Heavy Metal Pollution and its Effects on Wildlife Health and Ecosystem Dynamics

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Abstract

Heavy metals are abundant in the environment and pose major threats to the ecosystem and the health of living things via both natural and anthropogenic processes. The persistence of heavy metals in the environment leads to disruptions in ecological balance as well. These metals bioaccumulate in a wide range of creatures, increasing toxicity and affecting food supply chains. This study emphasizes the evaluation of heavy metal contamination and its impacts on the ecosystem and animal health. This chapter discusses the importance of indicators and biomarkers in evaluating environmental stresses caused by heavy metals and their impact on human populations and biota. The role of mitigation techniques such as bioremediation and phytoremediation, are specifically highlighted in reducing contamination caused by heavy metals. This provides a nuanced understanding of the heavy metal dynamics. Thus, enabling proactive monitoring strategies to reduce their detrimental impacts on environmental and animal health. Additionally, it provides significant insight into various technologies, ensuring long-term environmental sustainability.

Keywords: Heavy metals, Ecosystem Dynamics, Wildlife, Bioaccumulation, Bioremediation

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Introduction

Environmental pollution is a major threat to living organisms, which affects the ecosystem by polluting the biological and physical components of the atmosphere and earth. The increase in environmental pollution is due to toxicants released by both anthropogenic and natural activities, which have adverse effects and threats on various biotic forms residing on the planet (Bhavya et al., 2021). These toxic pollutants are affecting life in various ways. Among these toxins, heavy metals are much important in environmental pollution. The reason is not only their toxic nature but also their potential for bioaccumulation in biota. As they are transmitted from abiotic to biotic environment and are concentrated in the living organisms resulting in impurity of food chain. Living things are significantly impacted by the trophic transmission, bioaccumulation and biomagnification of dangerous metalloids in food chains and ecosystem. As they are discharged in the environment by exploitation of natural resources, combustion of fossil fuels and agriculture fertilizers therefore sustained in the ecosystem for long time (Chormare et al., 2022).

Heavy metal contaminants in farmland soil manifest an alarming threat to agricultural productivity and organism's health because metals are non-biodegradable and highly pervasive in soil. It is extremely challenging to recover soil fertility if soil is contaminated by such toxic pollutants. Toxicants that are residing in the soil are dangerous to the entire ecosystem because they change the soil's natural chemistry, soil's pH, its color, porosity and other characteristics. Metal pollution, like other pollutants, can induce stress that alters the properties of plants (Shaw et al., 2024). In the soil, these harmful substances are taken up by plants and affect plant growth and yield (Sun et al., 2020). These metals from air deposit on leaves and enter plant through the stomata openings. This transfer of pollutants cause severe risks to living organisms that feed on these contaminated plants (Shahid et al., 2017).

Toxicants are present widely in aquatic ecosystem as this is the convergence point for all contaminants. They get into the aquatic ecosystem by mining wastes, industrial effluents, household sewage, air deposition and geological matrix erosion. Water bodies polluted by these toxins can damage the equilibrium of aquatic ecosystem and biodiversity of organisms in it. These contaminants can easily dissolve in water thus enter into the body of aquatic organisms. Initially they cause formation of particular enzymes in fish that changes the metabolism, poses cellular toxicity, cause necrosis and even results in mass mortality (Baby et al., 2010). In aquatic environments, fish are considered to be important biomonitors for determining the degree of pollution. They provide various benefits in illustrating the spontaneous characteristics of aquatic ecosystems and also in analyzing alteration in territory. Additionally, as they are at the bottom of the food chain in the water column, fish can absorb metals through their gills, skin or digestive system from polluted food. These metals can then build up inside their organs and tissues. Fish can spread them to humans through food, which can lead to acute or chronic illnesses (Authman et al., 2015).

Subjected to the amount and period of interaction, metal pollution is harmful to human health and can have negative impacts. Toxic metalloid exposure in humans can occur through a variety of pathways, including as ingestion, inhalation and skin absorption (Eqani et al., 2016). Due to ingestion of food polluted with toxins a series of threatening effects on human metabolism are observed. They enter in the body and reside there for long period of time resulting in accumulation. Therefore, accumulation of these toxicants causes severe problems to humans such as renal failure, cancer, hair loss, respiratory problem, loss of fertility, damage to skin, liver and lungs (Singh et al., 2011). Since, metals are dangerous to biota, few biomonitoring techniques are formulated to detect these metals in living organisms and ecosystem. Moreover, it is also necessary to eliminate the toxicants from biotic and abiotic environments. In this regard some ecofriendly remedial approaches (bioremediation, phytoremediation) are presented. Thus, this chapter briefly explains the environmental pollution (heavy metals), its impacts on wildlife and ecosystem dynamics (Squadrone et al., 2022).

1. Types of Heavy Metals

Metals are segregated into two classes depending on their function in natural systems: essential and non-essential heavy metals. Living things require minute amount of essential heavy metals for critical physiological and biochemical processes. Toxic metals such as iron, copper, zinc and nickel are essential. Conversely, metals that are not required for any physiological or biochemical processes by living things are known as non-essential metals. The heavy metals cadmium, lead, arsenic and mercury are not necessary (Dabonne et al., 2010). Certain important metals have a great deal of biological significance, such as their role in the creation of hormones, the activity of enzymes (vanadium and manganese), cellular development (nickel) and metabolic growth (arsenic). However, humans only need trace amounts of these metals. If they are present in greater quantities, they can have fatal illnesses and negatively impact living things (Emsley, 2011. Figure 1 present forms of toxic metals in ecosystem.

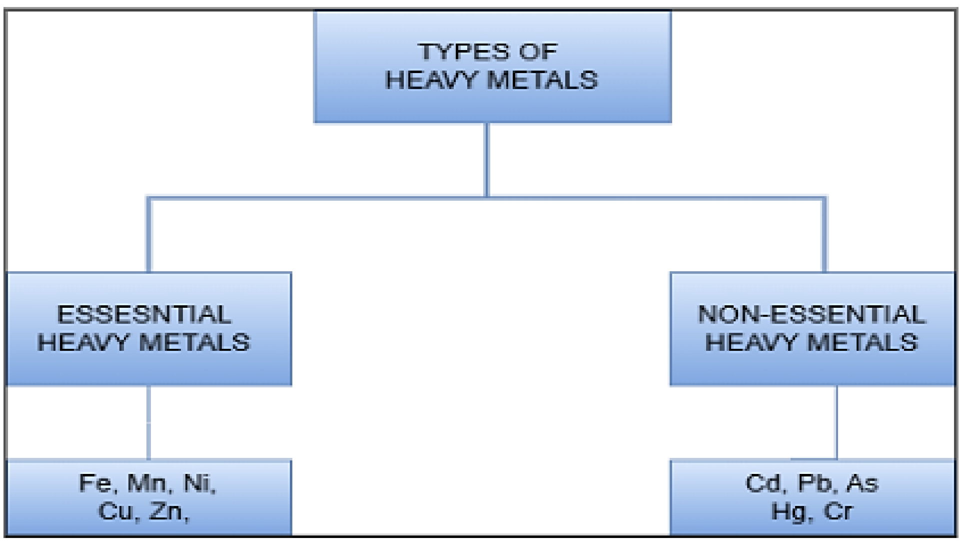

Fig. 1: Forms of Toxic Metals in Ecosystem

2. Sources of Heavy Metal

Plenty of toxic metal particles are discharged into the atmosphere in big industrial cities. These metals cling to dust particles that are widely distributed in the environment. Dust comes from both man-made and natural sources. Therefore, research has been done to find out where toxic substance emissions in roadway dust come from. According to the findings, areas with less traffic had less dust with more toxicants than those with greater traffic (Arsalani et al., 2021). These metals then make their way into soil and water through acid rain from the sky. These toxicants in soil also come from both natural and anthropogenic processes (Hooda, 2010). Pollutant concentrations in biogeochemical cycles have increased as a result of mining and factory operations (Ali et al., 2019). Water from the roots allows these harmful contaminants to enter the plant. In a similar vein, human activities including industrial processes, sewage pollution and agriculture allow these toxins to reach aquatic ecosystems. Surface water contamination by toxins is a worldwide environmental issue. Since water is the easiest means for toxicants to enter the bodies of plants and animals, they mostly enter through drinking thus pose negative consequences (Ali and Khan, 2018. Figure 2 shows sources of toxic metals in the ecosystem.

3. Heavy Metals in Ecosystem

Heavy metals come from both natural and anthropogenic sources; therefore, they are found in soil in significant quantities and stay in ecosystems for extended periods of time. Water bodies can be polluted by soil that contains heavy metal ions, including lead, zinc, cadmium, mercury, and arsenic, through a variety of methods. Among these methods is direct infiltration, whereby metal ions come straight from the soil into groundwater, particularly in regions where metal-intensive applications are prevalent or the soil is fragile (Li et al., 2021). Another process is surface runoff, which allows toxins from the soil to be carried to water sources like rivers and lakes by flowing waters (Haque et al., 2021). These hazardous elements can also be transferred by concentration and precipitation. Rainfall events have the potential to mobilize soil pollutants. Particulate contaminants from the soil surface can enter water bodies during heavy rains. Heavy metals may then be taken up by plants from the soil and then transported to bodies of water. Furthermore, certain plants can physiologically collect toxic metals, which can lead to a decline in plant development, production, and eventually, mortality. When ingested by living things, these tainted plants and vegetables cause serious health issues including renal failure and harm to the central nervous system. These pollutants then spread to bodies of water in a variety of ways, endangering the aquatic biota (Zhang et al., 2015).

Fig. 2: Sources of Toxic Metals in the Ecosystem

4.1 Bioaccumulation

Anthropogenic (industrial) activities and a variety of natural processes are causing heavy metal buildup in soil to increase quickly. Considering these substances non-biodegradable, they build up in tissues of living organisms, this process is known as biological accumulation (Khan et al., 2010). The main location for the buildup of various contaminants is the aquatic environment. Fish are particularly susceptible to toxins in aquatic environments. Fish absorb toxins, which can pose fatal consequences. These tainted fish are eaten by human beings. The primary risks for fish eaters are linked to exposure to lead, arsenic, mercury, and cadmium. In addition, humans are exposed to lead through paint, mercury through food and Cd/Ni through batteries. The ecology is seriously endangered by the absorption and buildup of several heavy metals. As bioindicators for the health of the fish ecosystem, Atobatele and Olutona (2015) investigated the varying concentrations of contaminants in the liver, kidneys, and gills of different kinds of fish. Cadmium, mercury, and lead levels were found to be 0.001–0.100 ppm, 0.000–0.067 ppm, and 0.001–0.125 ppm, respectively (Edo et al., 2024. Figure 3 shows bioaccumulation of toxic metals in the food chain.

4. Effect of Heavy Metal Pollution on Wildlife Health

5.1 Health and Immune System Disturbance

Pollutants of all types are finally gathered by aquatic habitats. Fish are a good subject for investigations of metal contamination in aquatic ecosystems since they are more susceptible to different toxicants than any other invertebrate (Gashkina et al., 2020). Metal buildup in fish is a severe issue as it endangers human populations who consume fish (Ali et al., 2019). Human consumption of contaminated fish can result in many illnesses, including liver damage, cancer, PNS impairment, brain failure, and renal failure (El-Gendy et al., 2016). Furthermore, the effects of toxic metals on the defense system might differ according to the dosage of the metal. For instance, whereas larger dosages of some toxicants, including Cd, Hg and Pb, are suppressive, lower quantities can enhance immune system activity. Moreover, a study revealed that mice treated with As or Pb had poor chemotaxis in their splenic macrophages. Similarly,, birds that are exposed to heavy metals are more vulnerable to illnesses like avian malaria, which makes them even more vulnerable (Durkalec et al., 2022). Besides, the theory most frequently used to explain the harmful effects of Cd is hypocalcemia (Sigel et al., 2013). Pb enters the body and participates in metabolic processes due to its striking resemblance to calcium (Li et al., 2020).

5.2 Reproduction

All facets of life on Earth are being impacted by pollutants. Heavy metal contaminants may also have detrimental impacts on biota through reproductive behaviors. The effects of copper on the fertilization of the eggs of the intertidal polychaete Galeolaria caespitosa provide evidence that these metals may have a direct impact on gamete interactions. As a spread spawner, this worm rapidly dilutes its sperm across distance. Cu affected fertilization more strongly at low sperm densities than at high ones, according to lab experiments. The researchers also conducted fieldwork and discovered that Cu can lower fertilization success rates. They came to the conclusion that for effective fertilization to take place in the field, eggs needed to be nearer to a sperm supply when Cu was present. For example, birds are less likely to produce eggs and hatch when exposed to the harmful effects of lead (Durkalec et al., 2022).

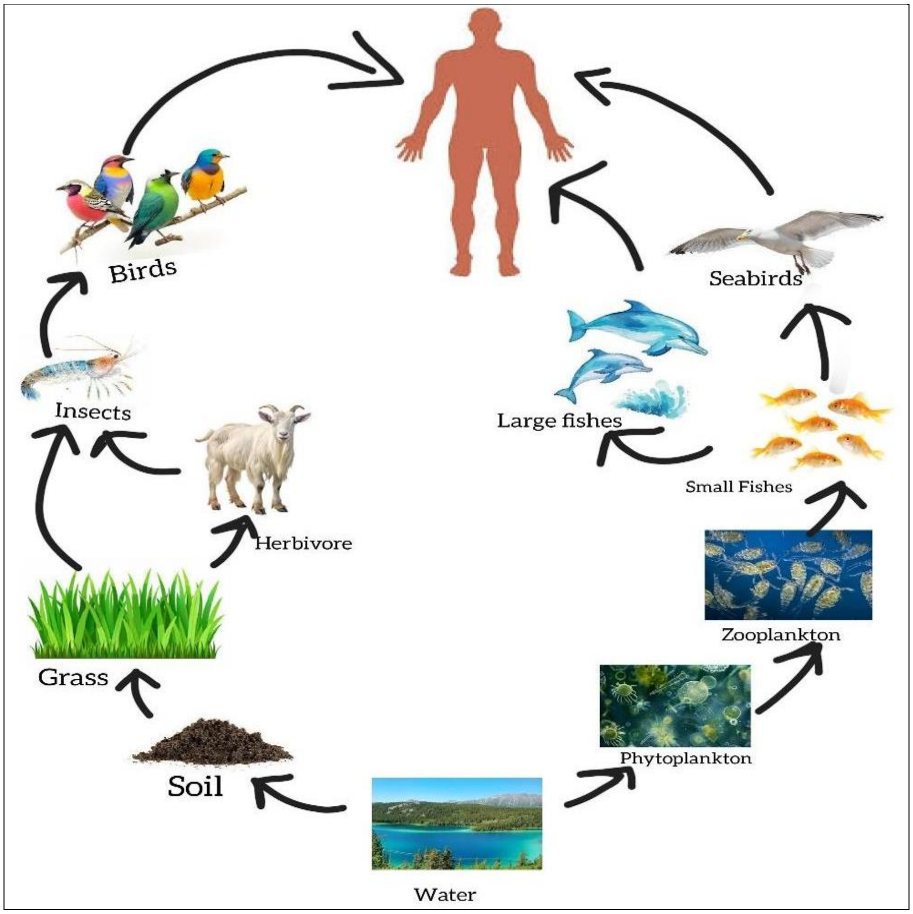

Fig. 3: Bioaccumulation of Toxic Metals in the Food Chain

5.3 Bioluminescence

Some marine animals are believed to exhibit bioluminescence as an anti-predator activity and there is proof that bioluminescence capacity may be impacted by heavy metal pollution. For instance, in a contaminated harbor in Spain, Deheyn and his associates gathered individuals of the fragile echinoderm, along a gradient of toxic metals (cadmium, copper, lead and zinc). Individuals moved from a less contaminated to a more polluted location showed weak and reduced bioluminescence responses. While species from the most heavily polluted area produced bioluminescence responses that were less strong and more slowly created. According to experts, certain bioluminescent creatures use light production as a defense, but in polluted environments, this defense would be less effective. Interaction with biological luminescence by metallic compounds may affect other organismal interactions since the bioluminescence of marine species may also be involved in mating or prey attraction (Edo et al., 2024).

5.4 Behavior Alteration

Impairing prey's capacity to react to predators, the toxic pollutants can change the dynamics between predators and prey, ultimately leading to a decline in prey populations as a result of an increase in predators. Heavy metals may have many more behavioral impacts than fatal ones. Numerous studies have demonstrated that fish exposed to pollution have a reduced capacity for reaction in terms of predator/prey relationships (Fox et al., 2012). Several studies showed that fish in polluted water bodies react differently than fish in unpolluted lakes. Scientist McPherson, for instance, demonstrated that although prey fish in an unpolluted lake responded to skin extracts of other prey species, those in a Ni/Zn-polluted Lake did not respond. In other instances, fish from lakes with and without pollution have been introduced to the lab to see how they react to skin extracts. Another researcher examined wild yellow perch from a water body that had been tainted by a combination of toxins, namely Cu, Ni, and Zn. The fish in the polluted Lake did not react to a chemical alarm signal, while the fish in an unpolluted lake did (Azizishirazi et al., 2014). Figure 4 presents effect of toxic metals on wildlife.

5. Effect of Heavy Metal Pollution on Ecosystem

6.1 Soil and Water quality degradation

The fertility, quality and porosity of soil can all be severely deteriorated by heavy metals. The wellbeing of the microorganisms necessary for maintaining the life of living things is significantly impacted by soil that is polluted with heavy metals. Plants acquire the metals found in the soil as they are difficult to break down (Singh et al., 2015). Metals such as Cr, Hg, Pb, and Cu are more deadly and are mostly found in biotic environments. In agricultural fields, these contaminants represent a significant risk (Zhang et al., 2020). More than 0.03 million tons of Chromium and 0.8 million tons of lead have entered the worldwide environment in the last 50 years, primarily accumulating in soil and causing significant metal pollution (Yang et al., 2018). Rapid industrialization and urbanization have also put water resource systems at risk since major Chinese rivers and lakes are often contaminated with heavy metals to varying degrees. Owing to its unique properties, including toxicity, carcinogenicity, bioaccumulation potential, non-biodegradability, and metal contamination, aquatic environments have raised serious concerns (Ashayeri & Behnam, 2019).

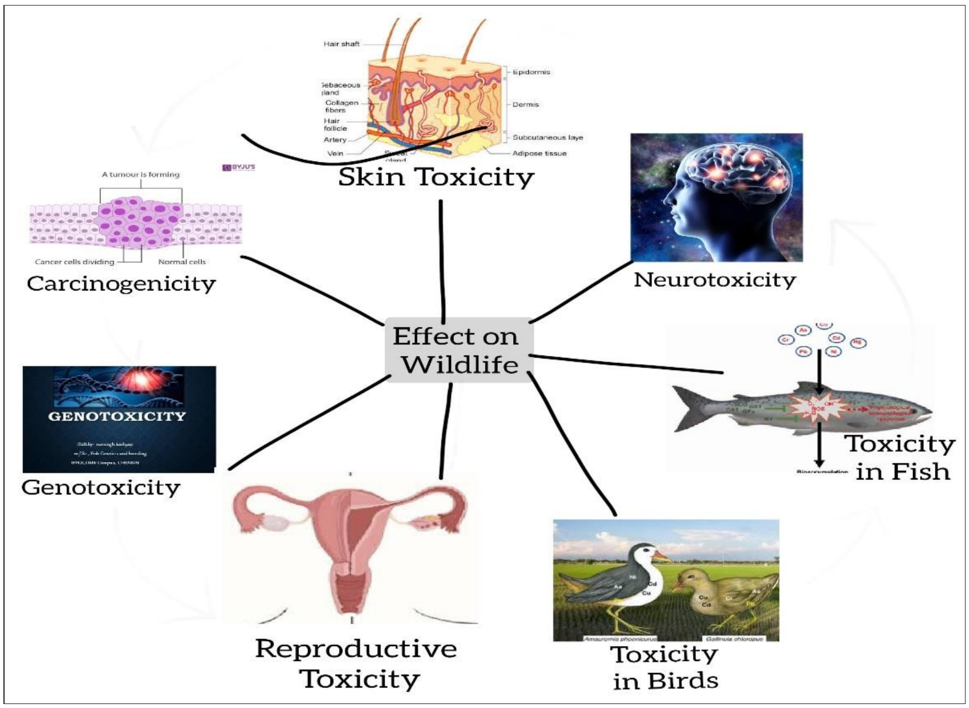

Fig. 4: Effect of Toxic Metals on Wildlife

6.2 Habitat Loss

The major causes of habitat loss are habitat fragmentation, degradation, and destruction (Klappenbach L., 2020). Urbanization-related activities, mining, pollution, logging, destructive fishing, the growth of agricultural practices, the depletion of resources such as food, water, and air quality, and the disturbance of ecosystem-related processes are the primary drivers of habitat degradation. The primary cause of habitat loss in the ecosystem is heavy metals. Beyond the threats to human health, habitat degradation impacts both the animals that call the area home and the people. Mining operations have a severe impact on the environment, resulting in habitat destruction, deforestation, biodiversity loss, and contaminated soil and water. It is alarming for the future that mine emissions of greenhouse gases contribute to global warming and climate change (Setia et al., 2023).

6.3 Altered Community Structure and Biodiversity

In simple words, biodiversity is the variety of life. The capacity of nature to supply the resources needed by humans is determined by the complex web of life or diversification on Earth. The loss of biodiversity is caused by several reasons, including habitat destruction, hunting, protruding species introduction, overutilization of preferred species, climate fluctuation, natural disasters, and pollution from heavy metals. The rate at which biodiversity is declining is concerning as biodiversity suffered as a result of water contamination. In order to increase agricultural yield, chemical fertilizers are given to the soil, they typically contain phosphate and nitrogen. From the soil, nitrogen and phosphorus are carried underground or to bodies of water. Eutrophication is caused by the existence of these minerals in water bodies. Biodiversity suffers a major drop in oxygen levels caused by eutrophication. Fish and other aquatic life die as the water does not have enough dissolved oxygen. Additionally, herbicides and fertilizers also accumulate in bodies of water (Bhateria et al., 2016). Figure 5 presents effect of toxic metals on ecosystem.

6. Monitoring and Assessing Heavy Metal Pollution in Wildlife

7.1 Biomonitoring Techniques

The ecosystem and the wellness of biota can be adversely affected by trace elements, especially heavy metals. To identify these pollutants, biomonitoring technologies are employed to assess the kind of pollution and its effects on ecological systems food chains and food webs. It is

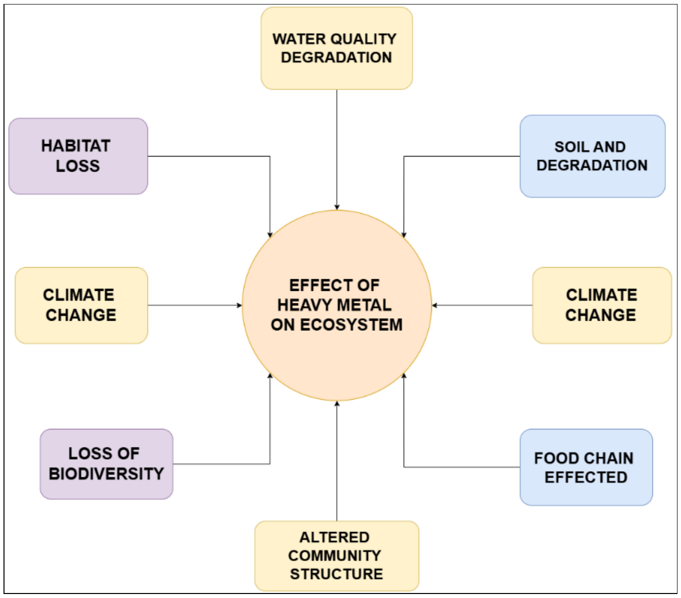

Fig. 5: Effect of Toxic Metals on Ecosystem

commonly accepted that microbial species are sensitive markers of the stress caused by metal pollution. Prior research has demonstrated that marsh soil's long-term heavy metal pollution also affected the community structure of microorganisms and that the stress of toxicants significantly reduced the number of bacteria and fungus (Li et al., 2021). Research on the Iberian Peninsula is carried out in this regard. Thirty species in all were captured of which eight are aquatic and twenty-two are terrestrial. Large populations of carnivores may be found in both types of habitats. Research was done on the liver and renal tissues of these animals. According to a biomonitoring approach, cadmium was found in high concentrations (Jota et al., 2022).

7.2 Monitoring Animal Hairs

An effective biomonitoring method for determining the presence of trace elements or contaminants in ecosystems is animal hair. The essential and non-essential components of badger, wild boar, marmot, wolf, fox and deer hair were examined. It was discovered that deer, wolves and foxes had the lowest metal bioaccumulation levels, whereas badgers had the highest levels. With the exception of wild boar, essential components contribute more to the total metal content of all species. According to research, omnivorous species like badgers, marmots and wild boar have greater levels of metals (particularly Al, As, Cr, Cu, Fe, Ni and V) than herbivores like deer and carnivores like wolves and foxes. As a result, they may be a useful indicator of metal exposure in the environment (Squadrone et al., 2022).

7.3 Monitoring Blood and Feather

Samples of blood, feathers and eggs were used to assess the effects of toxic metals on captive Indian Peafowl living in different parts of Punjab, named as Wildlife Park of Bahawalpur (WPB), Jallo Wildlife Park of Lahore (JWPL) and Wildlife Park of Murree (WPM). DNA damage was assessed using the technique known as single-cell gel electrophoresis. The findings demonstrated that the concentration of chromium was considerably higher in the JWPL blood, feather, egg shell and egg content samples than in Pb, Mn, Ni and Co. Owing to its porous nature, eggshell samples had the highest metal uptake in contrast to other samples. Analyses conducted by region revealed that JWPL seems to be much contaminated than other two parks. According to the study's findings the WPB is the best location for keeping captive animals and birds out of Punjab's three research locations (Naz et al., 2023. Figure 6 summarises techniques for the assessment of toxic metals.

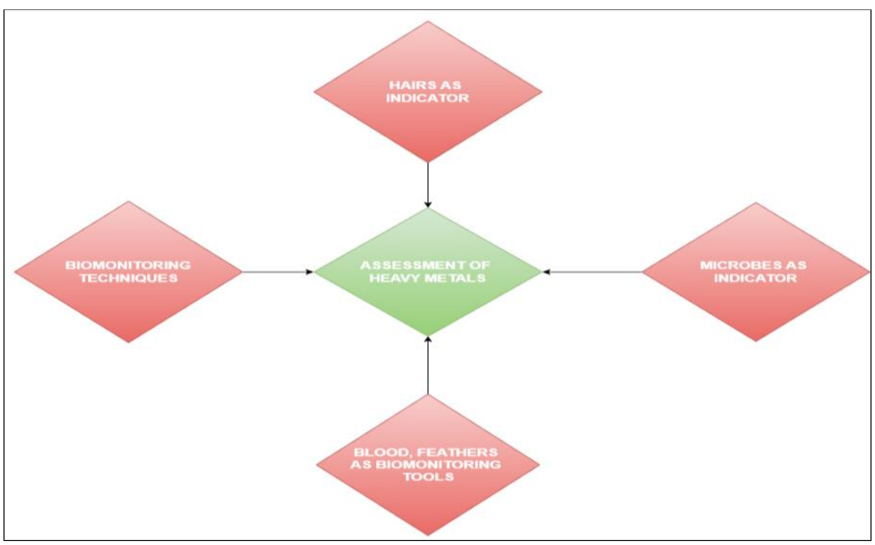

Fig. 6: Techniques for the Assessment of Toxic Metals

7. Management Strategies

Eliminating cumulative toxicants from an organism's body becomes crucial. Mining, smelting, agriculture and electronic waste are the main causes of soil contamination (Munanku et al., 2023). To tighten the rules controlling the production, usage and removal of industrial waste, stricter restrictions are required. Sustainable practices, such as ecologically friendly extraction, processing and production techniques must be used by industries. Systems for efficient waste management have to be put in place (Dembele et al., 2022). Metallic substances build up in the atmosphere and then pollute the food chain since they are not biodegradable. This pollution poses a threat to the ecology and human health. Some heavy metals are mutagenic, teratogenic, carcinogenic and endocrine disruptors. While other toxic metals cause neurological and behavioral problems especially in children. Therefore, toxic metal contamination cleanup merits careful consideration. For this, a variety of techniques are employed (Ali et al., 2013).

8.1 Physical Methods

Metal ions are essential raw materials for technological uses such as the extraction of metals from plants and water etc. Applications for ion exchange polymers in hydrometallurgy include the elimination of metal ions from saltwater and the elimination of toxic metal ion residues from trash. To separate significant metal ions from effluent and aqueous media, a polymerized ligand is utilized to selectively latch onto a particular metal ion in a combination. Uranium has the potential to pollute the environment, particularly in effluent from the mining sector. For the purpose of removing uranium from seawater and aqueous solutions, several adsorbent types have been created and investigated. The most successful of these was an amidoxime group that contained adsorbents. The size and density of the metal and the biosurfactant both affected how well the metal was removed. When evaluating a marine-derived microbial surfactant for heavy metal remediation, the test anionic detergent demonstrated the ability to bind to metal ions at concentrations below those of its carboxyl methyl cellulose counterpart (Tsekova et al., 2010).

8.2 Bioremediation

Toxic substances known as heavy metals are typically found throughout an environment. The traditional methods of precipitation, ion exchange, electrochemistry and reverse osmosis for treating metal-contaminated water are expensive and prone to produce secondary contaminants. Therefore, to address metal toxicity, we employ bacterial bioremediation. An economical and environmentally beneficial option for treating industrial wastewater polluted with metals is bacterial bioremediation (Naz et al., 2023). One of the key microbial systems that can be used for bioremediation is thought to be bacteria. The processes of bio-absorption and bio-accumulation are employed by bacteria. Potential chemical absorption sites for adhering and moving metallic ions to the microbial cytoplasm are provided by the bacterial cell wall. By implementing tactics and creating a conducive environment, the potential for microbial bioremediation can be increased. Through the use of genetic modification techniques including mutation, plasmid exchange and transposons, the bioremediation effectiveness of bacteria is anticipated to increase numerous times (Patil et al., 2024).

8.3 Phytoremediation

The use of plants and bacteria to lower the noxious effects of toxins in the ecosystem is described as phytoremediation (Greipsson, 2011). It is employed to eliminate harmful substances from the environment. Toxic metal hyper-enriched plants, sometimes referred to as "hyper-accumulator plants" absorb plenty of toxic metals from the soil (Guo et al., 2020). Owing to their affordability, landscaping potential and eco-friendliness, these plants have drawn a lot of interest from people all over the world (Cao et al., 2019). The halophyte has demonstrated a noteworthy treatment effect on contaminated alkaline soil in a number of recent studies on plants cultivated in various soil types with good rehabilitation effects on pollution from heavy metals (Khan et al., 2021). Furthermore, as a commercial crop, cotton has excellent potential for improving the rehabilitation of farming soil affected by heavy metals (Li et al., 2021). Figure 7 shows phytoremediation of toxic metals.

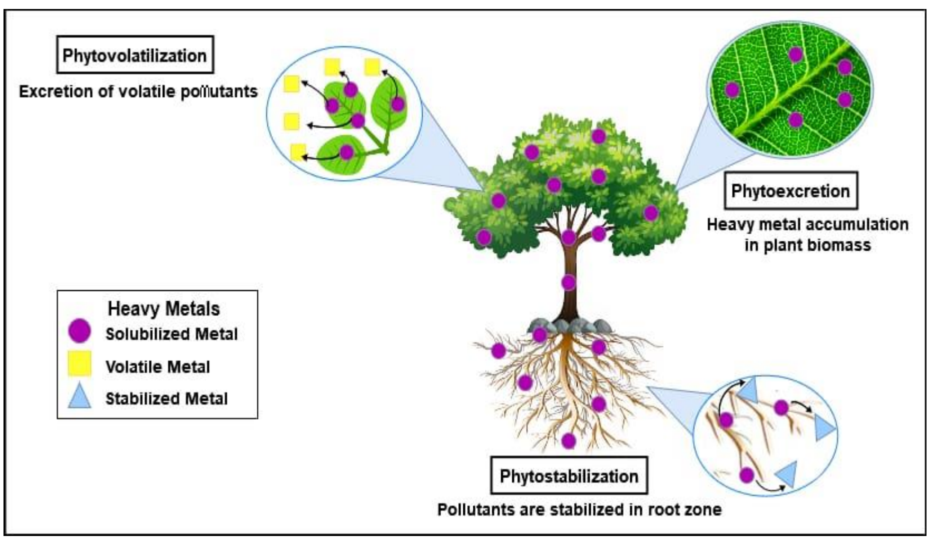

Fig. 7: Phytoremediation of toxic metals

Conclusion

Metal contamination is highly toxic to wildlife and ecosystem. They invade the organism's body through routes like; breathing, feeding and by means of skin. In aquatic environments these toxic pollutants are present in large quantities as this environment is the last collector for any kind of pollution. In aquatic system, fishes are more sensitive to any type of toxicants. Long term accumulation of these toxicants leads to bioaccumulation. As a result, several kinds of diseases occur in fish as well as in other organisms. Like organisms may become infertile and mutagenic. Ecosystem dynamics is also highly affected by heavy metals. These contaminants are responsible for biodiversity loss, habitat destruction and climate change. Therefore, this comprehensive study about toxicity of heavy metals on wildlife and ecosystem suggests that fundamental steps should be implemented to lower the toxicity of these contaminants.

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