), and $Hg(OH)_2$ using nonmetabolizing cells of *Bacillus subtilis*, *Shewanella oneidensis* MR-1, and *Geobacter sulfurreducens* in both chloride-free and chloride-bearing systems was achieved (Dunham-Cheatham et al. 2014). *Paecilomyces catenlannulatus* also exhibited high adsorption capacity for Hg(II) (Li et al. 2013a).

Due to the bonding interactions between Hg(II) and the thiol functional groups on the surface of cells, Hg(II) adsorption and methylation on the cell surface of *G. sulfurreducens* PCA were feasible (Hu et al. 2013). Also, high MeHg removal efficiency was possible by a *Pseudomonas putida* V1 strain (Cabral et al. 2013). Due to its higher adsorption capacity for Hg(II), *Bacillus mucilaginosus* might be a promising biosorbent in Hg species removal (Mo and Lian 2011).

Three-dimensional structures

Hydrogel

Polymer-crosslinked chains are formed through several intermolecular forces such as physical, ionic, or covalent interactions, and the prepared hydrogel could be used as a highly efficient adsorbent for Hg species (Elisseeff 2008). Besides chelation, electrostatic interaction also plays an important role in the adsorption of Hg(II). Due to its three-dimensional network structure and plenty of functional groups such as $-NH_2$, $-NHCOCH_3$, -C=N, and -OH, CTS/poly(vinyl alcohol) (CTS-PVA), a newly developed hydrogel, has shown superior adsorption properties for Hg(II) (Wang et al. 2014b). Its adsorption capacities reached up to 697.70 mg g^{-1} at 20 °C and 950.62 mg g^{-1} at 60 °C, respectively. A newly developed hydrogel, CTS-grafted polyacrylamide (PAA) (CTS-g-PAA) semi-interpenetrating polymer network (IPN) hydrogel, exhibiting extremely higher maximum adsorption capacity of 2001.8 mg g^{-1} toward Hg(II) than that of any existing adsorbents, is miraculous (Saber-Samandari and Gazi 2013). Specially, CTS-g-PAA could be regenerated without losing its original activity and stability.

Cage structures

Cage structures are also attractive because polyhedral cage-based frameworks could provide strong adsorption interactions for metal ions. Besides its high selectivity for Hg(II) and MeHg, the thiol-rich polyhedral oligomeric silsesquioxane (POSS-SH) also possessed high adsorption capacities (Wang et al. 2014a). Meanwhile, the cage type and adsorption sites can affect the adsorption performance of cage molecules. Due to its cage geometry, 1,4,7,10,13,16,21,24-octaazabicyclo[8.8.8]hexacosane [H_6Aza222] (Fig. 5) could be used for selective binding of Hg (Redko et al. 2006). Polymeric material-grafted H_6Aza222 showed both higher removal efficiency toward Hg(II) (e.g., $HgCl_2$ or Na_2HgI_4) and more easily regenerable properties (Redko et al. 2014). The surface nanocrystallization of H_6Aza222 polymer would increase its selectivity and affinity for Hg; therefore, it could be used as a regenerable ultrahigh affinity adsorbent (Tadayon et al. 2013).

Other materials

Zeolites

Zeolite Y, β-zeolite, and mordenite were used for Hg(II) removal, and the adsorption capacity of β-zeolite was found to be the highest (Murthy et al. 2013). Encapsulating superparamagnetic Fe_3O_4 nanocrystals into a hierarchical mesoporous zeolite and the magnetic self-assembled zeolite clusters showed adsorption selectivity toward Hg(II) (Yin et al. 2012).

Clays

Natural clay is mainly composed of silica, alumina, iron, calcium, and magnesium oxides (Guerra et al. 2012). As a type of natural layered material with abundant mesopores, clay possesses good thermal stability and high specific surface area, making them useful adsorbents for the removal of heavy metals from wastewater (Kumar et al. 2012). Naturally, the Hg(II) adsorption capacity of black soil was greater than that

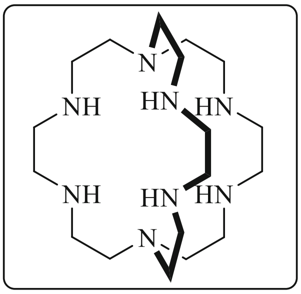

Fig. 5 Chemical structure of H_6Aza222

of red soil, and the concentration of an additive, chloride ion (Cl^-), had a great effect on the adsorption (Zhang et al. 2012d). Natural clay, aluminum pillared clay (Eloussaief et al. 2013). and Apatite II (TM) (Oliva et al. 2011) possessed relatively lower adsorption capacity for Hg(II). By introduction of halogen functional groups onto the adsorbents, the obtained KI- and KBr-modified clay (KI-clay and KBr-clay) showed enhanced adsorption capacities for Hg^0 (Cai et al. 2014).

As one kind of impure clay which mostly consists of montmorillonite, bentonite could be employed as an efficient adsorbent (Fernandez-Nava et al. 2011). Due to the emerging electrostatic interactions by the protonated amines, 4-aminoantipyrine-modified bentonite (Wang et al. 2011). trioctylamine (TOA)-modified sodium montmorillonite (Kumar et al. 2012). 3-aminopropyltriethoxysilane (APTES)-modified natural attapulgite (ATP) (ATP-APTES) (Cui et al. 2013). and PANI-modified ATP (PANI/ATP) (Cui et al. 2012) all showed increased maximum adsorption capacities toward Hg(II) and so did glycidyl methacrylate (GMA) and N,N′-methylene bis-acrylamide (MBA) copolymer and tetraethylenepentamine (TEP)-modified kaolinite mineral (Donia et al. 2011).

Ionic liquids (ILs)

Most of the existing adsorbents either are costly or may release by-products that are harmful to the environment. The development of novel adsorbents with high efficiency, low pollution, and low cost for Hg species removal is thus to be expected. As promising functional materials, ILs have attracted great attention recently. Fe-based ionic liquids, 1-butyl-3-methylimidazolium halide ([bmim]X, X = Cl or Br) (Fig. 6)-impregnated $FeCl_3 \cdot 6H_2O$, including ([bmim] $FeXCl_3$) and their analogs ([bmim]X), showed good Hg^0 removal efficiencies. Trioctylmethylammonium thiosalicylate (TOMATS), a task-specific IL containing -SH groups, was built on a carrier of palm shell AC (PSAC), and the TOMATS-PSAC exhibited a high adsorption capacity for Hg(II) at pH 8 (Abu Ismaiel et al. 2013).

Synthetic organic adsorbents

Synthetic, organic, thiol-containing bidentate chelate molecules could strongly bind heavy metals to realize high adsorption capacities (Zhao et al. 2013a, b). Due to the high chelating energy, 3-benzenediamidoethanethiolate [BD(S)] would combine with Hg(II) to form a chelate of BD(S)-Hg (Fig. 7). If sulfur groups were replaced by selenium (Se) or tellurium (Te), the chelating strength of BD(X) (X = Se or Te) complexes for Hg(II) would increase, and Hg(II) removal is thus predicted to form the BD(X)-Hg complex (Zou et al. 2013).

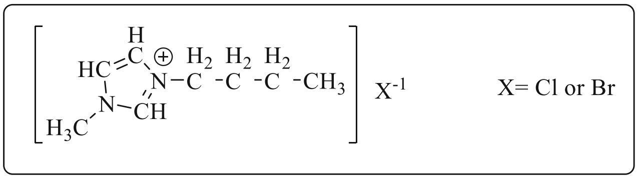

Fig. 6 Chemical structure of [bmim]X

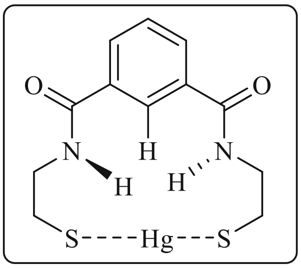

Fig. 7 Chemical structure of BD(S)-Hg

Membranes

Membranes always have a place in the field of adsorption. To remove Hg(II) from drinking water and industrial effluents, various membranes were developed in recent years. Epichlorohydrin-modified crosslinked CTS (CTS-ECH) membrane matrix (Rabelo et al. 2012). agarose gel trapped bovine serum albumin (BSA)-Au NPs (Au NPs@BSA/AGM) (Lee et al. 2012). and a mixed-matrix membrane made from the dispersion of thiol-functionalized metal oxide-coated carbon (MOCC) in the polysulfone (PSF) matrix (MOCC-PSF) (Meeks et al. 2013) all showed high maximum adsorption capacities for Hg(II). Specially, PVA-modified CTS-based ceramic ultrafiltration membrane exhibited almost 100 % removal for 500 $\mu g\ L^{-1}$ of Hg(II) through a polymer-enhanced ultrafiltration (PEUF) technique (Jana et al. 2011).

Emulsion liquid membranes (ELM) were also widely applied in separation technologies. To overcome the hindrance in the application of ELM at an industrial scale, great efforts have been made to get a desired level of stability. A stable emulsion was developed for the removal of Hg from aqueous solution (Gupta et al. 2013). The removal of ultralow levels of Hg species from an aqueous solution is a challenge. An oligothymonucleic acid (OTA)-modified polyethylene (PE) film was developed, which could selectively remove Hg(II) of sub-ppb level from an aqueous solution (Yu et al. 2012b).

Adsorption mechanisms

The relationship between material structure and its adsorption ability

To provide molecular-level understanding of the effects of chemical functional groups on Hg adsorption, systematic theoretical studies were performed. The mechanisms of adsorption of Hg^0, HgCl, and $HgCl_2$ molecules onto ZnO surface were investigated by density functional theory (DFT) (Ling et al. 2014). Hg^0 is physically adsorbed onto ZnO surface at the Zn atom, and $HgCl_2$ can be adsorbed in molecular mode. However, HgCl is difficult to be adsorbed and exists in dissociative mode. The formation of oxidized Hg complexes (e.g., $[HgX]^+$, $[HgX_2]$, and $[HgX4]_2$; X = Cl, Br, or I) might contribute to halogen-containing group-functionalized adsorbents in removing Hg^0; thus, their high Hg^0 adsorption performance is predictable (Yao et al. 2013).

To better understand the surface electronic structural changes upon adsorption, the adsorption of Hg^0 on CuO (110) surface was also investigated using first-principles quantum mechanical methods (Xiang et al. 2012). Hg^0 was found to bind weakly to the O-terminated CuO (110) surface and strongly on the Cu-terminated CuO (110) surface; therefore, the significant overlap between the d-state of Hg and the s-states of Cu might be beneficial to the strong Hg and Cu-terminated CuO (110) interactions. Also, Hg adsorption capacity of sulfur-impregnated adsorbent increased along with its decreased specific surface area; thus, the interaction of the lone pairs of electrons of sulfide groups might be associated with the higher adsorbent's Hg adsorption capability (Hu et al. 2013). The zigzag and armchair edges of functionalized carbonaceous adsorbents have a huge impact on Hg adsorption: the embedding of halogen atom can increase the adsorption activities, and the introduced phenol and carboxyl functional groups are beneficial for physisorption of Hg^0 and weaken Hg(II) adsorption (Liu et al. 2011).

As an electronic acceptor, Hg(II) would receive significant electrons transferred from the functional groups of adsorbents to form coordination bonds (Sun et al. 2011b). Therefore, functional groups such as sulfur, thiosemicarbazide, amino, sulfamine, AO, and so on could be applied as chelating media to modify the adsorbents. To form multidentate chelates, chelating adsorbents containing multityped functional groups that are capable of coordinating to Hg(II) are expected. Sulfur- and AO-containing bifunctional silica gel-based hybrid materials exhibited high adsorption capability for Hg(II) (Fig. 8) (Qu et al. 2013) and so did thiosemicarbazide-modified PET (Monier and Abdel-Latif 2013). The amino group is likely to form new structures such as imino bonds with Hg(II), which is one of the key factors that makes contribution to the higher adsorption capacity of amino group-functionalized adsorbents (Vieira et al. 2011). and selective and high efficient adsorption for Hg(II) could be achieved (Qi et al. 2013). An efficient Hg-specific adsorbent, AO group-modified PAN-grafted PS (PAN-g-PS), can selective remove Hg(II) from aqueous solutions (Zong et al. 2011).

Adsorption capacity contrast and isotherm and kinetic studies

A summary of the adsorption capacities of various adsorbents for Hg removal from aqueous solutions under optimum conditions is presented in Table 1. It can be seen from Table 1 and the "Absorbent development" section of this review that carbon material-based composites, NFs, and hydrogels have shown the most promising prospects in Hg removal. Tables 2 represents the applicable isotherm and kinetic models for Hg removal by various adsorbents, and the pseudo-second-order kinetic model and Freundlich and/or Langmuir isotherm models were found to fit well with the experimental data.

Future research directions and conclusions

Due to its high toxicity and bioaccumulation, the existence of Hg species in the environment is always a threat to human beings. In order to control Hg pollution, scientists have put great efforts and enthusiasm on the adsorption technologies in the past few decades. Based on a systematic review of the literature from 2011 to 2014, the following concluding remarks can be made:

1. Many factors of the adsorbents such as specific surface area, pore size distribution, polarity, and the introduced functional groups would affect their adsorption efficiencies. To develop novel adsorbents with high adsorption

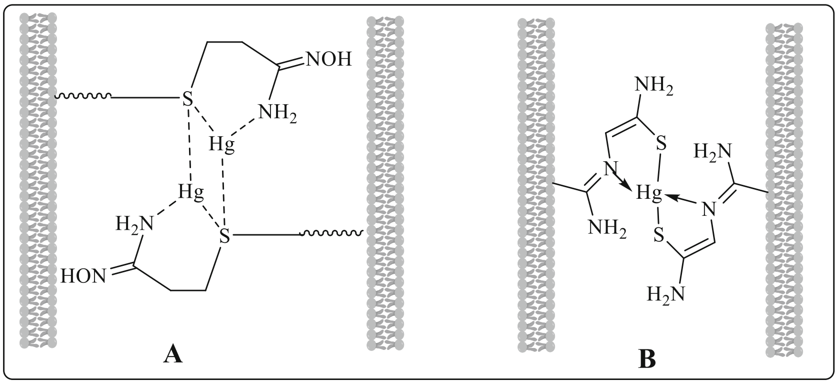

Fig. 8 The proposed interactions of sulfur/amidoxime- (**a**) and thiosemicarbazide- (**b**) modified adsorbents with Hg(II) (Monier and Abdel-Latif 2013; Qu et al. 2013)

Table 1 Adsorption of Hg by various adsorbents

Type of Hg	Type of adsorbent	Optimal adsorption conditions	The maximum adsorption capacity	Reference
Hg(II)	Sulfurized ACs	Not provided	Enhanced adsorption abilities than AC	Abdelouahab-Reddam et al. (2014). Feng et al. (2006a, b). Ie et al. (2012, 2013), Li et al. (2013c)
Hg(II)	Concurrent sulfurized/activated ACs	Not provided	293 mg g^{-1}	ShamsiJazeyi and Kaghazchi (2014)
Hg^0	Functionalized ACs	At 25 °C and mercury concentration of 230 μg m^3	AC<Cl-impregnated AC<Br-impregnated AC<I-impregnated AC	De et al. (2013)
Hg(II)	MAC	With a 3:1 for C/Fe	92.5 % sorbent recovery and 96.3 % Hg removal	Faulconer et al. (2012)
Hg(II)	Sulfurized MAC	Not provided	38.3 mg g^{-1}	Okamoto et al. (2011)
Hg(II)	Ox-MAC and SH-MAC	Not provided	34.5 mg g^{-1} for Ox-MAC and 39.4 mg g^{-1} for SH-MAC	Miura and Tachibana (2014)
Hg^0	AC from biomass material and sulfurized AC	Hg^0 concentration of 10 μg Nm^{-3}, at 70 °C	Sulfur introduction causes enhancements in Hg^0 adsorption; up to 97 % removal	Hsi et al. (2013, 2014). Hu et al. (2014)
Hg^0	ACFs-SH	Hg^0 concentration of ~21 ng mL^{-1}	11~15 mg g^{-1}	Yao et al. (2014b)
Hg(II)	AMT-OCMK-3	0.5 g L^{-1} of adsorbent and 10 mg L^{-1} mixed solutions, at pH 6	450.45 mg g^{-1}	Anbia and Dehghan (2014)
Hg(II)	ZnO-modified CMK-3	The agitation time of 120 min, the initial $C_{Hg(II)}$ of 10 mg L^{-1}, 35 °C, pH 6	99 % removal	Zolfaghari et al. (2011)
Hg(II)	Zeolite Y, β-zeolite, and mordenite	Not provided	β-Zeolite was found to be the highest	Murthy et al. (2013)
Hg(II)	Fe_3O_4 nanocrystals encapsulated hierarchical mesoporous zeolite	Not provided	Selective adsorption of Hg(II)	Yin et al. (2012)
Hg(II)	MWCNTs	At pH 6.5; equilibrated for 24 h at 27 °C; with initial concentration of 50 mg L^{-1}	90 % removal	Shadbad et al. (2011)
Hg(II)	Amino- and thiol-functionalized MWCNTs	At pH 6, 25 °C and 200 rpm agitation speed; adsorbent dose of 400 mg L^{-1}	84.66 mg g^{-1}	Hadavifar et al. (2014)
Hg(II)	SWCNT-SH	At pH 5.0; at an initial concentration of 0.4 mg mL^{-1}	131 mg·g^{-1}	Bandaru et al. (2013)
Hg(II)	ox-MWCNT (or MWCNT, or SWCNT)-impregnated CTS	At pH=4, contact time=40 min, and temperature=70 °C	183.2, 167.5, and 172.7 mg g^{-1}, respectively	Shawky et al. (2012)
Hg(II)	GO and GO/CS	25 °C, pH=4	381 and 187 mg g^{-1}, respectively	Kyzas et al. (2014)
Hg(II)	SRGO nanohybrid	At neutral pH under ambient conditions	90 % removal	Thakur et al. (2013)
Hg(II)	Dithiocarbamate group-modified iron magnetite Fe_3O_4	Initial $C_{Hg(II)}$ of 50 mg L^{-1}, at 21 °C	206 mg g^{-1}	Figueira et al. (2011)
Hg(II)	Fe_3O_4@SiO_2	Not provided	Hg(II) concentration reached a plateau at 0.0025 mg L^{-1}	Jing-po et al. (2014). Tavares et al. (2013)
Hg(II)	Fe_3O_4@SiO_2-SH	At pH 6.5	From 148.8 to 207.7 mg g^{-1}	Hakami et al. (2012). Zhang et al. (2013)
Hg(II)	SH-Fe_3O_4-NMPs	Not provided	256.4 mg g^{-1}	Pan et al. (2012a, b)
Hg(II)	CTS-Fe_3O_4	At 20 °C and pH=2.7~7	152 mg·g^{-1}	Katok et al. (2013)
Hg(II)	CTS-Fe_3O_4-PTU	At pH=5.0	135 mg g^{-1}	Monier and Abdel-Latif (2012)
Hg(II)	2-MBTZ-Fe_3O_4	At pH=9.0	98.6 % removal	Parham et al. (2012)
Hg(II)	$Zn_{0.46}Fe_{2.54}O_4$	At neutral pH, 5 min of contact time	416 mg g^{-1}	He et al. (2012)

Table 1 (continued)

Type of Hg	Type of adsorbent	Optimal adsorption conditions	The maximum adsorption capacity	Reference
Hg(II)	$CoFe_2O_4$	At pH 4.6 and 25 °C	157.9 mg g^{-1}	Zhang et al. (2014b)
Hg(II)	Au NPs mixed Al_2O_3	Flow rate of 2.5 mL min^{-1}	97 % removal	Lo et al. (2012)
Hg^0	AC-impregnated $CuCl_2$	At 333 K; 5 min; 20 ppm HCl of flue gas	90 % removal	Du et al. (2014)
Hg(II)	ZnO nanoparticles	At pH 5.5	714 mg g^{-1}	Sheela et al. (2012)
Hg(II)	Sulfur-functionalized silica	At pH 5.8~8.2	47.50 mg g^{-1}	Arsuaga et al. (2014). Saman et al. (2014)
Hg(II)	POSS xerogel	At pH 2.7~7	95 mg g^{-1}	Katok et al. (2013)
Hg(II)	BTESPT-SGs and MPTMS-SGs	Not provided	93.32 and 102.37 mg g^{-1}, respectively	Johari et al. (2014a, b)
Hg(II)	4-Amino-5-methyl-1,2,4-triazole-3(4H)-thion-modified silica	At pH 6.0–7.5	142.85 mg g^{-1}	Toubi et al. (2013)
Hg(II)	Aminophosphonic acid-supported silica gel	At pH=5.0	303.03 mg g^{-1}	Wang et al. (2012)
Hg(II)	VIM-modified silica	At pH=5.0	355.9 mg g^{-1}	Sun et al. (2013)
Hg(II)	PAOA/SBA-15	C_0=100 mg·L^{-1}, ionic strength is 0.2 M $NaNO_3$, sorbent dosage is 0.1 g·L^{-1} and pH=5.5	433.55 mg g^{-1}	Tang et al. (2011)
Hg(II)	L-cys-SBA-15	At room temperature; Hg(II) adsorption time <5 min	429 mg g^{-1}	Li et al. (2014)
Hg(II)	MPTMS, APTES, and AEAPTMS-modified diatom silica microparticles	At pH=6	185.2, 131.7, and 169.5 mg g^{-1}, respectively	Yu et al. (2012a)
Hg(II)	PAN-AT	At pH=6.5	454.9 mg g^{-1}	Xiong et al. (2013)
Hg(II)	AO-modified PAN	At pH=2.0	567 mg g^{-1}	Zong et al. (2012)
Hg(II)	AO PAN-CS-Br	At pH=4.0	826.43 mg g^{-1}	Xu et al. (2014)
Hg(II)	HA-PANI	C_0=500 mg L^{-1}; pH=5.0	671 mg g^{-1}	Li et al. (2011a)
Hg(II)	PS-AMI	At 298 K	335.6 mg g^{-1}	Xiong et al. (2012)
Hg(II)	Bis-8-oxyquinoline-terminated open-chain crown ether-modified PS	Not provided	1163.8 mg g^{-1}	Sun et al. (2012)
Hg(II)	Thiosemicarbazide-modified PET	At pH=5.0	120 mg g^{-1}	Monier and Abdel-Latif (2013)
Hg(II)	PVBU nanofiber	At pH=7.0	543.9 mg g^{-1}	Wang et al. (2013b)
Hg(II)	Acrylic acid copolymerized polypropylene fiber	Not provided	1144.86 mg g^{-1}	Ma et al. (2012)
Hg(II)	4-VP-PET	At pH=3.0	137.18 mg g^{-1}	Bozkaya et al. (2012)
Hg(II)	CTS-PVA hydrogel	At pH=5.50	585.90 mg g^{-1}	Wang et al. (2013a)
Hg(II)	CTS-functionalized generation 1.0, 2.0, and 3.0 of PAMAM	At 35 °C	398.41, 259.07, and 259.07 mg g^{-1}, respectively	Ma et al. (2009)
Hg(II)	CST	C_0=500 μg L^{-1}; pH=8.1	94 % removal	Lopes et al. (2014)
Hg(II)	GG-cl-CH=N-$(CH_2)_6$-N=CH-GG	At 20 °C; pH=5.0; C_0=25 ppm	41.13 mg g^{-1}	Thakur et al. (2014)
Hg(II)	Amine- and thiol-modified cellulose	Not provided	7.2 and 38 mmol g^{-1}, respectively	Donia et al. (2014)
Hg(II)	RS-GM and RS-Raw	C_0=50 mg L^{-1}; pH 9.0	161.30 and 103.1 mg g^{-1}, respectively	Song et al. (2013)
Hg(II)	GMA and diethylenetriamine-modified cellulose	Not provided	440 mg g^{-1}	Donia et al. (2013)

Table 1 (continued)

Type of Hg	Type of adsorbent	Optimal adsorption conditions	The maximum adsorption capacity	Reference
Hg(II)	FPBS	C_0=25 mg L^{-1}; pH=7.0	132.25 mg g^{-1}	Mullassery et al. (2014)
Hg(II)	UBC	Not provided	288.632 kJ/mol	Li and Maroto-Valer (2012)
Hg(II)	LCF wastes of coconut	Not provided	144.4 mg g^{-1}	Johari et al. (2014c)
Hg(II)	Buckwheat hulls	At 35 °C; pH=5.0	243.90 mg g^{-1}	Wang et al. (2013c)
Hg(II)	*Paecilomyces catenlannulatus*	At pH=7.0	140.85 mg g^{-1}	Li et al. (2013a)
Hg(II)	*Pseudomonas putida* V1 strain	At pH in the range 4.0–6.0; at 21–25 °C	Over 80 % removal	Cabral et al. (2013)
Hg(II)	*Bacillus mucilaginosus*	Not provided	393 mg L^{-1}	Mo and Lian (2011)
Hg(II)	CTS-PVA	At 60 °C	950.62 mg g^{-1}	Wang et al. (2014b)
Hg(II)	CTS-g-PAA		2001.8 mg g^{-1}	Saber-Samandari and Gazi (2013)
Hg(II)	POSS-SH	At pH=6.0	12.90 mg g^{-1}	Wang et al. (2014a)
MeHg	POSS-SH	At pH=6.0	46.73 mg g^{-1}	Wang et al. (2014a)
Hg(II)	Clay and pillared clay	At pH=3.2	9.70 and 49.75 mg g^{-1}, respectively	Eloussaief et al. (2013)
Hg(II)	Apatite II (TM)	C_0=75 mg L^{-1} at pH=2	38 mg·g^{-1}	Oliva et al. (2011)
Hg(II)	4-Aminoantipyrine-modified bentonite	At pH=4.0	52.9 mg g^{-1}	Wang et al. (2011)
Hg(II)	TOA-modified sodium montmorillonite	C_0=10 mg L^{-1}; pH=3.0	140.84 mg g^{-1}	Kumar et al. (2012)
Hg(II)	ATP and ATP-APTES	At pH range of 3~11	5 and 90 mg g^{-1}, respectively	Cui et al. (2013)
Hg(II)	PANI/ATP	At around pH 5–9	800 mg g^{-1}	Cui et al. (2012)
Hg(II)	TOMATS-PSAC	At pH=8	83.33 mg g^{-1}	Abu Ismaiel et al. (2013)
Hg(II)	CTS-ECH	Not provided	682 mg g^{-1}	Rabelo et al. (2012)
Hg(II)	MOCC and MOCC-PSF	C_0=150 mg L^{-1}	60 and 200 mg g^{-1}, respectively	Meeks et al. (2013)
Hg(II)	PEUF	C_0=500 μg L^{-1}	100 % removal	Jana et al. (2011)
Hg^0	K_2FeO_4	pH 8.0, 47 °C, $C_{K_2FeO_4}$ =0.25 mmol L^{-1}	81.4 % removal	Zhao et al. (2014)
Hg(II)	Polypyrrole-CTS	Not provided	40 mg g^{-1}	Salahi et al. (2014)
Hg(II)	AL-SH	pH 4.0, 20 °C, initial Hg(II) concentration of 200 mg L^{-1}	101.2 mg g^{-1}	Zhou et al. (2014)
Hg(II)	Hybrid nanosilica	pH 2.0, initial Hg(II) concentration of 0.178 M, 25 °C	134 mg g^{-1}	Perez-Quintanilla and Sierra (2014)
Hg(II)	$CoFe_2O_4$-RGO	pH 4.6, 25 °C	157.9 mg g^{-1}	Zhang et al. (2014b)
Hg(II)	FeS	pH 8, initial Hg(II) concentration of 1000 and 1250 mM	99 % removal	Han et al. (2014)
Hg(II)	ALP	pH 6, 30 °C, 40 min, initial Hg(II) concentration of 100 mg L^{-1}	107.5 mg g^{-1}	Aslam et al. (2013)
Hg(II)	*Vibrio* sp. cells	pH 6.0, 35 °C	193.2 mg g^{-1}	Jafari and Cheraghi (2014)
Hg(II)	HCMP-CuO-NFs	pH 6.0–7.0, initial Hg(II) concentration of 200–400 mg L^{-1}	1767.97 mg g^{-1}	Kumar et al. (2014)

Table 2 Adsorption isotherm and kinetic studies of Hg(II) removal from aqueous solution

Type of adsorbent	Applicable isotherm models	Applicable kinetic models	Reference
ZnO nanoparticles	The Langmuir model is better	Pseudo-second-order is better	Sheela et al. (2012)
TOMATS-PSAC	The Langmuir model is better	Pseudo-second-order is better	Abu Ismaiel et al. (2013)
AL-SH	Langmuir and Temkin better than Freundlich	Not provided	Zhou et al. (2014)
$CoFe_2O_4$-RGO	Langmuir is better than Freundlich	Pseudo-second-order is better	Zhang et al. (2014b)
Wheat straw, swine manure	Langmuir and Freundlich	Not provided	Zhang et al. (2014a)
AO PAN-CS-Br	Langmuir is better than Freundlich	Pseudo-second-order is better	Xu et al. (2014)
GG-cl-CH=N-$(CH_2)_6$-N=CH-GG	Freundlich is better than Langmuir	Pseudo-second-order is better	Thakur et al. (2014)
$ZnCl_2$-MCM-41	Not provided	Pseudo-second-order is better	Raji and Pakizeh (2014)
AAm-PET films	The Langmuir model is better	Pseudo-second-order is better	Rahman et al. (2014)
PMPSQs-SH	The Langmuir model is better	Pseudo-second-order is better	Niu et al. (2014)
FPBS	The Freundlich model is better	Pseudo-second-order is better	Mullassery et al. (2014)
GO/CS	The Langmuir model is better	Pseudo-second-order is better	Kyzas et al. (2014)
LCF and LCF-NaOH	Langmuir model is better	Pseudo-second-order is better	Johari et al. (2014c)
ALP	The Langmuir model is better	Pseudo-second-order is better	Aslam et al. (2013)
SRGO	The Langmuir model is better	Pseudo-second-order is better	Thakur et al. (2013)
TiO_2 nanocrystals	Freundlich is better than Langmuir	Pseudo-second-order is better	Ghasemi et al. (2012)
MSR	The Langmuir model is better	Pseudo-second-order is better	Anagnostopoulos et al. (2012)
AMT-OCMK-3	The Langmuir model is better	Not provided	Abdelouahab-Reddam et al. (2014)
BTESPT-SGs and MPTMS-SGs	The Langmuir model is better	Pseudo-second-order is better	Johari et al. (2014b)
HCMP-CuO-NFs	Fitted with both the Freundlich and Langmuir models	Pseudo-second-order is better	Kumar et al. (2014)

efficiencies, surface nanocrystallization (Singh and Kumary 2011) and modification of the materials are necessary. A newly developed nanoscale adsorbent, *pumice*-nanoscale *zero-valent iron* (P-NZVI), showed a very high adsorption ability for Hg(II) (Liu et al. 2014c). Oligonucleotide-modified magnetic silica sphere @Au nanoparticles (MSS@Au NPs) have the potential of effectively removing Hg(II) from surrounding solutions (Liu et al. 2014b) and so does thiol-functionalized MSS (Song et al. 2011).

2. Adsorbents with excellent properties such as high selectivity, high capacity, regenerability, and stability are expected. For example, newly developed FPBS could be easily regenerated by 0.1 M HCl (Mullassery et al. 2014). aerogel (Standeker et al. 2011). and xerogel (Singh and Singh 2011) possessing very high adsorption capacities.
3. To reduce the overall impact of the adsorption process on the environment, novel Hg treatment technologies with minimal generation of contaminated waste are expected. Ion exchange membrane bioreactor (IEMB) process might be a good choice (Oehmen et al. 2014). Hollow fiber-supported liquid membrane (HFSLM) can also provide a new concept in Hg removal (Lothongkum et al. 2011).
4. Being abundantly available and cheap, recycled solid waste materials could be reused as low-cost bioadsorbents for Hg(II) removal (Johari et al. 2014c).
5. Both the chemical structure and physical property of an adsorbent play important roles in its Hg adsorption capability. The relationship of the adsorbent's properties (including particle morphology, surface area, elemental composition, etc.) to adsorption is expected to clarify.
6. The adsorption mechanism for Hg species removal is still not well explained. Computer simulation of the interactions between the adsorbents and the Hg species still needs to be investigated deeply.

Acknowledgments We are very grateful for the financial support from the National Natural Science Foundation of China (Nos. 21471163 and 21571191), Hunan Provincial Natural Science Foundation of China (No. 14JJ2006), and Key Project of Philosophy and Social Sciences Research, Ministry of Education, PRC (No. 13JZD0016, Research on Institutional Building of Ecological Civilization).

References

Abdelouahab-Reddam Z, Wahby A, El Mail R, Silvestre-Albero J, Rodriguez-Reinoso F, Sepulveda-Escribano A (2014) Activated carbons impregnated with Na_2S and H_2SO_4: texture, surface chemistry and application to mercury removal from aqueous solutions. Adsorpt Sci Technol 32:101–115

Aboufazeli F, Zhad H, Sadeghi O, Karimi M, Najafi E (2013) Synthesis and characterization of novel poly-thiophene-nanoporous silica and its application for mercury removal from waste waters. J Macromol Sci A 50:18–24

Abu Ismaiel A, Aroua MK, Yusoff R (2013) Palm shell activated carbon impregnated with task-specific ionic-liquids as a novel adsorbent for the removal of mercury from contaminated water. Chem Eng J 225: 306–314

Anagnostopoulos VA, Manariotis ID, Karapanagioti HK, Chrysikopoulos CV (2012) Removal of mercury from aqueous solutions by malt spent rootlets. Chem Eng J 213:135–141

Anbia M, Dehghan R (2014) Functionalized CMK-3 mesoporous carbon with 2-amino-5-mercapto-1,3,4-thiadiazole for Hg(II) removal from aqueous media. J Environ Sci (China) 26:1541–1548

Arsuaga JM, Aguado J, Arencibia A, Lopez-Gutierrez MS (2014) Aqueous mercury adsorption in a fixed bed column of thiol functionalized mesoporous silica. Adsorption J Int Adsorption Soc 20: 311–319

Asasian N, Kaghazchi T (2013a) A comparison on efficiency of virgin and sulfurized agro-based adsorbents for mercury removal from aqueous systems. Adsorption J Int Adsorption Soc 19:189–200

Asasian N, Kaghazchi T (2013b) Optimization of activated carbon sulfurization to reach adsorbent with the highest capacity for mercury adsorption. Sep Sci Technol 48:2059–2072

Asasian N, Kaghazchi T, Soleimani M (2012) Elimination of mercury by adsorption onto activated carbon prepared from the biomass material. J Ind Eng Chem 18:283–289

Aslam M, Rais S, Alam M, Pugazhendi A (2013) Adsorption of Hg(II) from aqueous solution using Adulsa (Justicia adhatoda) leaves powder: kinetic and equilibrium studies. J Chem

Bae KM, Kim BJ, Rhee KY, Park SJ (2014) Roles of metal/activated carbon hybridization on elemental mercury adsorption. J Nanosci Nanotechnol 14:5811–5816

Bandaru NM, Reta N, Dalal H, Ellis AV, Shapter J, Voelcker NH (2013) Enhanced adsorption of mercury ions on thiol derivatized single wall carbon nanotubes. J Hazard Mater 261:534–541

Bozkaya O, Yigitoglu M, Arslan M (2012) Investigation on selective adsorption of Hg(II) ions using 4-vinyl pyridine grafted poly(ethylene terephthalate) fiber. J Appl Polym Sci 124:1256–1264

Cabral L, Giovanella P, Gianello C, Bento FM, Andreazza R, Camargo FAO (2013) Isolation and characterization of bacteria from mercury contaminated sites in Rio Grande do Sul, Brazil, and assessment of methylmercury removal capability of a Pseudomonas putida V1 strain. Biodegradation 24:319–331

Cai J, Shen BX, Li Z, Chen JH, He C (2014) Removal of elemental mercury by clays impregnated with KI and KBr. Chem Eng J 241: 19–27

Carro L, Barriada JL, Herrero R, de Vicente MES (2013) Surface modifications of Sargassum muticum algal biomass for mercury removal: a physicochemical study in batch and continuous flow conditions. Chem Eng J 229:378–387

Chen J, Qu RJ, Zhang Y, Sun CM, Wang CH, Ji CN, Yin P, Chen H, Niu YZ (2012) Preparation of silica gel supported amidoxime adsorbents for selective adsorption of Hg(II) from aqueous solution. Chem Eng J 209:235–244

Choi AL, Cordier S, Weihe P, Grandjean P (2008) Negative confounding in the evaluation of toxicity: the case of methylmercury in fish and seafood. Crit Rev Toxicol 38:877–893

Cui H, Qian Y, Li Q, Zhang Q, Zhai JP (2012) Adsorption of aqueous Hg(II) by a polyaniline/attapulgite composite. Chem Eng J 211: 216–223

Cui H, Qian Y, Li Q, Wei ZB, Zhai JP (2013) Fast removal of Hg(II) ions from aqueous solution by amine-modified attapulgite. Appl Clay Sci 72:84–90

De M, Azargohar R, Dalai AK, Shewchuk SR (2013) Mercury removal by bio-char based modified activated carbons. Fuel 103:570–578

Donia AM, Atia AA, Rashad RT (2011) Fast removal of Cu(II) and Hg(II) from aqueous solutions using kaolinite containing glycidyl methacrylate resin. Desalin Water Treat 30:254–265

Donia AM, Atia AA, Yousif SS (2013) Efficient adsorption of Cu(II) and Hg(II) from their aqueous solutions using amine functionalized cellulose. J Dispers Sci Technol 34:1230–1239

Donia AM, Yousif AM, Atia AA, Abd El-Latif HM (2014) Preparation and characterization of modified cellulose adsorbents with high surface area and high adsorption affinity for Hg(II). J Dispers Sci Technol 35:380–389

Dou BL, Chen HS (2011) Removal of toxic mercury (II) from aquatic solutions by synthesized TiO2 nanoparticles. Desalination 269:260–265

Du W, Yin LB, Zhuo YQ, Xu QS, Zhang L, Chen CH (2014) Catalytic oxidation and adsorption of elemental mercury over $CuCl_2$-impregnated sorbents. Ind Eng Chem Res 53:582–591

Dunham-Cheatham S, Farrell B, Mishra B, Myneni S, Fein JB (2014) The effect of chloride on the adsorption of Hg onto three bacterial species. Chem Geol 373:106–114

Elisseeff J (2008) Hydrogels: structure starts to gel. Nat Mater 7:271–273

Eloussaief M, Sdiri A, Benzina M (2013) Modelling the adsorption of mercury onto natural and aluminium pillared clays. Environ Sci Pollut Res 20:469–479

Faulconer EK, von Reitzenstein NVH, Mazyck DW (2012) Optimization of magnetic powdered activated carbon for aqueous Hg(II) removal and magnetic recovery. J Hazard Mater 199:9–14

Feng W, Borguet E, Vidic RD (2006a) Sulfurization of a carbon surface for vapor phase mercury removal—II: sulfur forms and mercury uptake. Carbon 44:2998–3004

Feng W, Borguet E, Vidic RD (2006b) Sulfurization of carbon surface for vapor phase mercury removal—I: effect of temperature and sulfurization protocol. Carbon 44:2990–2997

Fernandez-Nava Y, Ulmanu M, Anger I, Maranon E, Castrillon L (2011) Use of granular bentonite in the removal of mercury (II), cadmium (II) and lead (II) from aqueous solutions. Water Air Soil Pollut 215: 239–249

Figueira P, Lopes CB, Daniel-da-Silva AL, Pereira E, Duarte AC, Trindade T (2011) Removal of mercury (II) by dithiocarbamate surface functionalized magnetite particles: application to synthetic and natural spiked waters. Water Res 45:5773–5784

Ghasemi Z, Seif A, Ahmadi TS, Zargar B, Rashidi F, Rouzbahani GM (2012) Thermodynamic and kinetic studies for the adsorption of Hg(II) by nano-TiO_2 from aqueous solution. Adv Powder Technol 23:148–156

Ghorbani M, Lashkenari MS, Eisazadeh H (2011) Application of polyaniline nanocomposite coated on rice husk ash for removal of Hg(II) from aqueous media. Synth Met 161:1430–1433

Guerra DL, Oliveira SP, Silva RAS, Silva EM, Batista AC (2012) Dielectric properties of organofunctionalized kaolinite clay and application in adsorption mercury cation. Ceram Int 38:1687–1696

Gupta S, Chakraborty M, Murthy ZVP (2013) Removal of mercury by emulsion liquid membranes: studies on emulsion stability and scale up. J Dispers Sci Technol 34:1733–1741

Habuda-Stanic M, Nujic M (2015) Arsenic removal by nanoparticles: a review. Environ Sci Pollut Res 22:8094–8123

Hadavifar M, Bahramifar N, Younesi H, Li Q (2014) Adsorption of mercury ions from synthetic and real wastewater aqueous solution by functionalized multi-walled carbon nanotube with both amino and thiolated groups. Chem Eng J 237:217–228

Hakami O, Zhang Y, Banks CJ (2012) Thiol-functionalised mesoporous silica-coated magnetite nanoparticles for high efficiency removal and recovery of Hg from water. Water Res 46:3913–3922

Han DS, Orillano M, Khodary A, Duan YH, Batchelor B, Abdel-Wahab A (2014) Reactive iron sulfide (FeS)-supported ultrafiltration for removal of mercury (Hg(II)) from water. Water Res 53:310–321

Hashem A, Hussein HA, Sanousy MA, Adam E, Saad EE (2011) Monomethylolated thiourea–sawdust as a new adsorbent for removal of Hg (II) from contaminated water: equilibrium kinetic and thermodynamic studies. Polym-Plast Technol Eng 50:1220–1230

He F, Wang W, Moon JW, Howe J, Pierce EM, Liang LY (2012) Rapid removal of Hg(II) from aqueous solutions using thiol-functionalized Zn-doped biomagnetite particles. ACS Appl Mater Interfaces 4: 4373–4379

He DG, He XX, Wang KM, Zhao YX, Zou Z (2013) Regenerable multifunctional mesoporous silica nanocomposites for simultaneous detection and removal of mercury (II). Langmuir 29:5896–5904

He C, Shen BX, Chen JH, Cai J (2014) Adsorption and oxidation of elemental mercury over Ce-MnOx/Ti-PILCs. Environ Sci Technol 48:7891–7898

Heaven S, Ilyushchenko MA, Tanton TW, Ullrich SM, Yanin EP (2000) Mercury in the River Nura and its floodplain, Central Kazakhstan: I. River sediments and water. Sci Total Environ 260:35–44

Henneberry YK, Kraus TEC, Fleck JA, Krabbenhoft DP, Bachand PM, Horwath WR (2011) Removal of inorganic mercury and methylmercury from surface waters following coagulation of dissolved organic matter with metal-based salts. Sci Total Environ 409:631–637

Hou WH, Zhou JS, Qi P, Gao X, Luo ZY (2014) Effect of H_2S/HCl on the removal of elemental mercury in syngas over CeO_2-TiO_2. Chem Eng J 241:131–137

Hsi HC, Chen CT (2012) Influences of acidic/oxidizing gases on elemental mercury adsorption equilibrium and kinetics of sulfur-impregnated activated carbon. Fuel 98:229–235

Hsi HC, Rood MJ, Rostam-Abadi M, Chang YM (2013) Effects of sulfur, nitric acid, and thermal treatments on the properties and mercury adsorption of activated carbons from bituminous coals. Aerosol Air Qual Res 13:730–738

Hsi HC, Tsai CY, Lin KJ (2014) Impact of surface functional groups, water vapor, and flue gas components on mercury adsorption and oxidation by sulfur-impregnated activated carbons. Energy Fuel 28: 3300–3309

Hsiao HW, Ullrich SM, Tanton TW (2011) Burdens of mercury in residents of Temirtau, Kazakhstan I: hair mercury concentrations and factors of elevated hair mercury levels. Sci Total Environ 409:2272–2280

Hu HY, Lin H, Zheng W, Rao B, Feng XB, Liang LY, Elias DA, Gu BH (2013) Mercury reduction and cell-surface adsorption by Geobacter sulfurreducens PCA. Environ Sci Technol 47:10922–10930

Hu CX, Zhou JS, Li JX, Zheng J, Wang YC, Luo ZY, Cen KF (2014) Oxidative adsorption of elemental mercury by activated carbon from coconut shell in simulated flue gas. Sep Sci Technol 49:1062–1066

Huang L, Xiao CM, Chen BX (2011) A novel starch-based adsorbent for removing toxic Hg(II) and Pb(II) ions from aqueous solution. J Hazard Mater 192:832–836

Huang Y, Hu D, Wen S, Shen M, Zhu M, Shi X (2014) Selective removal of mercury ions using thymine-grafted electrospun polymer nanofibers. New J Chem 38:1533–1539

Husein DZ (2013) Adsorption and removal of mercury ions from aqueous solution using raw and chemically modified Egyptian mandarin peel. Desalin Water Treat 51:6761–6769

Ie IR, Chen WC, Yuan CS, Hung CH, Lin YC, Tsai HH, Jen YS (2012) Enhancing the adsorption of vapor-phase mercury chloride with an innovative composite sulfur-impregnated activated carbon. J Hazard Mater 217:43–50

Ie IR, Hung CH, Jen YS, Yuan CS, Chen WH (2013) Adsorption of vapor-phase elemental mercury (Hg^0) and mercury chloride ($HgCl_2$) with innovative composite activated carbons impregnated with Na_2S and S^0 in different sequences. Chem Eng J 229:469–476

Jafari SA, Cheraghi S (2014) Mercury removal from aqueous solution by dried biomass of indigenous Vibrio parahaemolyticus PG02: kinetic, equilibrium, and thermodynamic studies. Int Biodeterior Biodegrad 92:12–19

Jana S, Saikia A, Purkait MK, Mohanty K (2011) Chitosan based ceramic ultrafiltration membrane: preparation, characterization and application to remove Hg(II) and As(III) using polymer enhanced ultrafiltration. Chem Eng J 170:209–219

Jing-po Y, Jun Y, Han L, Fei L (2014) Fast response Hg(II) sensing and removal core-shell nanocomposite: construction, characterization and performance. Dyes Pigments 106:168–175

Johari K, Saman N, Mat H (2014a) Adsorption enhancement of elemental mercury onto sulphur-functionalized silica gel adsorbents. Environ Technol 35:629–636

Johari K, Saman N, Mat H (2014b) A comparative evaluation of mercury (II) adsorption equilibrium and kinetics onto silica gel and sulfur-functionalised silica gels adsorbents. Can J Chem Eng 92:1048–1058

Johari K, Saman N, Song ST, Heng JYY, Mat H (2014c) Study of Hg(II) removal from aqueous solution using lignocellulosic coconut fiber biosorbents: equilibrium and kinetic evaluation. Chem Eng Commun 201:1198–1220

Kamath SU, Pemiah B, Sekar RK, Krishnaswamy S, Sethuraman S, Krishnan UM (2012) Mercury-based traditional herbo-metallic preparations: a toxicological perspective. Arch Toxicol 86:831–838

Katok KV, Whitby RLD, Fayon F, Bonnamy S, Mikhalovsky SV, Cundy AB (2013) Synthesis and application of hydride silica composites for rapid and facile removal of aqueous mercury. ChemPhysChem 14:4126–4133

Khaloo SS, Matin AH, Sharifi S, Fadaeinia M, Kazempour N, Mirzadeh S (2012) Equilibrium, kinetic and thermodynamic studies of mercury adsorption on almond shell. Water Sci Technol 65:1341–1349

Kim BJ, Bae KM, An KH, Park SJ (2011) Elemental mercury adsorption behaviors of chemically modified activated carbons. Bull Kor Chem Soc 32:1321–1326

Kim BJ, Bae KM, Park SJ (2012) Elemental mercury vapor adsorption of copper-coated porous carbonaceous materials. Microporous Mesoporous Mater 163:270–275

Kumar ASK, Kalidhasan S, Rajesh V, Rajesh N (2012) A meticulous study on the adsorption of mercury as tetrachloromercurate (II) anion with trioctylamine modified sodium montmorillonite and its application to a coal fly ash sample. Ind Eng Chem Res 51:11312–11327

Kumar KY, Muralidhara HB, Nayaka YA (2014) Magnificent adsorption capacity of hierarchical mesoporous copper oxide nanoflakes towards mercury and cadmium ions: determination of analyte concentration by DPASV. Powder Technol 258:11–19

Kushwaha S, Sudhakar PP (2011) Adsorption of mercury (II), methyl mercury (II) and phenyl mercury (II) on chitosan cross-linked with a barbital derivative. Carbohydr Polym 86:1055–1062

Kyzas GZ, Travlou NA, Deliyanni EA (2014) The role of chitosan as nanofiller of graphite oxide for the removal of toxic mercury ions. Colloids Surf B Biointerfaces 113:467–476

Lee YF, Nan FH, Chen MJ, Wu HY, Ho CW, Chen YY, Huang CC (2012) Detection and removal of mercury and lead ions by using gold nanoparticle-based gel membrane. Anal Methods 4:1709–1717

Li JR, Maroto-Valer MM (2012) Computational and experimental studies of mercury adsorption on unburned carbon present in fly ash. Carbon 50:1913–1924

Li Q, Sun L, Zhang Y, Qian Y, Zhai JP (2011a) Characteristics of equilibrium, kinetics studies for adsorption of Hg(II) and Cr(VI) by polyaniline/humic acid composite. Desalination 266:188–194

Li SX, Zheng FY, Huang Y, Ni JC (2011b) Thorough removal of inorganic and organic mercury from aqueous solutions by adsorption on Lemna minor powder. J Hazard Mater 186:423–429

Li L, Tang SY, Ding DX, Hu N, Yang SY, He SY, Wang YD, Tan Y, Sun J (2012a) A core-shell structured nanocomposite material for detection, adsorption and removal of Hg(II) ions in water. J Nanosci Nanotechnol 12:8407–8414

Li XL, Ye ZF, Zhang Y, Ma XJ, Yang LQ, Li YF (2012b) Efficient removal of Hg(II) by polymer-supported hydrated metal oxides from aqueous solution. Sep Sci Technol 47:729–741

Li FB, Gao ZM, Li XY, Fang LJ (2013a) The adsorption of U(VI) and Hg(II) on Paecilomyces catenlannulatus proteases. J Radioanal Nucl Chem 298:2043–2047

Li RJ, Liu LF, Yang FL (2013b) Preparation of polyaniline/reduced graphene oxide nanocomposite and its application in adsorption of aqueous Hg(II). Chem Eng J 229:460–468

Li ZC, Wu LY, Liu HJ, Lan HC, Qu JH (2013c) Improvement of aqueous mercury adsorption on activated coke by thiol-functionalization. Chem Eng J 228:925–934

Li Q, Wang Z, Fang DM, Qu HY, Zhu Y, Zou HJ, Chen YR, Du YP, Hu HL (2014) Preparation, characterization, and highly effective mercury adsorption of L-cysteine-functionalized mesoporous silica. New J Chem 38:248–254

Lim DH, Aboud S, Wilcox J (2012) Investigation of adsorption behavior of mercury on Au (111) from first principles. Environ Sci Technol 46:7260–7266

Ling LX, Zhao SP, Han PD, Wang BJ, Zhang RG, Fan MH (2014) Toward predicting the mercury removal by chlorine on the ZnO surface. Chem Eng J 244:364–371

Liu JS, Du XZ (2011) Fast removal of aqueous Hg(II) with quaternary ammonium-functionalized magnetic mesoporous silica and silica regeneration. J Mater Chem 21:6981–6987

Liu J, Cheney MA, Wu F, Li M (2011) Effects of chemical functional groups on elemental mercury adsorption on carbonaceous surfaces. J Hazard Mater 186:108–113

Liu MM, Hou LA, Xi BD, Zhao Y, Xia XF (2013) Synthesis, characterization, and mercury adsorption properties of hybrid mesoporous aluminosilicate sieve prepared with fly ash. Appl Surf Sci 273:706–716

Liu H, Yuan B, Zhang B, Hu HY, Li AJ, Luo GQ, Yao H (2014a) Removal of mercury from flue gas using sewage sludge-based adsorbents. J Mater Cycles Waste Manage 16:101–107

Liu M, Wang ZY, Zong SF, Chen H, Zhu D, Wu L, Hu GH, Cui YP (2014b) SERS detection and removal of mercury (II)/silver (I) using oligonucleotide-functionalized core/shell magnetic silica sphere@Au nanoparticles. ACS Appl Mater Interfaces 6:7371–7379

Liu TY, Wang ZL, Yan XX, Zhang B (2014c) Removal of mercury (II) and chromium (VI) from wastewater using a new and effective composite: pumice-supported nanoscale zero-valent iron. Chem Eng J 245:34–40

Liu YX, Pan JF, Wang Q (2014d) Removal of Hg^0 from containing-SO_2/NO flue gas by ultraviolet/H_2O_2 process in a novel photochemical reactor. AIChE J 60:2275–2285

Lo SI, Chen PC, Huang CC, Chang HT (2012) Gold nanoparticle-aluminum oxide adsorbent for efficient removal of mercury species from natural waters. Environ Sci Technol 46:2724–2730

Lopes CB, Oliveira JR, Rocha LS, Tavares DS, Silva CM, Silva SP, Hartog N, Duarte AC, Pereira E (2014) Cork stoppers as an effective sorbent for water treatment: the removal of mercury at environmentally relevant concentrations and conditions. Environ Sci Pollut Res 21:2108–2121

Lothongkum AW, Suren S, Chaturabul S, Thamphiphit N, Pancharoen U (2011) Simultaneous removal of arsenic and mercury from natural-gas-co-produced water from the Gulf of Thailand using synergistic extractant via HFSLM. J Membr Sci 369:350–358

Lu XC, Jiang JC, Sun K, Wang JB, Zhang YP (2014) Influence of the pore structure and surface chemical properties of activated carbon on the adsorption of mercury from aqueous solutions. Mar Pollut Bull 78:69–76

Lv JT, Luo L, Zhang J, Christie P, Zhang SZ (2012) Adsorption of mercury on lignin: combined surface complexation modeling and X-ray absorption spectroscopy studies. Environ Pollut 162:255–261

Ma F, Qu RJ, Sun CM, Wang CH, Ji CN, Zhang Y, Yin P (2009) Adsorption behaviors of Hg(II) on chitosan functionalized by amino-terminated hyperbranched polyamidoamine polymers. J Hazard Mater 172:792–801

Ma XJ, Li YF, Ye ZF, Yang LQ, Zhou LC, Wang LY (2011) Novel chelating resin with cyanoguanidine group: useful recyclable materials for Hg(II) removal in aqueous environment. J Hazard Mater 185:1348–1354

Ma NF, Chen SX, Li TY, Zhang QK (2012) Removal of mercury by an aminated fiber prepared by irradiation grafting copolymerization. Sep Sci Technol 47:867–874

Macias-Garcia A, Cuerda-Correa EM, Olivares-Marin M, Alexandre-Franco M, Gomez-Serrano V (2012) Preparation of micropore-containing adsorbents from kenaf fibers and their use in mercury removal from aqueous solution. J Nat Fibers 9:98–116

Meeks ND, Davis E, Jain M, Skandan G, Bhattacharyya D (2013) Mercury removal by thiol-functionalized metal oxide-carbon black sorbent and mixed-matrix membranes. Environ Prog Sustainable Energy 32:705–714

Miura O, Tachibana S (2014) Mercury removal from solution by high gradient magnetic separation with functional group modified magnetic activated carbon. IEEE Trans Appl Supercond 24:3700904

Mo BB, Lian B (2011) Hg(II) adsorption by Bacillus mucilaginosus: mechanism and equilibrium parameters. World J Microbiol Biotechnol 27:1063–1070

Monier M, Abdel-Latif DA (2012) Preparation of cross-linked magnetic chitosan-phenylthiourea resin for adsorption of Hg(II), Cd(II) and Zn (II) ions from aqueous solutions. J Hazard Mater 209:240–249

Monier M, Abdel-Latif DA (2013) Modification and characterization of PET fibers for fast removal of Hg(II), Cu(II) and Co(II) metal ions from aqueous solutions. J Hazard Mater 250:122–130

Morris EA, Kirk DW, Jia CQ, Morita K (2012) Roles of sulfuric acid in elemental mercury removal by activated carbon and sulfur-impregnated activated carbon. Environ Sci Technol 46:10857

Mullassery MD, Fernandez NB, Anirudhan TS (2014) Removal of mercury (II) ions from aqueous solutions using chemically modified banana stem: kinetic and equilibrium modeling. Sep Sci Technol 49:1259–1269

Murthy ZVP, Parikh PA, Patel NB (2013) Application of beta-zeolite, zeolite Y, and mordenite as adsorbents to remove mercury from aqueous solutions. J Dispers Sci Technol 34:747–755

Naser-Azizi S, Dehnavi AR, Joorabdoozha A (2013) Synthesis and characterization of LTA nanozeolite using barley husk silica: mercury removal from standard and real solutions. Mater Res Bull 48:1753–1759

Niu YZ, Qu RJ, Liu XG, Mu L, Bu BH, Sun YT, Chen H, Meng YF, Meng LN, Cheng L (2014) Thiol-functionalized polysilsesquioxane as efficient adsorbent for adsorption of Hg(II) and Mn(II) from aqueous solution. Mater Res Bull 52:134–142

Oehmen A, Vergel D, Fradinho J, Reis MAM, Crespo JG, Velizarov S (2014) Mercury removal from water streams through the ion exchange membrane bioreactor concept. J Hazard Mater 264:65–70

Ojea-Jimenez I, Lopez X, Arbiol J, Puntes V (2012) Citrate-coated gold nanoparticles as smart scavengers for mercury (II) removal from polluted waters. ACS Nano 6:2253–2260

Okamoto T, Tachibana S, Miura O, Takeuchi M (2011) Mercury removal from solution by superconducting magnetic separation with nanostructured magnetic adsorbents. Phys C Supercond Appl 471:1516–1519

Oliva J, De Pablo J, Cortina JL, Cama J, Ayora C (2011) Removal of cadmium, copper, nickel, cobalt and mercury from water by Apatite II (TM): column experiments. J Hazard Mater 194:312–323

Pan SD, Shen HY, Xu QH, Luo J, Hu MQ (2012a) Surface mercapto engineered magnetic Fe_3O_4 nanoadsorbent for the removal of mercury from aqueous solutions. J Colloid Interface Sci 365:204–212

Pan SD, Zhang Y, Shen HY, Hu MQ (2012b) An intensive study on the magnetic effect of mercapto-functionalized nano-magnetic Fe3O4 polymers and their adsorption mechanism for the removal of Hg(II) from aqueous solution. Chem Eng J 210:564–574

Parham H, Zargar B, Shiralipour R (2012) Fast and efficient removal of mercury from water samples using magnetic iron oxide nanoparticles modified with 2-mercaptobenzothiazole. J Hazard Mater 205:94–100

Pena-Rodriguez S, Bermudez-Couso A, Novoa-Munoz JC, Arias-Estevez M, Fernandez-Sanjurjo MJ, Alvarez-Rodriguez E, Nunez-Delgado A (2013) Mercury removal using ground and calcined mussel shell. J Environ Sci (China) 25:2476–2486

Perez-Quintanilla D, Sierra I (2014) Factors affecting Hg(II) adsorption on hybrid nanostructured silicas: influence of the synthesis conditions. J Porous Mater 21:71–80

Pervukhina NV, Romanenko GV, Borisov SV, Magarill SA, Palchik NA (1999) Crystal chemistry of mercury (I) and mercury (I, II) minerals. J Struct Chem 40:461–476

Qi YX, Jin XL, Yu C, Wang Y, Yang LQ, Li YF (2013) A novel chelating resin containing high levels of sulfamine group: preparation and its adsorption characteristics towards p-toluenesulfonic acid and Hg(II). Chem Eng J 233:315–322

Qu RJ, Zhang Y, Qu WW, Sun CM, Chen J, Ping Y, Chen H, Niu YZ (2013) Mercury adsorption by sulfur- and amidoxime-containing bifunctional silica gel based hybrid materials. Chem Eng J 219:51–61

Rabelo RB, Vieira RS, Luna FMT, Guibal E, Beppu MM (2012) Adsorption of copper (II) and mercury (II) ions onto chemically-modified chitosan membranes: equilibrium and kinetic properties. Adsorpt Sci Technol 30:1–21

Rahman N, Sato N, Sugiyama M, Hidaka Y, Okabe H, Hara K (2014) Selective Hg(II) adsorption from aqueous solutions of Hg(II) and Pb(II) by hydrolyzed acrylamide-grafted PET films. J Environ Sci Health A Toxic/Hazard Subst Environ Eng 49:798–806

Raji F, Pakizeh M (2013) Study of Hg(II) species removal from aqueous solution using hybrid $ZnCl_2$-MCM-41 adsorbent. Appl Surf Sci 282:415–424

Raji F, Pakizeh M (2014) Kinetic and thermodynamic studies of Hg(II) adsorption onto MCM-41 modified by $ZnCl_2$. Appl Surf Sci 301:568–575

Reddy KSK, Al Shoaibi A, Srinivasakannan C (2014) Elemental mercury adsorption on sulfur-impregnated porous carbon—a review. Environ Technol 35:18–26

Redko MY, Huang R, Dye JL, Jackson JE (2006) One-pot synthesis of 1,4,7,10,13,16,21,24-octaazabicyclo[8.8.8]hexacosane—the peraza analogue of [2.2.2]cryptand. Synthesis 2006:759–761

Redko MY, Manes KM, Taurozzi JS, Jackson JE, Tarabara VV (2014) Synthesis and characterization of Aza222-based polymers for the removal of mercury from aqueous solutions. React Funct Polym 74:90–100

Rocha LS, Lopes CB, Borges JA, Duarte AC, Pereira E (2013) Valuation of unmodified rice husk waste as an eco-friendly sorbent to remove mercury: a study using environmental realistic concentrations. Water Air Soil Pollut 224:1599

Rocha LS, Lopes CB, Henriques B, Tavares DS, Borges J, Duarte AC, Pereira E (2014a) Competitive effects on mercury removal by an agricultural waste: application to synthetic and natural spiked waters. Environ Technol 35:661–673

Rocha LS, Lopes I, Lopes CB, Henriques B, Soares A, Duarte AC, Pereira E (2014b) Efficiency of a cleanup technology to remove mercury from natural waters by means of rice husk biowaste: ecotoxicological and chemical approach. Environ Sci Pollut Res 21:8146–8156

Saad DMG, Cukrowska EM, Tutu H (2012) Sulfonated cross-linked polyethylenimine for selective removal of mercury from aqueous solutions. Toxicol Environ Chem 94:1916–1929

Saber-Samandari S, Gazi M (2013) Removal of mercury (II) from aqueous solution using chitosan-graft-polyacrylamide semi-IPN hydrogels. Sep Sci Technol 48:1382–1390

Salahi S, Parvini M, Ghorbani M (2014) Equilibrium studies in adsorption of Hg(II) from aqueous solutions using biocompatible polymeric polypyrrole-chitosan nanocomposite. Polycycl Aromat Compd 34:225–236

Saman N, Johari K, Mat H (2014) Adsorption characteristics of sulfur-functionalized silica microspheres with respect to the removal of Hg(II) from aqueous solutions. Ind Eng Chem Res 53:1225–1233

Seco-Reigosa N, Pena-Rodriguez S, Novoa-Munoz JC, Arias-Estevez M, Fernandez-Sanjurjo MJ, Alvarez-Rodriguez E, Nunez-Delgado A (2013) Arsenic, chromium and mercury removal using mussel shell ash or a sludge/ashes waste mixture. Environ Sci Pollut Res 20: 2670–2678

Sen TK, Bin Azman AF, Maitra S, Dutta BK (2011) Removal of mercury (II) from aqueous solutions using the leaves of the rambai tree (Baccaurea motleyana). Water Environ Res 83:834–842

Shadbad MJ, Mohebbi A, Soltani A (2011) Mercury (II) removal from aqueous solutions by adsorption on multi-walled carbon nanotubes. Korean J Chem Eng 28:1029–1034

ShamsiJazeyi H, Kaghazchi T (2014) Simultaneous activation/sulfurization method for production of sulfurized activated carbons: characterization and Hg(II) adsorption capacity. Water Sci Technol 69:546–552

Shawky HA, El-Aassar AHM, Abo-Zeid DE (2012) Chitosan/carbon nanotube composite beads: preparation, characterization, and cost evaluation for mercury removal from wastewater of some industrial cities in Egypt. J Appl Polym Sci 125:E93–E101

Sheela T, Nayaka YA, Viswanatha R, Basavanna S, Venkatesha TG (2012) Kinetics and thermodynamics studies on the adsorption of Zn (II), Cd (II) and Hg (II) from aqueous solution using zinc oxide nanoparticles. Powder Technol 217:163–170

Shu T, Lu P, He N (2013) Mercury adsorption of modified mulberry twig chars in a simulated flue gas. Bioresour Technol 136:182–187

Siddiqui N, Don J, Mondal K, Mahajan A (2011) Development of bamboo-derived sorbents for mercury removal in gas phase. Environ Technol 32:383–394

Singh V, Kumary P (2011) Design of nanostructured tamarind seed kernel polysaccharide-silica hybrids for mercury (II) removal. Sep Sci Technol 46:825–838

Singh V, Singh SK (2011) Synthesis and characterization of gum acacia inspired silica hybrid xerogels for mercury (II) adsorption. Int J Biol Macromol 48:445–451

Singh R, Gautam N, Mishra A, Gupta R (2011) Heavy metals and living systems: an overview. Indian J Pharmacol 43:246–253

Song BY, Eom Y, Lee TG (2011) Removal and recovery of mercury from aqueous solution using magnetic silica nanocomposites. Appl Surf Sci 257:4754–4759

Song ST, Saman N, Johari K, Mat H (2013) Removal of Hg(II) from aqueous solution by adsorption using raw and chemically modified rice straw as novel adsorbents. Ind Eng Chem Res 52:13092–13101

Song N, Teng Y, Wang JW, Liu Z, Orndorff W, Pan WP (2014) Effect of modified fly ash with hydrogen bromide on the adsorption efficiency of elemental mercury. J Therm Anal Calorim 116:1189–1195

Standeker S, Veronovski A, Novak Z, Knez Z (2011) Silica aerogels modified with mercapto functional groups used for Cu(II) and Hg(II) removal from aqueous solutions. Desalination 269:223–230

Sun CM, Ma F, Zhang GH, Qu RJ, Zhang Y (2011a) Removal of mercury ions from ethanol solution using silica gel functionalized with amino-terminated dendrimer-like polyamidoamine polymers: kinetics and equilibrium studies. J Chem Eng Data 56:4407–4415

Sun XA, Hwang JY, Xie SQ (2011b) Density functional study of elemental mercury adsorption on surfactants. Fuel 90:1061–1068

Sun CM, Li CX, Wang CH, Qu RJ, Niu YZ, Geng HB (2012) Comparison studies of adsorption properties for Hg(II) and Au(III) on polystyrene-supported bis-8-oxyquinoline-terminated open-chain crown ether. Chem Eng J 200:291–299

Sun J, Chen ZM, Ge MY, Xu L (2013) Radiation synthesis and characterization of 3-(trimethoxysilyl) propyl methacrylate silanized silica-graft-vinyl imidazole for Hg(II) adsorption. Nucl Sci Tech 24: S010307

Sun CM, Li CX, Qu RJ, Zhang Y, Zhang BD, Kuang YZ (2014a) Syntheses of diethylenetriamine-bridged polysilsesquioxanes and their structure-adsorption properties for Hg(II) and Ag(I). Chem Eng J 240:369–378

Sun XM, Qu RJ, Sun CM, Zhang Y, Sun SY, Ji CN, Yin P (2014b) Sol-gel preparation and Hg(II) adsorption properties of silica-gel supported low generation polyamidoamine dendrimers polymer adsorbents. Ind Eng Chem Res 53:2878–2888

Tadayon F, Saber-Tehrani M, Motahar S (2013) Selective removal mercury (II) from aqueous solution using silica aerogel modified with 4-amino-5-methyl-1,2,4-triazole-3(4H)-thion. Korean J Chem Eng 30: 642–648

Tan ZQ, Sun LS, Xiang J, Zeng HC, Liu ZH, Hu S, Qiu JR (2012) Gas-phase elemental mercury removal by novel carbon-based sorbents. Carbon 50:362–371

Tang R, Li Q, Cui H, Zhang Y, Zhai JP (2011) Adsorption of aqueous Hg (II) by a novel poly(aniline-co-o-aminophenol)/mesoporous silica SBA-15 composite. Polym Adv Technol 22:2231–2236

Tavares DS, Daniel-da-Silva AL, Lopes CB, Silva NJO, Amaral VS, Rocha J, Pereira E, Trindade T (2013) Efficient sorbents based on magnetite coated with siliceous hybrid shells for removal of mercury ions. J Mater Chem A 1:8134–8143

Thakur S, Das G, Raul PK, Karak N (2013) Green one-step approach to prepare sulfur/reduced graphene oxide nanohybrid for effective mercury ions removal. J Phys Chem C 117:7636–7642

Thakur S, Kumari S, Dogra P, Chauhan GS (2014) A new guar gum-based adsorbent for the removal of Hg(II) from its aqueous solutions. Carbohydr Polym 106:276–282

Toubi Y, Radi S, Bacquet M (2013) Synthesis of pyridin-3-yl-functionalized silica as a chelating sorbent for solid-phase adsorption of Hg (II), Pb (II), Zn (II), and Cd (II) from water. Res Chem Intermed 39:3791–3802

Tsai CY, Hsi HC, Bai HL, Fan KS, Chen CC (2011) TiO_{2-x} nanoparticles synthesized using He/Ar thermal plasma and their effectiveness on low-concentration mercury vapor removal. J Nanoparticle Res 13: 4739–4748

Vieira RS, Oliveira MLM, Guibal E, Rodriguez-Castellon E, Beppu MM (2011) Copper, mercury and chromium adsorption on natural and crosslinked chitosan films: an XPS investigation of mechanism. Colloids Surf A Physicochem Eng Asp 374:108–114

Wahby A, Abdelouahab-Reddam Z, El Mail R, Stitou M, Silvestre-Albero J, Sepulveda-Escribano A, Rodriguez-Reinoso F (2011) Mercury removal from aqueous solution by adsorption on activated carbons prepared from olive stones. Adsorption J Int Adsorption Soc 17:603–609

Wang X, Andrews L, Riedel S, Kaupp M (2007) Mercury is a transition metal: the first experimental evidence for HgF4. Angew Chem Int Ed 46:8371–8375

Wang QH, Chang XJ, Li DD, Hu Z, Li RJ, He Q (2011) Adsorption of chromium (III), mercury (II) and lead (II) ions onto 4-aminoantipyrine immobilized bentonite. J Hazard Mater 186: 1076–1081

Wang ZD, Yin P, Wang Z, Qu RJ, Liu XG (2012) Chelating resins silica gel supported aminophosphonic acids prepared by a heterogeneous synthesis method and a homogeneous synthesis method and the removal properties for Hg(II) from aqueous solutions. Ind Eng Chem Res 51:8598–8607

Wang XH, Deng WY, Xie YY, Wang CY (2013a) Selective removal of mercury ions using a chitosan-poly(vinyl alcohol) hydrogel adsorbent with three-dimensional network structure. Chem Eng J 228:232–242

Wang YS, Cheng CC, Chen JK, Ko FH, Chang FC (2013b) Bioinspired supramolecular fibers for mercury ion adsorption. J Mater Chem A 1:7745–7750

Wang ZD, Yin P, Qu RJ, Chen H, Wang CH, Ren SH (2013c) Adsorption kinetics, thermodynamics and isotherm of Hg(II) from aqueous solutions using buckwheat hulls from Jiaodong of China. Food Chem 136:1508–1514

Wang WJ, Chen ML, Chen XW, Wang JH (2014a) Thiol-rich polyhedral oligomeric silsesquioxane as a novel adsorbent for mercury adsorption and speciation. Chem Eng J 242:62–68

Wang XH, Sun RZ, Wang CY (2014b) pH dependence and thermodynamics of Hg(II) adsorption onto chitosan-poly(vinyl alcohol) hydrogel adsorbent. Colloids Surf A Physicochem Eng Asp 441:51–58

Wang XH, Yang L, Zhang JP, Wang CY, Li QY (2014c) Preparation and characterization of chitosan-poly(vinyl alcohol)/bentonite nanocomposites for adsorption of Hg(II) ions. Chem Eng J 251:404–412

Wdowin M, Wiatros-Motyka MM, Panek R, Stevens LA, Franus W, Snape CE (2014) Experimental study of mercury removal from exhaust gases. Fuel 128:451–457

Xiang WJ, Liu J, Chang M, Zheng CG (2012) The adsorption mechanism of elemental mercury on CuO (110) surface. Chem Eng J 200:91–96

Xie JK, Xu HM, Qu Z, Huang WJ, Chen WM, Ma YP, Zhao SJ, Liu P, Yan NQ (2014) Sn-Mn binary metal oxides as non-carbon sorbent for mercury removal in a wide-temperature window. J Colloid Interface Sci 428:121–127

Xiong CH, Chen XY, Yao CP (2012) Preparation of a novel heterocycle-containing polystyrene chelating resin and its application for Hg(II) adsorption in aqueous solutions. Curr Org Chem 16:1942–1948

Xiong CH, Jia Q, Chen XY, Wang GT, Yao CP (2013) Optimization of polyacrylonitrile-2-aminothiazole resin synthesis, characterization, and its adsorption performance and mechanism for removal of Hg(II) from aqueous solutions. Ind Eng Chem Res 52:4978–4986

Xu WQ, Wang HR, Zhu TY, Kuang JY, Jing PF (2013) Mercury removal from coal combustion flue gas by modified fly ash. J Environ Sci (China) 25:393–398

Xu YY, Hao ZH, Chen H, Sun JM, Wang DJ (2014) Preparation of polyacrylonitrile initiated by modified corn starch and adsorption for mercury after modification. Ind Eng Chem Res 53:4871–4877

Xue T, Wang RQ, Zhang MM, Dai JL (2013) Adsorption and desorption of mercury (II) in three forest soils in Shandong Province, China. Pedosphere 23:265–272

Yao YX, Velpari V, Economy J (2013) In search of brominated activated carbon fibers for elemental mercury removal from power plant effluents. J Mater Chem A 1:12103–12108

Yao YX, Li HB, Liu JY, Tan XL, Yu JG, Peng ZG (2014a) Removal and adsorption of p-nitrophenol from aqueous solutions using carbon nanotubes and their composites. J Nanomater 2014:571745

Yao YX, Velpari V, Economy J (2014b) Design of sulfur treated activated carbon fibers for gas phase elemental mercury removal. Fuel 116: 560–565

Yau VM, Green PG, Alaimo CP, Yoshida CK, Lutsky M, Windham GC, Delorenze G, Kharrazi M, Grether JK, Croen LA (2014) Prenatal and neonatal peripheral blood mercury levels and autism spectrum disorders. Environ Res 133:294–303

Yin ML, Li ZH, Liu Z, Yang XJ, Ren JS (2012) Magnetic self-assembled zeolite clusters for sensitive detection and rapid removal of mercury (II). ACS Appl Mater Interfaces 4:431–437

Yu Y, Addai-Mensah J, Losic D (2012a) Functionalized diatom silica microparticles for removal of mercury ions. Sci Technol Adv Mater 13

Yu Y, Zhang BW, Yu M, Deng B, Li LF, Fan CH, Li JY (2012b) High-selective removal of ultra-low level mercury ions from aqueous solution using oligothymonucleic acid functionalized polyethylene film. Sci China Chem 55:2202–2208

Yu CT, Cheng HW, Chen YL (2014a) Removal of mercury using novel lamella carbonate sorbent at elevated temperature conditions. J Chin Chem Soc 61:831–835

Yu J-G, Zhao X-H, Yang H, Chen X-H, Yang Q, Yu L-Y, Jiang J-H, Chen X-Q (2014b) Aqueous adsorption and removal of organic contaminants by carbon nanotubes. Sci Total Environ 482–483:241–251

Yu J-G, Zhao X-H, Yu L-Y, Jiao F-P, Jiang J-H, Chen X-Q (2014c) Removal, recovery and enrichment of metals from aqueous solutions using carbon nanotubes. J Radioanal Nucl Chem 299:1155–1163

Yu J-G, Yu L-Y, Yang H, Liu Q, Chen X-H, Jiang X-Y, Chen X-Q, Jiao F-P (2015) Graphene nanosheets as novel adsorbents in adsorption, preconcentration and removal of gases, organic compounds and metal ions. Sci Total Environ 502:70–79

Zabihi M, Ahmadpour A, Asl AH (2011) Removal of mercury from water by carbonaceous sorbents derived from walnut shell. J Hazard Mater 185:512

Zhang HW, Chen JT, Liang P, Wang L (2012a) Mercury oxidation and adsorption characteristics of potassium permanganate modified lignite semi-coke. J Environ Sci (China) 24:2083–2090

Zhang L, Zhuo YQ, Du W, Tao Y, Chen CH, Xu XC (2012b) Hg removal characteristics of noncarbon sorbents in a fixed-bed reactor. Ind Eng Chem Res 51:5292–5298

Zhang LJ, Goh S, Hu X, Crawford R, Yu AM (2012c) Removal of aqueous toxic Hg(II) by functionalized mesoporous silica materials. J Chem Technol Biotechnol 87:1473–1479

Zhang MM, Liu J, Tian CY, Wang RQ, Dai JL (2012d) Effect of pH, temperature, and the role of ionic strength on the adsorption of mercury (II) by typical Chinese soils. Commun Soil Sci Plant Anal 43:1599–1613

Zhang SX, Zhang YY, Liu JS, Xu Q, Xiao HQ, Wang XY, Xu H, Zhou J (2013) Thiol modified $Fe_3O_4@SiO_2$ as a robust, high effective, and recycling magnetic sorbent for mercury removal. Chem Eng J 226: 30–38

Zhang MM, Wang RQ, Guo W, Xue T, Dai JL (2014a) Mercury (II) adsorption on three contrasting Chinese soils treated with two sources of dissolved organic matter: I Langmuir and Freundlich isotherm evaluation. Soil Sediment Contam 23: 49–62

Zhang YK, Yan LG, Xu WY, Guo XY, Cui LM, Gao L, Wei Q, Du B (2014b) Adsorption of Pb(II) and Hg(II) from aqueous solution using magnetic $CoFe_2O_4$-reduced graphene oxide. J Mol Liq 191: 177–182

Zhang YS, Duan W, Liu Z, Cao Y (2014c) Effects of modified fly ash on mercury adsorption ability in an entrained-flow reactor. Fuel 128: 274–280

Zhao PF, Guo X, Zheng CG (2012) The removal of elemental mercury by potassium permanganate-modified rice husk ash sorbents. Energ Source Part A 34:994–1003

Zhao Y, Xue FM, Ma TZ (2013a) Experimental study on Hg-0 removal by diperiodatocuprate (III) coordination ion solution. Fuel Process Technol 106:468–473

Zhao Y, Xue FM, Zhao XC, Guo TX, Li XL (2013b) Experimental study on elemental mercury removal by diperiodatonickelate (IV) solution. J Hazard Mater 260:383–388

Zhao Y, Han YH, Guo TX, Ma TZ (2014) Simultaneous removal of SO_2, NO and Hg^0 from flue gas by ferrate (VI) solution. Energy 67:652–658

Zheng YJ, Jensen AD, Windelin C, Jensen F (2012) Review of technologies for mercury removal from flue gas from cement production processes. Prog Energy Combust Sci 38:599–629

Zhong LC, Zhang YS, Liu Z, Sui ZF, Cao Y, Pan WP (2014) Study of mercury adsorption by selected Chinese coal fly ashes. J Therm Anal Calorim 116:1197–1203

Zhou JS, Hou WH, Qi P, Gao X, Luo ZY, Cen KF (2013a) CeO_2-TiO_2 sorbents for the removal of elemental mercury from syngas. Environ Sci Technol 47:10056–10062

Zhou YM, Hu XY, Zhang M, Zhuo XF, Niu JY (2013b) Preparation and characterization of modified cellulose for adsorption of Cd(II), Hg(II), and acid fuchsin from aqueous solutions. Ind Eng Chem Res 52:876–884

Zhou Y, Zhang JP, Luo XG, Lin XY (2014) Adsorption of Hg(II) in aqueous solutions using mercapto-functionalized alkali lignin. J Appl Polym Sci 131

Zolfaghari G, Esmaili-Sari A, Anbia M, Younesi H, Amirmahmoodi S, Ghafari-Nazari A (2011) Taguchi optimization approach for Pb(II) and Hg(II) removal from aqueous solutions using modified mesoporous carbon. J Hazard Mater 192:1046–1055

Zong GX, Chen H, Qu RJ, Wang CH, Ji NY (2011) Synthesis of polyacrylonitrile-grafted cross-linked N-chlorosulfonamidated polystyrene via surface-initiated ARGET ATRP, and use of the resin in mercury removal after modification. J Hazard Mater 186:614–621

Zong GX, Ma J, Chen H, Wang CH, Ji NY, Liu DL (2012) Synthesis of crosslinked polyacrylonitrile via atom transfer radical polymerization with activators regenerated by electron transfer and use of the resin in mercury removal after modification. J Appl Polym Sci 124:2179–2186

Zou WL, Filatov M, Atwood D, Cremer D (2013) Removal of mercury from the environment: a quantum-chemical study with the normalized elimination of the small component method. Inorg Chem 52:2497–2504