ADVANCES IN HEAVY METAL REMOVAL FROM WASTEWATER: CONVENTIONAL TO AI-BASED APPROACHES

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Abstract

Heavy metal pollution in wastewater is increasingly becoming an urgent problem, mainly due to its persistence, toxicity, and threat to ecosystems and human health. This review largely evaluates different treatment technologies designed to minimize heavy metal contaminants originating from industrial and municipal wastewater. From traditional techniques (such as ion exchange, membrane filtering, coagulation- flocculation, chemical precipitation, electrochemical, etc.), we assessed their efficiencies and drawbacks, especially cost, selectivity, and sludge production. New technologies in nanotechnology such as oxide nanoparticles, carbon nanotubes, and nano membranes come with new possibilities for increasing surface area and adsorption efficiency. Furthermore, biological processes such as bioleaching, phytostabilization, rhizofiltration, and bacteria bioremediation promote more environmentally acceptable solutions. Artificial intelligence and machine learning are becoming more prevalent in treatment systems and can help with predictive maintenance, process modifications, and real-time monitoring. Nonetheless, much still needs to be done to tackle the real life challenges such as, affordability of scaling up; selectivity for metal recovery; and proper waste management. In conclusion, there is room for both conventional and modern technologies, augmented by evidence-based solutions and green technologies.

Keywords: Heavy Metal Removal, Wastewater Treatment, Nanotechnology, Artificial Intelligence, Bioremediation

Introduction

The focus on decreasing heavy metal contamination in wastewater streams resulting from diverse industrial and human activities has intensified due to the growing global concern about water quality. Heavy metals, which are identified by their high atomic weight and density, are hazardous to the environment and public health due to their toxicity, persistence, and ability to accumulate over time in aquatic habitats and the food chain. [1].

Heavy metals enter aquatic environments primarily through mining activities, agricultural runoff, industrial discharges, and improper waste disposal techniques. [2]. The accumulation of these pollutants, which include but are not limited to lead, mercury, cadmium, chromium, arsenic, and copper, in sediments and living organisms can have detrimental effects on ecological integrity and human health. [3].

Because heavy metals are persistent, resistant to microbial degradation, and build up to toxic levels in plants and living cells, their presence in water sources is a major global concern. These metals can affect humans through the food chain and cause serious health issues like kidney and brain diseases [1].

The negative effects of heavy metal pollution go beyond environmental issues and have a substantial influence on human health. Numerous detrimental health effects, from acute poisoning to chronic illnesses such neurological problems, renal damage, developmental abnormalities, and an increased risk of cancer, can arise from exposure to high concentrations of heavy metals [2].

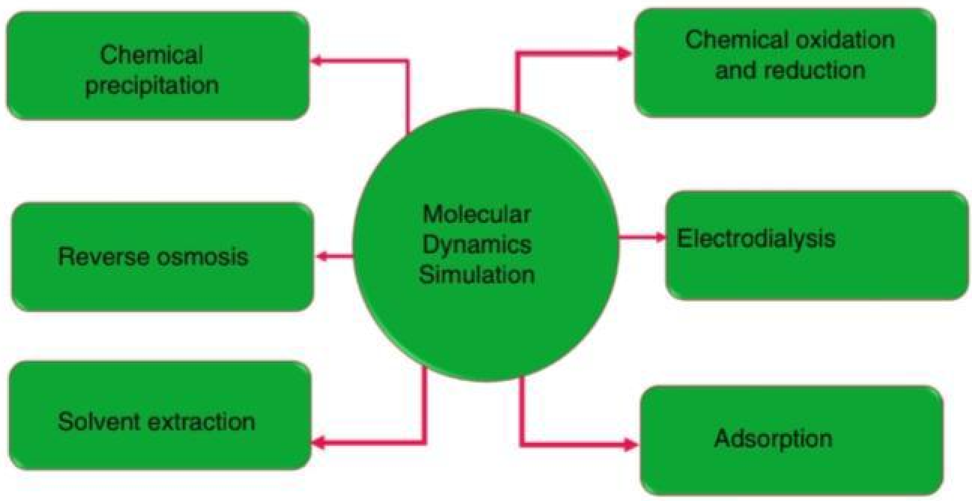

Fig. 1 Heavy metal remediation using a variety of traditional techniques (Goswami *et al*., 2022).

1. Conventional Removal Techniques

1.1 Chemical Precipitation

Chemical precipitation creates insoluble substances (precipitates) by reacting chemicals (reagents) with heavy metal ions in wastewater. Alum (aluminum sulfate), iron salts (ferric chloride or sulfate), and lime (calcium hydroxide) are often used reagents [4]. Lead, cadmium, zinc, copper, and other heavy metals can all be effectively removed with this method [5].

Besides heavy metals, chemical precipitation can also remove other pollutants like phosphates, fluoride, and cyanide [6].

The process requires chemicals which can increase the overall treatment cost. The formation of precipitates leads to the generation of sludge, which needs to be managed and disposed of. Proper operation requires careful control of pH, temperature, and reagent dosages [4].The effectiveness of chemical precipitation can be limited, especially for very low concentrations of heavy metals.

1.2 Coagulation-Flocculation

Coagulation is a conventional water treatment technique that is frequently used to treat wastewater and water [7], [8] because it efficiently lowers water pollutants such chemical oxygen demand (COD), turbidity, color, suspended solids (SS), heavy metals, oil, and organic matter [9] [10] [11]. High molecular weight compounds that promote floc aggregation and settling during the coagulation process result in larger flocs [12]. Meanwhile, flocs harden and settle to the bottom during the flocculation process. The water is further treated by filtering and sedimentation to eliminate impurities after this coagulation-flocculation step [13] [14].

1.3 Ion exchange

The process of exchanging ions between a liquid phase (wastewater) and a solid phase (ion exchange resin) is known as ion exchange. Synthetic polymers having charged functional groups that have the ability to bind to heavy metal ions selectively are known as ion exchange resins. High selectivity for specific heavy metals, can achieve very low metal concentrations in the treated water, resin can be regenerated and reused [15] relatively high cost, susceptible to interference from other ions, resin regeneration can generate concentrated waste streams [16]. Studies are focusing on the development of new and more selective ion exchange resins, including those based on nanomaterials or biomaterials. Researchers are also investigating the use of integrated ion exchange systems, combining different resins to simultaneously remove multiple heavy metals.

1.4 Membrane-Based Filtration

1.4.1 Ultra filtration

Ultrafiltration (UF) uses low transmembrane operating pressure (TMP).Since the pores of UF membranes may be la rger than those of heavy metal ions, additives may be added to metal ions to enlarge them. Micellar enhanced ultrafiltration (MEUF) and polymer enhanced ultrafiltration (PEUF) are hence recommended tec hniques [17].MEUF is created by the bonding of UF with surfactant.Because of its high flux and good selectivity, MEUF consumes less energy, has high removal efficiency, and occupies less space [18]. MEUF works well with wastewater that has low levels of heavy metals [19].

1.4.2 Nano filtration

Poly-benzimidazole (PBI) was co-extruded by nanofilterarion to generate a membrane. While poly (ether)sulfone (PES)/polyvinylpyrrolidone (PVP) is inexpensive, more spinnerable, hydrophilic, has superior mechanical qualities, and is easy to produce porous membranes, PBI offers superior chemical resistance and a distinct charge characteristic. Lead, chromium, and cadmium were rejected by this membrane at 95%, 98%, and 93%, respectively [21].

1.4.3 Reverse osmosis

Reverse osmosis is a physical filtration method that employs a higher pressure above the osmotic pressure to force water through a semi permeable membrane with particular properties in order to filter out unwanted molecules by pushing a solvent from an area of high concentration to an area of low concentration [22].

Reverse osmosis is not regarded as a practical technique for removing heavy metals from industrial effluent since it can only remove trace levels of the metals [23]. Using a polyamide thin-film composite membrane TW30-1812-50, reverse osmosis has been used to remove Cu (II), Ni (II), and Zn (II) [24].

Challenges in Conventional Techniques

Despite their widespread use, conventional techniques for heavy metal removal face several significant challenges:

Material costs - The large volume of chemical coagulation and precipitation and coagulation-flocculation involves a lot of chemicals and, hence large operational costs. Prices for these chemicals can be volatile and impact treatment costs.

Adsorbent Costs - Activated carbon and other high-quality adsorbents can be expensive, especially for larger applications. Operational costs also include reconditioning spent adsorbents.

Membrane Costs - Membrane filtration processes, especially NF and RO, are capital and operationally expensive, mainly due to the cost of membranes and the cost of replacing them on a frequent basis. Another operational cost is the cleaning of membranes due to fouling.

Energy Costs - Membrane filtration and other processes such as activated carbon regeneration are energy intensive processes that contribute to the treatment costs, particularly when energy is costly in the region.

Unselective - Conventional methods tend not to have selectivity towards certain heavy metals, meaning that they would also remove other desired ions in the wastewater in addition to the targeted metals. This is unsuitable for certain industrial processes where metal recovery needs to be at an individual level.

Complex Mixtures - The effectiveness of traditional methods for removing heavy metals from wastewater may be negatively impacted by the presence of pollutants and other interfering elements. These substances may compete with one another for binding sites or prevent the heavy metals from being absorbed through other means.

Sludge Management Challenge: It can be difficult to dispose of the sludge left over after heavy metal removal, especially for small and medium-sized businesses that lack the knowledge and technical means to properly handle and treat sludge.

1.5 Electrochemical Treatment

The basic idea of the electrochemical process is to use electricity to transfer a current through an aqueous metal-bearing solution, which also contains a cathode plate and an insoluble anode. In order to handle the heavy metals, they are precipitated as hydroxides in a neutralized or mildly acidic electrolyte. In this sense, the choice of electrode material not only provides specific application opportunities but also greatly improves the method's capacity to battle various types of contaminated substances. Furthermore, the quality of the treated wastewaters would be determined by the amount of produced ions or charged loading, which is the outcome of current and time [25]. Conductive carbon fibre clothing is commonly used as reinforcement in polymer materials due to its higher specific strength and modulus than other reinforces [26] [27].

2. Nanotechnology-based wastewater treatment

2.1 Nanoadsorbent based on metal

Metal-based nano adsorbents are inexpensive nanoparticles with potent adsorptive properties. These are mostly used to remove heavy metal pollutants from water. Among the metal-based nanoadsorbents that have been extensively studied and demonstrated to have promise in the removal of heavy metal pollutants from wastewater are ferric oxide, titanium oxide, manganese oxide, magnesium oxide, and aluminum oxides [28].

The high surface to volume ratio of nanosized metal oxides makes them more effective than conventional sorbents. The adsorbent and adsorbate have a stronger chemical contact as a result.The pH of the solution has a significant im pact on the quantity of heavy metal adsorption and also controls the surface chemistry of the nanoparticles.Nanoads orbents based on metals have several benefits.Easy synthesis, reduced toxicity, increased adsorption surface area, a nd chemical stability are some of these. Because of all these features, these metal oxide nanoadsorbents are unique and more appealing than other adsorbents [29] [30].

2.2 Carbon nanotube

The carbon nanotubes (CNTs) are cylindrical structures made of graphene sheets with a diameter of less than one n anometer.They may consist of one or many walled constructions.They are quite strong and sturdy in nature [31] [32] .The adsorption capacity and selectivity of CNTs can be enhanced by surface modifications, acid treatments, the ad dition of metals or metal oxides, functional groups or molecules, etc. [33].The addition of functional groups such as -COOH, -OH, and/or $–NH_2$ can improve the adsorption capacity of CNTs. The most common interaction forces between CNTs and water pollutants include Pi-pi electron coupling, ion exchange, hydrogen bonding, covalent bonds, hydrophobic and electrostatic interactions, and mesopore filling [34].

2.3 Nano membranes

Membrane filtration is a crucial technique for eliminating impurities from water. Depending on the molecules they contain and the size of their holes, membranes can act as a physical barrier against contaminants. The reverse osmosis (RO) method is widely used nowadays to filter water and make it safe for human consumption. In a similar vein, businesses employ nanotechnology-based membranes to filter out inorganic pollutants like industrial pollutants from water. The use of nano membrane technology for water purification has several benefits, including high efficacy, minimal space requirements, and simplicity of use. The filtering capacity can also be increased by adding suitable chemicals, nanoparticles, or a combination of the two [35].

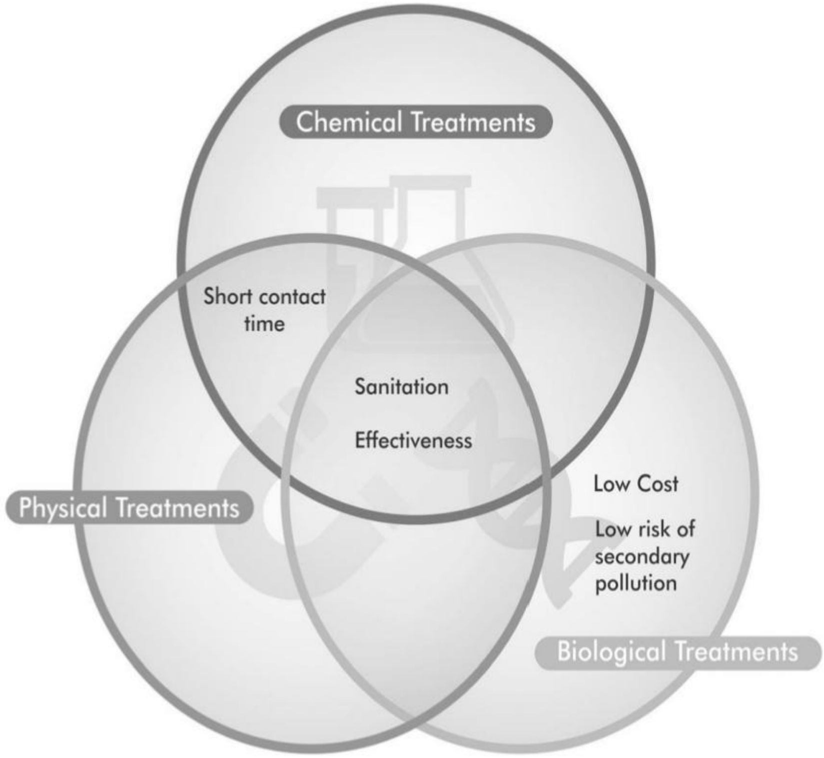

Fig. 2 Comparison of the main qualities of the chemical, physical, and biological treatments. The intersections show common qualities between treatments. Both the efficiency and the exposure time are related to the removal of metals [36]

3. Biological Treatments

3.1 Bioleaching

This technique has demonstrated promise in the removal of metals because of its affordability, efficiency, and ease of application [37]. While many microorganisms are known to take part in bioleaching, acidophilus bacteria from the *Acidithiobacillus* genus, specifically *A. ferrooxidans* and *A. Thiooxidans*, are the two most commonly used species in this process [37] [38]. These bacteria promote the solubilization of the metals by oxidizing reduced sulfur (also called elemental sulfur or sulfur compounds) to sulfuric acid and acidifying the media [39].

3.2 Phytostabilization

Phytostabilization lowers the bioavailability of heavy metals (HM) in the environment by immobilizing HM in contaminated soils with metal-tolerant plants [40]. As a result, they are unable to migrate to groundwater or join the food chain [41][42], combined four woody plants with organic supplements to investigate the feasibility of phytostabilizing zinc smelting slag. The results showed that direct vegetation planting in zinc smelting waste slag decreased the bioavailability of heavy metals (Cu, Zn, and Cd) and increased nutrient accumulation [43].

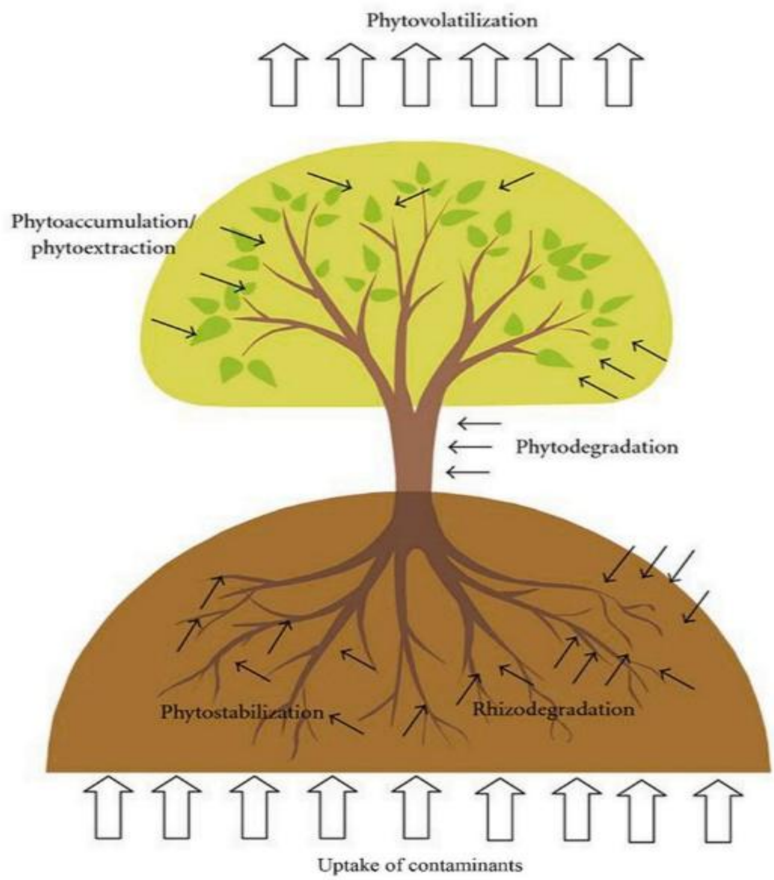

Fig.3 Heavy metal uptake mechanism of Phytoremediation technology [44].

Table 1: Different Phytoremediation process for HM uptake (Bian et.al. 2018)

Types of Phytoremediation	Scope of application	Mechanism	Contaminant
Phytovolatilization	Volatile contaminants	Volatilization by leaves	Organic/Inorganic
Phytostabilization	Mining contamination	Complexation	Inorganic
Phytoextraction	Low-to-medium contaminated sites	Hyper accumulation	Inorganic
Rhizofiltration	Wastewater	Rhizosphere accumulation	Organic/Inorganic

3.3 Rhizofiltration

Plant roots are used in a process called rhizofiltration to remove contaminants from wastewater. HMs can be absorbed by root exudates, changing the rhizosphere's pH [46]. Zea mays has a greater capacity for Hg absorption and bioaccumulation, according to a study [47]. The effectiveness of a rhizofiltration device planted with two species (Kyllinga nemoralis and Phragmites australis) in a sewage treatment facility in KwaZulu-Natal, a province in South Africa, was evaluated in terms of removing heavy metals (HMs) from municipal wastewater. Different concentrations of HMs were placed in the rhizofilter's reference and planted sections [48].

3.4 Bacterial bioremediation

The ability to produce acidic metabolites through acidolysis (the production of organic or inorganic acids), complexation (the excretion of complexing agents), and reduction (oxidation and reduction reactions) allows heterotrophic bacteria, specifically Pseudomonas sp., to extract and solubilize metals from non-sulfidic minerals found in sewage sludge. Heterotrophic bioleaching is currently used mostly for the recovery of metals from sewage, including gold, silver, titanium, aluminum, nickel, copper, manganese, chromium, and uranium [49].

4. AI and Machine learning for Optimisation

Predictive maintenance and real-time monitoring are only two of the many uses of AI in WTPs. Large volumes of data gathered from sensors and water quality monitoring equipment can be analyzed by machine learning algorithms, allowing for the early identification of anomalies or possible problems [50]. WTPs can minimize downtime and do proactive maintenance by using analytics to predict equipment faults. Water treatment plants can increase automation, boost energy efficiency, and eventually help communities receive dependable, high-quality water delivery by integrating AI [51].

Using historical data on heavy metal concentrations, the selected AI models are trained to identify patterns and correlations that are essential for forecasting and improving adsorption processes. Following successful training, the models are put through a thorough testing process using fresh data to confirm their efficacy and accuracy in practical situations [52].

Future Challenges

1. Selective Recovery of Metals

Most current technologies are focused on removing metals, few allow for selective recovery. For example, precious heavy metals like copper or nickel. The future technology will have to manage cleaning up the environment, with reclaiming resources; especially in industrial processes for which resource reclamation and metal recycling is more desirable.

2. Scalability of New Materials

Nanomaterials and bio-derived adsorbents have shown promise in laboratory studies, but face challenges in scaling larger for application due to limitations in cost, durability, and safe disposal. Making these materials work as intended is critical at higher scales, but may be difficult if we need to ensure reduced toxicity.

3. Complex Wastewater Matrices

Real wastewater has more than one contaminant, e.g., organic pollutants, dyes, and microorganisms, which can complicate heavy metal removal. Building robust systems that can process a range of contaminants and variable contaminant loads continues to remain a significant challenge.

4. Sludge and Waste Management

Most conventional methods, especially chemical precipitation processes, typically create toxic sludge that requires disposal. Compliance with stringent environmental regulations means that these secondary waste streams will require lower waste and more sustainable solutions in the future.

5. High Operating Costs

Utilizing energy-intensive techniques such as membrane filtration and electrochemical treatment will entail significant operating costs. The identification of energy-saving techniques or renewable energy for this process will be essential for ensuring long-term sustainability.

6. Regulatory and standardization gaps

Lack of internationally harmonized standards of acceptable levels of heavy metals and accredited treatment methods may hinder the application of new-generation technologies. There is a need for the development of more cohesive guidelines.

Future Prospects

1. Hybrid Treatment Systems

By harnessing the fusion of technology like nanomaterials with biological treatment, or AI-based filtration systems, we can not only increase the efficacy of removal but, also reduce costs and impact on the environment. The potential for hybrid systems is highly influential.

2. Green Development of Adsorbent

Utilizing biopolymer, crop wastes and bio-synthesized nanoparticles, offers a sustainable and environmentally friendly way for metal adsorption options. Research in bio-based or biodegradable adsorbents can help completely transform the field.

3. AI-Based Treatment Process Optimization

Machine learning can help achieve real-time monitoring, predictive maintenance, and autonomous adjustment of treatment parameters for optimal efficiency. Additionally, AI can also be utilized in the design of new adsorbents with improved selectivity.

4. Resource Recovery and Circular Economy

Advanced recovery processes can turn pollutants into resources by recovering valuable metals in e-waste contaminated water, such as gold, platinum or rare earth elements. This helps achieve a circular economy and helps create some economic value in the treatment process.

5. Portable and Decentralized Treatment System

There is significant potential to enhance portable nanomembrane and modular devices to connect the rising demand for small, mobile treatment to bring effective therapies to known faraway, or disaster relief regions; thereby, support off-grid communities and emergency response.

6. Policy-Driven Innovation

Environmental policy, along with economic incentives, pushes industries and researchers to create innovations that are cleaner and more efficient. Working with business, policymakers can play a vital role in improving innovation and uptake.

Conclusion

Heavy metal contamination in wastewater poses a significant threat to both our environment and public health. This review highlights various treatment methods aimed at removing heavy metal pollutants from wastewater. It covers traditional techniques like chemical precipitation, ion exchange, and membrane filtration, as well as more modern approaches such as electrochemical methods, nanotechnology, and biological treatments. Each of these methods comes with its own set of advantages and drawbacks regarding cost, efficiency, scalability, and environmental impact.

Recent advancements that merge nanotechnology with biotechnology offer exciting possibilities for enhancing removal efficiency and tackling the challenges that traditional methods face. Additionally, the rise of artificial intelligence and machine learning is revolutionizing real-time monitoring and predictive control, leading to a new level of optimization in wastewater treatment systems.

However, despite these advancements, we still grapple with challenges like the complex nature of wastewater compositions, the need for economically viable operations, poor selectivity, and sludge management. Future strategies should explore hybrid systems that leverage the strengths of multiple technologies, promote sustainable and eco-friendly materials, and utilize emerging data-driven technologies to foster intelligent operations. A multidisciplinary approach, bolstered by robust policy development and collaboration within the industry, will be crucial in turning innovative research into practical, scalable solutions for heavy metal removal.

References

1. Al-Sareji, O. J., Abdulredha, M., Mubarak, H. A., Grmasha, R. A., Alnowaishry, A., Kot, P., & AlKhayyat, A. (2021). Copper removal from water using carbonized sawdust. In IOP conference series: materials science and engineering (Vol. 1058, No. 1, p. 012015). IOP Publishing.
2. Chinmalli, R., & Vijayakumar, K. (2023). Evaluation of health risk and heavy metal pollution status in the Bhima River Water Kalaburagi, Karnataka, India. Current World Environment, 18(1), 197.
3. Khan, M. A., Majeed, R., Fatima, S. U., Khan, M. A., & Shahid, S. (2020). Occurrence, distribution and health effects of heavy metals in commercially available vegetables in Karachi. International Journal of Biology and Biotechnology, 17, 319-328.
4. Fig.1 Goswami, R. K., Agrawal, K., Shah, M. P., & Verma, P. (2022). Bioremediation of heavy metals from wastewater: a current perspective on microalgae based future. Letters in Applied Microbiology, 75(4), 701-717.
5. Sreekumar, N., Udayan, A., & Srinivasan, S. (2020). Algal bioremediation of heavy metals. In Removal of toxic pollutants through microbiological and tertiary treatment (pp. 279-307). Elsevier.
6. Barakat, M. A. (2011). New trends in removing heavy metals from industrial wastewater. Arabian journal of chemistry, 4(4), 361-377.
7. Zueva, S. B. (2018). Current legislation and methods of treatment of wastewater coming from waste electrical and electronic equipment processing. In Waste electrical and electronic equipment recycling (pp. 213-240). Woodhead Publishing.
8. Al-Sahari, M., Al-Gheethi, A. A. S., & Radin Mohamed, R. M. S. (2020). Natural coagulates for wastewater treatment; A review for application and mechanism. Prospects of fresh market wastes management in developing countries, 17-31.
9. Kakoi, B., Kaluli, J. W., Ndiba, P., & Thiong'o, G. (2017). Optimization of Maerua Decumbent bio-coagulant in paint industry wastewater treatment with response surface methodology. Journal of Cleaner Production, 164, 1124-1134.
10. Abubakar, U. S., Zulkifli, S. Z., & Ismail, A. (2018). Heavy metals bioavailability and pollution indices evaluation in the mangrove surface sediment of Sungai Puloh, Malaysia. Environmental Earth Sciences, 77, 1-12.
11. Deng, M., Yang, X., Dai, X., Zhang, Q., Malik, A., & Sadeghpour, A. (2020). Heavy metal pollution risk assessments and their transportation in sediment and overlay water for the typical Chinese reservoirs. Ecological Indicators, 112, 106166.
12. Owodunni, A. A., & Ismail, S. (2021). Revolutionary technique for sustainable plant-based green coagulants in industrial wastewater treatment—A review. Journal of Water Process Engineering, 42, 102096.
13. Huang, Y., Wang, L., Wang, W., Li, T., He, Z., & Yang, X. (2019). Current status of agricultural soil pollution by heavy metals in China: A meta-analysis. Science of the Total Environment, 651, 3034-3042.
14. De Freitas, F., Battirola, L. D., Arruda, R., & de Andrade, R. L. T. (2019). Assessment of the Cu (II) and Pb (II) removal efficiency of aqueous solutions by the dry biomass Aguapé: kinetics of adsorption. Environmental Monitoring and Assessment, 191(12), 751.
15. Iwuozor, K. O. (2019). Prospects and challenges of using coagulation-flocculation method in the treatment of effluents. Advanced Journal of Chemistry-Section A, 2(2), 105-127.
16. Inglezakis, V. J., & Zorpas, A. A. (2001). Hazardous waste management: a review
17. Wang, X., Li, X., Xing, Y., Wang, X., & Zhang, S. (2009). Removal of heavy metals from wastewater by ion exchange resin. Journal of Hazardous Materials, 166
18. Qasem, N. A. A., Mohammed, R. H., & Lawal, D. U. Removal of heavy metal ions from wastewater: A comprehensive and critical review.
19. Rahmati, N. O., Chenar, M. P., & Namaghi, H. A. (2017). Removal of free active chlorine from synthetic wastewater by MEUF process using polyethersulfone/titania nanocomposite membrane. Separation and Purification Technology, 181, 213-222.
20. Huang, J., et al. (2017). Repeating recovery and reuse of SDS micelles from MEUF retentate containing Cd^{2+} by acidification UF. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 520, 361–368.
21. Zhu, X., Wang, H., & Li, Y. (2014). Removal of heavy metals from wastewater: A review. Journal of Environmental Management, 141, 1–10. https://doi.org/10.1016/j.jenvman.2014.03.021
22. Mehdipour Ghazi, M., Mohammadi, M., & Modarres, H. (2015). Removal of heavy metal particles by LTJ, ANA, SVR, BEC and MER zeolites particles: A molecular dynamics simulation study. Journal of Particle Science and Technology, 1(2), 99-111.
23. Kanamarlapudi, S. L. R. K., Chintalpudi, V. K., & Muddada, S. (2018). Application of biosorption for removal of heavy metals from wastewater. In Biosorption. IntechOpen.
24. Ranitha, M., Nurlidia, M., Muhammad Rashid, S., & Yoshimitsu, U. (2016). Bioremoval of lead in industrial wastewater by microalgae. J. Eng. Sci. Technol, 11, 43-49.
25. Bakalár, T., Búgel, M., & Gajdošová, L. (2009). Heavy metal removal using reverse osmosis. Acta Montanistica Slovaca, 14(3), 250.
26. Chen, G. (2004). Electrochemical technologies in wastewater treatment. Separation and Purification Technology, 38(1), 11–41. https://doi.org/10.1016/j.seppur.2003.10.006
27. Tran, T. K., Chiu, K. F., Lin, C. Y., & Leu, H. J. (2017). Electrochemical treatment of wastewater: Selectivity of the heavy metals removal process. International Journal of hydrogen energy, 42(45), 27741-27748.
28. Tiwari, S., & Bijwe, J. (2014). Surface treatment of carbon fibers – A review. Procedia Technology, 14, 505–512. https://doi.org/10.1016/j.protcy.2014.08.064
29. Hua, M., Zhang, S., Pan, B., Zhang, W., Lv, L., & Zhang, Q. (2012). Heavy metal removal from water/wastewater by nanosized metal oxides: a review. Journal of hazardous materials, 211, 317-331.

30. Kumar, R., & Chawla, J. (2014). Removal of cadmium ion from water/wastewater by nano-metal oxides: a review. Water Quality, Exposure and Health, 5, 215-226.
31. Rajput, S., Pittman Jr, C. U., & Mohan, D. (2016). Magnetic magnetite (Fe3O4) nanoparticle synthesis and applications for lead (Pb2+) and chromium (Cr6+) removal from water. Journal of colloid and interface science, 468, 334-346.
32. Dai, H. (2002). Carbon nanotubes: opportunities and challenges. Surface science, 500(1-3), 218-241.
33. Tang, W. W., Zeng, G. M., Gong, J. L., Liu, Y., Wang, X. Y., Liu, Y. Y., … & Tu, D. Z. (2012). Simultaneous adsorption of atrazine and Cu (II) from wastewater by magnetic multi-walled carbon nanotube. Chemical Engineering Journal, 211, 470-478.
34. Ihsanullah, Abbas, A. M., Al-Amer, A. T., Laoui, T., Al-Marri, M. S., Nasser, M. S., Khraisheh, M., & Atieh, M. A. (2016). Heavy metal removal from aqueous solution by advanced carbon nanotubes: Critical review of adsorption applications. Separation and Purification Technology, 157, 141–161. https://doi.org/10.1016/j.seppur.2015.11.039
35. Das, R. (2017). Carbon nanotube in water treatment. In Nanohybrid catalyst based on carbon nanotube: A step-by-step guideline from preparation to demonstration (pp. 23–54). Springer International Publishing. https://doi.org/10.1007/978-3-319-58151-4_2
36. Zhao, M., Xu, Y., Zhang, C., Rong, H., & Zeng, G. (2016). New trends in removing heavy metals from wastewater. Applied Microbiology and Biotechnology, 100(15), 6509–6518. https://doi.org/10.1007/s00253-016-7646-x
37. Camargo, F. P., Sérgio Tonello, P., dos Santos, A. C. A., & Duarte, I. C. S. (2016). Removal of toxic metals from sewage sludge through chemical, physical, and biological treatments—a review. Water, Air, & Soil Pollution, 227, 1-11.
38. Fang, D., & Zhou, L. X. (2007). Enhanced Cr bioleaching efficiency from tannery sludge with co-inoculation of *Acidithiobacillus thiooxidans* TS6 and Brettanomyces B65 in an air-lift reactor. Chemosphere, 69(2), 303–310. https://doi.org/10.1016/j.chemosphere.2007.02.022
39. Pathak, A., Dastidar, M. G., & Sreekrishnan, T. R. (2009). Bioleaching of heavy metals from sewage: A review. Journal of Environmental Management, 90(8), 2343–2353. https://doi.org/10.1016/j.jenvman.2009.01.007
40. Mishra, D., & Rhee, Y. H. (2014). Microbial leaching of metals from solid industrial wastes. Journal of Microbiology, 52(1), 1–7. https://doi.org/10.1007/s12275-014-3439-2
41. Yan, A., Wang, Y., Tan, S. N., Yusof, M. L. M., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. Frontiers in Plant Science, 11, Article 570. https://doi.org/10.3389/fpls.2020.00570
42. Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—Concepts and applications. Chemosphere, 91(7), 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075
43. Luo, Y., Wu, Y., Qiu, J., Wang, H., & Yang, L. (2019). Suitability of four woody plant species for the phytostabilization of a zinc smelting slag site after 5 years of assisted revegetation. Journal of Soils and Sediments, 19(2), 702–715. https://doi.org/10.1007/s11368-018-2087-x
44. Saran, A., Fernandez, L., Cora, F., Savio, M., Thijs, S., Vangronsveld, J., & Merini, L. J. (2020). Phytostabilization of Pb and Cd polluted soils using Helianthus petiolaris as pioneer aromatic plant species. International Journal of Phytoremediation, 22(5), 459–467. https://doi.org/10.1080/15226514.2019.1671245
45. Tangahu, B. V., Sheikh Abdullah, S. R., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. International Journal of Chemical Engineering, 2011, Article 939161. https://doi.org/10.1155/2011/939161
46. Bhat, S. A., Bashir, O., Haq, S. A. U., Amin, T., Rafiq, A., Ali, M., & Sher, F. (2022). Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. Chemosphere, 303, 134788.
47. Yan, A., Wang, Y., Tan, S. N., Yusof, M. L. M., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. Frontiers in Plant Science, 11, Article 359. https://doi.org/10.3389/fpls.2020.00359
48. Benavides, L. C. L., Pinilla, L. A. C., Serrezuela, R. R., & Serrezuela, W. F. R. (2018). Extraction in laboratory of heavy metals through rhizofiltration using the plant Zea mays (maize). International Journal of Applied Environmental Sciences, 13(1), 9–26.
49. Odinga, C. A., Kumar, A., Mthembu, M. S., Bux, F., & Swalaha, F. M. (2019). Rhizofiltration system consisting of Phragmites australis and Kyllinga nemoralis: Evaluation of efficient removal of metals and pathogenic microorganisms. Desalination and Water Treatment, 169, 120–132. https://doi.org/10.5004/dwt.2019.24385
50. Ren, W. X., Li, P. J., He, N., Fan, S. X., & Verkhozina, E. V. (2007). Application of heterotrophic microorganisms in metals removal by bioleaching. Chinese Journal of Ecology, 26, 1835–1841.
51. Yaseen, Z. M. (2021). An insight into machine learning models era in simulating soil, water bodies and adsorption of heavy metals: Review, challenges and solutions. *Chemosphere, 277*, Article 130126. https://doi.org/10.1016/j.chemosphere.2021.130126
52. Zhu, X., Wan, Z., Tsang, D. C., He, M., Hou, D., Su, Z., & Shang, J. (2021). Machine learning for the selection of carbon-based materials for tetracycline and sulfamethoxazole adsorption. Chemical Engineering Journal, 406, Article 126782. https://doi.org/10.1016/j.cej.2020.126782
53. Hu, X., Alsaikhan, F., Majdi, H. S., Bokov, D. O., Mohamed, A., & Sadeghi, A. (2022). Predictive modeling and computational machine learning simulation of adsorption separation using advanced nanocomposite materials. Arabian Journal of Chemistry, 15(9), Article 104062. https://doi.org/10.1016/j.arabjc.2022.104062