

Heavy Metal Toxicity - Sustainable Mitigation Strategies for Their Remediation

Sally Lukose and Karuna Singh*

Sharda School of Allied Health Science, Sharda University, Greater Noida, Uttar Pradesh, India

*Corresponding Author: karuna.singh@sharda.ac.in

Abstract: Heavy metals are known to be present naturally in the earth's crust in trace quantities. However, their increased concentrations can be attributed to erratic human activities such as urbanization, industrialization, and extensive use in agricultural practices. Heavy metals such as arsenic, cadmium, mercury, chromium, and lead cause serious health hazards and deleterious effects on all life forms through chronic exposure and bioaccumulation into the food chain. Owing to the known carcinogenic effects of heavy metals, globally it is one of the most sought-after areas of research interest in the public health domain. While humans and animals are exposed to heavy metals via soil, water, and air, plants being sessile in nature, cannot avoid these contaminants and hence develop their mechanism of detoxification and tolerance for their survival resulting in phytotoxicity leading to reduced food quality. The need for sustainable and eco-friendly interventions is being researched, including phytoremediation and bioremediation, which are promising future and economically viable methods to reduce heavy metal toxicity.

Keywords: Anthropogenic sources, Exposure, Impact, Natural sources, Remediation.

I. INTRODUCTION

The term 'heavy metals' (HMs) refers to metals and metalloids that cause environmental pollution and toxicity and because of that lead to various adverse effects on biota [1]. Metals having atomic weight greater than 40.04 and specific density above 5 g/cm^3 are considered as heavy metals [2]. On behalf of health effect heavy metals can be classified as essential (Cu, Zn, Co, Cr, Mn, Fe), nonessential (Ba, Li, Zr), less toxic (Sn, Al) and highly toxic (Pb, Hg, Cd, As). Arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) are known to cause serious health hazards and deleterious effects on all life forms through chronic exposure and bioaccumulation into the food chain. Toxicity of HMs causes become more fatal when they reach food chain. Owing to the known carcinogenic effects of heavy metals, globally it is one of the most sought-after areas of research interest in the public health domain. United States Environmental Protection Agency (USEPA) has classified heavy metals as potent human carcinogens and ranked As, Pb, Cd, Hg, and Cr among the priority metals due to its higher

toxicity from public health point of view [3].

Humans, animals, and plants are exposed to HMs via soil, air, and water, which become life-threatening when they become part of the food chain. HMs entering the human body via different modes make changes in cellular structures, and disrupt various biological functions. Various factors determine the toxicity of The HMs in human body. These factors are exposure time, the metal reactivity, the concentration, and health status of individual who is exposed. The HMs once entered cannot be degraded but converted to a lesser toxic form. Heavy metal exposure can cause loss of cellular function, damage the cell, and often impair DNA repair mechanism or damage DNA regarded as a potent carcinogen and mutagen [4].

This review provides an analysis of occurrence and health hazards of some heavy metals. It will also encompass the recent research and advancements for the remediation of heavy metals from polluted environments that can further open up new avenues toward a sustainable approach to reducing and controlling heavy metal pollution.

II. SOURCES OF HEAVY METALS CONTAMINATION

Heavy metals are well-known environmental pollutants. These can enter the environment as they are present naturally in the earth and spread through various natural processes occurring as stinging of minerals, sea-salt sprays, volcanic eruptions, soil disintegration, particulate matter, forest fires, and biogenic sources [5]. Anthropogenic phenomena responsible for spreading arsenic pollution are agricultural activities, industrial effluents like wastewater discharge, leather polishing, mining, metallurgical processes, and combustion of fossil fuels [6] [7].

Agricultural chemicals like pesticides, insecticides, and fertilizers are the main reasons behind heavy metal contamination. Lead, smelting process releasing As, Zinc, Copper is some of the heavy metals released by automobile emissions responsible for heavy metal poisoning. Arsenic is a heavy metal commonly used in manufacturing rat poison, herbicides, and pesticides. Foods like fish and shellfish were also contaminated with organic arsenic. Sewage wastewater discharge is a common reason for heavy metal deposition in food crops; portable water is contaminated after the percolation of industrial wastewater & sewage water into the

groundwater. Nickel & cobalt are the common heavy metals discharged via industrial wastewater into freshwater bodies. Other miscellaneous sources of heavy metal contamination are mineral processing, paint manufacturing, and electroplating.

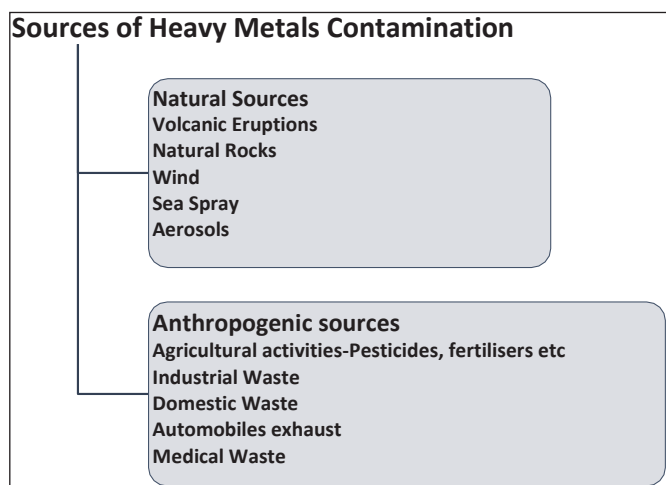


Fig. 1: Sources of Heavy Metals Contamination

Sources of human heavy metal poisoning are consumption of adulterated foodstuffs, seafood & contaminated water, air pollution & occupational exposure at workplaces like industries & mines. The heavy metal poisoning chain for humans follows a cyclic order, i.e., contamination of environment components like soil, water & foodstuffs from industrial effluents then to humans, which are further absorbed by several routes. Food & water in the easiest route through which heavy metals like arsenic, cadmium, lead, manganese, etc. find entry to the human body. Second common route is through inhalation of polluted air, which is responsible for the accumulation of lead in humans.

III. OCCURRENCE AND IMPACT OF HIGHLY TOXIC HEAVY METALS

A. Arsenic

Arsenic belongs to group 1 category by the WHO [8]. Additionally, it has also depicted that its toxicity can lead to adverse health impacts [9]. While arsenic found in nature are a consequence of the mobilization of metals naturally, anthropogenic activities have only added to cause further harm to environmental health. Arsenic has found its commercial utility in manufacturing transistors, glass, dyes and pigments, semiconductors, paper, wood, pharmaceuticals etc. [10]. Arsenic based compounds like pesticides, fungicides, various additives used for feeding livestock's etc. make its entry to agricultural practices [9]. Various countries like Mexico, Bangladesh, Taiwan, Chile and India have reported chronically

exposed to arsenic. Exposure to arsenic can be much greater in industries including wineries, ceramics, glassmaking, smelting, refining metallic ores, pesticide production and application, wood preservation, and semiconductor manufacture.

Exposure of workers to arsenic compounds lead to substantially higher levels of arsenic. Body gets exposed to arsenic via oral route (ingestion), nasal route (inhalation), dermal route (skin), and the parenteral route [11]. Pesticide usage and waste disposal can produce much higher values of Arsenic concentration in soil (> 40 mg/kg) [12]. As depicted in Fig. 2 high levels of arsenic are a reason for increase risk of cancer and other degenerative diseases [12] [13].

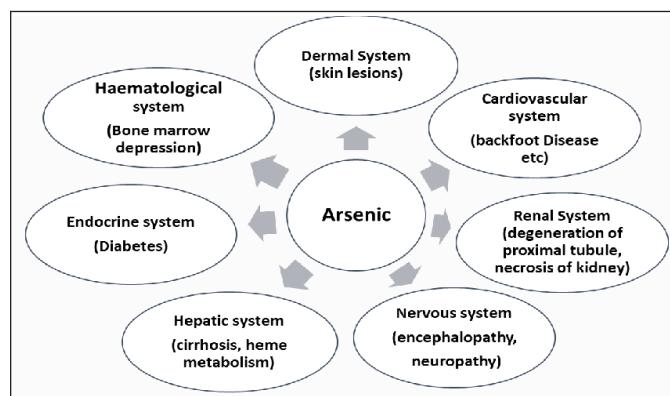


Fig. 2: Impact of Arsenic Exposure to Human Body

B. Cadmium

Cadmium is a heavy metal which is present in the earth's crust at an average concentration of about 0.1 mg/kg. Environment's highest concentration of cadmium compounds is found in sedimentary rocks, while marine phosphates have about 15 mg/kg cadmium content. Cadmium is useful in a variety of industrial processes, including the creation of alloys, pigments, and batteries [14]. Cadmium can enter to the human body via air, soil, food and water like inhalation or cigarette smoke and food and also via employment of a worker in primary metal industries, mining, smelting, manufacturing units dealing in production of batteries, pigments, alloys, and stabilizers, eating contaminated food, and smoking cigarettes [15].

Cadmium exposure can cause cellular dysfunctions, cellular edema, myocardial infraction, stroke, effect lungs, elevates the levels of SGPT, SGPT, ALK levels and hence affect liver. It also causes nephrotoxicity and lead to kidney damages. It can increase the release of ROS and hence can cause inflammation. Acute toxicity can cause symptoms to appear within 15 to 30 minutes of ingestion [16]. Norepinephrine, Serotonin, and Acetylcholine levels are depressed by chronic exposure to cadmium [17] [18].

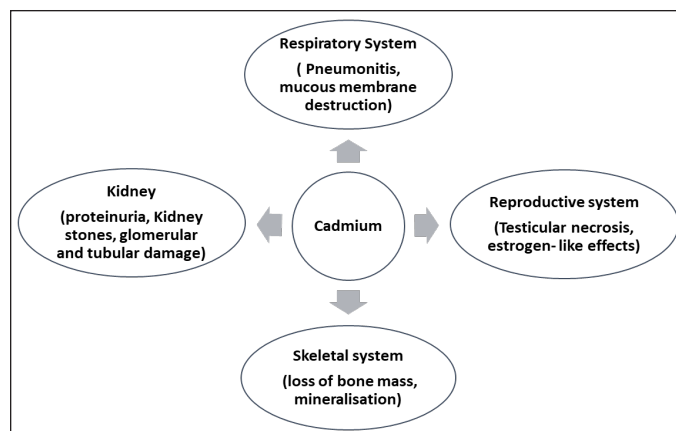


Fig. 3: Impact of Cadmium Exposure to Human Body

C. Chromium

Chromium (Cr) occur naturally in the earth's crust not as elemental chromium [Cr (0)] but in oxidation states ranging from chromium (II) to chromium (VI) [19]. Various natural and anthropogenic activities make chromium enters into the air, water, and soil, especially from industrial establishments involved in metal processing, tannery facilities, chromate production, stainless steel welding, and ferrochrome and chrome pigment production. It is well known that hexavalent chromium [Cr (VI)] causes cancer in humans. Moderate to high toxicity of the hexavalent form of chromium has been found to cause various forms of health problems. The human body is exposed to chromium through a variety of commercial activities. Occupational exposure has been a major concern because of the high risk of Cr-induced diseases in industrial workers occupationally exposed to Cr (VI) [20].

Inhalation is a frequent way for humans to become exposed to chromium, the lung is the major organ that is affected by its toxicity. Another key pathway is through the skin, which can result in extensive dermatitis, a condition commonly seen among construction workers [21]. Due to acute exposure to chromium (VI), nasal irritation and ulcers have been recorded. Severe respiratory, cardiovascular, gastrointestinal, hematological, hepatic, renal, and neurological consequences are caused by high concentrations of chromium (VI) compounds exposure.

D. Mercury

Mercury, a transition element in the periodic table exists in nature in three forms, i.e., in elemental, inorganic, and organic forms [22]. The various chemical forms of mercury include elemental mercury vapor (Hg₀), inorganic mercurous (Hg⁺¹), mercuric (Hg⁺²), and the organic mercury compounds. Ubiquitous nature of mercury lead to exposure of some form in the environment, humans, plants, and animals. This causes a variety of harmful health consequences by creating substantial modifications in the human tissues [23]. It is well recognized that all types of mercury are poisonous, and that they can

have negative effects on the kidneys, nervous system, and gastrointestinal tract [24].

Mercury is used in the electric industry to make switches, thermostats, and batteries. It was used in dentistry for dental amalgams. Caustic soda, nuclear reactors, antifungal agents for wood processing, and pharmaceutical product preservation are some important industrial uses for mercury. Human exposure to mercury in any form may occur accidentally or as a result of environmental pollution, tainted food, dental treatment, preventative medical procedures, industrial and agricultural operations, and operational activities [25]. The two main sources of chronic exposure are believed to be dental amalgams and fish consumption. Other than through industrial contamination, mercury enters water sources naturally by off-gassing from the earth's crust, where it is methylated by the algae and bacteria in the water bodies. The natural habitats of these aquatic bodies, such as fish and shellfish, then allow this methyl mercury to enter the food chain, eventually reaching human beings. Once ingested, mercury has an extremely low excretion rate and mostly accumulates in the liver, kidneys, and neurological tissue.

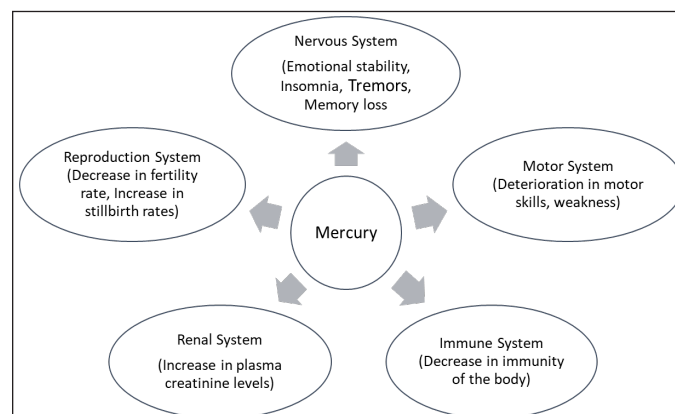


Fig. 4: Impact of Mercury Exposure to Human Body

IV. PROBLEMS ASSOCIATED WITH HEAVY METAL TOXICITY

Even at minute concentrations, heavy metals may accumulate & prove to be threatful to health. These heavy metals get accumulate in various body organs & disrupt their functioning. They also affect the soil biodiversity & hence lowers crop productivity. Some heavy metals like iron, copper, zinc, molybdenum & manganese, are necessary for the body to carry out crucial biochemical activities, but their higher concentration may cause toxicity & may hamper the normal functioning of organs [26] [27].

In general, heavy metals have an impact on the cell membrane, several metabolic enzymes, and cellular organelles such the nucleus and endoplasmic reticulum. Human growth can be slowed down by HMs, which can affect the bioregulatory system that controls physiological or psychological diseases.

Organ poisoning caused by HMs toxicity can harm human organs such the brain, liver, kidney, blood, and skin. The process of the alterations brought about by HMs in the body are shown in Fig. 5.

Heavy metal toxicity leads to changes in nervous system affecting neurotransmitters which can cause neuron damage and hence cause neurotoxicity variety of cognitive deficits and has been linked to a number of neurological conditions, including neurodevelopmental disorders and an overabundance of neurodegenerative diseases. Alzheimer's disease, and mul-

tiple sclerosis, result from neurotoxicity induced by cadmium. Many metals lead to increase in free radicals and ROS which further contribute to mitochondrial dysfunction. Toxicity of Heavy metals can also lead to nephrotoxicity, example higher dosage of cadmium leads clinical symptoms as glucosuria, aminoaciduria etc. [28]. Carcinogenicity and immunological toxicity are other ill effects of various heavy metal exposure. Along with this cardiovascular, skin, reproductive and developmental toxicity is prevalent among human and animals due to chronic and acute exposures of various heavy metals.

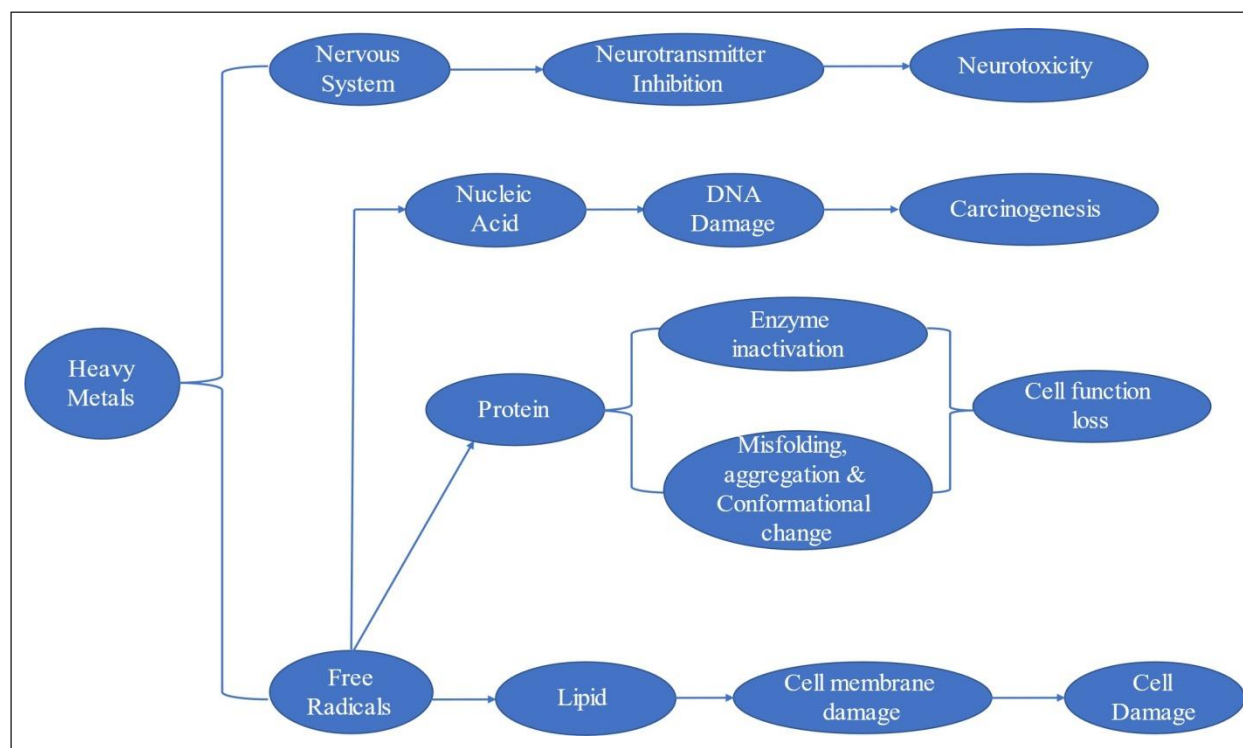


Fig. 5: Mechanism of Action of Heavy Metal and its Impact on Human Body

V. TECHNIQUES FOR REMEDIATION OF TOXIC HEAVY METALS

After studying the negative impacts of heavy metals, it is important to investigate a quick and effective way to remove these dangerous pollutants from soil and water bodies. Three major methods involved in heavy metal toxicity removal are:

1. *Physical Methods* - This include adsorption and biosorption methods. Use of algae, fungi, bacteria and yeast is utilised for removal of heavy metals for example, *Spirogyra* is used to adsorb Chromium IV, *Agaricus macrosporus* is used to adsorb mercury and Cadmium, *Aspergillus parasiticus* and *Lactobacillus bulgaricu* is used for the adsorption of lead.

2. *Chemical Method* - Various synthetic and natural chemicals can be used for the removal which deals with chelation of heavy metals. Alginates, citrates, flavonoids, and phytic acid are examples of natural substances that can be either animal or plant-derived.
3. *Phytoremediation* - The use of green plants for the removal of soil, water, and air pollutants is known as phytoremediation, which is also known as botanical bioremediation. Growing plant in a contaminated region use different steps to remove or immobilise various heavy metals and hence help in the removal of same [29]. Using adsorption and metabolic capacity plants helps in removal of toxic material through root system. Plants like *Eichhornia crassipes*, *Chamomilla recutita* and *Hypericum perforatum* L are used for the removal of mercury and cadmium [30] [31].

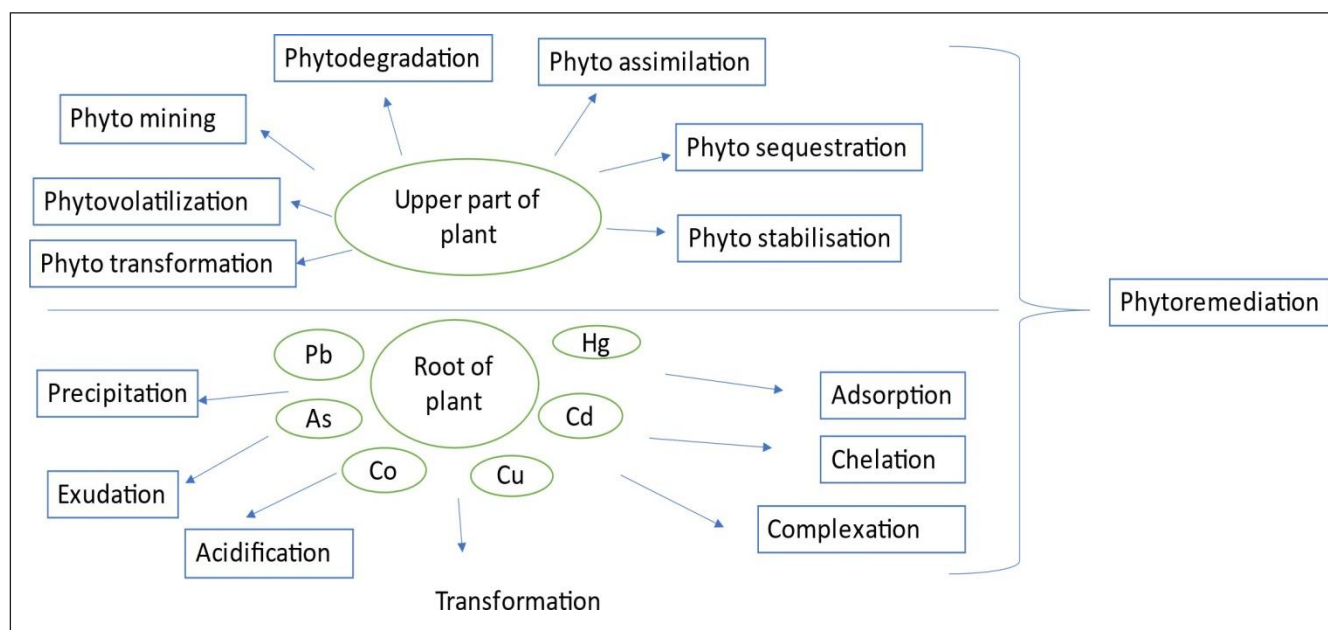


Fig. 6: Phytoremediation Process

Various other methods used for Heavy metal remediation are:

- Chlorination method
- Membrane filtration
- Electro-dialysis
- Chemical precipitation and extraction method
- Electrokinetic
- Ion exchange method
- Bioleaching method

Recent advances in the sustainable removal of heavy metals are:

- *Biocatalytic*: They are the biological armors that have the potential to transform organic & inorganic components chemically. Heavy metals can be reduced from the contaminated sites by the action of biocatalysts like microbial enzymes & whole microbial cells.
- *Microalgae*: It was discovered that microalgae flourish in environments with high levels of heavy metals and effectively contribute to the biosorption process used to remove heavy metal pollutants. Microalgae have a special complex cell wall structure, proteins that bind to metals, and functional groups (carboxyl or amino groups) that serve as a binding site for HMs ions.
- *Bioengineered Char*: Porous material which is enriched with black carbon is known as biochar and created through incomplete combustion or pyrolysis, of organic wastes including activated sludge.
- *Future Prospects*: The future prospects of sustainable mitigation strategies for the remediation of heavy metals

are promising. Some of the most promising areas of research and development include:

- *Phytoremediation*: Research continues to identify new plant species that are effective at absorbing and detoxifying heavy metals. Additionally, genetic engineering techniques are being used to create plants that are more efficient at phytoremediation.
- *Bioremediation*: Research is focusing on identifying and understanding the mechanisms used by microorganisms to break down heavy metals, with the goal of developing more effective and efficient bioremediation methods.
- *Nanotechnology*: The use of nanoparticles for heavy metal remediation is an active area of research. For instance, the use of magnetic nanoparticles to remove heavy metals from water and soil is showing promise.
- *Sustainable Mining and Industrial Practices*: The development and implementation of sustainable mining and industrial practices, such as closed-loop systems and zero-waste processes, will play an important role in reducing heavy metal pollution in the future.
- *Artificial Intelligence and Machine Learning*: These technologies are increasingly used for monitoring and predicting heavy metal contamination and for the design of more efficient and cost-effective remediation methods.

Overall, the future prospects of sustainable mitigation strategies for the remediation of heavy metals are promising, but more research and development are needed to fully understand and

harness the potential of these technologies.

VI. CONCLUSION

Different pathways allow the heavy metals to enter the body. Harmful metal bioaccumulation has a range of toxic consequences on various bodily tissues and organs. In the human body, metal toxicity can show acute or chronic manifestations. While humans and animals are exposed to heavy metals via soil, water, and air, plants being sessile in nature, cannot avoid these contaminants and hence develop their mechanism of detoxification and tolerance for their survival resulting in phytotoxicity leading to reduced food quality. Hence, consuming these heavy metal-fortified plants and their products leads to bioaccumulation in the successive food chain. In present times, several methods such as acid leaching, thermal treatment, excavation, and landfills, are being used to control heavy metal pollution, which needs to be more sustainable and cost-effective. The need for sustainable and eco-friendly interventions is being researched, including phytoremediation and bioremediation, which are promising future and economically viable methods to reduce heavy metal toxicity. More research and innovative activities required to understand the technologies for remediation of toxic heavy metals.

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