JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

FUNCTIONALIZED FULLERENES AND CARBON NANOTUBES AS HIGH-PERFORMANCE SORBENTS FOR HEAVY METAL REMOVAL: A SYSTEMATIC REVIEW

Kiran Jeet[1*], Sumali Bansal[2] and Priyanka[3]
[1 *]Electron Microscopy and Nanoscience Laboratory, Punjab Agricultural University, Ludhiana- 141004, India
[2] Department of Physics, DAV college, Sector -10, Chandigarh, India
[3]Department of Physics, Government PG college, Ambala Cantt, Haryana, India

*Email address of the author: kiranjeet@pau.edu,

Abstract: Heavy metal contamination in water systems has emerged as a critical global concern due to the toxicity, persistence, and bioaccumulative nature of metal ions such as Pb^{2+}, Cd^{2+}, As^{3+}, Cr^{6+}, Hg^{2+}, Ni^{2+}, and Cu^{2+}. Conventional treatment methods—including precipitation, ion exchange, coagulation, electrochemical processes, and membrane filtration—often face limitations such as low selectivity, high energy requirements, secondary waste generation, and reduced efficiencies at trace concentrations. In recent years, carbon-based nanomaterials have gained significant attention as advanced adsorbents for heavy metal remediation. Among them, fullerenes and carbon nanotubes (CNTs) stand out due to their unique structural properties, high surface area, tunable functional groups, and exceptional physicochemical stability. This review systematically summarizes developments in the application of fullerenes and CNTs for heavy metal ion removal, highlighting adsorption mechanisms, surface functionalization strategies, removal efficiencies, and reusability. Special attention is given to recent experimental breakthroughs and comparative performance analyses with conventional adsorbents. Current challenges and future prospects are discussed to guide the development of next-generation carbon-based materials for sustainable water purification.

Key words: Water purification; Carbon nanotubes (CNTs); Fullerenes; Adsorption; Nanomaterials; Surface functionalization; Wastewater treatment; Environmental remediation

I. INTRODUCTION

The available source of clean water, the shrinking levels of surface water and waste water pollution, and contamination of environment by toxic pollutants have emerged as the most serious problems facing our globe in the twenty-first century. The increasing population pressure, coupled with industrialization in India, has resulted in severe deterioration in quantity and quality of both surface and ground waters. The declining ground water resources are witnessing a parallel deterioration in water quality, leading to serious diseases like cancer. This is true in northern part of the country where good quality water is now becoming unportable.

The quality of groundwater may be impacted by naturally occurring processes as well as by the activities directly attributable to human interventions in different environs. Water contamination includes heavy metals, dyes, organic matter, pesticides, insecticides, fertilizers etc. which are leached into water through soil and other sources. Toxic heavy metal ions get introduced to the aquatic streams by means of various industrial activities viz. mining, refining ores, fertilizer industries, tanneries, batteries, paper industries; pesticides etc. and possess a serious threat to environment. The major toxic metal ions hazardous to humans as well as other forms of life are chromium (Cr), iron (Fe), selenium (Se), vanadium (V), copper (Cu), cobalt (Co), nickel (Ni), cadmium (Cd), mercury (Hg), arsenic (As), lead (Pb), zinc (Zn) etc. These heavy metals are of specific concern due to their toxicity, bioaccumulation tendency and persistency in nature. Various regulatory bodies have set maximum prescribed limits for the discharge of toxic heavy metals in the aquatic systems. However, the metal ions are being added to the water stream at a much higher concentration than the prescribed limits by industrial activities, thus leading to the health hazards and environmental degradation. Unlike organic contaminants, heavy metals do not degrade and tend to accumulate in ground water which further enters food chain through irrigation water. Removal of inorganic and organic pollutants from waters is considered as one of the major investigations in the last few decades.

In order to address the undeniable need of pure water, various water treatment technologies have been proposed and applied at experimental and field levels. However, most of the currently available technologies are not capable of decontaminating water from pollutants of ionic scale and those which are effective such as RO (membrane filters), face major drawbacks such as; they are energy and operationally intensive and have other limitations such as de-mineralisation of water, major loss of water (around 87% of water goes wasted while purifying) and rapid loss in efficacy of the membrane due to pollutant precipitation. Current/ Conventional purification methods also faces challenges like they are ineffective in the removal of low concentrations of heavy metals and pesticide residues and they are non-selective as well.

Conventional techniques for water remediation

Technique	Typical advantages	Typical limitations & operational challenges	Recent (2022–2025) literature examples
Chemical precipitation	Simple, low capital cost; effective for high metal loads	Large toxic sludge volumes; secondary waste disposal; limited metal selectivity	(Oladimeji et al 2024 and Dube et al 2025). (ScienceDirect)
Ion exchange	High removal at low concentrations; selective recovery possible	High cost; resin regeneration produces brine; competition from Na^+/Ca^{2+} reduces performance	(Jasim et al 2024 and Juve et al 2022). (ScienceDirect)
Adsorption	Flexible (many adsorbents); can functionalize for selectivity; simple deployment	Regeneration/disposal of spent adsorbent; variability in complex matrices; scale-up costs	(Mei et al 2025 and Nyairo et al 2025). (ScienceDirect)
Coagulation/Flocculation	Cost-effective for turbidity and suspended solids; well-established	Chemical use; pH control; sludge production; sensitivity to water chemistry	(Noor et al 2024 and Ali et al 2025) (ScienceDirect)
Electrodialysis (ED)	Selective ion removal/recovery; limited chemical use	Membrane fouling; concentrate stream management; capital cost	(Juve et al 2022 and Weisz et al 2024). (ScienceDirect)
Ultrafiltration (UF)	Effective for colloids/macromolecules; good pre-treatment role	Membrane fouling; cleaning & replacement costs	(Kammakakam et al 2023 and Hosseinzadeh et al 2025).(ScienceDirect)
Membrane filtration (NF/RO)	High rejection of dissolved ions; enables	High energy (RO); fouling; brine disposal; technical	(Zulu et al 2024 and Tayeh et al 2024).

	reuse & desalination	complexity	(ScienceDirect)
Reverse Osmosis (RO)	Produces high-quality permeate; proven technology	Energy intensive; concentrate disposal; high maintenance	(Kapepula et al 2024 and Tayeh et al 2024). (Frontiers)

Out of these methods, adsorption process is very suitable for wastewater treatment because of its simplicity, easy to use and being cost effective. The limitation of the current purification methods generates a strong demand for the introduction of new novel technology which should be free from the limitations of existing water purification methods and should be cost effective as well. Recent advances in the field of nanoscale science suggests that many of the current problems involving water quality could be resolved or greatly ameliorated using nanosorbents, nanocatalysts, organic polymeric nanoparticles, nanostructured catalytic membranes and nanoparticle enhanced filtration assemblies and other nanotechnology based products. The nanostructured materials are at an edge from their bulk counterparts due to their unique features such as high aspect ratio, high reactivity, tunable pore volume, electrostatic, hydrophilic and hydrophobic interactions which are useful in adsorption, catalysis, sensoring and optoelectronic activities. The high surface area and surface reactivity compared with bulk forms enable the nanomaterials to remediate more material at a higher rate and with a lower generation of hazardous by products. The surface of many nanomaterials can be functionalized to target specific contaminants for achieving high selectivity.

II. CARBON BASED NANOMATERIAL (FULLERENCE AND CARBON NANOTUBES) AS AN ALTERNATIVE TO CONVENTIONAL MATERIALS

Recently, carbon based nanomaterials have become a new adsorbent material with great potential as a trapping media for heavy metal ions from aqueous environment. Atomic carbon is very short-lived specie and, therefore, carbon stabilizes in various multi-atomic structures with different molecular configurations called allotropes. Before 1985, only two allotropes of carbon: Graphite and Diamond were known but after 1985, with the discovery of Fullerene, several other exotic allotropes registered their presence in this family. Among this family, mainly explored allotropes are fullerenes, Carbon Nanotubes (CNTs), and Graphene. These new carbon materials show properties completely different from those of the earlier known forms, diamonds and graphite and thus generated tremendous interest in the scientific community to study them.

2.1 FULLERENES

Fullerence is a closed carbon structure, and the most perfect and stable of these is the C_{60} Buckminister-fullerence or just bucky-ball. A regular C_{60} structure has carbon atoms at 60 chemically equivalent vertices that are connected by 32 faces, 12 of which are pentagonal and 20 hexagonal. Fullerenes are traditionally produced by the arc-discharge vaporization of graphite, by chemical vapor deposition methods, and by combustion processes Mojica et al (2013). The relatively high electron affinity, hydrophobic surface, and high surface/ volume ratio of fullerenes allows for employing them for extraction of different species from aqueous media. The sorption capacity of these materials is usually associated with surface defects (Zhang et al 2013 and Valcarcel et al 2008).

The metal ion sorption equilibrium data are commonly correlated with the Langmuir or the Freundlich equations (LeVan et al 1981). Studies have shown high Cu (II) removal efficiency of fullers in comparison to their composite film with polystyrene. The equilibrium isotherm of the Cu^{2+} sorption on the fullerene fits the Langmuir model. The Cu (II) sorption capacity of the monomolecular layer was found to be 14.6 mmol/g (Alekseeva et al 2016), Since their direct use is unprofitable, so modification of conventional sorbents (activated carbons, zeolites, etc.) using small amounts of fullerenes is better alternative in this field. The introduction of fullerenes leads to the development of the porous structure of the sorbent surface, increases hydrophobicity, and also improves the capacity of the material sorption of heavy metals from aquatic environments. It was observed that on introducing introduced 0.001–0.004% of the fullerenes into activated carbons, their sorption capacity for Pb (II) and Cu (II) increased by 1.5–2.5 times (Samonin et al 2014). Fullerenes are mostly employed to extract organic compounds from aquatic media and their use as their use as adsorbent for water treatment is less explored area of research.

Nanocomposite membranes infused with fullerenes have been synthesized and evaluated for features such as desalination, hazardous ion elimination, metal ion extraction or recovery, and microbe filtration from water (Brunet et al 2009). Diverse hazardous metals such as Lead, mercury, arsenic, and other contaminants have been eliminated utilizing the effective fullerenefilled membranes (Zhang et al 2013, Burakov et al 2018 and Samonin et al 2014). The separation efficacy of these membranes depends on their porosity and surface imperfections (Yashas et al 2021 and Ma et al 2014). Perera and associates (Perera et al 2018) documented findings on fullerene-based reverse osmosis membranes. The membranes exhibited a significant water flow of 26.1 L/m²h and demonstrated salt rejection capabilities. The nanocomposite membranes were efficiently utilized to segregate lithium ions from seawater (Shen et al 2019).

2.2 CARBON NANOTUBES

Carbon nanotubes (CNTs) are rolled tubes of graphene, such that their walls are hexagonal carbon rings. Different types of CNTs can be distinguished depending on their structure or form. The two major types of CNTs are Single-Walled Carbon nanotubes (SWCNTs) and Multi-Walled Carbon nanotubes (MWCNTs). Carbon nanotubes are generally produced by three main techniques, arc discharge, laser ablation and chemical vapour deposition (CVD).

CNTs exhibit specific adsorption properties in comparison with activated carbon due to their high surface to volume ratio, their ability to functionalize, their peculiar morphology, the role of defects and the probability of opening or closing of the tubes which are believed to induce cooperative interaction between metal ions and CNTs phase. CNTs are proven to be superior adsorbents for several divalent metal ions in water, because of their capability to establish (π-π) electrostatic interactions.

The adsorption capacity of CNTs can be utilised by introduction of new functional groups through acid oxidation. However, oxidized CNTs still show low metal ion uptake from aqueous solution and further requires functionalization for targeting the specific metal ion contaminant from aqueous media. The modification of CNTs can be divided into two categories: non-covalent and covalent functionalization. In Covalent functionalization, solubility and dispersion of CNTs in different solvents and polymers can be improved. This allowed more interactive forces between the CNTs and other materials. For example, the functional group at the surface of CNTs can increase the selectivity of CNTs as an adsorbent toward certain pollutants, whereas in noncovalent functionalization of nanotubes preserves the integrity and consequently the physical properties of CNTs can be achieved by wrapping CNTs by polymers or surfactants.

Maximum metal ion sorption capacities of raw and surface oxidized CNTs and other sorbents calculated by the Langmuir equation are reported by many researchers (Li et al 2002, Lu et al 2006, Li et al 2003, Lu et al 2006, Li et al 2006, Liang et al 2004, Li et al 2005, Li et al 2003 and Chen et al 2006). It is apparent that the sorption uptakes of metal ions to different CNTs follow roughly the order: Pb2+ >Ni2+ >Zn2+ >Cu2+ >Cd2+. The sorption capacities of metal ions by raw CNTs are very low but significantly increase after oxidized by HNO_3, NaOCl, and KMnO4 solutions. These functional groups cause a rise in negative charge on carbon surface and the oxygen atoms in functional groups donate single pair of electrons to metal ions, consequently increasing their cation exchange capacity (Li et al 2002). However, the maximum sorption capacities of metal ions by surface oxidized CNTs (Li et al 2002, Lu et al 2006, Li et al 2003, Lu et al 2006, Li et al 2006, Liang et al 2004, Li et al 2005, Li et al 2003 and Chen et al 2006) are higher as compared to green macroalga (Pavasant et al 2006), palm shell (Issabayeva et al 2006) activated carbon, activated carbon cloths (Kadirvelu et al 2000), kaolinite (Yavuz et al 2003), pinus sylvestris (Ucun et al 2003), granular activated carbon (GAC) (Lu et al 2006) , powdered activated carbon (PAC) Lu et al (19) . These comparisons suggest that the surface oxidized CNTs are promising sorbents for the removal of divalent metal ions from water and wastewater.

Recent researches have reinforced the fact that carbon nanotubes (CNTs), especially when surface-oxidized or chemically functionalized, have markedly improved adsorption capabilities for hazardous heavy-metal ions. Oxidized MWCNTs exhibit significantly enhanced absorption of Pb(II), Cd(II), and other divalent metals due to the presence of surface oxygenated groups, which augment negative charge density and facilitate metal–ligand interaction, as evidenced by (Li et al 2024). Hybrid CNT-based nanostructures, including graphene oxide–CNT–microalgal composites, have emerged as extremely effective sorbents for the removal of Pb(II) at low concentrations (Yokwana et al 2025). Functionalization remains crucial; for instance, amine-modified carbon nanotubes (MWCNT–NH_2) documented in 2025 have remarkable affinity for Pb(II) owing to potent electron-donating nitrogen groups and superior complexation capacity (Zhao et al 2025). Comprehensive reviews released in 2024 emphasize carbon nanotubes (CNTs) as highly promising carbon-based nanomaterials for wastewater remediation due to their substantial adsorption capacities, adjustable surface chemistry, and capability to engage in multiple mechanistic interactions, including electrostatic attraction, π–π bonding, and cation exchange (Waheeba et al 2024, Namita et al 2024, Nashra Sheraz et al 2004 and Karnwal et al 2024). These advancements indicate that CNTs, particularly when oxidized or functionalized, are leading candidates for next-generation adsorbents for the effective and selective removal of heavy-metal ions from aqueous environments.

III. CONCLUSION

The removal of heavy metal ions from contaminated water continues to be a major environmental challenge, particularly in regions experiencing rapid industrial expansion and groundwater deterioration. Conventional treatment methods, although widely used, often suffer from limitations related to selectivity, energy consumption, membrane fouling, and secondary waste generation. In contrast, carbon-based nanomaterials—especially fullerenes and carbon nanotubes—offer promising pathways for efficient, selective, and scalable heavy metal remediation. Their high surface area, stability, tunability through surface functionalization, and strong affinity for metal ions make them effective alternatives to traditional adsorbents. Recent studies demonstrate significant advancements in enhancing adsorption capacity, improving regeneration cycles, and integrating these nanomaterials into hybrid treatment systems.

Despite these advantages, challenges related to synthesis cost, nanomaterial recovery, environmental safety, and real-water applicability remain barriers to large-scale implementation. Continued research focused on greener synthesis routes, composite development, recyclability, and risk assessment will be essential. Overall, fullerenes and CNT-based systems represent a rapidly advancing field with strong potential to transform heavy metal removal technologies and contribute to sustainable water purification solutions.

References

1. Alekseeva OV, Bagrovskaya NA, Noskov AV (2016) Sorption of heavy metal ions by fullerene and polystyrene/fullerene film composite. Prot Met Phys Chem Surf 52(3):443–447
2. Ali, S. K., et al. (2025). Eco-friendly solutions: a comprehensive review of natural coagulants and their applications. Environmental Geochemistry and Health / Springer. SpringerLink
3. Brunet L, Lyon DY, Hotze EM, et al. Comparative Photoactivity and Antibacterial Properties of C60 Fullerenes and Titanium Dioxide Nanoparticles. Environmental Science & Technology. 2009; 43(12): 4355-4360. doi: 10.1021/es803093t
4. Burakov AE, Galunin EV, Burakova IV, et al. Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review. Ecotoxicology and Environmental Safety. 2018; 148: 702-712. doi: 10.1016/j.ecoenv.2017.11.034
5. C. Chen, X. Wang, Adsorption of Ni(II) from aqueous solution using oxidized multiwall carbon nanotubes, Ind. Eng. Chem. Res. 45 (2006) 9144–9149.
6. C. Lu, C. Liu, Removal of nickel (II) from aqueous solution by carbon nanotubes, J. Chem. Technol. Biotechnol. 81 (2006) 1932–1940.
7. C. Lu, H. Chiu, Adsorption of zinc (II) from water with purified carbonnanotubes, Chem. Eng. Sci. 61 (2006) 1138–1145.
8. Dube, A., et al. (2025). Electrochemical water treatment: a review of different electrochemical approaches. Journal Article. ScienceDirect
9. G. Issabayeva,M.K. Aroua, N. Meriam, N. Sulaiman, Removal of lead from\ aqueous solutions on palm shell activated carbon, Bioresource Technol. 97 (2006) 2350–2355.
10. H. Ucun, Y.K. Bayhan, Y. Kayab, A. Cakici, O.F. Algurb, Biosorption of lead (II) from aqueous solution by cone biomass of pinus sylvestris, Desalination 154 (2003) 233–238.
11. Hosseinzadeh, F., et al. (2025). Advances in tight ultrafiltration membranes: material approaches and applications. Journal Article. ScienceDirect
12. Jasim, A. Q., et al. (2024). Removal of heavy metal ions from wastewater: techniques and advances. Journal of Environmental Chemical Engineering / Journal Article. ScienceDirect

13. Juve, J. M. A., et al. (2022). Electrodialysis for metal removal and recovery: A review. Separation and Purification Technology. ScienceDirect

14. K. Kadirvelu, C.F. Brasquet, P.L. Cloirec, Removal of Cu(II), Pb(II), and Ni(II) by adsorption onto activated carbon cloths, Langmuir 16 (2000) 8404–8409.

15. Kammakakam, I., et al. (2023). Next-generation ultrafiltration membranes: a review. Science of The Total Environment / Advanced Materials review. ScienceDirect

16. Kapepula, V. L., et al. (2024). Removal of heavy metals from wastewater using reverse osmosis: advances and innovations. Frontiers in Chemical Engineering. Frontiers

17. Karnwal Arun , Malik Tabarak. Nano-revolution in heavy metal removal: engineered nanomaterials for cleaner water. Frontiers in Environmental Science. 2024;12:1393694. Frontiers

18. LeVan M D and Vermeulen T 1981. Binary langmuir and freundlich isotherms for ideal adsorbed solutions. J Phys Chem **85:** 3247-50.

19. Li X., Cui Y., Du W., Cui W., Huo L., Liu H. Adsorption kinetics and mechanism of Pb(II) and Cd(II) adsorption in water through oxidized multiwalled carbon nanotubes. Applied Sciences. 2024;14(5):1745. MDPI

20. Ma J, Guo Q, Gao HL, et al. Synthesis of C60/Graphene Composite as Electrode in Supercapacitors. Fullerenes, Nanotubes and Carbon Nanostructures. 2014; 23(6): 477-482. doi: 10.1080/1536383x.2013.865604

21. Mei, Y., et al. (2025). Adsorption of heavy metals by biochar in aqueous solution: mechanisms and applications. Science of The Total Environment (review). ScienceDirect

22. Mojica M., Alonso J.A. and Mendez F. (2013). Synthesis of fullerenes. J. Phys. Org. Chem. **26** (7): 526-539.

23. Namita Singh, Annu Yadav, Sumistha Das, Nitai Debnath. Recent advances in heavy metal / metalloid ion treatment from wastewater using nanocomposites and bionanocomposites. Frontiers in Nanotechnology. 2024;6:1307353. Frontiers

24. Nashra Sheraz· Afzal Shah. Abdul Haleem, Faiza Jan Iftikhar· Comprehensive assessment of carbon-, biomaterial- and inorganic-based adsorbents for the removal of the most hazardous heavy metal ions from wastewater. RSC Advances. 2024. RSC Publishing

25. Noor, M. H. M., et al. (2024). Global research landscape on coagulation-flocculation for wastewater treatment: bibliometric review. Journal/ScienceDirect. ScienceDirect

Nyairo, W., et al. (2025). Adsorption of heavy metals onto food wastes: a review. Frontiers in Environmental Chemistry. Frontiers

O¨. Yavuz, Y. Altunkaynak, F. Gu¨zel, Removal of copper, nickel, cobalt and manganese from aqueous solution by kaolinite, Wat. Res. 37 (2003) 948–952.

Oladimeji, T. E., et al. (2024). Review on the impact of heavy metals from industrial wastewater and treatment methods. Science of The Total Environment (review). ScienceDirect

P. Liang,Y. Liu, L. Guo, J. Zeng, Hanbing, Multiwalled carbon nanotubes as solid-phase extraction adsorbent for the preconcentration of trace metal ions and their determination by inductively coupled plasma atomic emission spectrometry, J. Anal. At. Spectrom 19 (2004) 1489–1492.

P. Pavasant, R. Apiratikul, V. Sungkhum, P. Suthiparinyanont, S. Wattanachira, T.F. Marhaba, Biosorption of Cu2+, Cd2+, Pb2+, and Zn2+ using dried marine green macroalga caulerpa lentillifera, Bioresource Technol. 97 (2006) 2321–2329.

Perera MGN, Galagedara YR, Ren Y, et al. Fabrication of fullerenol-incorporated thin-film nanocomposite forward osmosis membranes for improved desalination performances. Journal of Polymer Research. 2018; 25(9). doi: 10.1007/s10965-0181593-4

Samonin VV, Nikonova VYu, Podvyaznikov ML. Carbon adsorbents on the basis of the hydrolytic lignin modified with fullerenes in producing. Russian Journal of Applied Chemistry. 2014; 87(2): 190-193. doi: 10.1134/s1070427214020116

Shen Q, Xu S, Xu Z, et al. Novel thin-film nanocomposite membrane with water-soluble polyhydroxylated fullerene for the separation of Mg2+/Li+ aqueous solution. Journal of Applied Polymer Science. 2019; 136(41). doi: 10.1002/app.48029

Tayeh, Y. A., et al. (2024). A comprehensive review of reverse osmosis desalination: technology and operational challenges. Desalination / Review. ScienceDirect

Valcarcel M., Cardenas S., Simonet B.M., Moliner-Martinez Y. and Lucena R. (2008). Carbon nanostructures as sorbent materials in analytical processes. TrAC Trend. Anal. Chem. **27** (1):34-43.

Waheeba Ahmed Al-Amrani and Sagheer A. Onaizi. Adsorptive removal of heavy metals from wastewater using emerging nanostructured materials: A state-of-the-art review. Separation and Purification Technology. 2024;343:127018. ScienceDirect

Weisz, L., et al. (2024). Feasibility study of electrodialysis as an ammonium reuse strategy. Science of The Total Environment. ScienceDirect

Yokwana, K., Ajiboye, T.O., Ogunlaja, A.S. et al. Xin-doped graphene oxide–carbon nanotubes@microalgal nanostructured hybrids for highly efficient removal of Pb(II) from aqueous solutions. MRS Advances. 2025. SpringerLink

Y.H. Li, J. Ding, Z. Luan, Z. Di, Y. Zhu, C. Xu, D. Wu, B. Wei, Competitive adsorption of Pb2+, Cu2+ and Cd2+ ions from aqueous solutions by multiwalled carbon nanotubes, Carbon 41 (2003) 2787–2792.

Y.H. Li, S. Wang, J. Wei, X. Zhang, C. Xu, Z. Luan, D. Wu, B. Wei,Lead adsorption on carbon nanotubes, Chem. Phys. Lett. 357 (2002) 263–266.

Y.H. Li, S. Wang, Z. Luan, J. Ding, C. Xu, D. Wu, Adsorption of cadmium(II) from aqueous solution by surface oxidized carbon nanotubes,Carbon 41 (2003) 1057–1062.

Y.H. Li, Y. Zhu,Y. Zhao, D.Wu, Z. Luan, Different morphologies of carbon nanotubes effect on the lead removal from aqueous solution, Diamond Relat. Mater. 15 (2006) 90–94.

Y.H. Li, Z. Di, J. Ding, D.Wu, Z. Luan,Y. Zhu, Adsorption thermodynamic, kinetic and desorption studies of Pb2+ on carbon nanotubes, Wat. Res. 39 (2005) 605–609.

Yashas SR, Shahmoradi B, Wantala K, et al. Potentiality of polymer nanocomposites for sustainable environmental applications: A review of recent advances. Polymer. 2021; 233: 124184. doi: 10.1016/j.polymer.2021.124184

Zhang B.T., Zheng X., Li H.F. and Lin J.M. (2013). Application of carbon-based materials in sample preparation: a review. Anal. Chim. Acta. **784**:1-17.

Zhao, D., Zhang, Y., Wu, C. Adsorption of Pb(II) ions by functionalized multi-walled carbon nanotubes MWCNTs–NH_2. Journal of Hazardous Materials Advances. 2025;19:100764. ScienceDirect

Zulu, E., et al. (2024). A comprehensive review of recent advances in membrane technologies for mining effluent treatment. Journal Article. ScienceDirect