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Nano-materials: Novel and Promising Adsorbents for Water Treatment

Md. Ahmaruzzaman
Department of Chemistry, National Institute of Technology, Silchar – 788010, Assam, India
✉ mda2002@gmail.com

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Abstract: Recently, nanotechnology has been utilized in more or less all fields, such as physics, chemistry, materials science, biology, medicine, etc. In this relation, nanotechnology is also applied in the removal of various impurities/pollutants including pathogenic bacteria and virus from water and other water bodies. Among the various methods used for wastewater treatment, adsorption is found to be one of the better methods because of its low-cost and simplicity of operation. Recently, nanoadsorbents have been explored for the removal of various pollutants from waste water. In this paper, the utilization of nanomaterials, as an effective adsorbent for the removal of heavy metals, organic compounds, pesticides, pharmaceuticals and other pollutants, is reviewed and discussed. It is to be mentioned that adsorption capacities of the adsorbents vary depending on the characteristics of the adsorbents, the extent of chemical modification and the concentration of adsorbates. There are also few issues and drawbacks on the utilization of nanoadsorbents that have been addressed. To find out the practical utilization of nanomaterials as low-cost adsorbents on the commercial scale, more research should be conducted in this direction. This review article demonstrated that nanomaterials may be effectively utilized for the treatment of wastewater and may be the future novel and promising adsorbents/materials for water treatment.

Key words: Nano-materials, water treatment, metal-oxide, carbon nanotubes, pesticides.

Introduction

Water is the most vital component on the globe for the various activities of human being. Therefore, clean hygienic water is the primary necessity of the human being for their good health. Water pollution is growing worldwide because of rapid growth of industry, large human population, and domestic and agricultural activities (Schwarzenbach et al., 2010). Nanotechnology has a wide range of applications in various fields of science and technology. Recently, researchers worldwide utilized this technology for the treatment of waste water and other water bodies. Nanomaterials have emerged as a lucrative, efficient and environmental friendly alternative in relation to that of existing water treatment facilities for the removal of various water pollutants (Khajeh et al., 2013; Ali, 2012; Thatai et al., 2014). These nanomaterials represent a promising novel process for the wastewater treatment. This is because of their high removal efficiency and cost–effectiveness. Attempts have been made to describe several aspects of water treatment using nanomaterials because of the immense importance of water quality.

Various nanomaterials, such as nanometallic-oxide, magnetic nanomaterials, etc. are utilized for the treatment of wastewater and other water bodies (Das et al., 2012; Dave et al., 2014; Pradeep and Anshup, 2009). Polymer-based nanomaterials and carbon nanotubes may also be the potential future adsorbents for the removal of various pollutants, including virus and fungi from the drinking and other water bodies. Because of their useful properties, such as excellent thermal stability, higher adsorption ability, broad range of pH, etc. carbon nanotubes have been utilized for the removal of various contaminants. The application of various nanomaterials has been reviewed and discussed below.

Metal-oxide Nanomaterials

It is known that nanoscale metal-oxides possess different chemical, physical, morphological and other properties than that of their corresponding microscale parts. Generally, Al_2O_3, ZnO and TiO_2 nanoscale oxides are widely used in the water and wastewater treatment. Because of high surface area, catalytic properties, high surface to volume ratio, and other favourable properties, these metal-oxide nanomaterials showed strong adsorption capacity towards various pollutants present in water. The adsorption capacity also depends on the disparity in metal ion radius, interaction energy and oxidation states of the heavy metal ions (Tiemann et al., 2000).

Various impurities, such as organic, inorganic, and other harmful impurities can be easily removed from the water bodies using adsorption process (Ahmaruzzaman, 2008, 2010, 2011). In this respect, metal-oxide nanomaterials may be excellent adsorbents for the removal of heavy metals and other organic pollutants from aqueous phase (Khoshhesa, 2015). The most frequently used metal-oxide nanomaterials for the elimination of organic, inorganic and other pollutants are magnesium oxides, titanium oxides, ferric oxides, manganese oxides, aluminum oxides, cerium oxides, etc. (Pacheco, 2006; Jegadeesan, 2010; Binlin, 2011). Low-cost metal-oxide nanoparticles are utilized for the removal of various metal ions, such as arsenic, cadmium, mercury, iron, chromium, lead, cobalt, copper, selenium, etc. from wastewater (Hristovski, 2007; Lagashetty, 2004; Kumar, 2013). Fakhri (2015) investigated the adsorption of Hg(II) onto copper oxide nanoparticles from aqueous solution.

The author studied the influence of adsorbent dose, pH and temperature on the mercury removal unto copper oxide nanoparticles and reported the optimum pH, adsorbent dose and temperature were 9.0, 0.05 g and 278 K, respectively. The removal of As(III) and As(V) species on nanosized amorphous and crystalline TiO_2 was reported by Jegadeesan et al. (2010). The authors reported that binuclear bidentate inner sphere complexation of As(III) and As(V) on amorphous TiO_2 at a neutral pH is responsible for the adsorption. Pacheco et al. (2006) utilized alumina silica nanoparticles for the adsorption of cadmium from wastewater and reported 96.4% removal of cadmium on Si-Al particles. The presence of hydroxyl, alkoxy and oxy groups in the reported nanoparticles are responsible for the adsorption of cadmium and cationic exchange may be mechanism for their removal. Hristovski et al. (2007) discussed As(V) removal on sixteen (16) nanomaterials of metal oxides, and most vital were TiO_2, Fe_2O_3, ZrO_2 and NiO. The adsorption capacity was around 98% for all the studied nanoparticles except for ZrO_2.

Recently, adsorption of reactive black 8 (RB8) from their aqueous solutions was reported using zinc oxide nanoparticles (Khoshhesa, 2015). The various affecting parameters such as solution pH, contact time, initial dye concentration, and sorbent dosage on the removal efficiency were reported. The equilibrium adsorption data of RB8 on ZnO nanoparticles surface were analyzed by Langmuir and Freundlich isotherms. The adsorption process correlated with Langmuir model better than Freundlich isotherm and the maximum adsorption capacity was reported to be 27.6 mg g^{-1}. The authors found that the adsorption process followed the pseudo-second-order kinetic equation and could best describe the sorption kinetics.

Several modifications and functionalization of the metal-oxide nanomaterials may enhance their adsorption capacity (Neyaz et al., 2013). Surface coated metal-oxide nanomaterials with various materials, such as, carbon, EDTA, rice husk, saw-dust etc. probably gives higher adsorption capacity than pure metal-oxide nanoadsorbent. Recently, various researchers reported the adsorption of inorganic pollutants from wastewater using surface modified nano metal-oxides (Neyaz et al., 2013; Bhandari et al., 2016; Khare et al., 2018). It is evident from the above findings that nano metal oxide may be effective adsorbents for the removal of heavy metals and dyes from water and wastewater. It is also evident that very few studies were reported for the removal of pesticides, pharmaceutical and other organic compounds from water. Therefore, more research should be directed towards the utilization and surface modification of nano metal oxide for the removal of PPCPs, pesticides and other emerging pollutants from wastewater.

Metal Nanoparticles

Metal nanoparticles, such as Ag, Au, Sn, Cu, etc. are another group of inorganic materials and may be used for the removal of dyes, heavy metals, organic pollutants, pesticides, pathogenic and other harmful bacteria, fungi, etc. from water and wastewater. Metal nanoparticles with controlled size and shape are of immense interest because of their diverse applications and morphology-dependent properties. They have attracted substantial attention to the scientists and researchers throughout the world due to their potential application and novel properties (Du et al., 2008). The binding capacity of various dyes with noble metal nanoparticles may be higher compared to that of other nanoparticles. The composition, size, morphology and stability are the various factors affecting the adsorption of dyes on nanoparticles. The removal of congo red (CR) dye by adsorption on silver and gold nanoparticles coated activated carbon (AC) has been discussed and reported (Pal and Deb, 2014).

The equilibrium time is reported to be independent of the initial CR concentration and the percentage removal of CR increased with increase in contact time. Kinetic studies showed that the adsorption of CR followed pseudo-first-order kinetics. AgNPs and AuNPs-coated AC is found to be suitable adsorbent for the adsorption of CR. CR was effectively removed 88.0 ± 0.8 % from aqueous solution using AuNPs beads as the adsorption process. Desorption studies were made to elucidate recovery of the adsorbate and adsorbent for the economic competitiveness of the removal system. The PVP-supported AgNPs and AuNPs-coated AC were successfully recycled for ten successive adsorption–desorption cycles indicating its high reusability.

The same research group (Pal et al., 2013) utilized silver nanoparticles (AgNPs) coated activated carbon (AC) for the removal of methyl orange (MO) dye. Using AgNPs-coated AC, 72.5% of MO was removed, whereas only 50.0% when using AC after reacting for 16 h with an initial MO concentration of 2 mg/L (pH = 7). The authors reported that the adsorption of MO followed pseudo-second-order kinetics and AgNPs-coated AC is found to be suitable adsorbent for the adsorption of MO. Recently, silver nanoparticles has also been utilized for the removal of atrazine from aqueous solution (Pal et al., 2015). It was reported that the percent removal of atrazine decreases on increasing the initial atrazine concentrations. A contact time of 14 h was found to be sufficient for maximum removal of atrazine. The authors concluded that silver nanoparticles beads can be an effective adsorbent for the removal of atrazine from aqueous solution.

Silver nanoparticle loaded on activated carbon were synthesized and used for the removal of methyl orange (MO) from aqueous solutions (Karimi et al., 2012). The influence of variables such as initial solution pH, amount of adsorbent, initial MO concentration and adsorption time on its removal percentage was studied. The equilibrium adsorption isotherms have been analyzed by Langmuir, Freundlich and Tempkin models. It was found that Langmuir model has the highest correlation coefficients. The fitting experimental data to different conventional kinetic models such as pseudo-first and pseudo-second-order, Elovich and intraparticle diffusion kinetic models show that adsorption follow the second-order equation in addition to intraparticle diffusion as the rate-limiting factor. Femila et al. (2014) synthesised the AgNPs using aqueous leaf extract of Aegle marmelos and utilized as nanoadsorbent for the removal of Malachite Green dyes from aqueous solution.

Nano zerovalent iron (ZVI) loaded with activated carbon was also utilized for the removal of arsenic from aqueous phase and adsorption capacity was reported as 1.997 mg/g (Zhang, 2003). These nano ZVI and starch stabilized ZVI was also used for the adsorption of chromium from water and reported that modified nano-adsorbents was better than its unmodified form (Ponder et al., 2000; Niu et al., 2005). Nano ZVI and its bimetallic form may be utilized as efficient redox adsorbent for the removal of various pollutants from water sources. These nanomaterials possess higher surface area and reactivity than that of bulk ZVI particles (Schrick, 2002). They are also used for the conversion of Cr(VI) to less toxic, Cr(III) ions. Li et al. (2006) used (NZVI) as a bactericidal for the removal of *Escherichia coli* from groundwater. Immobilized nanomaterials have emerged as a potential adsorbent for the treatment of wastewater because of its high adsorption capacity and antimicrobial activity. Ag nanomaterials and its embedded form with various materials were found to be very effective against both Gram-positive and Gram-negative bacteria.

Even though, Ag nanoparticles were effectively used for the removal of pathogenic bacteria and viruses, precautions have to be taken for their long-term utilization because of their toxicity into the environment and human being. Modification of Ag nanoparticles with metal oxide and other materials may improve their pollutants removal capacity and might be used for the removal of dyes, heavy metals, organic compounds and pesticides from water bodies.

Silver nanoparticles loaded on activated carbon were utilized for the removal of dyes, such as malachite green and methyl orange from aqueous phase (Mortazavi et al., 2016; Ghaedi et al., 2018; AbdEl-Salam et al., 2017).

Magnetic Nanomaterials

Another group of nanomaterials which needs much attention is the magnetic nanomaterials and possesses special advantages in the water and wastewater treatment. The unique size, shape, morphology and other properties of the magnetic nanomaterials need attention for their fruitful application. The changes of these properties may control their magnetic properties which influence the removal of various pollutants, specially the heavy metals from wastewater and other water bodies. A large number of inorganic and organic pollutants may be removed through the modification of the surface of engineered magnetic nanoparticles. The performance of the magnetic nanoparticle-based adsorption process requires the analyses and development of various parameters, such as regeneration and management of the exhausted adsorbent and solution, magnetic recovery, etc.

Iron oxide nanoparticles are highly dispersible in solutions. These nanoparticles possess a high surface area and superparamagnetic properties. Therefore, iron oxide nanoparticles will be a very useful and potent adsorbent in novel separation process. In particular, unmodified maghemite (γ-Fe_2O_3) was reported to be better adsorbent for the removal of Cr(VI) (Hu et al., 2005). The adsorption of As(III) and As(V) was also reported with magnetite (Fe_3O_4) nanoparticles modified with an oleic acid ligand (Yavuz et al., 2006). The removal of these metals was explained by the strong reactivity between iron oxide nanoparticles and heavy metals. Modification of γ-Fe_2O_3 nanoparticles with undecanoic acid (Hai et al., 2005) and chitosan on Fe_3O_4 nanoparticles with chitosan (Chang and Chen, 2005) make them excellent magnetic adsorbents for the removal of Cd and Cu, respectively. Recently, surface engineered and functionalized iron oxide magnetic nanoparticles with humic acid, amino group, chitosan, α-ketoglutaric acid polyethylenimine, carboxymethyl-β-cyclodextrin have been reported for the removal of heavy metals from water (Wang et al., 2010; Liu et al., 2008; An et al., 2011; Zhou et al., 2009; Goon et al., 2010; Singh et al., 2011; Badruddoza et al., 2011; Souad et al., 2017; Moradinasab and Mahdi, 2016; Song et al., 2011). They provide easy separation after the adsorption of various pollutants from wastewater. In addition, these magnetic nanomaterials are not always target specific and not appropriate for complex systems.

Physical and chemical modification of the magnetic nanomaterials surface with various chelating agents may overcome these problems. Therefore, the modification of these magnetic nanomaterials with appropriate agents may be effective for their application in the removal of various heavy metals, organic pollutants, pharmaceutical and other pollutants from aqueous phase. The iron-oxide magnetic nanoparticles have also been functionalized with various materials and utilized for the removal of heavy metals (Laurent et al., 2008; Jiang et al., 2004). These magnetic nanoparticles are capable to treat large volume of water and also no by-products are formed, and easy separation by magnet makes its potential application in water and wastewater treatment. The small size of iron oxide nanosorbents (2 to 20 nm) is favourable for the diffusion of metal ions from solution onto the active sites (functional groups like -COOH, $-NH_2$, -OH, -SH etc.) of adsorbent surface. It is evident from the literature that preparation method and surface modification play a vital role for shape and size distribution, surface chemistry and morphology of the iron-oxide nanoparticles (Ciesla et al., 1994; Chin et al., 2007; Sun et al., 2009). The size and shape of iron-oxide nanoparticles are very significant for the adsorptive removal of heavy metals from water and wastewater. Further research work will be very much required for making these magnetic nanomaterials very effective for the fruitful treatment of water and wastewater.

The removal of As(V) and Cu(II) from the contaminants in municipal water supply was carried out using magnetite (Fe_3O_4) nanoparticles (Sai et al., 2013). The magnetic nanoparticles is synthesised by co-precipitation method obtained by aging stoichiometric mixture of ferrous and ferric salts in aqueous medium. At optimized pH the obtained Fe_3O_4 nanoparticles are coated with coating agents which develop surface functionalized groups. The sorption of As(V) and Cu(II) take place on these aggregates which are removed with the help of external magnetic field leaving the supernatant free from copper and arsenic.

Superparamagnetic iron oxide (Fe_3O_4) nanoparticles with a surface functionalization of dimercaptosuccinic acid (DMSA) are also reported to be an effective sorbent material for the removal of toxic soft metals, such as Hg, Ag, Pb, Cd, and Tl, which effectively bind to the DMSA ligands and for As, which binds to the iron oxide lattices (Yantasee et al., 2007). The nanoparticles are highly dispersible and stable in solutions, have a large surface area (114 m^2/g), and have a high functional group content (1.8 mmol thiols/g). They are attracted to a magnetic field and can be separated from solution within a minute with a 1.2 T magnet. The chemical affinity, capacity, kinetics, and stability of the magnetic nanoparticles were compared to those of conventional resin-based sorbents (GT-73), activated carbon, and nanoporous silica (SAMMS) of similar surface chemistries in river water, groundwater, and seawater. DMSA-Fe_3O_4 had a capacity of 227 mg of Hg/g, a 30-fold larger value than GT-73. The authors reported that the nanoparticles removed 99 wt. % of 1 mg/L Pb within a minute, while it took over 10 and 120 min for Chelex-100 and GT-73 to remove 96% of Pb.

Recently, Wang et al. (2014) investigated and reported the competitive removal of Pb(II) and Cr(III) using magnetite nanoparticles synthesized by co-precipitation methods. Removal of Pb(II) significantly decreased from 80.56 to 41.41% when Cr(III) was co-presented, while decrease of Cr(III) was negligible when Pb(II) was present, falling from 42.37 to 38.48%. The authors indicated that the removal mechanism occurred through adsorption rather than chemical redox reaction. A co-adsorption mechanism is based on Pb(II) involved surface complexation, while Cr(III) was firstly adsorbed onto magnetite, followed by a partially substitution of Cr(III) for Fe(III) in Cr-Fe_3O_4 through ion exchanges.

The magnetic iron oxide nanoparticles may be effective adsorbent for the removal of dyes from water and wastewater. Several studies were reported for the adsorption of dyes using these magnetic nanoparticles. The adsorption of various dyes on iron oxide nanoparticles is discussed below.

The iron oxide nanoparticles, having an average size of 20−40 nm with a surface area of ~70 m^2g^{-1}, have been synthesized and used for selective adsorption of various dyes (selectively containing hydroxyl groups) from aqueous solutions (Saha et al., 2011). The nanoparticles are ferromagnetic in nature at both room and low temperature and can be separated by an external magnetic field. The erichrome black-T, bromophenol blue, bromocresol green, and fluorescein dyes were adsorbed more on the iron oxide surface as compared to methyl red, methylene blue, and methyl orange dyes, which does not have any hydroxyl (−OH) groups. The authors found that the adsorption process was dependent on solution pH, initial dye, and iron oxide concentration. Moreover, the adsorbed dyes could be desorbed completely from nanoparticle surfaces at higher pH and efficient for multicyclic use as reported by the authors.

The applicability of magnetite (Fe_3O_4) nanoparticles as an adsorbent for the removal of Acridine orange, Comassie Brilliant Blue R-250 and Congo red from their aqueous solution was investigated (Chaudhary et al., 2013). The Fe_3O_4 nanoparticles were synthesized via simple chemical precipitation method using CTAB, as surfactant. The authors reported that the adsorption process follows pseudo-second-order kinetics for the removal of all the three dyes. Shi et al. (2014) reported a simple and environmentally friendly method for the preparation of highly stable dispersions of Fe_3O_4 nanoparticles with controlled morphologies, and utilized for the removal of dyes from aqueous phase and investigated their potential for application in wastewater treatment.

In another study, magnetic nanoparticles (MNPs) modified with aminoguanidine (AG) were synthesized and utilized for the adsorption of acid dyes by the variation of pH, contact time and initial dye concentration (Li et al., 2013). Maximum adsorption capacity reached from pH 1.3 to 2.5 for different dyes. The investigators reported that the adsorption process can be better described by Langmuir isotherm and pseudo-second-order kinetic model. The mean energy of adsorption (E) confirmed the involvement of chemical adsorption as claimed by the authors.

Magnetic nanoparticles (Fe_3O_4) coated with activated maize cob were also investigated for the removal of methylene blue (MB) from aqueous phase (Tan et al., 2012). They showed that the adsorption of MB dye was pH dependent and the higher efficiency of dye removal was at pH 6.0 and followed the pseudo-second-order kinetic model. The authors claimed that coating of Fe_3O_4 with activated maize cob powder significantly enhanced the dye removal from aqueous phase.

Carbon Nanotubes

Carbon nanotubes (CNTs) offer a potential for the water treatment and may be the future materials for the elimination of various harmful toxic substances from drinking and other wastewater, because of their unique and well-defined structures. In addition, CNTs may enter the environment during their wide application (Lines et al., 2008; Shvedova et al., 2009). CNTs are also regarded as an emerging contaminant because of their significant toxic effects. It is a hollow graphitic nanomaterial consisting of various grapheme layers. These nanotubes furnish easy transfer of water molecules and make them appropriate for the separation of various pollutants. Carbon nanotubes have indicated immense potential in the treatment of drinking and other water bodies because of their distinctive and adjustable characteristics. Numerous studies also reported strong interactions between CNTs and heavy metal ions or organic compounds because of CNT surface functional groups and hydrophobic surfaces

(Ren et al., 2011). Therefore, CNTs are considered to be an effective adsorbent to control the environmental behaviour of various contaminants. The understanding of pollutant-CNT interaction mechanisms is expected to offer important information on assessing risks and potential applications of both CNTs and various pollutants present in water. Carbon nanotubes can be modified to improve its selectivity and removal of metals or ions from aqueous streams (Bakajin et al., 2009). Functionalization of carbon nanotubes may also improve its properties for application in water treatment.

A wide range of organic compounds, pesticides, pharmaceuticals, antibiotics and inorganic ions, such as heavy metal ions, have been removed utilizing carbon nanotubes (Brooks et al., 2012; Chen et al., 2011; Chen et al., 2012; Cho et al., 2008; Cho et al., 2010; Yang et al., 2007; Yang et al., 2008; Yao et al., 2011; Rahman et al., 2017; Farghali et al., 2017; Salam, 2017; Wan et al., 2017; Chávez-Guajardo et al., 2015; Nei et al., 2015; Razzaz et al., 2015; Zhao et al., 2015a; 2015b). The effects of various parameters, such as pH, pHzpc, initial concentration, ionic strength, and presence of competing ions was also discussed during their adsorption study. Adsorption kinetics and mechanisms were explained through these studies and reported that, π–π electron-donor-acceptor (EDA) interaction, electrostatic interaction, and hydrogen bonding are the driving mechanisms and force for the adsorption process. The morphology of the carbon nanotube may also play a significant role on the adsorption of various organic and inorganic pollutants. These nanoadsorbents may be more efficient than activated carbons in terms of their lesser equilibrium time, higher adsorption capacity and selectivity, and easier regeneration. The development of cost-effective, facile, green, and extremely effective manufacturing methods for the production of carbon nanotubes is highly recommended for its real/fruitful application in water and wastewater treatment.

Recently, magnetic polymer multi-wall carbon nanotube (MPMWCNT) nanocomposite was synthesized, which was composed of multi-wall carbon nanotubes, poly(1-glycidyl-3-methylimidazolium chloride) (ionic liquid-based polyether) and ferroferric oxide and utilized for the removal of orange II, sunset yellow FCF and amaranth dyes from aqueous phase (Gaoa et al., 2013). It was reported that a low pH value favours the adsorption of these dyes and the adsorption kinetics and isotherms were well fitted by a pseudo-second-order model and Langmuir model, respectively. The introduction of ionic liquid-based polyether and ferroferric oxide moieties into the multi-wall carbon nanotubes brings significant improvements in the adsorption and separation performance. They also reported that MPMWCNT effectively removes colour from dye-containing wastewater and has high adsorption capacity, fast adsorption rate and can easily be separated from the water by external magnetic field.

Of late, the adsorption of ofloxacin (OFL) on carbon nanotubes (CNTs) has been investigated using the solubility, pH and co-solvent effects (Peng et al., 2012). The solubilities of OFL and sorption of OFL on three multi-walled CNTs at different pHs and different methanol volume fractions (fc) of methanol/water mixture solutions were systematically reported in this study. The authors found that the highest sorption was not observed at the pH with lowest OFL solubility, indicating hydrophobic interaction was not the dominant sorption mechanism. The sorption decreasing in pH range of 5–8 was consistent with cationic OFL species distribution, suggesting cation exchange may play an important role. With the increased methanol fraction, both OFL solubility and sorption decreased, which was different from hydrophobic organic contaminants (HOCs). They suggested that cosolvent–sorbent (methanol–CNTs) interactions were much stronger than solute–cosolvent (OFL–methanol) interactions and evidenced by decreased sorption and increased linearity of the isotherms in methanol than those in water. The authors also suggested that solute-cosolvent interactions should be performed in future studies.

Polymer-based Nanoadsorbents

Polymer-based nanoadsorbents also have the potential to be used as adsorbents for the wastewater treatment. The adsorption and other thermal and chemical properties of the polymer may be improved by the incorporation of nanomaterials into the polymer matrix. The most advantages of these nanoadsorbents are their superior adsorption properties and stability over a wide range of pH. The surface of these polymer-based nanoparticles may be customized through chemical and physical process. The selective removal of various heavy metals may be possible by using these nanoadsorbents. These developed polymeric nanoadsorbents are reported to be utilized for the removal of various heavy metals from their aqueous phase (Zhang et al., 2008; Chen et al., 2011; Wang et al., 2007). The adsorption of various dyes from water phase is also reported by several authors. The authors also reported the adsorption mechanism and adsorption kinetics. The other factors affecting the adsorption are also discussed and reported in the literature.

The prolonged contact of the nanoadsorbents may lead to environmental problems and its recycling is not so easy. Therefore, the discharge of these nanoadsorbents should be quantified. The separation of nanoadsorbents from water phase is usually difficult along with its regeneration and reutilization. Petrik et al. (2006) showed that nonporous carbonaceous and nanostructured adsorbents may be regenerated by mechanical, thermal and electromagnetic energy. The nanoadsorbents loaded compound may also be smashed by heating in furnace and microwave irradiation.

Discussions and Future Prospects of Nanomaterials

There are some issues that should be addressed for the safety of the drinking water and other water bodies using nanomaterials as adsorbents. The utilization of nanomaterials in water treatment may be a serious concern in the coming years. There is a chance that nanoparticles may enter into the human body. However, the exact ways by which these nanoparticles can enter into the human body is still a matter of in-depth research. Therefore, more research work should be required for the fruitful utilization of nanoparticles into environmental research, especially drinking water and wastewater treatment systems. There is a greater need to develop safe and sustainable technologies for the disposal of nanomaterials after suitable treatment. Recently, greener methodologies are adopted worldwide for the preparation of nanomaterials and its utilization in various fields. The conversion of various organic and inorganic pollutants into the more lethal products is also an important concern in the water treatment process.

The cytotoxicity and genotoxicity test of the nanomaterials are also urgently required for their utilization at large scale. Therefore, the future of the nanoparticles in the water treatment depends on various factors which should be looked into and further research work is highly needed for their fruitful application. Generally, low-cost adsorbents were utilized for the removal of various impurities from wastewater and other water bodies. However, the development of nanotechnology slowly replaced the utilization of low-cost available materials/adsorbents for the same. Therefore, a comparison of nanomaterials with the low-cost available adsorbents was required for the assessment of nanoparticles with their potential future applications in the water treatment systems. Ahmaruzzaman and his research group (Ahmaruzzaman, 2008, 2009, 2010, 2011, Ahmaruzzaman and Gupta, 2011; Ahmaruzzaman and Sharma, 2005) investigated and reviewed the potential of low-cost adsorbents for the removal of phenolic and heavy metals from wastewater. They also discussed the role of coal fly ash, rice husk and its ash as low-cost adsorbents in water and wastewater treatment. The authors discussed various factors such as, pH, ionic strength, initial concentration of adsorbate, presence of other substances, adsorption isotherm, kinetics and adsorption capacity of the pollutants/adsorbate. However, the accurate evaluation/comparison is not achievable between low-cost and nanoadsorbents, because of the various experimental conditions utilized for nanoparticle and other low-cost adsorbents for the elimination of the identical organic and inorganic pollutants. Efforts were made to compare the performance of nanomaterials with low-cost adsorbents.

The large scale application of nanoparticles as well as low-cost adsorbents for the treatment of wastewater and drinking water is still reported in scanty cases. Although low-cost adsorbents are utilized for the removal of all type of impurities/pollutants, nanomaterials may be the better alternative for the effective treatment of water bodies (Khajeh et al., 2013; Ali, 2012). The faster adsorption capacity, lesser contact time and anti-bacterial properties, ease of separation, etc. may be the encouraging factors for their application in water treatment compared to that of low-cost adsorbents. The quantity of various pollutants, especially the heavy metals, such as arsenic, iron, lead, mercury, fluoride etc. in the drinking water are very less (μg/L) and, therefore, nanomaterials may be the good alternative for bringing down the level of impurities to the standard level required for drinking water. Nanoadsorbents may be effective not only in an exceptionally small range of pollutant concentration but also in an extremely high concentration range, where other processes are unsuccessful, time-consuming and expensive (Nassar, 2010). Further research should be carried out to develop, optimize novel nanomaterials and make them cost effective for their large scale application at various levels.

A potential and outstanding adsorbent must have low-cost, higher adsorption capacity, higher surface area, higher regeneration ability and lesser equilibrium time, and other important properties for the removal of various types of pollutant in very less time. In addition to that it must not generate any objectionable odour and least amount of wastes/sludge. The future of nanotechnology for water treatment depends on their toxicity, public health concern, awareness, fate, impact, etc. on the human health and environment. It is also reported that nanomaterials may undergo remarkable/considerable alternations/changes in the liquid/aqueous phase (Pradeep and Anshup, 2009).

Conclusion

This article showed that nanomaterials have the potential to be used as adsorbents for the treatment of wastewater. During the last decades, potential of nanomaterials in various fields have been the primary focus of research. The nanomaterials have been utilized for the removal of various heavy metals, dyes, etc. from wastewater. However, very few studies were reported on the removal of pesticides, phenols, pharmaceuticals, antibiotics, pathogenic bacteria and viruses and other emerging contaminants from wastewater. The future of nanomaterials in the water treatment requires better control of their composition, size, shape, and other important properties. The world, especially third world countries, is facing huge challenges in the drinking water requirement because of the shortage of fresh water. Because of the various advantages of the nanomaterials over the conventional adsorbents, they may be utilized as novel and promising adsorbents for the future water treatment. In my opinion and recent advances in this field, the nanoparticles in their various forms will be the significant components/parts in the drinking and other wastewater treatment systems.

References

AbdEl-Salam, A.H., Ewais, H.A. and A.S. Basaleh (2017). Silver nanoparticles immobilised on the activated carbon as efficient adsorbent for removal of crystal violet dye from aqueous solutions—A kinetic study. *Journal of Molecular Liquids*, **248:** 833-841.

Ahmaruzzaman, M. (2008). Adsorption of phenolic compounds on low-cost adsorbents: A review. *Advances in Colloid and Interface Science*, **143(1-2):** 48-67.

Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. *Progress in Energy and Combustion Science*, **36(3):** 327-363.

Ahmaruzzaman, M. (2011). Industrial wastes as low-cost potential adsorbents for the treatment of wastewater laden with heavy metals. *Advances in Colloid and Interface Science*, **166(1-2):** 36-59.

Ahmaruzzaman, M. and V.K. Gupta (2011). Rice husk and its ash as low-cost adsorbents in water and wastewater treatment. *Industrial & Engineering Chemistry Research*, **50(24):** 13589-13613.

Ahmaruzzaman, M. (2009). Role of fly ash in the removal of organic pollutants from wastewater. *Energy & Fuels*, **23:** 1494-1511.

Ahmaruzzaman, M. and D.K. Sharma (2005). Adsorption of phenols from wastewater. *Journal of Colloid and Interface Science*, **287(1):** 14-24.

Ali, M. (2012). New Generation Adsorbents for Water Treatment. *Chem. Rev.*, **112:** 5073-5091.

An, B., Liang, Q. and D. Zhao (2011). Removal of arsenic(V) from spent ion exchange brine using a new class of starch-bridged magnetite nanomaterials. *Water Research*, **45:** 1961-1972.

Badruddoza, A.Z.M., Tay, A.S.H., Tan, P.Y., Hidajat, K. and M.S. Uddin (2011). Carboxymethyl-β-cyclodextrin conjugated magnetic nanomaterials as nano-adsorbents for removal of copper ions: Synthesis and adsorption studies. *Journal of Hazardous Materials*, **185:** 1177-1186.

Bakajin, O., Noy, A., Fornasiero, F., Grigoropoulus, C.P., Holt, J.K., In, J.B., Kim, S. and H.G. Park (2009). Nanofluidic Carbon Nanotube Membranes: Applications for Water Purification and Desalination Savage (Ed.), et al.Willian Andrew Inc./Elsevier, New York.

Bhandari, R., Gupta, P., Dziubla, T. and J.Z. Hilt (2016). Single step synthesis, characterization and applications of curcumin functionalized iron oxide magnetic nanoparticles. *Mater Sci Eng C*, **67:** 59-64.

Brooks, A.J., Lim, H.N. and J.E. Kilduff (2012). Adsorption uptake of synthetic organic chemicals by carbon nanotubes and activated carbons. *Nanotechnology*, **23(29):** 294008-294018.

Chang, Y.C. and D.H. Chen (2005). Preparation and adsorption properties of monodisperse chitosan-bound Fe_3O_4 magnetic nanoparticles for removal of Cu(II) ions. *J. Colloid Interface Sci.*, **283:** 446-451.

Chaudhary, G.R., Saharan, P., Kumar, A., Mehta, S.K., Mor, S. and A. Umar (2013). Adsorption studies of cationic, anionic and azo-dyes via monodispersed Fe_3O_4 nanoparticles. *J. Nanosci. Nanotechnol.*, **13(5):** 3240-3245.

Chávez-Guajardo, A.E., Medina-Llamas, J.C., Maqueira, L., Andrade, C.A.S., Alves, K.G.B. and P. Celso de Melo (2015). Efficient removal of Cr(VI) and Cu(II) ions from aqueous media by use of polypyrrole/maghemite and polyaniline/maghemite magnetic nanocomposites. *Chemical Engineering Journal*, **281:** 826-836.

Chen, H.Z., Yang, S.G., Yu, K., Ju, Y.M. and C. Sun (2011). Effective photocatalytic degradation of atrazine over titania-coated carbon nanotubes (CNTs) coupled with microwave energy. *The Journal of Physical Chemistry A*, **115(14):** 3034–3041.

Chin, A.B. and I.I. Yaacob (2007). Synthesis and characterization of magnetic iron oxide nanoparticles via w/o microemulsion and Massart's procedure. *Journal of Materials Processing Technology*, **191:** 235-237.

Cho, H.H., Smith, B.A., Wnuk, J.D., Fairbrother, D.H. and W.P. Ball (2008). Influence of surface oxides on the adsorption of naphthalene onto multiwalled carbon nanotubes. *Environmental Science and Technology*, **42(8):** 2899-2905.

Cho, H.H., Wepasnick, K., Smith, B.A., Bangash, F.K., Fairbrother, D.H. and W.P. Ball (2010). Sorption of aqueous Zn[II] and Cd[II] by multiwall carbon nanotubes: The relative roles of oxygen-containing functional groups and graphenic carbon. *Langmuir*, **26(2):** 967-981.

Ciesla, U., Demuth, D., Leon, R., Petroff, P., Stucky, G., Unger, K. and F. Schüth (1994). Surfactant controlled preparation of mesostructured transition-metal oxide compounds. *Journal of the Chemical Society, Chemical Communications*, **11:** 1387-1388.

Das, S.K., Khan, M.M.R., Guha, A.K., Das, A.R. and A.B. Mandal (2012). Silver-nano biohybride material: Synthesis, characterization and application in water purification. *Bioresource Technology*, **124:** 495-499.

Dave, P.N. and L.V. Chopda (2014). Application of Iron Oxide Nanomaterials for the Removal of Heavy Metals. *Journal of Nanotechnology*, 1-15.

Dou, B. and H. Chen (2011). Removal of toxic mercury(II) from aquatic solutions by synthesized TiO_2 nanoparticles, *Desalination*, **269:** 260-265.

Du, B.D., Phu, D.V., Duy, N.N., Lan, N.T.K., Lang, V.T.K., Thanh, N.V.K., Phong, N.T.P. and N.Q. Hien (2008). Preparation of colloidal silver nanoparticles in ploy (N-vinylpyrrolidone) by c-irradiation. *J. Exp. Nanosci.*, **3(3):** 207-213.

Elfeky, S.A., Mahmoud, S.E. and A.F. Youssef (2017). Applications of CTAB modified magnetic nanoparticles for removal of chromium (VI) from contaminated water. *Journal of Advanced Research*, **8:** 435-443.

Gaoa, H., Zhao, S., Cheng, X. Wang, X. and L. Zheng (2013). Removal of anionic azo dyes from aqueous solution using magnetic polymer multi-wall carbon nanotube nanocomposite as adsorbent. *Chemical Engineering Journal*, **223(1):** 84-90.

Ghaedi, M., Roosta, M., Ghaedi, A.M., Ostovan, A., Tyagi, I., Agarwal, S. and V.K. Gupta (2018). Removal of methylene blue by silver nanoparticles loaded on activated carbon by an ultrasound-assisted device: Optimization by experimental design methodology. *Research on Chemical Intermediates*, **44(5):** 2929-2950.

Goon, I.Y., Zhang, C., Lim, M., Gooding, J.J. and R. Amal (2010). Controlled fabrication of polyethylenimine-functionalized magnetic nanomaterials for the sequestration and quantification of free Cu^{2+}. *Langmuir*, **26:** 12247-12252.

Fakhri, A. (2015). Investigation of mercury(II) adsorption from aqueous solution onto copper oxide nanoparticles: Optimization using response surface methodology. *Process Safety and Environmental Protection*, **93**: 1-8.

Farghali, A.A., Abdel Tawab, H.A., Abdel Moaty, S.A. and R. Khaled (2017). Functionalization of acidified multi-walled carbon nanotubes for removal of heavy metals in aqueous solutions. *J. Nanostruct. Chem.*, **7:** 101-111.

Hai, B., Wu, J., Chen, X., Protasiewicz, J.D. and D.A. Scherson (2005). Metal-ion adsorption on carboxyl-bearing self-assembled monolayers covalently bound to magnetic nanoparticles. *Langmuir*, **21:** 3104-3105.

Hristovski, K., Baumgardener, A. and P. Westerhoff (2007). Selecting metal oxide nanomaterials for arsenic removal in fixed bed column: From nanopowders to aggregated nanoparticle media. *J. Hazard. Mater.*, **147:** 265-274.

Hu, J., Chen, G. and I.M.C. Lo (2005). Removal and recovery of Cr(VI) from wastewater by maghemite nanoparticles. *Water Res.*, **39:** 4528-4536.

Jegadeesan, G., Al-Abed, S.R., Sundaram, V., Choi, H., Scheckel, K.G. and D.D. Dionysiou (2010). Arsenic sorption on TiO_2 nanoparticles: Size and crystallinity effects. *Water Res.*, **44:** 965.

Jiang, W., Yang, H.C., Yang, S.Y., Horng, H.E., Hung, J.C., Chen, Y.C. and C.Y. Hong (2004). Preparation and properties of superparamagnetic nanoparticles with narrow size distribution and biocompatible. *Journal of Magnetism and Magnetic Materials*, **283:** 210-214.

Khajeh, M., Laurent, S. and K. Dastafkan (2013). Nanoadsorbents: Classification, Preparation, and Applications (with Emphasis on Aqueous Media). *Chem. Rev.*, **113:** 7728-7768.

Khare, N., Bajpai, J. and A.K. Bajpai (2018). Graphene coated iron oxide (GCIO) nanoparticles as efficient adsorbent for removal of chromium ions: Preparation, characterization and batch adsorption studies. *Environmental Nanotechnology, Monitoring and Management*, **10:** 148-162.

Kumar, K.Y., Muralidhara, H.B., Arthoba Nayaka, Y., Balasubramanyam, J. and H. Hanumanthappa (2013). Low-cost synthesis of metal oxide nanomaterials and their application in adsorption of commercial dye and heavy metal ion in aqueous solution. *Powder Technology*, **246:** 125-136.

Lagashetty, A.K. and A. Venkataraman (2004). Adsorption study of Pb^{2+} ions on nanosized SnO_2, synthesized by self-propagating combustion reaction. *Bulletin of Materials Science*, **27(6):** 491-495.

Laurent, S., Forge, D., Port, M., Roch, A., Robic, C., Vander Elst, L. and R.N. Muller (2008). Magnetic Iron Oxide Nanoparticles, Synthesis, Stabilization, Vectorization, Physicochemical Characterizations and Biological Applications. *Chemical Reviews*, **108:** 2064-2110.

Li, D.P., Zhang, Y.R., Zhao, X.X. and B.X. Zhao (2013). Magnetic nanoparticles coated by aminoguanidine for selective adsorption of acid dyes from aqueous solution. *Chemical Engineering Journal*, **232:** 425-433.

Li, Z.P., Duan, X.R., Liu, C.H. and B.A. Du (2006). Selective determination of cysteine by resonance light scattering technique based on self-assembly of gold nanomaterials. *Anal. Biochem.*, **351:** 18-25.

Lines, M.G. (2008). Nanomaterials for practical functional uses. *Journal of Alloys and Compounds*, **449:** 242-245.

Liu, J.F., Zhao, Z.S. and G.B. Jiang (2008). Coating Fe_3O_4 Magnetic Nanomaterials with Humic Acid for High Efficient Removal of Heavy Metals in Water. *Environmental Science & Technology*, **42:** 6949-6954.

Monsef Khoshhesa, Z., Gonbadi, K. and G. Rezaei Behbehani (2015). Removal of reactive black 8 dye from aqueous solutions using zinc oxide nanoparticles: Investigation of adsorption parameters. *Desalination and Water Treatment*, **56(6):** 1558-1565.

Mortazavi, K., Rajabi, H., Ansari, A., Ghaedi, M. and K. Dashtian (2016). Preparation of silver nanoparticle loaded on activated carbon and its application for removal of malachite green from aqueous solution. *Synthesis and Reactivity in Inorganic, Metal-Organic, and Nano-Metal Chemistry,* August, DOI: 10.1080/15533174.2016.1228670

Moradinasab, S. and B. Mahdi (2016) Removal of heavy metals from aqueous solution using Fe_3O_4 nanoparticles coated with Schiff base ligand. *Desalination Water Treat.*, **57(9):** 4028–4036.

Nassar, N.N. (2010). Rapid removal and recovery of Pb(II) from wastewater by magnetic nanoadsorbents. *Journal of Hazardous Materials*, **184:** 538-546.

Neyaz, N., Siddiqui,W.S. and K.K. Nair (2013). Application of surface functionalized iron oxide nanomaterials as a nanosorbents in extraction of toxic heavy metals from ground water: A review. *International Journal of Environmental Sciences*, **4(4):** 472-483.

Nie, G., Wang, J., Pan, B. and L. Lv (2015). Surface chemistry of polymer-supported nano-hydrated ferric oxide for arsenic removal: Effect of host pore structure. *Science China Chemistry*, **58(4):** 722-730.

Niu, S.F., Liu, Y., Xu, X.H. and Z.H. Lou (2005). Removal of hexavalent chromium from aqueous solution by iron nanomaterials. *J. Zhejiang Univ. Sci. B*, **6:** 1022-1027.

Pacheco, S., Tapia, J., Medina, M. and R. Rodriguez (2006). Cadmium ions adsorption in simulated wastewater using structured alumina-silica nanoparticles. *J. Non-Cryst. Solids*, **352(52-54):** 5475-5481.

Pal, J., Deb, M.K., Deshmukh, D.K. and D. Verma (2013). Removal of methyl orange by activated carbon modified by silver nanoparticles. *Applied Water Science*, **3(2):** 367-374.

Pal, J. and M.K. Deb (2014). Efficient adsorption of congo red dye from aqueous solution using green synthesized coinage nanoparticles coated activated carbon beads. *Appl. Nanosci.*, **4:** 967-978.

Pal, J., Deb, M.K., Sircar, J.K. and P.K. Agnihotri (2015). Microwave green synthesis of biopolymer-stabilized silver nanoparticles and their adsorption behavior for atrazine. *Applied Water Science*, **5(2):** 181-190.

Peng, H., Pana, B., Wu, M., Liu, R., Zhang, D., Wu, D. and B. Xing (2012). Adsorption of ofloxacin on carbon nanotubes: Solubility, pH and co-solvent effects. *Journal of Hazardous Materials*, **211-212:** 342-348.

Petrik, V.I. and A. Bobarykin (2006). U.S. Patent 2006/0189475 A1, 2006.

Ponder, S.M., Darab, J.G. and T.E. Mallouk (2000). Remediation of Cr(VI) and Pb(II) Aqueous Solutions Using Supported, Nanoscale Zero-valent Iron. *Environ. Sci. Technol.*, 34: 2564-2569.

Pradeep, T. and Anshup (2009). Noble metal nanomaterials for water purification: A critical review. *Thin Solid Films*, **517(24):** 6441-6478.

Qing Wan, Meiying Liu, Yili Xie, Jianwen Tian, Qiang Huang, Fengjie Deng, Liucheng Mao, Qingsong Zhang, Xiaoyong Zhang and Yen Wei (2017). Facile and highly efficient fabrication of graphene oxide-based polymer nanocomposites through mussel-inspired chemistry and their environmental pollutant removal application. *J. Mater. Sci.*, **52:** 504-518.

Rahman, M.M., Sime, S.A., Hossain, M.A., Shammi, M., Uddin, M.K., Sikder, M.T. and M. Kurasaki (2017). Removal of Pollutants from Water by Using Single-Walled Carbon Nanotubes (SWCNTs) and Multi-walled Carbon Nanotubes (MWCNTs). *Arab. J. Sci. Eng*., **42:** 261-269.

Ren, X., Chen, C., Nagatsu, M. and X. Wang (2011). Carbon nanotubes as adsorbents in environmental pollution management: A review. *Chemical Engineering Journal*, **170:** 395-410.

Razzaz, A., Ghorban, S., Hosayni, L., Irani, M. and M. Aliabadi (2016). Chitosan nanofibers functionalized by TiO_2 nanoparticles for the removal of heavy metal ions. *Journal of the Taiwan Institute of Chemical Engineers*, **58:** 333-343.

Saha, B., Das, S., Saikia, J. and G. Das (2011). Preferential and Enhanced Adsorption of Different Dyes on Iron Oxide Nanoparticles: A Comparative Study. *J. Phys. Chem. C*, 115(16): 8024-8033.

Sai Bhargav, S. and I. Prabha (2013). Removal of Arsenic and Copper Metals from Contaminated Water using Iron (III) Oxide Nanoparticle. *International Journal of Chemistry and Chemical Engineering*, **3(2):** 107-112.

Salam, M.A. (2017). Preparation and characterization of chitin/magnetite/multiwalled carbon nanotubes magnetic nanocomposite for toxic hexavalent chromium removal from solution. *Journal of Molecular* Liquids, **233:** 197-202.

Schrick, B., Blough, J.L., Jones, A.D. and T.E. Mallouk (2002). Hydrodechlorination of trichloroethylene to hydrocarbons using bimetallic nickel-iron nanomaterials. *Chem. Mater.*, **14(12):** 5140-5147.

Schwarzenbach, R.P., Egli, T., Hofstetter, T.B., Von Gunten, U. and B. Wehrli (2010). Global water pollution and human health. *Annual Review of Environment and Resources*, **35:** 109-136.

Shi, H., Tan, L., Du, Q., Chen, X., Li, L., Liu, T., Fu, C., Liu, H. and X. Meng (2014). Green synthesis of Fe_3O_4 nanoparticles with controlled morphologies using urease and their application in dye adsorption. *Dalton Trans.*, **43:** 12474-12479.

Shvedova, A.A., Kisin, E.R., Porter, D., Schulte, P., Kagan, V.E., Fadeel, B. and V. Castra-nova (2009). Mechanisms of pulmonary toxicity and medical applications of carbon nanotubes: Two faces of Janus? *Pharmacology & Therapeutics*, **121:** 192-204.

Singh, S., Barick, K.C. and D. Bahadur (2011). Surface engineered magnetic nanomaterials for removal of toxic metal ions and bacterial pathogens. *Journal of Hazardous Materials*, **192:** 1539-1547.

Song, J., Kong, H. and J. Jang (2011). Adsorption of heavy metal ions from aqueous solution by polyrhodanine-encapsulated magnetic nanoparticles. *Journal of Colloid and Interface Science*, **359(2)**: 505-511.

Sun, X., Zheng, C., Zhang, F., Yang, Y., Wu, G., Yu, A and N. Guan (2009). Size-controlled synthesis of magnetite (Fe_3O_4) nanoparticles coated with glucose and gluconic acid from a single Fe(III) precursor by a sucrose bifunctional hydrothermal method. *Journal of Physical Chemistry*, **113:** 16002-16008.

Tan, K.A., Morad, N., Teng, T.T., Norli, I. and P. Panneerselvam (2012). Removal of Cationic Dye by Magnetic Nanoparticle (Fe_3O_4) Impregnated onto Activated Maize Cob Powder and Kinetic Study of Dye Waste Adsorption. *APCBEE Procedia*, **1:** 83-89.

Thatai, S., Khurana, P., Boken, J., Prasad, S. and D. Kumar (2014). Nanomaterials and core–shell nanocomposite based new generation water remediation materials and analytical techniques: A review. *Microchemical Journal*, **116:** 62-76.

Tiemann, K.J., Gardea-Torresdey, J.L., Gamez, G., Dokken, K., Cano-Aguilera, I., Renner, M.W. and L.R. Furenlid (2000). Effects of oxidation state on metal ion binding by *Medicago sativa* (Alfafa): Atomic and X-ray absorption spectroscopic studies with Fe(II) and Fe(III). *Environ. Sci. Technol.*, **34:** 693-698.

Wang, L. and A. Wang (2007). Adsorption characteristics of Congo Red onto the chitosan/montmorillonite nanocomposite. *J. Hazard. Mater.*, **147:** 979-985.

Wang, J., Zheng, S., Shao, Y., Liu, J., Xu, Z. and D. Zhu (2010). Amino-functionalized $Fe_3O_4@SiO_2$ core-shell magnetic nanomaterial as a novel adsorbent for aqueous heavy metals removal. *Journal of Colloid Interface Science*, **349:** 293-299.

Yao, Y.J., He, B., Xu, F.F. and X.F. Chen (2011). Equilibrium and kinetic studies of methyl orange adsorption on multiwalled carbon nanotubes. *Chemical Engineering Journal*, **170(1):** 82-89.

Yantasee, W., Warner, C.L., Sangvanich, T., Addleman, R.S., Carter, T.G., Wiacek, R.J., Fryxell, G.E., Timchalk, C. and M.G. Warner (2007). Removal of Heavy Metals from Aqueous Systems with Thiol Functionalized Superparamagnetic Nanoparticles. *Environ. Sci. Technol.*, **41(14):** 5114-5119.

Yavuz, C.T., Mayo, J.T., Yu, W.W., Prakash, A., Falkner, J.C., Yean, S., Cong, L., Shipley, H.J., Kan, A., Tomson, M., Natelson, D. and V.L. Colvin (2006). Low-field magnetic separation of monodisperse Fe_3O_4 nanocrystals. *Science*, **314:** 964-967.

Wang, T., Jin, X., Chen, Z., Megharaj, M. and R. Naidu (2014). Simultaneous removal of Pb(II) and Cr(III) by magnetite nanoparticles using various synthesis conditions. *Journal of Industrial and Engineering Chemistry*, **20(5):** 3543-3549.

Zhang, W.X. (2003). Nanoscale iron particles for environmental remediation. *J. Nanopart. Res.*, **5:** 323-332.

Zhou, Y.T., Nie, H.L., Branford-White, C., He, Z.Y. and L.M. Zhu (2009). Removal of $Cu^{2+}$from aqueous solution by chitosan-coated magnetic nanomaterials modified with α-ketoglutaric acid. *Journal of Colloid and Interface* Science, **330:** 29-37.

Zhao, F., Repo, E., Yin, D., Meng, Y., Jafari, S. and M. Sillanpää, (2015a). EDTA-Cross-Linked β-Cyclodextrin: An Environmentally Friendly Bifunctional Adsorbent for Simultaneous Adsorption of Metals and Cationic Dyes. *Environmental Science & Technology*, **49(17):** 10570-10580.

Zhao, F., Repo, E., Sillanpää, M., Meng, Y., Yin, D. and W.Z. Tang (2015b). Green Synthesis of Magnetic EDTA-and/or DTPA-Cross-Linked Chitosan Adsorbents for Highly Efficient Removal of Metals. *Industrial & Engineering Chemistry Research*, **54(4):** 1271-1281.

Zhang, Q., Pan, B., Pan, B., Zhang, W., Jia, K. and Q. Zhang (2008). Selective Sorption of Lead, Cadmium and Zinc Ions by a Polymeric Cation Exchanger Containing Nano-$Zr(HPO_3S)_2$. *Environ Sci. Technol.*, **42:** 4140-4145.

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