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Review

Sources and toxicological effects of some heavy metals—A mini review

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Abstract: Heavy metals play essential roles in biological activities as enzyme cofactors in trace amounts. However, their significance is overshadowed by potential harm in excess. Bio-accumulation, toxicity, non-biodegradability, and persistence are hallmarks that impact the environment and human health. Bio-accumulation is critical as metals accumulate in organisms, posing risks in ecosystems, especially in the food chain. This leads to elevated metal concentrations in the human food chain. Even at trace levels, heavy metals like lead, mercury, cadmium, chromium, and arsenic exhibit toxicity, causing various health issues, emphasizing the need to regulate exposure. Non-biodegradability distinguishes heavy metals; they persist in the environment, enhancing the risks associated with prolonged exposure and accumulation. Due to their recognized toxicity, heavy metals are a focus of research. Understanding sources, pathways, and effects is crucial for effective mitigation strategies. Researchers explore pollution control, improved industrial practices, and remediation techniques. Anthropogenic activities, such as industrialization, urbanization, waste disposal, and agricultural practices, release heavy metals into the environment. This contaminates air, water, and soil, contributing to environmental and health risks. The present paper discusses the sources and toxicological effects of various heavy metals.

Keywords: heavy metals; sources; toxicology; pollution; environment; biosorption

1. Introduction

The widespread existence of heavy metals in the environment presents a significant risk to human health and ecosystems; hence, efforts must be made to address and reduce their effects. Heavy metals such as mercury (Hg), chromium (Cr), lead (Pb), zinc (Zn), arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), and nickel (Ni) play essential roles in various biological functions; their excessive accumulation can lead to severe hazards [1]. Heavy metals are necessary for living things to carry out a variety of biological functions, but larger amounts of these elements can be hazardous. Toxic metals (like Hg, Cr, Pb, Zn, Cu, Ni, Cd, As, Co, Sn, etc.), precious metals (like Pd, Pt, Ag, Au, Ru, etc.), and radionuclides (like U, Th, Ra, Am, etc.) are the three main categories of heavy metals [2,3]. Among the group of metals that are classified as toxic, heavy metals such as Pb, Cr, Hg, Zn, As, Cd, Co, Cu, and Ni are released into the environment in unfavorable amounts that are harmful to human health [4]. Through the food chain, humans and other living things may come into contact with heavy metals, which can become extremely toxic when they combine with other environmental variables like water, soil, and air [5]. Heavy metals are toxic, bioaccumulate, and do not biodegrade, which makes their presence in the environment a major cause for concern. These characteristics provide heavy metals with detrimental effects on the environment and human health. The metal ions are generally soluble in an aqueous medium and do not biodegrade [6]. Toxic metals, therefore, quickly accelerate and build up in the human food chain. The detrimental impact of heavy metals is not confined to environmental degradation alone; it extends to human well-being. Exposure to toxic metals through contaminated food, water, or air can result in a range of health issues, including toxicity and carcinogenicity. The significance of this issue is further magnified by the rapid release of metal-containing wastes into the environment, both directly and indirectly, during various industrial processes. This unchecked release poses a direct threat to ecosystems, contributing significantly to pollution. The detrimental effects of heavy metals are exacerbated when they interact with other environmental factors [7]. Consequently, the urgent need to address this issue arises from the fact that heavy metals, being non-biodegradable and poisonous, have the potential to cause long-lasting and far-reaching consequences [8]. Many researchers have focused their attention on heavy metals because of their toxicity and carcinogenicity [9]. Rapid urbanization, industrialization, and human activity release heavy metals into the environment [10,11]. Metal-containing wastes are either directly or indirectly released into the environment, endangering ecosystems and causing major pollution [12,13]. Therefore, before releasing the solid or watery waste into the environment, these metals must be removed or sequestered.

To safeguard the environment and human health, it becomes imperative to understand the origins and toxicological consequences of these heavy metals. Moreover, strategies for the effective removal or sequestration of these metals from solid or liquid waste before their release into the environment are crucial. This study delves into the multifaceted challenges posed by heavy metals, shedding light on their origins, the toxicological implications of several significant heavy metals present in the environment, and the pressing need for proactive measures to curb their environmental impact.

2. Sources and toxicological effects of heavy metals

Heavy metals, including lead, mercury, and cadmium, are pervasive environmental contaminants with diverse sources, such as industrial discharges and agricultural runoff. Their toxicological effects pose serious health risks, affecting vital organs and causing long-term harm. Understanding and mitigating heavy metal exposure are crucial for safeguarding public health and environmental well-being. The sources and effects of some heavy metals of important heavy metals are presented in **Table 1**.

Table 1. Sources and effects of some heavy metals.

Heavy metals	Sources	Effects	Reference
Arsenic (As)	Industrial effluents, fossil fuel, pesticides, fungicides, paint, dyes textiles industries	Hemolysis, hepatomegaly, pneumonia, and dermatitis are disorders of the nervous system	[14]
Cadmium (Cd)	Nuclear fission reactor, welding, electroplating, fertilizers, insecticides, Cd-Noorul Islam Centre for Higher Education batteries	Renal damage, pneumonia, cancer, gastrointestinal issues, and bone marrow	[15]
Chromium (Cr)	Rubber, textile, tannery, metallurgical, and photographic industries	Quick hair loss and breathing issues	[16]
Cobalt (Co)	Dyes, mining, decomposition of organic matter and minerals	Wilson's illness toxicity to development, reproduction, and nervous system	[17]
Copper (Cu)	Pesticides, mining, electronics trash, electroplating	Failure of the Kidney and Brain Intense anemia and gastrointestinal discomfort	[18]

Table 1. (*Continued*).

Heavy metals	Sources	Effects	Reference
Iron (Fe)	Engineering industries	Anemia	[19]
Lead (Pb)	Vehicle emissions, wastewater, paint, pesticides, mining, and coal burning	Kidney, liver, digestive system damage, and childhood mental impairment	[20]
Mercury (Hg)	Chemical industries, insecticides, batteries, paper industry, contaminated water, scientific instruments	Damage to nervous system	[21]
Nickel (Ni)	Fertilizers, iron-steel, battery, zinc base casting, and electroplating industries	Cancers of the lungs, throat, and stomach; immunotoxin; neurotoxic; genotoxic; hepatotoxic; rapid hair loss	[22]
Zinc (Zn)	Refineries, the production of brass, metal plating, painted idol immersion, and galvanization	Zinc fumes harm nerve membranes and have a corrosive effect on skin	[23]

2.1. Arsenic

Anionic species of arsenate (V) (H_2AsO_4-) at pH 2–6 and arsenite (III) (H_2AsO_3-) at pH 9–12, which exist as oxoanions, are the most prevalent arsenic species found in water bodies. These have varying effects on the biological system [24]. Arsenic pollution can be from man-made and natural sources. Large-scale groundwater and hot spring water contamination with arsenic has been reported in West Bengal, India, as well as in a number of minerals and chemical processes [25,26]. According to WHO estimates, arsenic poisoning alone affects roughly 70 million people in these regions [27].

Naturally occurring processes such as weathering, fire, volcanic eruptions, mineral ores, long-term geochemical changes, etc. lead to the distribution of arsenic. Also, from a variety of industrial effluents, such as those from the metallurgical, ceramic, and smelting sectors; energy generation from fossil fuels; rock sediments; dye; and industries that manufacture fungicides and pesticides, among others. According to Balakumar and Kaur [28], arsenic poisoning can result in bronchitis, cardiovascular failure, gastrointestinal symptoms, abnormalities of the neurological system, bone marrow depression, hemolysis, hepatomegaly, melanosis, polyneuropathy, encephalopathy, and liver tumors. The highest amount of arsenic contamination was 0.050 mg/L [29].

2.2. Cadmium

Natural ore deposits contain cadmium as well as zinc, lead, and copper in common. The main sources of cadmium are released from nickel-cadmium batteries, electroplating, mining, and metallurgy industries. Waste streams from nuclear power plants also contain undesirable levels of $Cd2^{+}$ ions [30–32]. Other ways to come into contact with cadmium include welding, usage of pesticides and fertilizers, smoking cigarettes, and operating smelters. For example, wheat and rice from Cd-polluted districts of Japan have Cd levels of approximately 1 mg/kg, which is ten times higher than global averages [33]. The maximum amount of lead that the EPA allowed in drinking water was 0.005 mg/L. The WHO determined that a man's daily acceptable consumption of lead was 0.06 mg, while a woman was 0.07 mg.

Cadmium has toxic influence mainly on the respiratory system, bones, and kidneys. It can cause fatal renal failure, osteoporosis, osteomalacia, lung diseases, bone lesions, gastrointestinal disorders, bronchitis, and cancer. The characteristic symptoms of acute Cd poisoning in many patients include the loss of the sense of smell, weight loss, hypertension, pulmonary edema, headache, nausea, vomiting, and diarrhea [34,35]. Long-term exposure to Cd leads to kidney problems and affects the human bones, resulting in Itai Itai disease [36]. Heavy metals like Cd affect mineral assimilation and physiological and biochemical characteristics of plants; they also retard plant growth [37,38].

2.3. Chromium

One of the most dangerous heavy metals that is frequently discovered in industrial effluent is chromium. The two primary chromium oxidation states found in water are trivalent chromium (Cr (III)) and hexavalent chromium (Cr (VI)). The most poisonous element is thought to be Cr (VI), which is typically found in oxygen as chromate or dichromate ions. Because of its mutagenic and carcinogenic qualities, the hexavalent form of chromium is regarded as a group “A” human carcinogen [39].

Exposure to chromium occurs when human skin comes into contact with chromium or its compounds, as well as when breathing, ingesting, or drinking chromium. Food components that contain chromium (III) are the primary source of chromium absorption because many fruits, vegetables, meats, cereals, yeasts, and vegetables naturally contain chromium (III). The production of dyes, paints, and pigments, film and photography, wood preservatives, galvanometry, steel fabrication, canning, textile dyeing, leather tanning, electroplating, metal cleaning, and finishing industries are among the industries that frequently release Cr (VI) into water bodies through wastewater [40]. Approximately 100 mg/L of Cr (VI) is present in the electroplating industry’s untreated effluent; nevertheless, De Filippis and Pallaghy [41] reported that 0.05 to 1 mg/L was the allowable limit. The element chromium is extremely toxic and carcinogenic. Chromium (VI) inhalation might result in nosebleeds and irritations. Trace levels of chromium exposure can result in genetic material changes that can lead to lung tumors and cancer, as well as allergic dermatitis, nausea, vomiting, severe diarrhea, respiratory issues, compromised immune systems, damage to the kidneys and liver, and altered kidney and liver function [42–44].

2.4. Cobalt

Cobalt is a component of vitamin B12, or cobalamin, which is vital to human health. However, cobalt may have a greater impact on human health. Cobalt is a metal that is frequently utilized in radioisotope therapy, turbines, alloys, electronics, and porcelain [45]. Plants that are produced in polluted soil or that receive greater irrigation levels of cobalt acquire the metal, which then finds its way into the food chain that feeds humans. Increased cobalt consumption may result in anemia, cardiac problems, vomiting, nausea, thyroid damage, and visual problems [46].

High copper intake causes severe mucosal irritation, neurotoxicity, toxicity to reproduction and development, upset stomach and ulcer, hepatic irritation, irritation of the central nervous system, followed by depression, gastrointestinal irritation, and potentially necrotic changes in the liver and kidneys [47]. Wilson’s disease, which damages the liver and brain, can also be brought on by persistent copper poisoning [48]. It has been reported to accumulate in the liver, pancreas, brain, skin, and myocardium [49,50].

2.5. Iron

There are two forms of iron: ferrous iron (Fe^{2+}), which is soluble, and ferric particulate iron (Fe^{3+}), which is insoluble. Iron is typically found in water in its ferric condition. The disintegration of rocks and minerals, acid mine drainage, landfill leachate sewage, or the engineering industries may be the cause of iron in natural water. When iron concentrations surpass 0.1 mg/L, fish gills will also be harmed. The free radicals have a brief lifespan and are very reactive. The iron on the gill surface produces free radicals that oxidize the surrounding tissue, severely damaging the gill tissue and resulting in anemia [19].

2.6. Lead

Lead is found in nature in three different oxidation states: Pb (0), Pb (II), and Pb (IV). Lead is found in mineral formations. Of them, lead (II) is the most prevalent and readily bioaccumulates via the food chain. It is frequently linked to other heavy metals like zinc, copper, mercury, and zinc. Pb comes from a variety of sources, such as vehicular emissions from vehicles, mining, burning coal and plastics, battery manufacturing industry effluents, gasoline additives, fertilizer, pesticides, paint, pigments, alloys, and sheets, among others. Pb in drinking water was allowed to be as low as 0.015 mg/L [51].

Lead exposure has a lot of negative health impacts, including reduced fertility, cardiovascular disorders, impaired renal function, and neurodevelopmental abnormalities [52]. Kidney illnesses as well as problems with the brain system and circulatory system are the main signs of lead poisoning. This causes anemia, brain damage, anorexia, malaise, loss of appetite, delirium, sleeplessness, convulsions, seizures, gastrointestinal damage, and mental retardation in children [53]. Although lead can be absorbed through the skin, the digestive and respiratory systems absorb the majority of it. Pb exposure can cause oxidative, inflammatory, and immune-modulating illnesses, as well as respiratory, urinary, and cardiovascular problems. Additionally, Pb poisoning has been connected to delayed physical or mental development as well as a lower intelligence quotient (IQ), particularly in children with attention spans and learning deficiencies. According to Jarup [30], further symptoms include encephalopathy, kidney failure, headaches, and stomach pain.

2.7. Mercury

The primary cause of pollution is the process of producing mercury. Mercury was commonly used as a softening agent for various materials. One of the most hazardous elements in the environment and the strongest neurotoxins is mercury. Industries such as paints, paper and pulp, oil refining, volcanic eruptions, spontaneous forest fires, biogenic emissions, burning fossil fuels, mining, metallurgical processes, pharmaceutical and battery manufacturing, rubber processing, thermometers, fluorescent light tubes and high-intensity streetlamps, fertilizer, pesticides, and cosmetics are the main sources of mercury pollution in the environment [54]. Mercury gradually builds up in people and other animals once it enters the food chain. Mercury even has fumes that are easily absorbed by mucous membranes, the skin, and the respiratory system. They can also harm the kidneys, neurological system, circulatory system, and endocrine system. The tongue, teeth, and gums are also impacted due to the organism's invasion route. According to Boening [55], Manohar et al. [56], and Morel et al. [57], mercury can induce dermatitis, rheumatoid arthritis, deterioration of the skin, eyes, and muscles, dyspnea, pulmonary function impairment, and neurological and renal abnormalities. Prolonged exposure to mercury fumes damages the brain severely and can even be fatal [58,59]. Additionally, genetic abnormalities brought on by Mercury can result in chromosome splitting and disruption during cell division, which can lead to an aberrant distribution of chromosomes. Mercury contamination can reach a maximum of 0.00003 mg/L [29].

2.8. Nickel

As a necessary heavy metal, nickel takes part in a number of metabolic processes, including acidogenisis and ureolysis. According to Akhtar et al. [60] and Farooq et al. [61], the primary sources of Ni (II) released into the environment are industrial discharges from electroplating units, magnets, steel alloys, silver refineries, aircraft industries, coinage, zinc base casting, battery manufacturing plants, paint formulation, porcelain enameling, mining and metallurgy, copper sulphate manufacture, and steam-electric power plants.

The maximum allowable concentration of Ni^{2+} in drinking water, as recommended by the WHO, is 0.07 mg/L. Large-scale nickel consumption has a negative impact on human health, causing birth deformities, a variety of allergic reactions, heart problems, bronchial bleeding, nausea, lethargy, and dizziness. Prolonged exposure to nickel can also cause pulmonary fibrosis, gastrointestinal distress, skin dermatitis, lung and prostate malignancies, neurotoxicity, nephrotoxicity, immunotoxicity, and reproductive toxicity [62]. The most common consequence of nickel exposure, such as coins and jewelry, is dermatitis, which manifests as itching, red skin, and rashes [63].

2.9. Zinc

Zinc is a micronutrient that is vital to bioorganisms. Zinc (II) is the most prevalent oxidation state of zinc found in nature. The production of bronze, zinc-based alloys, stabilizers, thermoplastics, pigment formation, battery manufacturing, municipal wastewater treatment facilities, and galvanization—the process of applying anti-corrosion coatings to steel—are among the main causes of zinc pollution in wastewater. The production of rubber, paints, wood preservatives, dry cell batteries, ointments, glass, ceramics, and coatings for other metals, including steel and iron, are further sources. Zn is also frequently employed as an addition in the paint, plastic, pharmaceutical, and cosmetics sectors. Metal plating, home wastewater, manufacturing of metal, and atmospheric precipitation are the main sources of zinc pollution in water. For men and women, respectively, the Recommended Dietary Allowance (RDA) for zinc is 11 mg/day and 8 mg/day. Zn has the highest permissible level among other heavy metals, 5 mg/L, determined by the EPA as the maximum limit in drinking water. Zinc pollution exposure can result in corrosive effects on skin, damage to nerve membranes, nausea, vomiting, and cramping in the stomach [64].

2.10. Heavy metal removal

Heavy metals were extracted from wastewater and effluents using a variety of techniques. Chemical precipitation, oxidation-reduction [65], filtration, lime coagulation, ionic exchange [65], electrochemical treatment [66], membrane techniques, solvent extraction, adsorption on activated carbon, evaporation, etc. are some of the techniques used to remove the metal ions from an aqueous solution [67]. However, these methods are costly and lead to a partial removal of metal. However, these methods are costly and leave behind some metal [68].

Because of its crucial use, using the biological pathway to control, sequester, and remove metal pollution has received a lot of attention in recent years and is steadily becoming a hot topic in the field of metal pollution control. One such technique is biosorption, which removes hazardous heavy metals from wastewater or effluents by using a variety of naturally occurring materials with a biological origin [69,70]. Low operating costs, environmental friendliness, ease of use, high metal removal efficiency from diluted solutions, minimal chemical and/or biological sludge, no additional nutrient requirements, biosorbent regeneration, and the potential for metal recovery are the main benefits of biosorption over conventional treatment methods [16]. In place of more traditional techniques, biosorption for the removal of heavy metal ions may offer an alluring option [71].

3. Conclusion

Due to rapid industrialization and technological advancements, heavy metals are released into the environment from a variety of sources, endangering both human health and the environment. The study covered the origins, effects, and implications of a few heavy metals. We are currently dealing with a major problem with heavy metal contamination, which can be eliminated by employing organic material. Because of its availability, ability to complete the reaction process, and biodegradability, the technique—known as biosorption—is shown to be effective.

Conflict of interest: The author declares no conflict of interest.

References

1. Jacob JM, Karthik C, Saratale RG, et al. Biological approaches to tackle heavy metal pollution: A survey of literature. Journal of Environmental Management. 2018; 217: 56-70. doi: 10.1016/j.jenvman.2018.03.077
2. Bishop PL. Pollution prevention: Fundamentals and practice. Tsinghua University Press; 2002.
3. Wang J, Chen C. Biosorption of heavy metals by Saccharomyces cerevisiae: A review. Biotechnology Advances. 2006; 24(5): 427-451. doi: 10.1016/j.biotechadv.2006.03.001
4. Kortenkamp A, Casadevall M, Faux SP, et al. A Role for Molecular Oxygen in the Formation of DNA Damage during the Reduction of the Carcinogen Chromium(VI) by Glutathione. Archives of Biochemistry and Biophysics. 1996; 329(2): 199-207. doi: 10.1006/abbi.1996.0209
5. Mitra S, Chakraborty AJ, Tareq AM, et al. Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. Journal of King Saud University - Science. 2022; 34(3): 101865. doi: 10.1016/j.jksus.2022.101865
6. Fred AO. A 50-year review on heavy metal pollution in the environment: Bivalves as bio-monitors. African Journal of Environmental Science and Technology. 2019; 13(6): 220-227. doi: 10.5897/ajest2018.2597
7. Kumar R, Verma A, Shome A, et al. Impacts of Plastic Pollution on Ecosystem Services, Sustainable Development Goals, and Need to Focus on Circular Economy and Policy Interventions. Sustainability. 2021; 13(17): 9963. doi:

10.3390/su13179963
8. Briffa J, Sinagra E, Blundell R. Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon. 2020; 6(9): e04691. doi: 10.1016/j.heliyon.2020.e04691
9. MacCarthy P, Klusman RW, Cowling SW, et al. Water Analysis. Analytical Chemistry. 1995; 67(12): 525-582. doi: 10.1021/ac00108a039
10. Nriagu JO. Global inventory of natural and anthropogenic emissions of trace metals to the atmosphere. Nature. 1979; 279(5712): 409-411. doi: 10.1038/279409a0
11. Sarker A, Masud MAA, Deepo DM, et al. Biological and green remediation of heavy metal contaminated water and soils: A state-of-the-art review. Chemosphere. 2023; 332: 138861. doi: 10.1016/j.chemosphere.2023.138861
12. Volesky B. Removal and recovery of heavy metals by biosorption. Biosorption of heavy metals. CRC Press. 1990. pp. 7-44.
13. Ahalya N, Kanamadi RD, Ramachandra TV. Biosorption of chromium (VI) from aqueous solutions by the husk of Bengal gram (Cicer arientinum). Electronic Journal of Biotechnology. 2005; 8(3): 258-264. doi: 10.2225/vol8-issue3-fulltext-10
14. Balali-Mood M, Naseri K, Tahergorabi Z, et al. Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic. Frontiers in Pharmacology. 2021; 12. doi: 10.3389/fphar.2021.643972
15. Tamele IJ, Vázquez Loureiro P. Lead, Mercury and Cadmium in Fish and Shellfish from the Indian Ocean and Red Sea (African Countries): Public Health Challenges. Journal of Marine Science and Engineering. 2020; 8(5): 344. doi: 10.3390/jmse8050344
16. Kim EJ, Park S, Hong HJ, et al. Biosorption of chromium (Cr(III)/Cr(VI)) on the residual microalga Nannochloris oculata after lipid extraction for biodiesel production. Bioresource Technology. 2011; 102(24): 11155-11160. doi: 10.1016/j.biortech.2011.09.107
17. Fosu-Mensah BY, Addae E, Yirenya-Tawiah D, et al. Heavy metals concentration and distribution in soils and vegetation at Korle Lagoon area in Accra, Ghana. Cogent Environmental Science. 2017; 3(1): 1405887. doi: 10.1080/23311843.2017.1405887
18. Chileshe MN, Syampungani S, Festin ES, et al. Physico-chemical characteristics and heavy metal concentrations of copper mine wastes in Zambia: implications for pollution risk and restoration. Journal of Forestry Research. 2019; 31(4): 1283-1293. doi: 10.1007/s11676-019-00921-0
19. Yang Q, Li Z, Lu X, et al. A review of soil heavy metal pollution from industrial and agricultural regions in China: Pollution and risk assessment. Science of The Total Environment. 2018; 642: 690-700. doi: 10.1016/j.scitotenv.2018.06.068
20. Matta G, Gjyli L. Mercury, lead and arsenic: Impact on environment and human health. Journal of Chemical and Pharmaceutical Sciences. 2016; 9: 718-725.
21. Rahman Z, Singh VP. The relative impact of toxic heavy metals (THMs) (arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. Environmental Monitoring and Assessment. 2019; 191(7). doi: 10.1007/s10661-019-7528-7
22. Blewett TA, Leonard EM. Mechanisms of nickel toxicity to fish and invertebrates in marine and estuarine waters. Environmental Pollution. 2017; 223: 311-322. doi: 10.1016/j.envpol.2017.01.028
23. Li C, Zhou K, Qin W, et al. A Review on Heavy Metals Contamination in Soil: Effects, Sources, and Remediation Techniques. Soil and Sediment Contamination: An International Journal. 2019; 28(4): 380-394. doi: 10.1080/15320383.2019.1592108
24. Zhao FJ, Ma JF, Meharg AA, et al. Arsenic uptake and metabolism in plants. New Phytologist. 2008; 181(4): 777-794. doi: 10.1111/j.1469-8137.2008.02716.x
25. Raab A, Ferreira K, Meharg AA, et al. Can arsenic-phytochelatin complex formation be used as an indicator for toxicity in Helianthus annuus? Journal of Experimental Botany. 2007; 58(6): 1333-1338. doi: 10.1093/jxb/erl300Ajmal M, Hussain Khan AH, Ahmad S, Ahmad A. Role of sawdust in the removal of copper (II) from industrial wastes. Water Research. 1998; 32(10): 3085-3091. doi: 10.1016/S0043-1354(98)00067-0
26. Xu XY, McGrath SP, Zhao FJ. Rapid reduction of arsenate in the medium mediated by plant roots. New Phytologist. 2007; 176(3): 590-599. doi: 10.1111/j.1469-8137.2007.02195.x
27. WHO. World Health Organization—Guidelines for Drinking water Quality, 4th ed. WHO; 2011. pp. 327-397
28. Balakumar P, Kaur J. Arsenic Exposure and Cardiovascular Disorders: An Overview. Cardiovascular Toxicology. 2009; 9(4): 169-176. doi: 10.1007/s12012-009-9050-6
29. Babel S, Kurniawan TA. Low-cost adsorbents for heavy metals uptake from contaminated water: A review. Journal of

Hazardous Materials. 2003; 97(1-3): 219-243. doi: 10.1016/s0304-3894(02)00263-7
30. Jarup L. Health effects of cadmium exposure - A review of the literature and a risk estimate. Scandinavian Journal of Work, Environment and Health. 1998; 24(Suppl) 1: 11-51.
31. Volesky B. Detoxification of metal-bearing effluents: Biosorption for the next century. Hydrometallurgy. 2001; 59(2-3): 203-216. doi: 10.1016/S0304-386X(00)00160-2
32. Zouboulis AI, Loukidou MX, Matis KA. Biosorption of toxic metals from aqueous solutions by bacteria strains isolated from metalpolluted soils. Process Biochemistry. 2004; 39(8): 909-916. doi: 10.1016/S0032-9592(03)00200-0
33. Volesky B, Naja G. Biosorption: Application strategies. In: Proceedings of the 16th International Biohydrometallurgy Symposium; 25-29 September 2005; Cape Town, South Africa. pp. 531-542
34. Chen JM, Hao OJ. Microbial Chromium (VI) Reduction. Critical Reviews in Environmental Science and Technology. 1998; 28(3): 219-251. doi: 10.1080/10643389891254214
35. Low KS, Lee CK, Liew SC. Soprtion of cadmium and lead from aqueous solutions by spent grain. Process Biochemistry. 2000; 36(1-2): 59-64. doi: 10.1016/S0032-9592(00)00177-1
36. Singh KK, Singh AK, Hasan SH. Low cost bio-sorbent "wheat bran" for the removal of cadmium from wastewater: Kinetic and equilibrium studies. Bioresource Technology. 2006; 97(8): 994-1001. doi: 10.1016/j.biortech.2005.04.043
37. Pinto A, Mota A, Devarennes A, et al. Influence of organic matter on the uptake of cadmium, zinc, copper and iron by sorghum plants. Science of The Total Environment. 2004; 326(1-3): 239-247. doi: 10.1016/j.scitotenv.2004.01.004
38. Rai V, Khatoon S, Bisht SS, Mehrotra S. Effect of cadmium on growth, ultramorphology of leaf and secondary metabolites of Phyllanthus amarus Schum and Thonn. Chemosphere. 2005; 61(11): 1644-1650. doi: 10.1016/j.chemosphere.2005.04.052
39. Cieslak-Golonka M. Toxic and mutagenic effects of chromium (VI). Polyhedron. 1995; 15(21): 3667-3689.
40. Vinodhini V, Das N. Relevant approach to assess the performance of sawdust as adsorbent of chromium (VI) ions from aqueous solutions. International Journal of Environmental Science & Technology. 2009; 7(1): 85-92. doi: 10.1007/bf03326120
41. De Filippis LF, Pallaghy CK. Heavy metals: Sources and biological effects. In: Rai LC, Gaur JP, Soeder CJ (editors). Advances in Limnology Series, Algae and Water Pollution. E. Scheizerbartsche Press; 1994. pp. 31-77.
42. Dupont L, Guillon E. Removal of Hexavalent Chromium with a Lignocellulosic Substrate Extracted from Wheat Bran. Environmental Science & Technology. 2003; 37(18): 4235-4241. doi: 10.1021/es0342345
43. Eastmond DA, MacGregor JT, Slesinski RS. Trivalent Chromium: Assessing the Genotoxic Risk of an Essential Trace Element and Widely Used Human and Animal Nutritional Supplement. Critical Reviews in Toxicology. 2008; 38(3): 173-190. doi: 10.1080/10408440701845401
44. Singh KK, Hasan SH, Talat M, et al. Removal of Cr (VI) from aqueous solutions using wheat bran. Chemical Engineering Journal. 2009; 151(1-3): 113-121. doi: 10.1016/j.cej.2009.02.003
45. Guo W, Chen R, Liu Y, et al. Preparation of ion-imprinted mesoporous silica SBA-15 functionalized with triglycine for selective adsorption of Co(II). Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2013; 436: 693-703. doi: 10.1016/j.colsurfa.2013.08.011
46. Friberg L. Handbook on the Toxicology of Metals. Elsevier Science Publishers; 1986.
47. Yao ZY, Qi JH, Wang LH. Equilibrium, kinetic and thermodynamic studies on the biosorption of Cu(II) onto chestnut shell. Journal of Hazardous Materials. 2010; 174(1-3): 137-143. doi: 10.1016/j.jhazmat.2009.09.027
48. Jaman H, Chakraborty D, Saha P. A Study of the Thermodynamics and Kinetics of Copper Adsorption Using Chemically Modified Rice Husk. CLEAN - Soil, Air, Water. 2009; 37(9): 704-711. doi: 10.1002/clen.200900138
49. Davis TA, Volesky B, Vieira RHSF. Sargassum seaweed as biosorbent for heavy metals. Water Research. 2000; 34(17): 4270-4278. doi: 10.1016/S0043-1354(00)00177-9
50. Papandreou A, Stournaras CJ, Panias D. Copper and cadmium adsorption on pellets made from fired coal fly ash. Journal of Hazardous Materials. 2007; 148(3): 538-547. doi: 10.1016/j.jhazmat.2007.03.020
51. Tunali Akar S, Arslan S, Alp T, et al. Biosorption potential of the waste biomaterial obtained from Cucumis melo for the removal of Pb^{2+} ions from aqueous media: Equilibrium, kinetic, thermodynamic and mechanism analysis. Chemical Engineering Journal. 2012; 185-186: 82-90. doi: 10.1016/j.cej.2012.01.032
52. World Health Organization. Available online: http://www.who.int/mediacentre/factsheets/Fs210/en (accessed on 1 June 2023).
53. Gaballah I, Kilbertus G. Recovery of heavy metal ions through decontamination of synthetic solutions and industrial

effluents using modified barks. Journal of Geochemical Exploration. 1998; 62(1-3): 241-286. doi: 10.1016/S0375-6742(97)00068-X

54. El-Shafey EI. Removal of Zn(II) and Hg(II) from aqueous solution on a carbonaceous sorbent chemically prepared from rice husk. Journal of Hazardous Materials. 2010; 175(1-3): 319-327. doi: 10.1016/j.jhazmat.2009.10.006Alomá I, Martín-Lara MA, Rodríguez IL, et al. Removal of nickel (II) ions from aqueous solutions by biosorption on sugarcane bagasse. Journal of the Taiwan Institute of Chemical Engineers. 2012; 43(2): 275-281. doi: 10.1016/j.jtice.2011.10.011
55. Boening DW. Ecological effects, transport, and fate of mercury: A general review. Chemosphere. 2000; 40(12): 1335-1351. doi: 10.1016/s0045-6535(99)00283-0
56. Manohar DM, Krishnan KA, Anirudhan TS. Removal of mercury (II). Water Research. 2002; 36(6): 1609-1619. doi: 10.1016/s0043-1354(01)00362-1
57. Morel FMM, Kraepiel AML, Amyot M. THE CHEMICAL CYCLE AND BIOACCUMULATION OF MERCURY. Annual Review of Ecology and Systematics. 1998; 29(1): 543-566. doi: 10.1146/annurev.ecolsys.29.1.543
58. Risher JF, Amler SN. Mercury exposure: Evaluation and intervention the inappropriate use of chelating agents in the diagnosis and treatment of putative mercury poisoning. Neurotoxicology. 2005; 26(4): 691-699. doi: 10.1016/j.neuro.2005.05.004
59. Clifton JC. Mercury Exposure and Public Health. Pediatric Clinics of North America. 2007; 54(2): 237.e1-237.e45. doi: 10.1016/j.pcl.2007.02.005
60. Akhtar N. Removal and recovery of nickel (II) from aqueous solution by loofa sponge-immobilized biomass of Chlorella sorokiniana: characterization studies. Journal of Hazardous Materials. 2004; 108(1-2): 85-94. doi: 10.1016/j.jhazmat.2004.01.002
61. Farooq U, Kozinski JA, Khan MA, et al. Biosorption of heavy metal ions using wheat based biosorbents - A review of the recent literature. Bioresource Technology. 2010; 101(14): 5043-5053. doi: 10.1016/j.biortech.2010.02.030
62. Gupta VK, Rastogi A, Nayak A. Biosorption of nickel onto treated alga (*Oedogonium hatei*): Application of isotherm and kinetic models. Journal of Colloid and Interface Science. 2010; 342(2): 533-539. doi: 10.1016/j.jcis.2009.10.074
63. Underwood EJ. Trace Elements in Human and Animal Nutrition, 4th ed. Academic Press; 1977. p. 545.
64. Seaman JC, Bertsch PM, Schwallie L. In Situ Cr(VI) Reduction within Coarse-Textured, Oxide-Coated Soil and Aquifer Systems Using Fe(II) Solutions. Environmental Science & Technology. 1999; 33(6): 938-944. doi: 10.1021/es980546
65. Tiravanti G, Petruzzelli D, Passino R. Pretreatment of tannery wastewaters by an ion exchange process for Cr(III) removal and recovery. Water Science and Technology. 1997; 36(2-3): 197-207. doi: 10.2166/wst.1997.0518
66. Kongsricharoern N, Polprasert C. Chromium removal by a bipolar electro-chemical precipitation process. Water Science and Technology. 1996; 34(9): 109-116. doi: 10.2166/wst.1996.0189
67. Puranik PR, Paknikar KM. Biosorption of Lead, Cadmium, and Zinc by Citrobacter Strain MCM B-181: Characterization Studies. Biotechnology Progress. 1999; 15(2): 228-237. doi: 10.1021/bp990002r
68. Basso MC, Cerrella EG, Cukierman AL. Lignocellulosic Materials as Potential Biosorbents of Trace Toxic Metals from Wastewater. Industrial & Engineering Chemistry Research. 2002; 41(15): 3580-3585. doi: 10.1021/ie020023h
69. Volesky B, Holan ZR. Biosorption of Heavy Metals. Biotechnology Progress. 1995; 11(3): 235-250. doi: 10.1021/bp00033a001
70. Kratochvil D, Volesky B. Advances in the biosorption of heavy metals. Trends in Biotechnology. 1998; 16(7): 291-300. doi: 10.1016/S0167-7799(98)01218-9
71. Kapoor A, Viraraghavan T. Fungal biosorption- an alternative treatment option for heavy metal bearing wastewater: A review. Bioresource Technology. 1995; 53: 195-206.