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Environmental and health effects of some heavy metals pollution: a review on source, effect, mitigation strategies

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Abstract :

Human activities over the past century have caused significant human contact with hazardous metallic elements in the environment. Lead, mercury, cadmium, arsenic, and chromium are among the primary heavy metals known to be toxic to human. These toxic metals are naturally present on the external layer of the earth, but the role of human practices are the major sources of environment disruption. These metals are incapable of being decompose naturally, therefore accumulate within the natural surroundings. People come into contact with heavy metals in various ways, including consuming chemically polluted soil or water, inhaling dust particles, or consumption the contaminated organisms. The retention of toxic metals in the body might trigger various toxic impacts, disrupting many body tissues and any related physiological organ systems. The toxic properties of heavy metals rely on specific metal involved, its concentration, exposure time, route of entry, and differences in bioaccumulation potential. The regulations have been designed to prevent the accumulation of harmful chemicals in environment, reducing the potential release of toxicant into the surrounding driven by human activity, and eventually minimize human exposure. In that context, various technologies are applied at pollution sources to monitoring the liberation of toxic metals into natural ecosystem. The implemented technological methods are help in preventing environmental contamination by harmful chemicals and supporting industries in fulfilling regulatory standard. The goal of the present review is to highlights the sources and ecological consequences of toxic heavy metals. Additionally, various identified techniques for controlling pollution associated with heavy metals found in ecosystems are discussed.

Key words: Heavy metals, toxicity, Human health, pollution in environment.

التأثيرات البيئية والصحية للتلوث ببعض المعادن الثقيلة: مراجعة حول مصدرها وتأثيرها واستراتيجيات تقليلها

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مستخلص:

ان الأنشطة البشرية تسببت على مدار القرن الماضي في تعرض الإنسان بشكل كبير للعناصر المعدنية الخطرة في البيئة. و يُعد الرصاص والزئبق والكادميوم والزرنيخ والكروم من بين المعادن الثقيلة الأساسية المعروفة بسميتها للإنسان. توجد هذه المعادن السامة بشكل طبيعي على سطح الأرض، إلا أن دور النشاطات البشرية يُعدّ المصدر الرئيسي لاضطراب البيئة. هذه المعادن غير قادرة على التحلل بشكل طبيعي، ولذلك تتراكم في بيئتها الطبيعية. يتعرض الناس للمعادن الثقيلة بطرق مختلفة، بما في ذلك استهلاك التربة أو المياه الملوثة كيميائيًا، أو استنشاق جزيئات الغبار، أو تناول الكائنات الحية الملوثة. قد يُؤدي تراكم المعادن السامة في الجسم إلى آثار سامة مختلفة، مما يُسبب خللًا في العديد من أنسجة الجسم وأي أجهزة فسيولوجية أخرى ذات صلة. تعتمد الخصائص السامة للمعادن الثقيلة على نوع المعدن ، وتركيزه، ومدة التعرض، ومسار دخوله، واختلافات إمكانية التراكم البيولوجي. وضعت قوانين لمنع تراكم المواد الكيميائية الضارة في البيئة، والحد من احتمالية إطلاق المواد السامة في البيئة المحيطة بسبب النشاط البشري، وبالتالي تقليل تعرض الإنسان لها. في هذا السياق، تُطبّق تقنيات متنوعة على مصادر التلوث لمراقبة انبعاث المعادن السامة في النظام البيئي الطبيعي. تُساعد هذه التقنيات في منع التلوث البيئي بالمواد الكيميائية الضارة، وتُساعد الصناعات على استيفاء المعايير التنظيمية. تهدف هذه المراجعة إلى تسليط الضوء على مصادر المعادن الثقيلة السامة وعواقبها البيئية. كما تُناقش تقنيات مُحددة مُختلفة للسيطرة على التلوث المُرتبط بالمعادن الثقيلة الموجودة في النظم البيئية.

الكلمات المفتاحية: المعادن الثقيلة ، السمية ، صحة الانسان ، التلوث البيئي .

Introduction

The presence of heavy metal pollution has regarded as a significant global environmental concern over the past several years, as a consequence of urbanization and industrialization (Das *et al*., 2023). metals with high atomic weight like cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), Chromium (Cr), and nickel (Ni) are available naturally chemicals that can cause significant adverse effects to human health (Balali-Mood *et al*., 2021), ecosystem and wildlife when accumulated in the environment (Angon *et al*., 2024). Compared to organic pollutant, heavy metals do not undergo natural decomposition over time, making them persistent and potentially harmful even at minute concentrations (Phaenark *et al*., 2024). Toxic metal contamination across atmospheric, hydrological, and soil media has been linked with the human activities like industry, mining, agricultural applications, and improper waste removal, which release contamination to the ecosystems leading hazardous compound particularly heavy metals to accumulate that cause an ecological challenge (Fei *et al*., 2022). Pollution caused by toxic metal is among the most urgent environmental problems that reduces agricultural productivity and posse both direct or indirect threats to the survival of all forms of life on this planet and disrupts the entire natural ecosystems (Hama *et al*., 2023). When toxic metals contaminate the soil, the plant absorb these metals causing toxic materials residues on marketable product causing nucleic acid mutagen which leading to cancer in human (Kamaruzaman *et al*., 2023). Also they can kill or destroy the fertility potential of beneficial animals such as nematodes, pollinator organisms, avian species and soil-dwelling worms (Ankit *et al*., 2020). Thus, preventing leakage of toxic metal elements into land, air and aquatic environment, as well as remediating affected lands, is essential.

Metals classified as a heavy metal are a special group in the periodic table, they have relatively significant atomic mass, greater density, and increased atomic numbers (Pourret *et al*., 2022). These metals are known for their long term persist in the environ-

ment (Suman *et al*., 2018). And they are constituting a major risk to living organisms because exhibit toxic properties, even at trace concentrations (Di *et al*., 2023). Main sources of pollutants derived from toxic metal include farming related practices, industry, and improper waste disposal (Alengebawy *et al*., 2021). Agricultural activities cause pollution by utilization of agrochemicals and sewage sludge with heavy metals (Srivastava *et al*., 2017). Industries like mining, smelting, and manufacturing produce large amount of toxic metals into the soil structure (Singh *et al*., 2023). In addition, unsuitable disposal of batteries, electronic waste, and other items containing metals exacerbates the problem. (Jain *et al*., 2023; He *et al*., 2023). The metallic pollutants are known to enter the different environments by many pathways (Singh et al., 2022; Chuai *et al.,* 2023). They can be emitted into the air and then fall on surfaces of land and water through rainfall (Ding *et al*., 2024). Within aquatic environments, these metals may exist in dissolved form, become trapped within sediment layers, or deposit in fauna of aquatic systems. In soil, they can, be absorbed by organisms, adhere to particles of soil or leak into groundwater. (Guo *et al*., 2024). The metals toxicity is usually aggravated by their property to accumulate and biomagnify in food chains, which finally accumulate in the human tissues. (Coxon *et al.*, 2018). Many population groups are specially at risk, comprises pregnant women, infants, and individuals with impaired immune function (Wai *et al*., 2017). The health effects of heavy metal pollution in human are wide-ranging and varied. Excessive intake of heavy metals has the potential to cause acute and chronic adverse health effects, affecting many body systems (Singh and Mishra, 2021).

Treatment heavy metal pollution requires effective remediation strategies to remove heavy metals in polluted sites (Singh and Mishra, 2021). Many chemical, physical, and biological ways have been developed for this issue. Chemical and physical methods are cost-effective and may cause secondary pollutants during treatment. Biological methods such as bioremediation are environmentally friendly and less expensive than other methods.

(Song *et al*., 2017).

The objective of this review to explore the most toxic kinds of toxic metals, their influence on human body and the ecosystems, and strategies for reducing their contamination.

1. Types of heavy metals and pollution sources

Heavy metals are metals with relatively significant atomic weight and greater densities, can be defined by atomic mass more than 63.5 g/mol and a density more than5 g/cm³ (Sani 2011). Some heavy metals are crucial for various physiological and biochemical functions in trace amounts but become toxic when present at high levels among which are Iron (Fe), Zinc (Zn), and Copper (Cu) (Kim *et al*., 2019). Other heavy metals are harmful even at low concentrations in particular Lead (Pb), arsenic (As), and mercury (Hg) have no beneficial role in the body and. Human activities cause the human being subjected to toxic metal which can inter the human body by many ways, such as ingestion, respiration and skin absorption (Al-Tohamy *et al*., 2022; Sarker *et al*., 2023).

1.1. Lead (Pb)

Lead is a highly toxic polluting agent and has extremely negative impacts on several organs. It is primarily interring the body through the respiratory and digestive systems and the skin absorption. (Balali-Mood *et al*., 2021). Lead is a harmful metallic element which extensively utilized in paints, gasoline, plumbing pipe, batteries, and various industrial products. Its primary source of pollution includes industrial emission, lead containing paint, and contaminated water supply soil, buildings, dust and even trees (Levin *et al*., 2021). Lead exposure is especially concerning for children, as it leads to developmental and neurological impairments (Olufemi *et al*., 2022).

1.2. Mercury (Hg)

Mercury is a toxic heavy metallic element which can appear in many forms, including metallic mercury, inorganic form of mercury compound, organomercury compound (e.g. methylmercury) and as various organic molecules (Ferreira-Rodríguez *et al*., 2021). Mercury is commonly found in terrestrial crustal rocks and charcoal deposits. (Liu *et al*., 2021). Also,

there are many anthropogenic sources cause the release of mercury into environment include fossil fuel burning in power plants, industrial emission, mining activities (especially gold mining), cement production, non-ferrous metal production and the use of mercury in thermometers, batteries, and certain chemicals (Outridge *et al*., 2018). Methyl mercury, an organic form, is highly toxic form and accumulates in aquatic ecosystem, especially in fish and other organisms (Karri *et al*., 2018). Children are more vulnerable to lead toxicity. The severity of lead toxicity increases when they are exposed to air contaminated with air (Loh *et al*., 2016).

1.3. Cadmium (Cd)

Cadmium is among the highest important poisonous metal, it primarily emitted into the environment as a result of human activities particularly in the production of manufactures of nickel–cadmium batteries, pigment, mining, and metallurgy industry (Khan *et al*., 2022). Some natural sources are major factors of environmental Cd pollution like erosion of rock, volcano, air dust, marine droplets, and forest fire. It also leaches to soil and water from the use of phosphate fertilizers (Liuet *et al*., 2015). Cadmium is a effective carcinogen and can cause kidney and lung damage, and bone disease, when absorbed into human body (Yang *et al*., 2025).

1.4. Arsenic (As)

Arsenic founds naturally in earth's rocks, additionally release by human activities like mining, agriculture, and geothermal fluids. Arsenic is also used in medicine, electronics, and industrial manufacturing (Morales-Simfors *et al*., 2020). Arsenic contamination of groundwater is an important issue, certainly in parts of Asia and the United State (Khalid *et al*., 2024). As has linked to the serious health effects including heart disease, developmental effects, diabetes, neurotoxicity, skin lesions, tumors in lung, liver, skin, and bladder (Ettinger *et al*., 2009, Naujokas *et al*., 2013, Abdul *et al*., 2015, He *et al*., 2020, Wei *et al*., 2021).).

1.5. Chromium (Cr)

Chromium (Cr) is naturally occurs in the outer layer of the earth as well as in aquatic environments. It is usually emitted during manufacturing process-

es like electroplating, metallurgical, refractory, chemical industries, leather tanning, ferrochrome industry and the production of dyes. (Tchounwou *et al*., 2012) Chromium is a toxic and carcinogenic element exist in many oxidation numbers chromium (III), chromium (IV), and (VI) (Vincent, 2019). Hexavalent chromium Cr(VI) is associated with range of diseases and pathologies conditions. Loomis *et al*., (2018) mentioned that the International Agency for Research on Cancer (IARC) report (2018) has been considered hexavalent chromium falls under the group I category of known human carcinogens. Chromium exposure can be associated with respiratory complications, skin ulcers, and induction of many cancers like thyroid, lungs, testicles, larynx, kidneys, skeletal tissue, and bladder (Fang *et al*., 2014).

2. Impacts of heavy metals in human health

Heavy metals can inter individuals body and gather in tissue disrupting various biological processes. The toxic impacts of heavy metals on the health of individuals differ according to the kind of metal, the degree of exposure, and the period of interaction.

2.1. Neurological and developmental effects

Lead exposure is one of the most well-known causes of neurological damage, especially in fetus and people under 12 years old. It may lead to delayed growth, learning disabilities, reducing IQ, and behavioral abnormalities (Olufemi *et al*., 2022). Yan *et al*., (2022) associated the susceptibility to neurodegenerative conditions (such as Alzheimer's and Parkinson's diseases) in adulthood with lead exposure in childhood. This investigator further confirm that many adult people diagnosed with neurodegenerative diseases were more probability to have been in contact with lead in childhood. In adult prolonged exposure to lead may lead to cognitive decline and memory loss (Fenga *et al*., 2016).

Mercury, especially in methylated form, can damage nervous system. It is particularly to developing fetuses, as it can cause growth delays, cognitive impairments, and motor disinfection. In adults, chronic inhalation of mercury vapor impacts the function of central

nervous system CNS. The CNS penetrated by mercury vapor, which associated with proteins and inhibit the enzymes involved in neuromuscular and synaptic transmission. The suppression of these signaling pathways can trigger degenerative consequences. Consequently, the affected people may feel a slight tremor in their hands and fingers, which may extend to the rest of their limbs (Yang *et al*., 2020). These studies highlight potential associations between neurodegenerative diseases and mercury exposure. (Karri *et al*., 2018).

When arsenic is ingested, the CNS experience from cognitive impairment. It's also correlated to a various neurological conditions, like alteration in the growth of nervous system, alters the balance between synaptic signaling and neurotransmitter release (Garza-Lombó *et al*., 2019).

2.2. Kidney and liver damage

Cadmium is very toxic metal to the kidney, where it collects and disrupts normal kidney function. In chronic exposure to the cadmium, the renal proximal tubule of the kidney filters and accumulates the metallothionein-bound metal, which is disintegrated in endosomes and lysosomes (Ferraro *et al*., 2010). This process lead to the mobilization of free cadmium into the cytosolic compartment where it may create highly reactive oxygen containing compounds and trigger cell death pathways, kidney failure, damaging glomeruli and proximal tubules and the developmental of bone disease such as osteomalacia and osteoporosis (Khan *et al*., 2022). Similarly, Arsenic exposure can damage kidney and liver, leading to organ failure in extreme cases.

2.3. Cancer

Several heavy metals, like arsenic, Lead and cadmium, are considered as carcinogens. Arsenic causes epigenetic modification, disrupting the DNA, protein's biosynthesis alterations, modulation of nucleosome protein, epigenetic modification of DNA, and decreased gene transcription activity, associating to DNA-binding proteins and decrease the DNA-repair process. Prolonged exposure to arsenic is implicated to many type of tumors like skin, lung, and bladder (Garcia-Esquinas *et al*., 2013).

Lead is a cancer-inducing metal by releasing reactive oxygen species that lead to destruction to the DNA recov-

ery process, genes involved in tumor regulation, and chromosomal abnormalities. It shifts zinc from certain regulatory proteins and disrupts DNA transcription (Mitra *et al*., 2022).

Cd represents as a carcinogen by trigger the damage of DNA, initiating cell proliferation, and suppressing apoptosis, therefore initiating the formation and diffusion of tumors (Sun *et al*., 2023).

Mercury induced the production of considerable considerable amount of reactive oxygen intermediates, which may induce tumor and development of cancerous cells. ROS can damage DNA, cellular proteins, and lipids causing cancer (Zefferino *et al*., 2017).

2.4. Respiratory issues

Inhalation of heavy metals, particularly from industrial missions and air pollution, can lead to range of respiratory problems. Chromium and nickel exposure, have been associated with lung cancer, while cadmium inhalation can cause pulmonary Damage and emphysema (2- Balali-Mood, *et al*., 2021)

It has been reported that children between the ages of 5 and 14 years with bronchial asthma have a greater blood lead concentration which lead to the appearance of eosinophilia (Bjerregaard *et al*., 2022). Factories workers who are exposed daily to toxic metals, experience asthma and respiratory disease, the high lead levels in body fluid have also been mentioned in factory workers (Mishra and Dash, 2022).

Inhaling high quantity of mercury vapor may lead to pneumonitis and acute corrosive bronchitis, muscle pain, cough with fever, headache, and breath shortness (Boerleider *et al.,* 2017). Primary clinical symptoms are breath shortness, fever, shivers, taste of metal, and chest pain. The mercury inhaled exposure may additionally result in lung problems like collapsed lung, lung fibrosis, pneumatocele, emphysema, and pneumomediastinum. furthermore, exposure of individuals to elemental mercury at increased concentrations can lead to lethal acute respiratory distress syndrome (Wu *et al*., 2024).

3. Environmental impacts of heavy metals

The presence of heavy metals has notable effects on human well-being, and also have significant adverse impacts on ecosystem and wildlife. When these metals release to the surrounding, they are capable to spread to the soil, water, and air, affecting biodiversity as well as growth of plant and animal.

3.1. Deterioration of soil and water resources

Heavy metals, especially those from industrial discharges and agricultural runoff, can leach into soil and water bodies, causing long term environmental degradation. These metal bind to organic matter in soil, making theme unavailable to the plants or creating a toxic condition that inhibit plant growth. A plant contains a high level of lead, stimulate the generation of reactive oxygen species (ROS), leading to phospholipid membrane disruption that may cause destruction of chlorophyll and photosynthetic mechanisms and reduces plant development (Najeeb *et al*., 2014). A study has appeared that lead can suppress the tea plants growth and decreasing the biomass and quality of tea by modifying the test of its constitutes. The ion uptake by plants affected by lead, even at trace concentrations, which can cause considerable metabolic modifications in photosynthetic process and finally suppress the plant development (Yongsheng *et al*., 2011). Once in the water, metals like mercury and cadmium can aggregate in aquatic organisms, causing biomagnification up in the food chain. These effects not only on fishes and other aquatic life, but also animals and humans that consume contaminated water and seafood (Hama *et al*., 2023).

3.2. Bioaccumulation and Biomagnification

Bioaccumulation means the temporal aggregation of heavy metals in biota. Some metals do not degrade or leave the body easily, and they build up in the tissue, especially in liver and kidney. Biomagnification occurs when these metals accumulate in higher concentrations in organisms at the end of food chain, involving predators like, bird, mammals, and humans (Sani, 2011).

Heavy metals could enter from industrial pollutants and naturally from

the earth's outer most layer into the trophic chain and may concentrate in the food chain and finally be eaten by animals and people (Numa Pompilio *et al* 2021).

Many studies have confirmed As accumulated in tissues of human and animal after drinking water contain high level of As. Gault *et al*. (2008) revealed that the arsenic component of groundwater is closely related to arsenic levels in hair and nails. Khalid *et al*., (2024) mentioned that there is a correlation between As in groundwater and human biological specimens like hair and nail, Also, As traces were diagnosed in animal milk. Kharkwal *et al*. (2023) assessed health risks in people utilize the animal milk containing arsenic, lead and cadmium. They confirmed that 25% of rural children and 86% of urban females and 50% of city males were at cancer risk due to As contamination in milk samples. Similarly, the Cd accumulate in plant due to the exposure plant roots to high amount of Cd (Raj *et al*., 2022). Augustine *et al*., (2016) demonstrated that the Pb concentrated in the leaves of some plants. Food crops play a vital role in human nutrition, and they could contain both essential and toxic metals (Waqas *et al.*, 2015). Among various sources, edible vegetables are principle contributor to human exposure to heavy metals, which represent about 90% of the total intake, whereas the remainder 10% originate from inhalating polluted air and skin contact (Khan *et al*., 2014)

3.3. Impact on wildlife

Wildlife can be highly affected by heavy metals contamination, since they form the most dangerous side of water pollution because of their ability to bioaccumulation and biomagnifying and cannot be eliminated by metabolic activities. Aquatic organisms, including fish, are particularly expose to mercury and other metals in water. Heavy metals can damage fish gills, disrupt their respiratory system, and cause behavioral changes that affect their survival (Elbeshti *et al*., 2018). In terrestrial ecosystems, plant exposed to contaminated soil may experience growth inhibition, reduced respiratory (Yadav and Shukla, 2023).

Metal pollution can cause a decline in many pollinating and decomposers populations (Ghannem *et al.*, 2016),

difficulties for certain species to reproduce or to feed themselves (Xun *et al.*, 2018), alter the physiology of organism, the anatomy and the characteristic of the biotope of local populations (Jia *et al*., 2011). The results of disturbances are detected at different levels, among others at the level of individual, populations and at dynamics of biological communities. Populations, expose to pollution, striving to preserve their balance and limit disturbance, by reducing competing species and finally the number of taxa present (Ghannem *et al*., 2023).

4. Strategies to reduce heavy metals contamination

The adverse health consequences of heavy metals on the environmental systems result from their toxic nature, non-biodegradability accumulation and persistency. It is important to develop efficient measures to mitigates its damages. Several strategies can be employed at the regional, national, and global scales.

4.1. Pollution control and waste management

One of the highly efficient applications to minimize heavy metals contamination is through better industrial practices and waste management. Industrial that release heavy metals into environment most applied cleaner technologies and follow stricter environmental regulation. The proper disposal of industrial and household waste, particularly electronics and batteries, is fundamental in preventing the spread of heavy metals into the land, air, and water. Monitoring and removing toxic metal residues from environmental samples is necessary for human safety (Dagdag *et al*., 2023).

Nanomaterials have emerged as promising approaches to address heavy metal toxicity in the environment, providing many advantages in comparison with traditional methods (Alhalili, 2023). The kind of sensors designed to detection and elimination of toxic metals are made of different metallic nanostructures like iron, gold, silver, copper, furthermore carbon-based compounds like graphene, carbon nanotubes, and graphite. Nanomaterials is effective agent for the immobilization of heavy metals from divers matrix systems, because of their increased surface area

relative to volume, allowing more efficient exposure of the active surface, there is an improvement in the sensitivity and selectivity of HM ions in such an advanced nanotechnology system. Based on the type of nanosensor, it greatly enhances sensitivity and specificity. (Maghsoudi *et al*., 2021).

4.2. Remediation techniques

Bioremediation involves the employ of living organisms to mitigate the effects of contamination on natural surrounding result from human practices. The informed application eliminates toxic metals originated from contaminated sources and it promotes ecological balance (Bala *et al*., 2022). Environmental remediation technique for instance, using light-based remediation techniques which use the plants to uptake heavy metals, technically known as green biotechnology like *Solanum lycopersicum* (Teng *et al*., 2022), *Pteris vittate* (Yan *et al*., 2022), *Helianthus annuus* (Panwar and Mathur *et al*., 2023), *Salix viminalis* (Nandillon *et al*., 2022), and *Brassica juncea* (Mir *et al*., 2022), and bioremediation that use microorganisms to detoxify or immobilize pollutants like *Bacillus subtilis* (Ganesh Kumar *et al*., 2023), *Pseudomonas* sp*., P. putida, P. aeruginosa* (Maity *et al*., 2023), *Acinetobacter* sp. (Liu *et al*., 2022), *Microbacterium* sp. (Onder Erguven *et al*., 2021), *Corynebacterium propinquum* (Toribio *et al*., 2017), and *Ralstonia* sp. (Zhao *et al*., 2023). These methods can be beneficial in minimizing the concentration of harmful metals in the environment, although they are often slow and may require long term monitoring (Kuppan *et al*., 2024).

4.3. Public awareness and education

Raising awareness regarding the danger of heavy metals pollution and the importance of reducing exposure is essential. Educational programs about the sources of contamination, its health effects, preventive measures, safe disposal of household products containing heavy metals like batteries and electronics, campaigns can promote safer agricultural practices, and the reduction of heavy metals in consumer products, can help decrease the burden of pollution. Environmental NGOs and public health organizations often play an instrumental role in raising aware-

ness through media, workshops, and community outreach (Williamson et al., 2014; Chen *et al*., 2023).

4.4. Legislation and Policy

Governments must have implemented and enforce stringent regulation regarding the use, disposal, and release of heavy metals. International agencies like U.S. Environmental Protection Agency (EPA), the European Union (EU), and similar agencies in the world, have established instructions for acceptable concentrations of hazardous metals in water bodies, soil, and air. The frameworks often ensure industries respond with regulations, Through the application of stringent monitoring and enforcement mechanisms, including reduce on emissions, waste disposal practices, and pollution in agricultural products. Further strengthen global efforts to decrease the use of toxic metals and prevent its hazardous effect on human being and environment. (Rai *et al*., 2008; Das *et al*., 2023).

5. Conclusion

Heavy metals pollution is a significant environmental challenge that requires immediate and sustained action to protect both public health and the environment. With sources of pollution coming from various industries, mining, and agricultural practices, it is crucial to address the issue through combination of control measures, cleaner technologies, and effective waste management. Given the long-lasting and toxic nature of heavy metals, comprehensive strategies to reduce their contamination and mitigate their impact are essential for safeguarding future generations and the planet's ecosystem. Through global cooperation, regulatory frameworks, and adoption of cleaner technologies, people can minimize the burden of heavy metals pollution and work to improve their health.

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