Chemical Science Review and Letters ISSN 2278-6783

Review Article

Review on Advanced Nanomaterials to Remove Heavy Metals from Waste Water

Bhargavi Ram Thimmiah and Gobi Nallathambi*

Department of Textile Technology, Anna University, Chennai, Tamil Nadu, India

Abstract

The pollution in water by heavy metals is a serious global issue and it becomes major threat for ecological system. Nano technology is an emerging field for various industrial applications. New materials with enhanced functionality are required to adsorb heavy metals from wastewater. This paper reviews, advanced nano-materials that have been used effectively to adsorb heavy metal ions. Different types of nano-materials are briefly discussed with their adsorption capacities. These nano-materials have been used to overcome conventional water filtration techniques. Efficiency of the heavy metal ion adsorption using nano-materials is very high while comparing conventional methods of filtration.

Keywords: Nano materials; Heavy metal; adsorption; waste water; efficiency.

***Correspondence**
Author: Gobi Nallathambi
Email: gobsnn@gmail.com

Introduction

During the latest century, environmental pollution by heavy metals has become serious global problem. Heavy metal discharge into the environment is increasing day by day due to fastest development of industries such as metal plating facilities, mining operations, fertilizer industry, tannery industry, battery industry, paper industry, pesticides manufacturing industry, etc., [1, 2]. Heavy metals are major pollutants in marine, ground, fresh-water and even in treated effluent. Toxic heavy metals like chromium (Cr), mercury (Hg), arsenic (As), cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu) can cause severe threat to living organisms and agriculture because they are non-degradable and has capacity to accumulate in high concentrations in the living systems [3]. The toxicity of heavy metals depends on several factors including the dose, route of exposure as well as the genetics, gender, age and nutritional status of exposed individuals [4]. Heavy metals generally possess a specific density of more than 5 g/cm^3 and seriously affect the environment and living organisms [5]. **Table 1** reveals the maximum contaminant level of toxic metals. Once the heavy metals get deposited on the living organism, they directly cause many health effects including, cancer, organ damage, nervous system damage, development of autoimmunity, rheumatoid arthritis, damaging of the kidneys, circulatory system, and in extreme cases the deposition of heavy metals may cause death too [6].

Table 1 The Maximum Contamination Level standard and toxicity for the most hazardous heavy metals [11-13]

Heavy metal	Toxicities	MCL(mg/L)
Arsenic (Ar)	Leukemia, cancers, gene damage, anemia and neurobehavioural disorders.	0.050
Cadmium (Cd)	Human carcinogen, pulmonary adenocarcinomas, muscle cramps and abdominal pain.	0.01
Chromium (Cr)	Damage of reproductive system, carcinogenic, gene damage and skin allergic reactions.	0.05
Lead (Pb)	Damage of nervous system, reduced birth-weight, damage of kidneys and nervous system	0.006
Mercury (Hg)	Rheumatoid arthritis, and damage of kidneys, carcinogenic, and nervous system	0.00003

Metal toxicity has high impact on soil and ecosystems. Plants growing in metal-polluted sites exhibits growth reduction, altered cellular metabolism, lack of development, early maturation of plant. Some metals including copper, manganese, cobalt and zinc are considered to be essential for plant growth. These trace metals takes part in various functions such as redox reactions, electron transfer and structural functions in nucleic acid metabolism [7,8]. The other metals like Hg, Ag, Pb, Ni comes under non-essential elements, which are highly toxic in nature. These heavy metals can penetrate into ecological food chain through metal polluted water, soil and environment [9,10].

Nano-materials are promising candidate in removing heavy metal ions at low concentrations with high selectivity and adsorption capacity. Nano-materials can exhibits a number of physicochemical properties such as huge surface to volume ratio, high porosity, high aspect ratio and tunable pore volume [14]. Figure 1 shows the various nanomaterials. The main advantage of using nano-materials, as opposed to conventional techniques is the need of less pressure to pass water across the filter [15]. Nowadays several conventional techniques have been used to remove heavy metals from wastewater such as chemical precipitation [16], ion-exchange [17], adsorption [18], membrane filtration [19], electrochemical treatment technologies [20], etc. Moreover, these methods also have advantages, disadvantages and limitations. Adsorption is based on sorption mechanism. It has certain merits over conventional methods such as low energy, less maintenance costs, the simplicity and the reliability. The efficiency of adsorbents depends on size of adsorbents and properties of adsorbents to remove the heavy metals. Membrane filtration processes relatively simple, easy to handle and requires low space. The disadvantages are high membrane cost and fouling [21, 22].

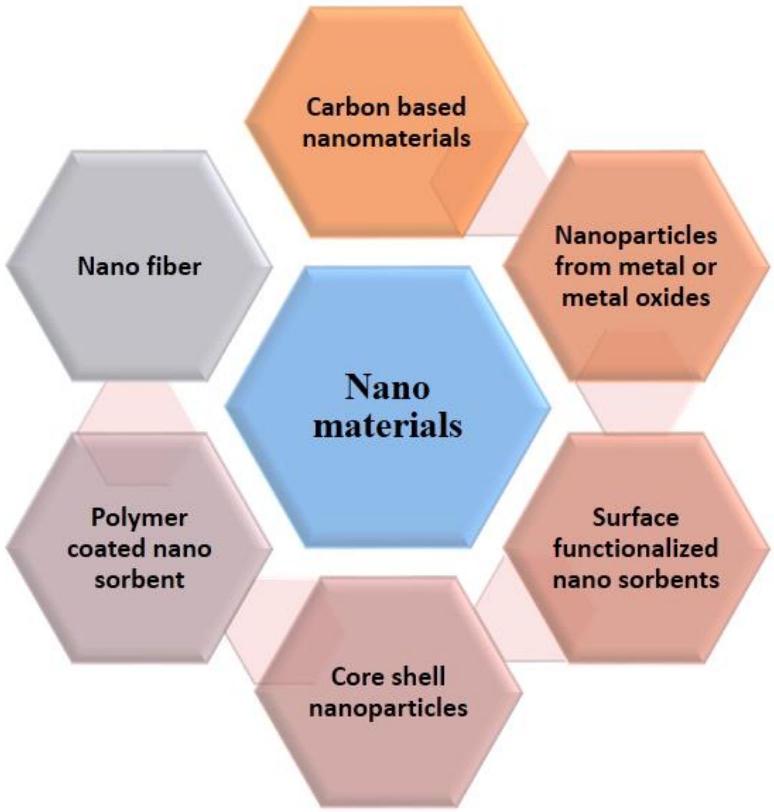

Figure 1 Different type of nanomaterials for heavy metal ion adsorption

This article is an extensive review on usage of various nanomaterials in different forms and its effect on adsorption of heavy metals from wastewater. This review also covers materials like carbon-based nanomaterials, nanoparticles from metal or metal oxides, surface functionalized nanosorbents, core shell nanoparticles, polymer coated nanosorbents and nano fibre.

Carbon Based Nanomaterial

Carbon based nanomaterials are used in many forms to adsorb heavy metal ions in recent decades, due to its cost effective, tunable properties and high sorption capacities. Materials include carbon nanotubes, graphene and fullerene are promising candidates to remove heavy metals. Table 2 shows the maximum adsorption efficiency of heavy metals on various nano adsorbents. The CNTs are effective candidates for the adsorption of divalent metal ions [23, 24]. Gaurav Bhanjana et al [25] have reported multi-walled carbon nanotubes (MWCNTs) were prepared by chemical vapour deposition (CVD) technique to remove cadmium metal ion and the results show that maximum adsorption capacity of 181.8 mg/g which has good removal efficiency comparing with single-walled carbon nanotubes (10.86 mg/g). Divyansh and Sanjay [26] proposed carbon nanotubes have tendency to remove Mn^{+7} ions. The result shows that the decrease in metal ion concentration is purely based on increase in time period. The initial 1 hour mixing time gives 20 % efficiency. After 5 hours mixing time, the Mn^{+7} concentration was brought down to 94 % efficiency.

Due to the further development to enhance the sorption capacities, CNTs were encapsulated with magnetic nanoparticles [27], coated with other metal ions [28], and functionalize with organic compounds [29]. Yue Liu et al [30], used multi walled carbon nanotubes functionalized with biomolecule L-cysteine to remove cadmium. The result shows that adsorption is rapid and the entire quantitative adsorption of Cd^{2+} take place in only 60 min. Functionalized MWCNTs being encouraging as selective sorbent to successfully remove heavy metals in environmental and biological samples. Meanwhile, Krystyna and Michal [31] synthesized three different carbon materials: Activated carbon, carbon nanotubes, and carbon-encapsulated magnetic nanoparticles. The results reveals that carbon-encapsulated magnetic nanoparticles attain high sorption efficiency and large sorption capacities than the other two materials to remove heavy metals from aqueous solutions.

Graphene is another effective carbon material used as nanosorbent, due to its large surface area, high-speed electron mobility, high youngs modulus, electrocatalytic activities, good thermal conductivity etc. Arthi Gopalakrishnan et al., [32] succeeded in removing heavy metal ions such as lead, nickel and chromium from pharma effluents using graphene-oxide(GO) nanosheets. Adsorption isotherm and kinetics shows that 70 mg GO removes all the heavy metal ions effectively with pH of 8 and with very low conductivity. Vishal et al., [33] synthesized graphene based composites (ZnO-GO and TiO_2GO) to adsorb toxic metal ions Pb, Hg, Co, Cr and Cd. They suggested that ZnO-GO is good nanoadsorbent and are effective than TiO_2-GO.

Nanoparticles from Metal or Metal Oxides

Metal oxide nanoparticles are used as adsorbent to remove heavy metal ions due to cost effective, non-toxic synthesis route, easy fabrication and environmentally friendly nature [34]. T. Sheela et al., [35] used ZnO nanoparticles to remove Zn^{2+}, Cd^{2+} and Hg^{2+} ions from aqueous solutions. Adsorption capacity of ZnO has been studied based on effects of pH, initial concentration, and temperature and contact time. The Langmuir model showed significant effects and obtained maximum adsorption capacities of 714, 387 and 357mg/g for mercury, Cadmium and zinc ions respectively. Susan et al., also [36] prepared ZnO nanoparticles using zerumbone extract to remove Pb(II) ions. The adsorption kinetics models and the thermodynamics of adsorption proved that using of zerumbone extract achieved maximum adsorption efficiency of Pb^{2+}. It was found to be 19.65 mg/g under pH of 5 in aqueous solution.

Shokati Poursani et al., [37] achieved uniform size and shape of nano-TiO_2 particles by sol-gel method. Nano-TiO_2 particles have great potential to adsorb Pb^{2+} ions from aqueous solutions. After desorption process particles can be reused with high efficiency. Nan Zhang et al., [38] studied Nano-TiO_2 for effective removal of heavy metals and it can be used to adsorb heavy metals fast. The adsorption conditions were optimized including pH, adsorption condition and elution condition.

Xiaoming et al., [39] reported that manganese oxide adsorbed Cd(II) ions from aqueous solution. Langmuir adsorption model revealed maximum adsorption capacity 104.17 mg/g at pH 6.0 and 298 K. Based on surface complexation modeling, Mn oxide increases its ionic strength at pH < 5.0 because its negatively charged above pH 3.5 which could be helpful in adsorbing positively charged Cd(II) ions. Haipeng et al., [40] prepared different crystallographic phases of manganese oxides, α, β, γ, and α -MnO_2. Among all those phases, column test revealed that β-MnO_2 has maximum adsorption capacity and durability.

Stietiya and Wang [41] investigated Al_2O_3 nanoparticles adsorbing Zn and Cd ions. It can be significantly enhanced by the addition of PO_4 or HA. Sadott Pacheco et al., [42] proposed alumina silica nanoparticles used as promising nano-adsorbent to remove Cd (II) metal ion. Maximum removal capacity achieved at pH of 6 in 30 min.

Magnetic nanoparticles themselves are used as the active component for removal of heavy metals from water because of its unique properties compared to their bulk form, such as superpara magnetism behavior, high dispersion degree and enhanced catalytic activity [43, 44]. Liliana Giraldo et al [45]., synthesized effective, convenient and low-cost Fe_3O_4 nanoparticles by co-precipitation method. The result shows maximum adsorption capacity of 0.140 mmol/g^{-1}, 0.160 mmol/g^{-1}, 0.170 mmol/g^{-1} and 0.180 mmol/g^{-1} for manganese, zinc, copper and lead, respectively, under optimized conditions of pH and temperature. The Fe_3O_4 nanoparticles creates significant impression of electrostatic attraction between metal ions due to hydrated ionic radius of the metal cations. S.A. Elfeky et al. [46]., obtained magnetic nanoparticles (MNPs) coated with CTAB to adsorb toxic Cr(VI) from wastewater. CTAB enhance the adsorption capacity of Fe_3O_4 nanoparticles and the advantage of Fe_3O_4/CTAB is that low-cost and easy collection from the Cr(VI) contaminated wastewater.

Lisandra de Castro Alves et al. [47] achieved novel iron oxide nanoparticles using co precipitation method. The adsorption data exhibits good and fast adsorption capacity to remove toxic metal ions such as cadmium, copper and nickel. Wherein, cadmium attains the maximum adsorption capacity when compared to other metal ions. Lixia et al. [48] synthesized water-soluble Fe_3O_4 nanoparticles using hydrothermal method. Experimental analysis showed that water-soluble Fe_3O_4 NPs exhibited relatively high saturation magnetization (83.4 emu g^{-1}) and efficiency of water-soluble Fe_3O_4 NPs is higher than water-insoluble Fe_3O_4 NPs for Pb^{2+} and Cr^{6+}. Jing Hu et al. [49] prepared various magnetic nanoparticles for the removal of Cr(VI) from electroplating waste water. Among them $MnFe_2O_4$ magnetic nanoparticles can reach equilibrium within 1 h and adsorption efficiency is higher (99.5%) with the shortest adsorption time.

Surface Functionalized Nano Sorbents

Surface functionalization of nano sorbents enhances or adsorbs specific metal ions from waste water [50]. Zhili Li et al [51]., investigated surface-functionalized porous lignin (SFPL) to remove lead ions. Polyethylenimine is a grafting agent to link primary and secondary amine groups to make high-branched structure of SFPL. SFPL nanoparticles with BET surface area of 22.3 m2/g and large number of mesopores are effectively used as adsorbent. Rahele Rostamian et al [52] obtained silica nano hollow spheres and then functionalized it with the thiol group to remove toxic ions such as Hg(II), Pb(II) and Cd(II) from water samples. The adsorption isotherms indicates thiol functionalization enhances adsorption capacity towards the metal ions. Thiol-SNHS shows higher adsorption rates towards Hg^{2+} ions compared to Pb^{2+} and Cd^{2+} ions.

Jerina Majeed et al [53]. Proposed cost effective ZnO nanoparticles functionalized by thiol group. Thiol functionalization on ZnO nanoparticles is highly efficient for sorptive removal of Pb2+ and Hg2+ from waste-water. Xiaodong Xin et al [54] obtained amine-functionalized mesoporous Fe_3O_4 nanoparticles which is cost effective, environment friendly and has good reproducibility. Langmuir adsorption model shows maximum adsorption capacities for Pb^{2+}, Cd^{2+}, and Cu^{2+} from 369.0 to 523.6 mg/g. AF- Fe_3O_4 nanoparticles would be reusable and reduce water treatment expenses. Renu Verma et al., [55] synthesized arginine functionalized magnetic nanoparticles. The result shows the maximum adsorption capacity found to be Cu (II) 172.4, Co(II) 161.2, and Ni(II) 103.0 mg g1. The adsorption capacity is based on amino groups on its surface. M. Anbia and S. Amirmahmoodi [56] prepared amino functionalized mesoporous silica SBA-15 materials to adsorb halophenols. Result has showed that functionalized mesoporous silica SBA-15 had maximum efficiency to remove 4-chlorophenol (CP), 4-bromophenol (BP) and 4-iodophenol (IP) compared to untreated SBA-15. The Langmuir and Freundlich adsorption isotherms reveals the maximum adsorption capacities, which indicates that the amino groups can attain maximum adsorption capacity due to potential charge association.

Kong Xiang et al [57] reported surface functionalized silica nanoparticles prepared by different silane coupling agents. The results show that amine and thiol can be successfully functionalized on silica surface. The sulfur functionalized silica nanoparticles exhibited good adsorption on Cu^{2+} and Hg^{2+} and amine functionalized silica nanoparticles attains maximum adsorption capacity towards Pb^{2+} and Hg^{2+}.

Table 2 Maximum adsorption effficiency of different adsorbate on various nano materials

Adsorbents	**Adsorbate**	**Maximum adsorption efficiency mg.g^{-1}**	**Reference**
Chemically modified PAN fibre (PAN-DR-EDTA)	Cu(II)	47.6	[58]
PAN_{MW} Thio fibres	Hg(II), Cd(II)	322.8, 350.6	[59]
Thiol functionalized PAN nanofibre	Hg(II)	53.6	[60]
Thiol functionalized silica	Hg(II)	59	[61]
Amino functionalized silica nano holo sphere	Pb(II), Cd(II)	143.295, 49.52	[62]
Carbon nanotube	Cu(II), Pb(II)	3.49, 2.96	[63]
Graphene multilayer nanosheets	Co(II)	67	[64]
Chromium doped nickel oxide nanoparticles	Cd(II), Pb(II) and Cu(II)	5.243, 1.79 and 1.302	[65]
Chitosan coated magnetic nanoparticles	Cu(II)	60.606	[66]
Ni@$Mg(OH)_2$ core shell Nano composite	Zn(II), Cd(II) and Cu(II)	36.03, 45.02 and 40.49	[67]

Core Shell Nanoparticles

Core shell nanoparticles are promising candidates in nano materials because it can exhibits two different properties [68]. Chunrong Ren et al [69] constructed amino-functionalized super paramagnetic $CoFe_2O_4$@SiO_2–NH_2 core–shell nanospheres showing homogeneous and uniform morphology with a thickness of 35 nm. The first cycle of adsorption efficiency found to be Cd(II) 99.85%, Cu(II) 87.80% and Pb(II) 90.10%. Suyue Jin et al [70] synthesized amine-functionalized ferromagnetic Fe_3O_4-mesoporous silica ($mSiO_2$) core-shell nanoparticles. Optimization of magnetic core size of the amine functionalized nanoparticles enhances the removal efficiency of heavy meal ions. The result shows the microstructures of the Fe_3O_4-mSiO2 nanoparticles with core size 103 nm. Adjusting the core size influences the magnetic susceptibility of nano-adsorbents, more than super paramagnetic property. Optimization of core size enhanced adsorption of heavy metal ions in a shorter time.

Shushan Hou et al [71] prepared magnetic mesoporous silica microspheres and functionalized with carboxyl groups to enhance adsorption performance. The silica coated magnetic microsphere adsorbent regenerated by acid treatment and reusability of the Fe_3O_4@SiO_2@- $mSiO_2$–COOH microspheres slightly decreases in sequential cycles. Na Wu and coworkers [72] synthesized mesoporous titania beads and alginate biopolymer used as template. The maximum adsorption capacity reaches due to electrostatic adsorption of negatively charged $HCrO^{4-}$ absorbed by positively charged titania beads meanwhile Cr (VI) reduced to Cr (III) due to surface hydroxyl groups on the titania beads. Jiahua Zhu et al [73] magnetic graphene nanocomposites (MGNCs) were synthesized by thermo decomposition process. The core shell nanoparticles composed of crystalline iron core, iron oxide inner shell and amorphous silica outer shell. These are highly stable even when immersed in 1M HCl aqueous acid so it could attain maximum adsorption capacity at relatively lower pH value solutions. Siping Ji et al [74] reported that core-shelled Fe_3O_4@C hybrid nanoparticles via solvothermal method. The result shows the microsphere structure and the magnetic saturation value reached at 53 emu/g. The maximum adsorption efficiency is attained at 100% for Pb^{2+}, 99.2% for Cd^{2+}, 96.6% for Cu^{2+}, and 94.8% for Cr^{2+}, respectively.

Polymer Coated Nano Sorbent

Ahmed fawzy el-kafrawy et al [75] prepared modified b-cyclodextrin coated magnetic particles to adsorb metal ions. It is pH dependent due to complexation nature of cyclodextrin. Gui-yin Li et al [76] synthesized Fe_3O_4 nanoparticles coated with chitosan which showed higher adsorption of metal ions after 45 min. While synthesizing magnetized nanoparticles the super para magnetism and saturated magnetism was reached as 21.5 emu g^{-1}. Several polymers are used as a carrier to embedded magnetized nanoparticles such as PMMA, PEDOT, chitosan, alginate etc., Adil denizli et al [77] prepared mPMMA for the removal of selective metal ion. The chemically modified magnetic PMMA micro beads attains a maximum adsorption capacity of 201 mmol/g for Cu (II), 186 mmol/g for Pb (II), 162 mmol/g for Cd (II), and 150 mmol/g for Hg (II)). Arameh Masoumi et al., [78] suggested that modified methyl methacrylate maleic anhydride (MMA) was synthesized by radical polymerization and analyzed the effect of various parameters such as pH, reaction time, adsorbent dosage and initial metal ion concentration. In the development of polymer-coated nanoparticles, core will be metal oxide or magnetic nano sorbents and shell will be a polymer layer. S. Nasirimoghaddam et al [79] developed chitosan coated magnetic nanoparticles for the removal of Hg^{2+} ions from industrial waste water. Chitosan-bound Fe3O4 nanoparticles showed higher adsorption efficiency in aqueous solution.

Nano Fibre

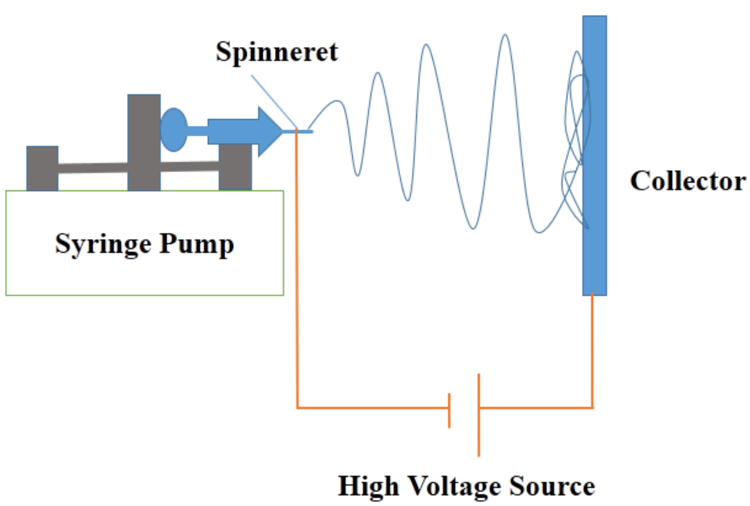

Figure 2 Schematic diagram of electrospinning set up

Nanofibre spinning is a promising technique to develop high efficiency water filtration membranes [80].Quan Feng et al [81] prepared blended Polyacrylonitrile/cellulose acetate (PAN/CA) composite nanofibrous membranes and it was chemically modified into amidoxime ployarcylonitrile/regenerate cellulose (AOPAN/RC) composite nanofibrous membranes. The modified composite membrane showed good reusability and desorption (~nearly 80%) after their first desorption. PAN polymer is widely used to prepare nanofibrous membrane and those fibres are chemically modified with various reagents such as ethylenediamine (EDA), ethylene glycol (EG) or diethylenetriamine (DTA) [82-84]. ZnO, TiO2 were embedded on nanofibrous membrane to enhance the rate of metal ion adsorption. Many chemical modifications of PAN nanofibre were attained such as Amidoxime PAN [85, 86], phosphorylated polyacrylonitrile-based (P-PAN) nanofibres [87] and thiol functionalized PAN [88]. Among them Amidoxime PAN widely used to improve the efficiency of nanofibre membrane [89-91].

In general, Fe (III), Cu (II), Cd (II), Zn (II), Ni (II), Ag + are adsorbed by all the above process. However, the rate of adsorption of individual metal ions varies depending on the polymers being selected, nanoparticles embedded on them and type of chemical modifications.

Commercialization and practical utility

The review highlights the heavy metal ion removal efficiency of above-mentioned nano materials. In future, large amount of commercialized of nano materials or nano sorbents required to remove heavy metal from large water bodies such as rivers, lakes. Currently nano materials lagging the practical utility due to its scale up process and agglomeration of nano materials in large scale [92]. Researchers have been working to scale up large scale production and practical utility.

Conclusion

In this review, an overview was given on the different types of nanomaterials and their maximum adsorption capacities and desorption rates. Nano materials gave significant contribution to adsorb heavy metals from waste water. The main advantages of nano-sorbents are that their properties can be modulated based on the adsorbate considered. Even though there are some challenges like fouling, reusability and reliability, these nanomaterials can still be considered as effective sorbents at the cost of high adsorption efficiencies. It is evident from literature survey of 90 articles proved that nanosorbents can effectively adsorb heavy metals from waste-water than conventional techniques.

Reference

[1] F. Fu and Q. Wang 2011 J. Environ Manage 92 407-418.
[2] I. M. Grześ 2010 Eur J Soil Biol. 46 350-367.
[3] Y. Huang, Y. E. Miao and T. Liu 2014 J. Appl. Polym. Sci 131- 141.
[4] M.A Iqbal and S.G. Gupta 2009 African J. of Basic & Appl. Sci 1 117-122.
[5] M. Jaishankar, T. Tseten, N. Anbalagan, B. B. Mathew and K. N. Beeregowda 2014 Interdiscip Toxicol 7 60-72.
[6] M. Barakat 2011 Arab. J. Chem 4 361-377.
[7] P. C. Nagajyoti, K. D. Lee and T. Sreekanth 2010 Environ Chem Lett 8 199-216.
[8] R. A. Wuana and F. E. Okieimen 2011 Isrn Ecology 2011.
[9] R. K. Sharma and M. Agrawal 2005 J. Environ. BioI 26 301-313.
[10] J. O. Duruibe, M. Ogwuegbu and Egwurugwu 2007 Int. J. Phys. Sci 2 112-118.
[11] P.B Tchounwou, C,G. Yedjou, A.K. Patlolla and D.J. Sutton 2012 (ED) Hand book of Experientia Supplementum National Institute of Health p 133.
[12] L. Xiao, G. G. Wildgoose, A. Crossley, R. Knight, J. H. Jones and R. G. Compton 2006 Chem. Asian J. 1 614-622.
[13] E. Rosenberg 2015 Johnson Matthey Technology Review 59 293-318.
[14] H. Kahrizi, A. Bafkar and M. Farasati 2016 J. Cent. South Univ 23 2526-2535.
[15] K.R. Kunduru, M. Nazarkovsky, S. Farah, R.P Pawar, A. Basu 2017
[16] D. M. Ayres, A. P. Davis and P. M. Gietka 1994 Engineering Research Centre Report 90
[17] T. Zewail and N. Yousef 2015 Alexandria Eng. J 54 83-90.
[18] A. Guijarro-Aldaco, V. Hernandez-Montoya, A. Bonilla-Petriciolet, M. A. Montes-Morán and D. I. Mendoza-Castillo 2011 Ind. Eng. Chem. Res 50 9354-9362.
[19] J. Gao, S.-P. Sun, W.-P. Zhu and T.-S. Chung 2014 Water Res 63 252-261.
[20] T. A. Kurniawan, G. Y. Chan, W.-H. Lo and S. Babel 2006 Chem Eng J 118 83-98.
[21] Renu, M. Agarwal and K. Singh 2017 Interdisciplinary Environmental Review 18 124-144.
[22] J. C. Moreno-Piraján and L. Giraldo 2012 J Chem 9 926-937.
[23] J. Ruparelia, S. Duttagupta, A. Chatterjee and S. Mukherji 2008 Desalination 232 145-156.
[24] K. Pyrzyńska and M. Bystrzejewski 2010 Colloid Surface A 362 102-112.
[25] N. Mubarak, J. Sahu, E. Abdullah and N. Jayakumar 2014 Sep Purif Rev 43 311-323.
[26] G. Bhanjana, N. Dilbaghi, K.-H. Kim and S. Kumar 2017 J Mol Liq 242 966-970.
[27] D. K. Yadav and S. Srivastava 2017 Materials Today: Proceedings 4 4089-4094.
[28] M. Bystrzejewski, K. Pyrzyńska, A. Huczko and H. Lange 2009 Carbon 47 1189-1206.
[29] V. K. Gupta, S. Agarwal and T. A. Saleh 2011 J Hazard Mater 185 17-23.

[30] S. A. Kosa, G. Al-Zhrani and M. A. Salam 2012 Chem Eng J 181 159-168.
[31] Y. Liu, Y. Li and X. P. Yan 2008 Adv Funct Maters 18 1536-1543.
[32] A. Gopalakrishnan, R. Krishnan, S. Thangavel, G. Venugopal and S.-J. Kim 2015 J Ind Eng Chem 30 14-19.
[33] Vishal D. Gohel, Abhishek Rajput, Swati Gahlot, and Vaibhav Kulshrestha 2017 micromolecular symposia p 371-375.
[34] J. S. Hu, L. S. Zhong, W. G. Song and L. J. Wan 2008 Adv Mat 20 2977-2982.
[35] T. Sheela, Y. A. Nayaka, R. Viswanatha, S. Basavanna and T. Venkatesha 2012 Powder Technol 217 163-170.
[36] S. Azizi, M. Mahdavi Shahri and R. Mohamad 2017 Molecules 22 831-845.
[37] A. S. Poursani, A. Nilchi, A. Hassani, S. M. Shariat and J. Nouri 2016 Journal of Water Resource and Protection 8 438-448.
[38] Nan Zhang, Pu Liu, Benquan Fu, Lina Wang 2012 Adv Matt Res 521-525.
[39] X. Huang, T. Chen, X. Zou, M. Zhu, D. Chen and M. Pan 2017 Int J Environ Res Public Health 14 1145-1156.
[40] H. Zhang, A. Wu, H. Fu, L. Zhang, H. Liu, S. Zheng, H. Wan and Z. Xu 2017 RSC Advances 7 41228-41240.
[41] M. H. Stietiya and J. J. Wang 2014 J Environ Manage 43 498-506.
[42] S. Pacheco, J. Tapia, M. Medina and R. Rodriguez 2006 J Non-Cryst Solids 352 5475-5481.
[43] D. Shirsath and V. Shirivastava 2015 Appl Nanosci 5 927-935.
[44] B. R. Thimmiah, G. Nallathambi, Mater Sci-Poland 38 116-121.
[45] L. Giraldo, A. Erto and J. C. Moreno-Piraján 2013 Adsorption 19 465-474.
[46] S. A. Elfeky, S. E. Mahmoud and A. F. Youssef 2017 J. Adv. Res. 8 435-443.
[47] L. de Castro Alves, S. Yáñez-Vilar, Y. Piñeiro-Redondo and J. Rivas 2019 Nanomaterials 9 356-371.
[48] L. Wang, J. Li, Q. Jiang and L. Zhao 2012 J. Chem. Soc., Dalton Trans 41 4544-4551.
[49] J. Hu, I. M. Lo and G. Chen 2007 Sep Purif Technol 56 249-256.
[50] J. Yang, B. Hou, J. Wang, B. Tian, J. Bi, N. Wang, X. Li and X. Huang 2019 Nanomaterials 9 424-453.
[51] Z. Li, D. Xiao, Y. Ge and S. Koehler 2015 4 ACS Appl. Mater. Interfaces 7 15000-15009.
[52] R. Rostamian, M. Najafi and A. A. Rafati 2011 Chem Eng J 171 1004-1011.
[53] J. Majeed, J. Ramkumar, S. Chandramouleeswaran and A. Tyagi 2014 International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering 8 513-515.
[54] X. Xin, Q. Wei, J. Yang, L. Yan, R. Feng, G. Chen, B. Du and H. Li 2012 Chem Eng J 184 132-140.
[55] R. Verma, A. Asthana, A. K. Singh and S. Prasad 2017 RSC Advances 7 51079-51089.
[56] M. Anbia and S. Amirmahmoodi 2011 Scientia Iranica 18 446-452.
[57] X.-f. Kong, B. Yang, H. Xiong, Y. Zhou, S.-g. Xue, B.-q. Xu and S.-x. Wang 2014 J. Cent. South Univ. 21 3575-3579.
[58] X. Zhang, S. Yang, B. Yu, Q. Tan, X. Zhang and H. Cong 2018 Scientific reports 8 1260-1269.
[59] S. Deng, G. Zhang, S. Liang and P. Wang 2017 ACS Sustain Chem Eng. 5 6054-6063.
[60] J. Wang, X. Wang, P. Zhang, J. An, B. Cao, Y. Geng, T. Luo, L. Wang and K. Pan 2016 Chem Eng Res Des 113 1-8.
[61] S. Li, X. Yue, Y. Jing, S. Bai and Z. Dai 2011 Colloid Surf A Physicochem Eng Asp 380 229-233.
[62] M. Najafi, Y. Yousefi and A. Rafati 2012 Sep Purif Technol 85 193-205.
[63] A. Stafiej and K. Pyrzynska 2007 Sep Purif Technol 58 49-52.
[64] G. Zhao, J. Li, X. Ren, C. Chen and X. Wang 2011 Environ. Sci. Technol. 45 235-238.
[65] H. Zhu, X. Xu and X. Zhong 2016 Pol J Environ Stud 1-7.
[66] Y. S. Krishna, G. Sandhya and R. R. Babu 2018 Bull. Chem. Soc. Ethiopa 32 225-230.
[67] N. Rahbar, A. Jahangiri, S. Boumi and M. J. Khodayar 2014 Jundishapur J Nat Pharm Prod. 9.
[68] M. Zhang, W. Song, Q. Chen, B. Miao and W. He 2015 ACS Appl. Mater. Interfaces 7 1533-1540.
[69] Z.-Y. Chu, W.-N. Wang, C.-Y. Zhang, J. Ruan, B.-J. Chen, H.-M. Xu and H.-S. Qian 2019 Chem Eng J. 121927-121941.
[70] C. Ren, X. Ding, H. Fu, W. Li, H. Wu and H. Yang 2017 RSC Advances 7 6911-6921.
[71] S. Hou, X. Li, H. Wang, M. Wang, Y. Zhang, Y. Chi and Z. Zhao 2017 RSC Advances 7 51993-51998.
[72] N. Wu, H. Wei and L. Zhang 2011 Environ Sci Technol 46 419-425.
[73] J. Zhu, S. Wei, H. Gu, S. B. Rapole, Q. Wang, Z. Luo, N. Haldolaarachchige, D. P. Young and Z. Guo 2011 Environ Sci Technol 46 977-985.
[74] S. Ji, C. Miao, H. Liu, L. Feng, X. Yang and H. Guo 2018 Nanoscale research letters 13 178-188.
[75] A. F. El-Kafrawy, S. M. El-Saeed, R. K. Farag, H. A.-A. El-Saied and M. E.-S. Abdel-Raouf 2017 Egyptian Journal of Petroleum 26 23-32.
[76] G.-y. Li, Y.-r. Jiang, K.-l. Huang, P. Ding and J. Chen 2008 J Alloy Compd. 466 451-456.
[77] A. Denizli, G. Özkan and M. Y. Arica 2000 J Appl Polym Sci 78 81-89.

[78] A. Masoumi, M. Ghaemy and A. N. Bakht 2014 Ind. Eng. Chem. Res. 53 8188-8197.
[79] S. Nasirimoghaddam, S. Zeinali and S. Sabbaghi 2015 Ind. Eng. Chem. Res. 27 79-87.
[80] H. Malik, U. A. Qureshi, M. Muqeet, R. B. Mahar, F. Ahmed and Z. Khatri 2018 E Environ Sci Pollut Res 25 3557-3566.
[81] Q. Feng, D. Wu, Y. Zhao, A. Wei, Q. Wei and H. Fong 2018 J Hazard Mater 344 819-828.
[82] D. M. Martín, M. Faccini, M. García and D. Amantia 2018 J. Environ. Chem. Eng. 6 236-245.
[83] M. Y. Haddad and H. F. Alharbi 2019 J. Appl. Polym. Sci. 136 47209-47220.
[84] M. Y. Haddad, H. F. Alharbi, M. R. Karim, M. O. Aijaz and N. H. Alharthi 2018 J Polym Res 25 218-223
[85] J. Dena-Aguilar, J. Jauregui-Rincon, A. Bonilla-Petriciolet and J. Romero-Garcia 2015 J. Chil. Chem. Soc 60 2876-2881.
[86] P. Kampalanonwat and P. Supaphol 2010 ACS Appl Mater Inter 2 3619-3627.
[87] Y. Hu, X. Wu, X. He and D. Xing 2019 Polym Adv Technol. 30 545-551.
[88] O. Pereao, C. Bode-Aluko, K. Laatikainen, A. Nechaev and L. Petrik 2019 J Polym Environ. 1 18-37.
[89] F. Huang, Y. Xu, S. Liao, D. Yang, Y.-L. Hsieh and Q. Wei 2013 Materials 6 969-980.
[90] K. Saeed, S. Haider, T.-J. Oh and S.-Y. Park 2008 J Membrane Sci 322 400-405.
[91] S. Deng, R. Bai and J. P. Chen 2003 Langmuir 19 5058-5064
[92] M. N. Subramaniam, P. S. Goh, W. J. Lau and A. F. Ismail 2019 nanomaterials. 9 625-657.

Publication History

Received	19.12.2020
Revised	01.06.2021
Accepted	08.08.2021
Online	30.09.2021