Chemical Pollutants: Heavy Metals and their Health Consequences

Farwa Shafique[1]*, Gulzareen Javaid[1], Marrium Bibi[1], Nouman Saeed[2], Iqra Perveen[1], Nosheen Zahra[1], Mahjabeen Khan[1] and Ayesha Ghafoor[3]

[1]Department of Zoology, University of Agriculture, Faisalabad, Pakistan
[2]Department of Zoology, University of Jhang, Jhang, Pakistan
[3]Department of Zoology, Government College University, Faisalabad, Pakistan
*Corresponding author: farwashafique448@gmail.com

Abstract

Pollution involves harmful alterations in the environment, causing health issues and ecological disturbances. Heavy metal toxicity has been shown to provide a considerable risk, associated with many health issues. Examples of these metals include arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb) and nickel (Ni) among others. Heavy metals bioaccumulate in living organisms, contaminate the food chain and can threaten animal health. Numerous sectors including fertilizers, transportation, automobiles, groundwater and animal feed contribute to heavy metal pollution. Certain metals such as aluminum, may be removed by elimination mechanisms, however, other metals like lead, arsenic and cadmium accumulate in the body and food chain, resulting in chronic toxicity in animals. Cadmium and lead adversely affect several physiological and biochemical systems upon exposure to sub-lethal amounts. The nephrotoxic effects of lead, arsenic and cadmium are well-documented. Metal toxicity is influenced by the absorbed dosage, exposure route as well as exposure period. This may cause various illnesses and may also lead to significant damage owing to oxidative stress from free radical generation. Heavy metal concentration may be reduced by several methods, including micro remediation, phytoremediation and plant-microbe joint remediation. Furthermore, greater study is required in this domain, highlighting the importance of animal studies in clarifying the risks and possible impacts of heavy metal toxicity.

Keywords: Heavy metals, Toxicity, Animals, Biomagnification, Food chain

Cite this Article as: Shafique F, Javaid G, Bibi M, Saeed N, Perveen I, Zahra N, Khan M, and Ghafoor A. 2025. Chemical pollutants: Heavy metals and their health consequences. In: Abbas RZ, Akhtar T and Arshad J (eds), One Health in a Changing World: Climate, Disease, Policy, and Innovation. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 92-99. https://doi.org/10.47278/book.HH/2025.431

A Publication of Unique Scientific Publishers

Chapter No: 25-013

Received: 09-Jan-2025
Revised: 31-Apr-2025
Accepted: 05-May-2025

Introduction

Heavy metals are a group of metals and metalloids that have relatively high density and are toxic even at low levels (Duruibe et al., 2007). Examples include Pb, As, Hg, Cd, Zn, Ag, Cu, Fe, Cr, Ni, Pd and Pt. In fact, most of them are known to be potential carcinogens. Various adverse health hazards are known due to long term and continuous exposure to heavy metals. Since they are nondegradable and tend to bioaccumulate, suitable methods need to be established for their efficient removal from the environment (Edition, 2011).

1.1. Sources of Heavy Metals

In respect of natural sources, it is noteworthy that igneous and sedimentary rocks are considered the major sources of heavy metals. The soils contain heavy metals in concentrations which are proportional to the parent material with which they were first shaped. This distribution of the earth crust is 5% of sedimentary rocks and 95% of igneous rocks. Small or large quantities of the heavy metals have been detected in the igneous and sedimentary rocks. This is due to the weathering process of heavy metals which originate from earth crust that is why there is a natural occurrence of these metal's in the soil. Most of the heavy metals that are present on rocks can be mobilized and released into the soil environment through several processes such as erosion, leaching, volcanic activities, biological activities, terrestrial activities, and surface winds (Muradoglu et al., 2015). Some major sources of heavy metals in the environment are shown in Figure 1.

Insufficient regulation of industrial waste disposal, along with unplanned urban expansion and deforestation has exacerbated anthropogenic pollution to hazardous levels, adversely impacting all components of ecosystem. Anthropogenic activities introduce substantial quantities of metals into the environment, resulting in contamination of ecosystems and food chains beyond acceptable limits. Significant volumes of untreated sewage, sludge and industrial waste containing toxic pollutants are regularly discharged into temporary watercourses, ultimately reaching rivers. This practice detrimentally affects ecosystems, leading to air, soil and water pollution. Industries such as pigment manufacturing, pharmaceuticals, agrochemicals, plastics, battery production and electroplating contribute to pollution by releasing untreated effluents (Batool et al., 2019).

2. Types of Heavy Metals Affecting Wildlife

The World Health Organization (WHO) has documented that approximately one-fourth of diseases and disorders affecting humans and animals today are attributed to long-term exposure to metal contents in the surroundings, causing pollution.

Cadmium and lead, non-essential heavy metals widely distributed due to fossil fuel combustion and industrial activities, present significant toxic risks to avian species. High exposure levels can dislocate flight capabilities, bone density, endocrine and renal functions, reproductive success, behavior, molting, migration and enzymatic processes crucial for hemoglobin formation and growth (Battaglia et al., 2005). Nickel, commonly introduced into aquatic ecosystems through industrial waste discharge, impacts respiratory systems in animals and is associated with asthma, congenital disabilities, vomiting, and genetic damage. Excessive zinc, used in alloying and manufacturing, reduces species diversity and abundance, causing symptoms such as syncope, nausea, and gastrointestinal issues (Pérez-López et al., 2008). Copper, an essential trace element, can cause additional stress in birds living in challenging environments when present in excess. Naturally accumulated in soil, air, and water, arsenic triggers cirrhosis, anemia, malignancies, abnormal genes, liver failure, and decreased weight, among other health problems (Ullah et al., 2014).

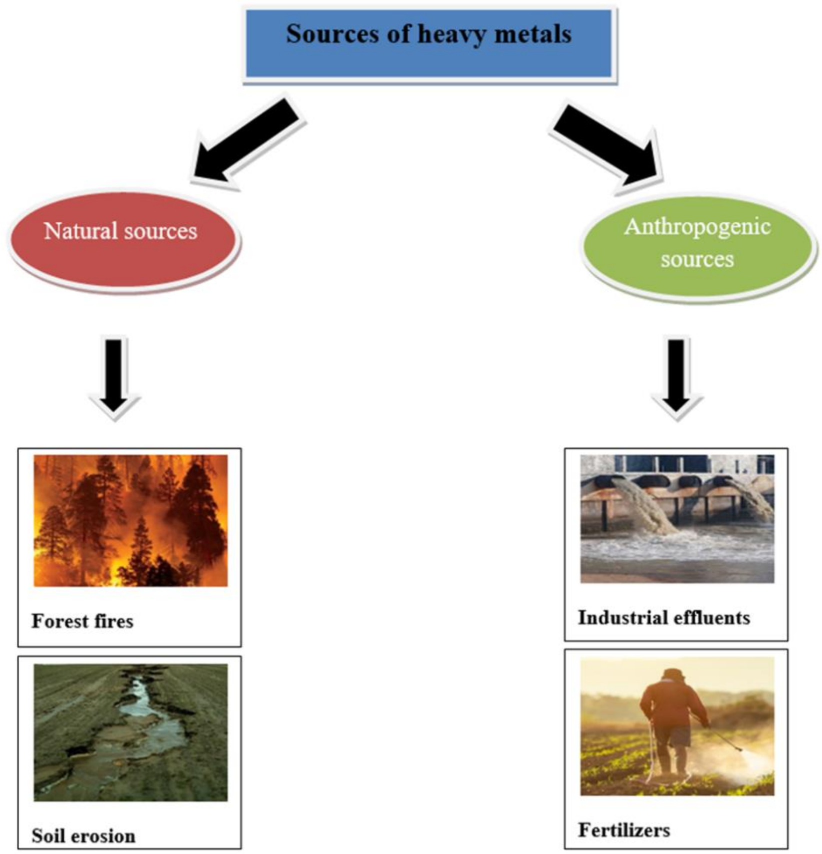

Fig. 1: Some major sources of heavy metals in the environment

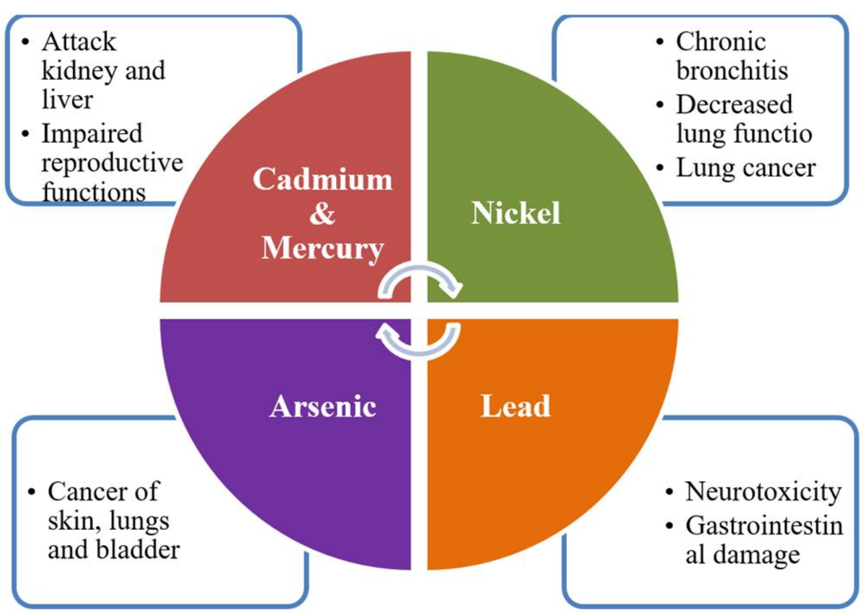

Fig. 2: Types of heavy metals affecting wildlife

2.1. Heavy Metals in the Food Chain and Wildlife

Heavy metals not only impact humans but also have significant implications for other organisms. Once they enter the food chain, these metals can accumulate or be eliminated through various biological processes. They affect reproductive success, eggshell quality, growth rates, and immune responses in birds, often leading to developmental anomalies (Lin et al., 2021). Birds, due to their sensitivity to environmental changes, serve as valuable indicators of habitat integrity, pollution levels and biodiversity declines, which can have direct implications for human populations (Furtado et al., 2019). Moreover, heavy metals contribute to oxidative stress in mammals, birds and other life forms, impairing DNA repair mechanisms and potentially increasing mutation rates (Eeva et al., 2006). Additionally, oxidative stress further leads to inflammatory and apoptotic responses (Ghafoor et al., 2024; Salar et al., 2024). Types of heavy metals affecting wildlife are shown in Figure 2.

3. Biomagnification and Bioaccumulation

3.1. Biomagnification

Biomagnification is an ecological phenomenon characterized by the increased accumulation of a material, such as a hazardous chemical or heavy metal, in organisms at successive trophic levels of a food chain. The increased movement of hazardous heavy metals in the environment leads to the unavoidable buildup of these detrimental elements within the human food chain. This phenomenon has significant implications for ecosystems and human health (Nriagu, 1988).

Example: A prominent instance of biomagnification is DDT (DichloroDiphenylTrichloroethane), a pesticide widely used in agricultural practices and mosquito management initiatives. DDT accumulates in aquatic environments, where it is absorbed by marine creatures. As these animals are consumed by bigger fish and subsequently by birds and mammals, the concentration of DDT escalates, leading to significant health consequences, including reproductive failure in avian species such as eagles and pelicans (Abbasi et al., 2015).

3.2. Bioaccumulation

The process by which chemicals, like pesticides or heavy metals, accumulate inside an organism over time due to both direct and indirect exposure to contaminated environments. Bioaccumulation occurs when an organism assimilates a material at a pace above the rate of its degradation and excretion. This process may result in the accumulation of the chemical in the organism's tissues to potentially hazardous levels.

Example: Different tissues and organs in fish accumulate varying amounts of heavy metals. Metabolically active organs, such as the liver, gills and kidneys, tend to accumulate higher concentrations compared to tissues like skin and muscle. Thus, the accurate quantification of biomagnification ideally requires measuring whole-body concentrations of heavy metals across all representative organisms in the food chain. However, in practice, heavy metal concentrations in invertebrates are often measured on a whole-body basis, while in larger fish, muscle tissue is typically used for analysis due to practical and methodological limitations (Huang, 2016).

3.3. Impact of Biomagnification

The effects of biomagnification are particularly evident in marine habitats. Toxic chemicals, like mercury and polychlorinated biphenyls (PCBs), are absorbed or swallowed by aquatic creatures and accumulate in greater amounts as they ascend the food chain. Plankton assimilates hazardous compounds from polluted water. Small fish consume substantial quantities of plankton, resulting in elevated toxin levels, which are then transferred to bigger predators like tuna and sharks. This results in elevated concentrations of chemicals in apex predators, adversely affecting their reproductive and survival rates (Hossini et al., 2022).

4. Health Consequences on Wildlife

Heavy metal pollution represents a critical threat to wildlife health, as demonstrated by biomonitoring studies conducted in Pakistan. The health risks as well as toxic effects associated with heavy metals in animals are influenced by various factors, including the type and chemical form of the metal, duration of exposure, the sex and age of the animal, its nutritional and physiological condition and the route through which poisoning occurs. The bioaccumulation significantly jeopardizes health and adversely impacts the production performance of animals, highlighting the urgent need for effective monitoring and mitigation strategies (Oktapodas-Feiler, 2020)

4.1. Reproductive and Developmental Effects

In animals, reproductive toxicity can result from chronic exposure, though in some cases, it may also occur acutely. In cynomolgus monkeys, in-vivo exposure to lead suppresses circulating follicle-stimulating hormone (FSH), luteinizing hormone (LH) as well as estradiol without affecting progesterone levels, showing signs of menstrual irregularity (Foster, 1992). In mice, no changes are observed in antral follicles, however, there is decline in primordial follicles along with an increase in growing and atretic follicles (Taupeau et al., 2001). However, some research reports suggest a prominent decrease in the number of ovarian primordial follicles. In rabbits and sheep, lead exposure can result in spontaneous abortions and fetal anomalies (Piasek and Laskey, 1994).

Mercury is a known spermatotoxic, steroidotoxic and fetotoxic agent. Intraperitoneal administration of mercury over 90 days in male rats and mice leads to persistent disruptions in testicular steroidogenesis, inhibiting several steps in the process and causing decreased testosterone and LH levels (Choe et al., 2003). Mercury exposure also causes spontaneous abortions and fetal malformations in animals. In hamsters, subcutaneous treatment with mercuric chloride disturbs estrus cycles, impairs follicular maturation, lowers luteal and plasma progesterone levels and may interfere with hypothalamus-pituitary gonadotropin secretion. In rats, mercury exposure lengthens the estrus cycle and causes morphological alterations in corpus luteum (Sukocheva et al., 2005).

Cadmium exposure in male rats can cause testicular necrosis (Jurasovićet al., 2004). Research using rat leydig cells has shown that cadmium is highly toxic as it disrupts steroidogenesis. In females, cadmium hinders the steroidogenesis process. Maternal susceptibility to excessive cadmium significantly increases the risk of premature delivery, likely by compromising placental function (Kawai et al., 2002).

4.2. Organ Damage

Heavy metals pose significant risks to animal health, affecting kidney function, the cardiovascular and nervous system and various organs, including the reproductive, respiratory, nervous, gastrointestinal, liver as well as endocrine systems (Volkov & Ezhkova, 2020; Hossini et al., 2022). Common toxicants which include lead, arsenic and cadmium are associated with kidney injury, particularly when exposed to higher levels (Egendorf et al., 2022). The kidney damaging effects of As, Pb and Cd are well-documented as well as studies on occupational populations with high exposure levels show a clear link between toxic metal exposure and kidney damage (Butler-Dawson et al., 2022).

Heavy metals exhibit mutagenic, teratogenic and carcinogenic properties and contribute to poor body condition, diminished reproductive efficieny as well as immunosuppression in animals, even at minimal exposure levels. This is due to their ability to easily enter food chains and their lack of recognized biological functions (Dasharathy et al., 2022). Lead, in particular, disrupts various physiological processes and causes gastrointestinal damage, with symptoms including distension, pain, cramping and diarrhea (Slivinska et al., 2020).

4.3. Immune System Suppression

Heavy metals are pervasive environmental pollutants known for their immunotoxic effects. Epidemiological findings have demonstrated that exposure to heavy metals can suppress antibody-mediated immunity (Zheng et al., 2023). Animal studies also point out to the fact that heavy metals also hinder non-specific immune responses. These metals disrupt immune function by impairing the formation of immune cells, changes in inflammation indices and cytokine levels (Ebrahimi et al., 2020).

Cadmium exposure, for instance, significantly impairs the immunomodulatory functions of macrophages that play a crucial role for pathogen defense (Cox et al., 2016). This dysfunction increases its susceptibility infections, especially in those individuals with chronic obstructive pulmonary disease. Similarly, lead exposure causes immunosuppressive toxicity, thereby, increasing vulnerability to infections such as hepatitis B virus and influenza virus (Oktapodas-Feileret al., 2020).

4.4. Behavioral Changes

Heavy metals are genotoxic, teratogenic and carcinogenic to animals, resulting in poor body condition, lower rates of reproduction as well as immunosuppression in domestic animals, even at low concetrations (Dasharathy et al., 2022). This is because of their ability to easily enter food chains and their lack of essential biological functions (Biswal, 2022). Toxic metals including lead, cadmium, mercury and arsenic have been reported to contaminate milk (Rahman et al., 2021).

4.5. Neurological Effects

Chronic exposure to lead induces inflammation in the central nervous system (CNS) of embryonic rat brains, possibly through the activation of glial cells (Strużyńskaet al., 2007). Neurological symptoms associated with lead exposure include lethargy, blindness, head pressing, opisthotonus, seizures as well as coma.

Similarly, certain organic mercury compounds are highly neurotoxic and can affect the nervous system even at low concentrations. In fish, mercury has been shown to cause various biochemical disorders in the CNS. For example, in catfish exposed to waterborne HgCl, the brain exhibits a remarkable rise in lipid peroxidation as well as depletion of total lipids (Bano & Hasan, 1989). Table 1 presents impacts of heavy metals on wildlife.

Table 1: Impacts of heavy metals on wildlife

Heavy metal	Animal model	Effects	Reference
Mercury	Rats, mice, rabbits	Neurological damage, developmental toxicity, cancer	(Ebrahimi et al., 2020).
Lead	Rats, dogs, monkeys	Brain damage, kidney damage, anemia, behavioral problems	Debroy et al. (2024)
Cadmium	Rats, mice, guinea pigs	Kidney damage, liver damage, reproductive problems	Brancaet al. (2020)
Arsenic	Rats, dogs, monkeys	Cancer, skin lesions, neurological damage	Liu et al. (2016)

5. Case Studies in Animals

5.1. Birds

The accumulation of small amounts of heavy metals including cadmium, lead and chromium, with elevated levels of essential elements such as copper and zinc in living tissues, has become a significant concern owing to their detrimental health impacts on avian species (Abbasi et al., 2015). Research indicates that heavy metals tend to build up in the organs of birds, particularly in waterfowl and other species reliant on aquatic environments for sustenance. Moreover, elevated levels of these metals may be detrimental and posing significant risks to their reproduction and survival (Savinov et al., 2003).

Example: The lead pellets accumulate in the gizzard, where they are gradually eroded by contact with gastrolites present. Simultaneously, several acids that aid in food digestion are produced, resulting in gradual breakdown of lead. The lead salts generated enter the stomach, then intestine, where they are absorbed by the blood-stream, ultimately reaching the bird's tissues and organs. Symptoms of poisoning include lethargy, anemia, muscular atrophy, depletion of fat reserves, green diarrhea staining the vent, impaired balance as well as coordination (Pattee & Pain, 2003).

Key findings

The liver and kidney play a vital role in detoxification processes, promoting substantial research on the toxicity of heavy metals including cadmium, lead, nickel and mercury in birds However, lead concentrations are often assessed in the bone and brain of birds due to their lifelong accumulation and their impact on nervous system (Kalisinska, 2000). In the past few years, human activities that have raised heavy metal levels, such as intensive agriculture, contamination of groundwater through leaks, drainage and hunting, have become a substantial hazard to animals (Angelidis & Albanis, 1996).

5.2. Fish

Heavy metal contamination in fish occurs due to the absorption of toxic waste released into the water. Mercury accumulates in the tissues of aquatic species as they ingest contaminated soil and its concentration rises through the food chain (Clarkson & Strain, 2020). Moreover, fish are regarded as apex predators in the marine ecosystem and occupying the highest trophic levels (Xu et al., 2021). Additionally, it has been reported that mercury levels in fish species increase with the depth of the ocean water column. For instance, benthic species tend to have higher Hg levels than pelagic species, such as sardines and mackerels (da Silva et al., 2020).

Example: Even at minimal quantities, low levels of mercury in ocean may induce biochemical, genetic, morphological, physiological as well as behavioral alterations in fish. Malformations resulting from mercury exposure have a detrimental impact on fish. Prevalent malformations include those affecting the spine, bladder, head region and fins. The most abnormalities reported in fish manifest in the spine. Mercury exposure may induce liver histopathological damage and results in other syndromes. A prior investigation of the liver in marine medaka (*Oryzias melastigma*) subjected to varying doses of mercuric chloride showed that mercury exposure increased mercury buildup in the liver and subsequently compromised the liver's ultrastructure (Wang et al. 2019).

Key Findings

Fish is a primary food source with high mercury concentrations due to bioaccumulation and biomagnification. However, developed nations will continue to emit elevated levels of Hg, leading to higher exposure to mercury in fish. Furthermore, the impact of emissions from these nations or regions must be considered, as they can undermine global mitigation efforts (da Silva et al., 2020).

6. Impact on Ecosystems

Heavy metal toxicity poses substantial ecological threats to ecosystems and wildlife populations. One of the environmental issues associated with heavy metal toxicity is biomagnifications which is the accumulation of heavy metals in animal tissues at a rate faster than the rate of excretion; the latter may occur either directly or indirectly via the food web. This process can lead to elevated levels of heavy metals within individuals, potentially reaching toxic concentrations. Bioaccumulation not only affects individual organisms' health and survival but also has broader implications at the population level. Furthermore, the environmental consequences of heavy metal toxicity extend beyond individual species, leading to ecosystem-wide impacts that disrupt ecological balance and function (Storelli et al., 2019).

6.1. Effecting Broader Ecosystems

Heavy metals impose profound effects on the flow of energy and nutrient cycling in ecosystems, thus significantly disrupting ecosystem processes and functions. For instance, in a study conducted in amphibian habitats, heavy metals can impact basic food chain species such as green algae and phytoplankton, leading to reduced productivity and alterations in food web dynamics (Wang et al., 2019). Such disruptions can occur at more than one trophic levels and lead to distortions of species' interactions and disturbances of ecological homeostasis (Nedjimi, 2021).

6.2. Biodiversity Loss

Heavy metal toxicity also has impacts on various aspects of diverse ecosystem and its stability, thereby, bringing about other environmental effects. It is agreed that heavy metals make species more sensitive or vulnerable, which changes species distribution and ultimately brings less species diversification. Moreover, it has been demonstrated that the fragmentation or removal of some of the most important species within a habitat can compromise the stability and performance of ecosystems (Lemus et al., 2018).

Additionally, heavy metals persist in the environment for extended periods, hence, result in long-term pollution. Such persistent contamination has the potential to impact future generations of both humans and other living organisms, perpetuating ecological and health challenges over time (Wang et al. 2019).

7. Conservation and Mitigation Strategies

Various techniques are implemented to decontaminate the environment and prevent the introduction of toxic metals into ecosystems.

7.1. Phytoremediation

Phytoremediation is an economic, technology that has drawn a lot of attention over the last few years in decontamination of polluted environments. This is a technique, whereby the plants are used to uptake, sequester or immobilize elemental pollutants within the soil or water. Today, phytoremediation is known in modern science for its operating capacity with relation to the environment, effectiveness and cost-saving feature as a result of its ability to use the selective absorption properties of plant root systems as well as its translocation, bioaccumulation and degradation potentials. Aquatic and terrestrial plants are employed to eradicate environmental pollution (Nedjimi, 2021). Accumulation of heavy metals in plants is described in Table 2.

7.2. Chemical Remediation

Chemical remediation involves using chemical reagents to mobilize or transform contaminants in soil or to immobilise them by changing their physical or chemical forms through oxidation, reduction, precipitation as well as polymerisation. Chemical redox processes are unique in that they occur between heavy metals. Although this method is general and may be used in a variety of settings, its effectiveness may be influenced by some issues such as recontamination and site conditions (Savinov et al., 2003).

Table 2: Heavy metal accumulation in plants

Plant Name	Contaminant	Reference
Arabidopsis halleri	Cadmium	Grignet et al. (2022)
Brassica juncea	Lead	Rathika et al. (2021)
Solanum nigrum	Cadmium, Lead	Li et al. (2019)
Eichhornia crassipes	Chromium	Rai, (2019)
Azolla caroliniana	Arsenic	Sebastian et al. (2021)
Nicotiana tabacum	Cadmium	Yang et al. (2019)
Callitriche brutia	Mercury	Kaur et al. (2023)
Zeamays	Lead	Huang et al. (2019)
Ranunculus trichophyllu	Arsenic	Stefanidis et al. (2019)

7.3. Microbial Remediation

Microbial remediation utilises certain group of microorganisms to treat soil through adsorption, sedimentation, oxidation and reduction processes to eliminate heavy metals. This approach is based on two primary principles: The two methods include; biological oxidation-reduction as well as biological adsorption. It includes processes where microbes trigger electron transfers of heavy metals in redox reactions that either reduces or eliminates their impacts on the environment (Parveen et al., 2020).

7.4. Plant-Microbial Joint Remediation

Flora and microbial mediated technology add up as a viable possibility for site remediation. This combined approach is more commonly used in engineering operations – with pollution treatment outcomes complemented by the beautification of the surrounding landscape (Parveen et al., 2019).

8. Future Directions

Metals are dangerous to wildlife in that they bio-accumulate in organisms and contaminate the food web. In order to counter this problem, essential technologies are called for to decrease occupational exposure to toxic metals. To prevent further contamination in animals and the environment, people should monitor exposure and do something to eliminate it. An urgent need exists to reduce the concentration of these harmful metals by modern scientific methods including bioremediation and pyrolysis to mitigate worldwide economic losses. In the future, developing more advanced methods to control heavy metals in wildlife will be essential. Collaboration at both national and international levels is crucial for creating effective strategies to prevent heavy metal toxicity and safeguard both wildlife and human health.

Conclusion

Heavy metal poisoning has become a significant environmental issue, with severe consequences for wildlife health as well as production. These metals are generally considered as bioaccumulative and are acknowledged to enter animals through the natural and anthropogenic processes. While some of it is used in physiological and biochemical activities, all metals may cause toxicity as well as interfere with metabolic processes and produce mutations. These metals are toxic to animals' bodies with the liver being the organ most commonly showing elements of toxicity, followed by the kidneys, brain as well as reproductive system. The prevention measures are important in the cases of controlling heavy metal pollution in animals. Other methods of bioremediation including phytoremediation may successfully remove heavy metals from the environment before they are consumed by animals. More investigations are needed to identify the molecular mechanisms and the physiological consequences associated with the exposure of animals to multiple hazardous metals.

References

Abbasi, N. A., Jaspers, V. L. B., Chaudhry, M. J. I., Ali, S., & Malik, R. N. (2015). Influence of taxa, trophic level, and location on bioaccumulation of toxic metals in bird's feathers: a preliminary biomonitoring study using multiple bird species from Pakistan. *Chemosphere*, *120*(2015), 527-537.

Angelidis, M. O., & Albanis, T. A. (1996). Pesticide residues and heavy metals in the Evros River Delta, NE Greece. *Toxicological & Environmental Chemistry*, *53*(1-4), 33-44.

Bano, Y., & Hasan, M. (1989). Mercury induced time-dependent alterations in lipid profiles and lipid peroxidation in different body organs of cat-fish *Heteropneustes fossilis*. *Journal of Environmental Science & Health Part B*, *24*(2), 145-166.

Batool, R., Mahmood, K., Ahmad, S. R., & Naeem, M. A. (2019). Geographic scenario of drinking water quality of Lahore Metropolitan, Pakistan, in response to urbanization and water demand: a GIS perspective. *Applied Ecology & Environmental Research*, *17*(2), 3973-3988.

Battaglia, A., Ghidini, S., Campanini, G., & Spaggiari, R. (2005). Heavy metal contamination in little owl (*Athene noctua*) and common buzzard (Buteo buteo) from northern Italy. *Ecotoxicology and Environmental Safety*, *60*(1), 61-66.

Biswal, T. (2022). Phytoremediation of soils contaminated with heavy metals: techniques and strategies. In *Advances in Bioremediation and Phytoremediation for Sustainable Soil Management: Principles, Monitoring and Remediation* (pp. 31-55). Cham: Springer International Publishing.

Butler-Dawson, J., James, K. A., Krisher, L., Jaramillo, D., Dally, M., Neumann, N.,& Newman, L. S. (2022). Environmental metal exposures and kidney function of Guatemalan sugarcane workers. *Journal of Exposure Science & Environmental Epidemiology*, *32*(3), 461-47.

Choe, S. Y., Kim, S. J., Kim, H. G., Lee, J. H., Choi, Y., Lee, H., & Kim, Y. (2003). Evaluation of estrogenicity of major heavy metals. *Science of the Total Environment*, *312*(1-3), 15-21.

Clarkson, T. W., & Strain, J. J. (2020). Methyl mercury: loaves versus fishes. *Neurotoxicology*, *81*, 282-287.

Cox, J. N., Rahman, M. A., Bao, S., Liu, M., Wheeler, S. E., & Knoell, D. L. (2016). Cadmium attenuates the macrophage response to LPS through inhibition of the NF-κB pathway. *American Journal of Physiology-Lung Cellular and Molecular Physiology*, *311*(4), 754-765.

da Silva, J. M., Alves, L. M., Laranjeiro, M. I., Silva, A., Angelico, M. M., Norte, A. C.,& Ceia, F. R. (2020). Mercury levels in commercial mid-trophic level fishes along the Portuguese coast–Relationships with trophic niche and oxidative damage. *Ecological Indicators*, *116*, 106500.

Dasharathy, S., Arjunan, S., Maliyur Basavaraju, A., Murugasen, V., Ramachandran, S., Keshav, R., & Murugan, R. (2022). Mutagenic, carcinogenic, and teratogenic effect of heavy metals. *Evidence-Based Complementary and Alternative Medicine*, *2022*(1), 8011953.

Debroy, S., Paul, A., & Shikha, D. (2024). Environmental Lead Exposure—A Continuing Challenge. In *Lead Toxicity Mitigation: Sustainable Nexus Approaches* (pp. 3-13). Cham: Springer Nature Switzerland.

Duruibe, J. O., Ogwuegbu, M. O. C., & Egwurugwu, J. N. (2007). Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences*, *2*(5), 112-118.

Ebrahimi, M., Khalili, N., Razi, S., Keshavarz-Fathi, M., Khalili, N., & Rezaei, N. (2020). Effects of lead and cadmium on the immune system and cancer progression. *Journal of Environmental Health Science and Engineering*, *18*, 335-343.

Edition, F. (2011). Guidelines for drinking-water quality. *WHO Chronicle*, *38*(4), 104-8.

Eeva, T., Belskii, E., & Kuranov, B. (2006). Environmental pollution affects genetic diversity in wild bird populations. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, *608*(1), 8-15.

Egendorf, S. P., Li, E., He, E., Cheng, Z., Spliethoff, H. M., Shayler, H. A.,& McBride, M. B. (2022). Effectiveness of washing in reducing lead concentrations of lettuce grown in urban garden soils. *Journal of Environmental Quality, 51*(4), 755-764.

Foster, W. G. (1992). Reproductive toxicity of chronic lead exposure in the female cynomolgus monkey. *Reproductive Toxicology*, *6*(2), 123-131.

Furtado, R., Pereira, M. E., Granadeiro, J. P., & Catry, P. (2019). Body feather mercury and arsenic concentrations in five species of seabirds from the Falkland Islands. *Marine Pollution Bulletin*, *149*(2019), 110574.

Ghafoor, N., Mehar, T., Batool, M., Salar, M. Z., Ahmed, M. Z. and Atique, U., 2024. Attenuative effects of poncirin against polyethylene microplastics-prompted hepatotoxicity in rats. *Journal of King Saud University-Science*, *36*(10), p.103475.

Grignet, A., Sahraoui, A. L. H., Teillaud, S., Fontaine, J., Papin, A., & Bert, V. (2022). Phytoextraction of Zn and Cd with Arabidopsis halleri: A focus on fertilization and biological amendment as a means of increasing biomass and Cd and Zn concentrations. *Environmental Science and Pollution Research*, 1-12.

Hossini, H., Shafie, B., Niri, A. D., Nazari, M., Esfahlan, A. J., Ahmadpour, M.,& Hoseinzadeh, E. (2022). A comprehensive review on human health effects of chromium: Insights on induced toxicity. *Environmental Science and Pollution Research*, *29*(47), 70686-70705.

Huang, J. H. (2016). Arsenic trophodynamics along the food chains/webs of different ecosystems: a review. *Chemistry and Ecology*, *32*(9), 803-828.

Huang, X., Luo, D., Chen, X., Wei, L., Liu, Y., Wu, Q.,& Liu, L. (2019). Insights into heavy metals leakage in chelator-induced phytoextraction of Pb-and Tl-contaminated soil. *International Journal of Environmental Research and Public Health*, *16*(8), 1328.

Jurasović, J., Cvitković, P., Pizent, A., Čolak, B., & Telišman, S. (2004). Semen quality and reproductive endocrine function with regard to blood cadmium in Croatian male subjects. *Biometals*, *17(6)*, 735-743.

Kalisinska, E. (2000). Lead and other heavy metals in the brain of geese hunted in the vicinity of Slonsk, Poland. *Biological Bulletin of Poznań*, *37*(2).87-95.

Kaur, S., Midha, T., Verma, H., Muduli, R. R., Dutta, O., Saini, O.,& Dhiman, M. (2023). Bioremediation: A favorable perspective to eliminate heavy metals from polluted soil. In *Metagenomics to Bioremediation* (pp. 209-230). Academic Press.Kawai, M., Swan, K. F., Green, A. E., Edwards, D. E., Anderson, M. B., & Henson, M. C. (2002). Placental endocrine disruption induced by cadmium: effects on P450 cholesterol side-chain cleavage and 3β-hydroxysteroid dehydrogenase enzymes in cultured human trophoblasts. *Biology of Reproduction*, *67*(1), 178-183.

Lemus, J.A., Blas, J., Pérez-Rodríguez, L., Piersma, T., & Carmona-Isunza, M.C. (2018). Current perspectives on the oxidative stress hypothesis in avian ecology. *Journal of Avian Biology, 49*(2), 01629.

Li, X., Zhang, X., Wang, X., & Cui, Z. (2019). Phytoremediation of multi-metal contaminated mine tailings with Solanum nigrum L. and biochar/attapulgite amendments. *Ecotoxicology and Environmental Safety*, *180*, 517-525.

Lin, Y. P., Anthony, J., Mukhtar, H., & Lin, C. M. (2021). A spatial prioritization method for identifying potential eco-risk distributions of heavy metals in soil and birds. *Ecotoxicology and Environmental Safety*, *220*(76) 112383.

Liu, J. Y., Yang, X., Sun, X. D., Zhuang, C. C., Xu, F. B., & Li, Y. F. (2016). Suppressive effects of copper sulfate accumulation on the spermatogenesis of rats. *Biological Trace Element Research*, *174*(2016), 356-361.

Muradoglu, F., Gundogdu, M., Ercisli, S., Encu, T., Balta, F., Jaafar, H. Z., & Zia-Ul-Haq, M. (2015). Cadmium toxicity affects chlorophyll a and b content, antioxidant enzyme activities and mineral nutrient accumulation in strawberry. *Biological Research*, *48*(2015), 1-7.

Nedjimi, B. (2021). Phytoremediation: a sustainable environmental technology for heavy metals decontamination. *SN Applied Sciences*, *3*(3), 286.

Nriagu, J. O. (1988). A silent epidemic of environmental metal poisoning?. *Environmental Pollution*, *50*(1-2), 139-161.

Oktapodas-Feiler, M., Caserta, M. T., van Wijngaarden, E., Thevenet-Morrison, K., Hardy, D. J., Zhang, Y. V., ... & Jusko, T. A. (2020). Environmental lead exposure and influenza and respiratory syncytial virus diagnoses in young children: A test-negative case-control study. *International Journal of Environmental Research and Public Health*, *17*(20), 7625.

Parveen, N., Zaidi, S., & Danish, M. (2019). Support vector regression (SVR)-based adsorption model for Ni (II) ions removal. *Groundwater for Sustainable Development*, *9(2019)*, 100232.

Parveen, N., Zaidi, S., & Danish, M. (2020). Support vector regression: A novel soft computing technique for predicting the removal of cadmium from wastewater. *Indian Journal of Chemical Technology (IJCT)*, *27*(1), 43-50.

Pattee, O., & Pain, D. 2003. Lead in the environment. In D.J. Hoffman, B.A. Rattner, G.A. Burton Jr, and J. Cairns Jr (Eds.), *Handbook of ecotoxicology, (2),* (pp. 373-408). Boca Raton, Florida, USA: CRC Press.

Pérez-López, M., de Mendoza, M. H., Beceiro, A. L., & Rodríguez, F. S. (2008). Heavy metal (Cd, Pb, Zn) and metalloid (As) content in raptor species from Galicia (NW Spain). *Ecotoxicology and Environmental Safety*, *70*(1), 154-162.

Piasek, M., & Laskey, J. W. (1994). Acute cadmium exposure and ovarian steroidogenesis in cycling and pregnant rats. *Reproductive Toxicology*, *8*(6), 495-507.

Rahman, M. M., Rahaman, M. S., Islam, M. R., Rahman, F., Mithi, F. M., Alqahtani, T.,& Uddin, M. S. (2021). Role of phenolic compounds in human disease: current knowledge and future prospects. *Molecules*, *27*(1), 233.

Rai, P. K. (2019). Heavy metals/metalloids remediation from wastewater using free floating macrophytes of a natural wetland. *Environmental Technology & Innovation*, *15(2019)*, 100393.

Rathika, R., Srinivasan, P., Alkahtani, J., Al-Humaid, L. A., Alwahibi, M. S., Mythili, R., & Selvankumar, T. (2021). Influence of biochar and EDTA on enhanced phytoremediation of lead contaminated soil by Brassica juncea. *Chemosphere*, *271*, 129513.

Salar, M. Z., Bibi, Z., Hassan, T., Hussain A., & Ijaz, M. U. (2024). Cellular crossroads: Oxidative stress, inflammation and apoptosis in molecular biology. In M.U. Ijaz, N. Ehsan, M. Imran & S. Yousaf (Eds.), *Zoology: Advancements and Research Trends* (pp. 37-43). FahumSci, Lahore, Pakistan.

Savinov, V. M., Gabrielsen, G. W., & Savinova, T. N. (2003). Cadmium, zinc, copper, arsenic, selenium and mercury in seabirds from the Barents Sea: levels, inter-specific and geographical differences. *Science of the Total Environment*, *306*(1-3), 133-158.

Sebastian, A., Deepa, P., & Prasad, M. N. V. (2021). Azolla farming for sustainable environmental remediation. *Handbook of assisted and amendment: Enhanced sustainable remediation technology*, 517-533.

Slivinska, L. G., Shcherbatyy, A. R., Lukashchuk, B. O., & Gutyj, B. V. (2020). The state of antioxidant protection system in cows under the influence of heavy metals. *Regulatory Mechanisms in Biosystems*, *11*(2), 237-242Stefanidis, K., Sarika, M., & Papastegiadou, E. (2019). Exploring environmental predictors of aquatic macrophytes in water-dependent Natura 2000 sites of high conservation value: Results from a long-term study of macrophytes in Greek lakes. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*(7), 1133-1148.

Storelli, M. M., Giacominelli-Stuffler, R., & Marcotrigiano, G.O. (2019). Heavy metals in the environment and their health risks in some animal species. *Environmental Monitoring and Assessment, 191*(4), 192.

Strużyńska, L., Dąbrowska-Bouta, B., Koza, K., & Sulkowski, G. (2007). Inflammation-like glial response in lead-exposed immature rat brain. *Toxicological Sciences*, *95*(1), 156-162.

Sukocheva, O. A., Yang, Y., Gierthy, J. F., & Seegal, R. F. (2005). Methyl mercury influences growth-related signaling in MCF-7 breast cancer cells. *Environmental Toxicology: An International Journal*, *20*(1), 32-44.

Taupeau, C., Poupon, J., Nomé, F., & Lefèvre, B. (2001). Lead accumulation in the mouse ovary after treatment-induced follicular atresia. *Reproductive Toxicology*, *15*(4), 385-391.

Ullah, K., Hashmi, M. Z., & Malik, R. N. (2014). Heavy-metal levels in feathers of cattle egret and their surrounding environment: a case of the Punjab Province, Pakistan. *Archives of Environmental Contamination and Toxicology*, *66(2014)*, 139-153.

Volkov, R., & Ezhkova, A. (2020). Migration of heavy metals in the system "soil-plant-animal-livestock products". In *BIO Web of Conferences*, 27, 00068.EDP Sciences.

Wang, L., Zhang, X., Ma, W., Chen, X., & Liu, C. (2019). Toxic effects of heavy metals on aquatic animals. In: A.A. Ansari, S.S. Gill, R. Gill, & G.R. Lanza (Eds.), *Heavy Metal Contamination of Soils*, (pp. 169-191). Springer.

Xu, C., Yan, H., & Zhang, S. (2021). Heavy metal enrichment and health risk assessment of karst cave fish in Libo, Guizhou, China. *Alexandria Engineering Journal*, *60*(1), 1885-1896.

Yang, Y., Ge, Y., Tu, P., Zeng, H., Zhou, X., Zou, D.,& Zeng, Q. (2019). Phytoextraction of Cd from a contaminated soil by tobacco and safe use of its metal-enriched biomass. *Journal of Hazardous Materials*, *363(2019)*, 385-393.

Zheng, K., Zeng, Z., Tian, Q., Huang, J., Zhong, Q., & Huo, X. (2023). Epidemiological evidence for the effect of environmental heavy metal exposure on the immune system in children. *Science of the Total Environment*, *868*, 161691.