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Mercury and lead in environment and their impact on plants, animals and humans: A review

O.P. Bansal

Chemistry Department, D.S. College, Aligarh

Abstract:
Due to rapid industrialization, urbanization, mining, fossil fuel combustion, agricultural activities, and improper waste disposal, lead (Pb) and mercury (Hg) non-essential, highly toxic metals with no known biological functions in animals and humans are globally present in all compartments of the environment. Climate change and human activities further influence the concentrations of these metals across different ecosystems. The Agency for Toxic Substances and Disease Registry has ranked mercury third most hazardous substance. Mercury in aquatic food (seafood and fish) exists in the more toxic organic form methylmercury. Once inside an organism's body, these metals affect almost all biological systems. These metals, even at very low concentrations, seriously impact healthcare systems and cause public health threats. These metals in animals and humans mainly impact the nervous system, respiratory, cardiovascular and reproductive systems. Mercury is associated with cancer and disorders in the kidney, liver and neurotoxicity, as well as neurodegenerative diseases including Parkinson's and Alzheimer's disease. Lead, because of its chemical similarity to calcium, accumulates predominantly in bone tissues, particularly in children, and negatively impacts skeletal development. Lead also replaces essential metal ions in enzymes and proteins, causing mitochondrial dysfunction, oxidative stress, and DNA damage with negative effects on neurodevelopmental processes in animals and humans. This review summarizes recent findings on the effects of these metals on plants, aquatic organisms, terrestrial animals, and humans. The present study will provide data for policymakers to formulate guidelines for the reduction of health risks to humans caused by these most persistent pollutants

Keywords: Lead and mercury, toxicity, plants, aquatic organisms, sources, health effects

1. Introduction:

Potentially toxic metals (Cu, Zn, Co, Ni, Cr, Mn, Fe, Ba, Hg, Cd, Pb, As, Mo, and Sn) that are 5 or more times heavier than water with atomic weight ranging from 64 to 201, are present in the Earth crust because of their unique physical and chemical properties are utilized by human civilizations, including the Indians, Romans, Greeks, and Egyptians. Mercury and lead metals are termed as non-essential toxic metals, as these metals, even in small amounts, are not required by plants, humans and other animals for their metabolic activities (Jomova et al., 2025). Mercury (Hg) most toxic, non-radioactive metal and is widely used in medicine, agriculture, industry, mining, electrical equipment, and scientific instruments (Charkiewicz et al., 2025). Lead, which occupies 0.002% of the Earth's crust, is the second most toxic metal and is used in cosmetics, traditional medicines, pigments, paints, stained glass, lead-acid batteries, radiation shielding for X-ray equipment and nuclear reactors, bullets and shotguns, electrical soldering, toys, children's jewellery, and in the preparation of industrial alloys (ATSDR, 2020). The recent literature data suggest that globally approximately 5000-8000 metric tonnes of mercury enter the environment per year (Noto, 2021). The data also denote that the global mercury market, valued at approximately USD 5.334 billion in 2025, is projected to reach USD 6.19 billion by 2035. Similarly, the global production of lead in 2025 was 16 million tonnes, of which 4.6 million tonnes were from lead mines **(**Kinally et al., 2025). The worldwide lead market, valued at nearly USD 30.9 billion in 2025, is expected to increase to USD 43.1billion by 2035 (Global Market Insights, 2026). The extensive utilization of mercury and lead in different sectors has resulted in their widespread presence in all the compartments of the environment, i.e. air, water, soil, food chain, fish and other aquatic animals, medicines and other consumer products (Laoye et al., 2025). When humans and animals (aquatic and terrestrial animals) are exposed to these toxicants, these metals are accumulated in the body due to the formation of lipophilic ions by forming covalent bonds between metal-organic groups and non-metallic elements of cellular macromolecules. These metals are distributed throughout the body via the circulatory system. The accumulation of these metals in the body is via the blood circulation system; upon accumulation, these toxicants cause organ dysfunction (Ohiagu et al., 2022). Accumulation of these toxicants depends on several factors such as metal concentration, exposure route and duration, age, gender, nutritional status of the human/animal and genetic susceptibility of the exposed organism. The research data denote that globally, approximately 800 million children in their blood have lead concentration exceeding than 5ug/dL, with reported levels reaching as high as upto14.3ug/dL in some individuals (UNICEF, 2020). The data also denote that the global economic burden due to lead exposure in children is approximately USD 3.4 trillion USD per year. Consumption of methylmercury-contaminated seafood and fish is the major source of mercury contamination to humans and a public health concern worldwide. These toxic metals bind with DNA and nuclear proteins, causing structural and functional damage that contributes to DNA strand breaks, chromosomal abnormalities, impaired DNA repair mechanisms, cell cycle modulation, apoptosis, and carcinogenesis (Mousavi et al., 2024). Neurological damage, central nervous system disorders, kidney diseases, liver diseases, and cardiovascular risks in humans are reported due to the accumulation of these toxic metals. In animals, these metals also act as endocrine disruptors, significantly reducing reproductive success, egg hatchability, and offspring survival rates. Intellectual disabilities and behavioural changes leading towards violence are reported in those children who are exposed to a low dose of these toxic metals for a longer period (Gonzalez-Villalva et al., 2025; Choudhary & Koppala, 2022).

The present review examines the most recent available literature on the sources, environmental distribution, toxicity, and adverse effects of mercury and lead on plant growth and crop productivity, aquatic organisms, terrestrial animals, and human health. Current knowledge gaps and future strategies for monitoring, remediation, and sustainable management of these toxic metals are discussed.

2. Sources of Potentially Toxic Metals: mercury and lead;

Mercury (Hg) and lead (Pb) enter the environment through natural sources as well as due to anthropogenic activities. Anthropogenic activities are the major contributors of these metals in air, water, soil, and living organisms.

2.1 Natural Sources

Mercury is naturally present in the Earth's crust, primarily as cinnabar (HgS). It also occurs in naturally occurring raw materials such as coal, crude oil, other fossil fuels, and various metal ores. Weathering of rocks, volcanic eruptions, and geothermal activities release mercury into the environment in elemental (Hg^0), inorganic (Hg^{2+}), and particulate forms. Additional natural sources include volcanic ash, forest fires, and wind-blown soil particles. Furthermore, mercury previously deposited on vegetation, soils, and water bodies in its oxidised form can be reduced through photochemical and biological processes and subsequently re-emitted into the atmosphere. According to recent estimates, natural terrestrial emissions of mercury range from 2,000 to 2,500 metric tonnes annually, while re-emissions from terrestrial ecosystems contribute an additional 1,000–2,000 metric tonnes per year. Oceanic re-emissions are even greater, amounting to approximately 7,200 metric tonnes annually (Zhang et al., 2023**)**. Recent studies have also indicated that climate change has increased atmospheric deposition of mercury by approximately 12% and deposition into the oceans by about 9%.

Lead is the second most abundant naturally occurring toxic metal and constitutes approximately 0.002% of the Earth's crust. It occurs mainly as galena (PbS), anglesite ($PbSO_4$), and cerussite ($PbCO_3$). Natural weathering of lead-containing rocks releases lead into surrounding soils, sediments, surface water, and groundwater. Volcanic eruptions and forest fires also emit lead-containing particles into the atmosphere. In coastal environments, marine aerosols and ocean spray serve as additional natural sources of atmospheric lead.

2.2 Anthropogenic Sources

Human activities are the predominant contributors to mercury contamination of the environment. Coal combustion in thermal power plants and residential heating systems is a major source of atmospheric mercury because coal naturally contains mercury. Significant emissions also arise from iron and steel manufacturing, non-ferrous metal smelting, and cement production. Globally, artisanal and small-scale gold mining (ASGM) represents the largest source of anthropogenic mercury emissions. It has been estimated that ASGM provides the primary livelihood for nearly 100 million people across 55 countries in Asia, South Asia, Africa, and Latin America (Gupta and Yadav, 2024). Mercury is also released into the environment through the manufacture and disposal of rechargeable batteries, chlor-alkali plants, hospital spills involving thermometers and barometers, dental amalgam and associated waste, incineration of municipal and biomedical waste, fluorescent lamps, electrical switches and relays, pharmaceutical manufacturing, cosmetic products, paints, latex gloves, diapers, and explosives.

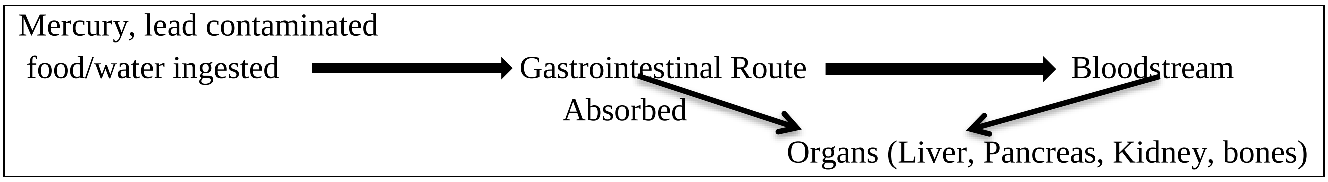
Anthropogenic activities are likewise the principal cause of lead accumulation in the environment. Lead contamination originates from a wide range of domestic, industrial, and agricultural sources. Lead-based paints remain an important source, particularly during renovation or demolition of older buildings, where sanding and weathering generate lead-contaminated dust and soil. Mining, smelting, and processing of lead, zinc, and copper ores release substantial quantities of lead into the atmosphere, water bodies, and surrounding soils. Lead-acid batteries used in automobiles and backup power systems are among the largest contributors to global lead pollution, especially during informal recycling and repair operations. Other important sources include leaded aviation gasoline, old toys, furniture, lead-glazed ceramics, jewellery, soldered food cans, contaminated spices, fertilizers, pesticides, pottery glazing, shooting ranges (from lead ammunition), municipal solid waste, and sewage sludge. Collectively, these activities have significantly increased human exposure to lead and its accumulation in terrestrial and aquatic ecosystems (Wroblewski et al., 2025; Raj and Das, 2023).

3. Routes of Contamination:

Primarily, the toxic metals mercury and lead enter the human and animal body through dietary ingestion and environmental exposure; the airborne toxic metals emitted from industrial processes impact the human or animal body via inhalation and/or skin absorption. After absorption, these metals are transported to various organs and tissues through the bloodstream.

3.1 Ingestion (Gastrointestinal Route): The major route of exposure in humans to both mercury and lead is ingestion. The mercury in the organic form (methyl mercury) enters the human body by eating contaminated fish and shellfish. Inorganic mercury enters the body by ingesting certain traditional medicinal products, contaminated plant foods, mercury contaminated water and drinking contaminated beverages. Mercury also enters the body of children via ingestion due to consumption of contaminated soil or dust. Low levels of mercury are also absorbed by the body which is released from dental amalgam.

Lead is primarily absorbed through the gastrointestinal tract due to the consumption of contaminated vegetables, fruits, cereals, meat, seafood (including fish), and drinking water contaminated by lead pipes, or drinking contaminated beverages. Lead is also ingested by humans via hand-to-mouth contact with lead-contaminated dust and soil, particularly among young children.



3.2 Inhalation (Respiratory Route): Another major route of exposure of mercury and lead to humans and animals is inhalation. During breathing, airborne elemental mercury vapor and lead dust fumes originating from industrial settings or household items, renovation, and dental amalgam are inhaled by humans or pet animals. These toxic metals in very small particles are deposited in the respiratory tract; from there, they reach the lungs and bloodstream. Elemental mercury vapour easily crosses the alveolar membrane and can cross the blood-brain barrier, resulting in neurotoxicity.

3.3 Dermal absorption: Mercury in the inorganic form enters the skin due to the use of unregulated skin-lightening soaps, creams and cosmetic products containing inorganic mercury**.** In aquatic animals and, in workers who handle these toxic metals, dermal absorption is the major pathway of contamination. After absorption, these metals are bioaccumulated in the epidermis, hair, hair follicles, and nails.

After entering the bloodstream, mercury and lead are accumulated in the liver, kidneys, pancreas, brain, bones, skin, hair, nails, and myocardial tissues. Lead is mainly accumulated in bones and teeth.

4. Impact of mercury and lead on plants:

Entry of potentially toxic metals mercury and lead in the plant system primarily occurs through roots and foliar uptake from contaminated soils. Environmental factors such as soil pH, soil organic matter, humidity, cation exchange capacity, plant species, growth stage, and concentration of competing cations influence uptake and accumulation of these metals by plant tissues. The roots of the plant absorb metal ions from the soil with nutrients and transport them to the endodermis and aerial tissues via xylem vessels (Asiedu et al., 2023; Ali and Gill, 2022). Foliar uptake occurs through cuticular penetration and stomatal absorption. The processes of bioavailability, absorption, bioconcentration and biomagnification are the processes that lead to the accumulation of lead and mercury in plant tissues. The accumulation of mercury and lead in plants causes morphological, anatomical, biochemical and molecular changes through the excessive generation of reactive oxygen species (ROS) (Viswanthan and Nagella, 2026; Patnaik et al., 2025; Gupta et al., 2024).

Elevated concentrations of these metals significantly inhibit seed germination rate, root elongation, shoot growth, root biomass, leaf development, nutrient uptake, root respiration, and soil microbial activity (Viswanthan and Nagella, 2026; Gupta et al., 2024). Collin et al (2022**),** during their studies on rice, found that lead accumulation reduces root growth by 42% and seed germination by 14-30%. Similarly, Elik and Gül (2025) observed that lead accumulation in maize reduces plant height by 20%, dry biomass by 25% and relative water content of leaves by 62%.

Accumulation of mercury and lead adversely affects plant growth and productivity by disrupting several fundamental physiological and metabolic processes. These metals decrease the rate of photosynthesis by negatively impacting chlorophyll biosynthesis, ATP production and altering carbohydrate, protein, and nitrogen metabolism. They also impair the activity of numerous enzymes and structural proteins by interacting with sulfhydryl (–SH) groups, resulting in protein denaturation and enzyme inactivation. Mercury and lead interfere with the uptake and translocation of essential mineral nutrients such as magnesium (Mg), iron (Fe), calcium (Ca), zinc (Zn), and manganese (Mn), essential for chlorophyll synthesis, photosynthesis, and normal plant metabolism. A decrease in chlorophyll content causes chlorosis and reduced photosynthetic capacity (Mohamed et al., 2025; Labudda et al., 2022). When mercury and lead are accumulated in higher amounts these metals damage the cellular membrane which increases membrane permeability and electrolyte leakage. These metals also induce stomatal closure, thereby reducing transpiration, limiting carbon dioxide diffusion into leaves, and further suppressing photosynthetic carbon assimilation in several species, viz., tobacco (Nicotiana tabacum), white lead tree (Leucaena leucocephala), black gram (Vigna mungo), and soybean (Glycine max). Accumulation of lead in plants not only interferes in the uptake of essential nutrients (Ca^{2+}, Zn^{2+}, Mg^{2+}, Mn^{2+}, Fe^{2+}) but also produce excessively reactive oxygen species (ROS) via hydrogen peroxide (H_2O_2), superoxide radicals ($O_2{\bullet}^-$), and hydroxyl radicals (•OH) that results oxidative stress, membrane damage, DNA injury, and cellular dysfunction (Gupta et al., 2024; Ur Rahman et al., 2024).

5. Impact of mercury and lead on aquatic organisms:

Contamination of surface waters with the toxic metals mercury (Hg) and lead (Pb) not only deteriorates water quality by altering dissolved oxygen concentrations, pH, turbidity, etc., but also disrupts the ecology by interfering with the physiological, metabolic and cellular functions of aquatic organisms. Ahmad et al. (2021**)** reported mercury concentrations of 4-10ug/L and lead concentrations 20-45 ug/L in river water; while Ahmad et al. (2024) found lead concentrations ranged from15.6-50mg/kg in river sediments.

Microorganisms present in waterways convert the inorganic mercury into a more hazardous bioorganic form, methylmercury (MeHg). Studies have shown that MeHg in waterways causes toxic effects on phytoplankton by inducing oxidative stress, impairing photosynthesis, and inhibiting growth (Jeong et al., 2024; Guo et al., 2023). These effects cause physiological and metabolic abnormalities impacting development and reproduction. Similarly, Nys & De Schamphelaere (2023), during their research studies, found that lead, even at a very low concentration, inhibits phytoplankton growth and reduces cell abundance. Accumulation of lead in water also adversely affects aquatic microorganisms. Ashkan (2023) observed that protein content and enzyme activity are reduced in the bacterium Thermus thermophilus strain Samu-SA1 on exposure to lead. Likewise, Li et al. (2024) and Titilawo et al. (2023), during their studies, reported that lead exposure induces morphological and physiological alterations in fungal cells, e.g. cell deformation and cell wrinkling. Lead accumulation in fungi disrupts cellular membranes, DNA structure, and enzymatic functions by producing excessive reactive oxygen species (ROS) that result in oxidative stress (Collin et al., 2022). Lead exposure also markedly reduces the concentrations of photosynthetic pigments such as chlorophyll-a, phycocyanin, and phycoerythrin, that retards the light-harvesting capacity of phytoplankton, particularly of algae (Gao et al., 2025**).** Lead accumulation lowers the photochemical efficiency of phytoplankton and reduces photosynthetic activity. Studies have also shown that the toxicity of lead to phytoplankton is higher in acidic and phosphorous-deficient water media, which increases the availability and uptake of the metal (Gao et al., 2025; Chang et al., 2023; Nys and De Schamphelaere, 2023). Anjum & Kumari (2025) and Isibor et al. (2020) reported that methylmercury adversely impacts not only phytoplankton but also zooplankton, the base of the aquatic food web. These metals adversely impact the diversity of the Zooplankton community; impair their growth and reproduction, and very rapidly biomagnify and bioaccumulate in the food chains. Mercury, a potent neurotoxin, also causes neurological impairment, including cognitive and motor dysfunction, in zooplankton (Zhang et al., 2025; Kumar et al., 2023**).** Due to the presence of high-quality proteins, vitamins, minerals, other nutrients and unsaturated fatty acids (having cardio protective capacity), fish and other seafood are considered an essential part of the balanced diet. Fish and other seafood absorb toxic metals, such as lead and mercury, from the surrounding water and food, i.e., plants and animals. The accumulation of these metals depends on the concentration of these metals in the surrounding environment, food quality; animal characteristics, water pH, and water dissolved organic content (Brodziak-Dopierala & Fischer, 2023). In fish and other seafood, mercury is accumulated in organic form, i.e. methyl mercury, which is more toxic than inorganic mercury, whereas lead accumulates in calcium-rich tissues such as bones and gills. The mercury concentrations in marine fish have been reported from 17-278 ug/kg, whereas freshwater fish contain 0.10-606 ug/kg (Garofalo et al., 2025; Brodziak-Dopierala & Fischer, 2023; Mielcarek et al., 2022). Lead concentrations range from 0.23-220 ug/kg in marine fish and 0.22-171.4 ug/kg in freshwater fish. Chen and Dong (2022) further reported that carnivorous fish generally accumulate more mercury than omnivorous fish. In other seafood, including bivalve mollusks, cephalopods, marine gastropods, and echinoderms, mercury and lead concentrations range from 0-1.9mg/kg and 0-3.2mg/kg respectively **(**Garofalo et al., 2025). These toxic metals, after entering the fish body, are accumulated in the liver, kidney, gills and digestive tract **(**Mahi et al., 2022**).** Accumulation of mercury in marine and freshwater fish and other seafood affects skeletal development, skin, central and peripheral nervous system, gastrointestinal tract, kidney function, liver function, reproductive system, neurological and behavioral disturbances, and enzyme function (De Almedia et al., 2024; Zhao et al., 2024; Mielcarek et al., 2022). Similarly, lead accumulation significantly reduces growth, disrupts enzyme activity, impairs reproductive capability, induces histological changes in liver and gills with DNA damage, haemorrhage, blood clot formation, cellular degeneration, and necrosis, in addition to causing severe neurological dysfunction (De Almedia et al., 2024; Banday et al., 2023; Kontas, 2022).

6. Impact of mercury and lead on terrestrial animals:

Mercury and lead are non-essential metals without any beneficial biological functions in living organisms. These metals persist in terrestrial ecosystems and undergo bioaccumulation and biomagnification through the food chain, resulting in adverse effects on domestic animals, wildlife, and birds**.** Hussain et al. (2024), during their studies, found lead concentrations of 2.47 mg/L in the blood of buffaloes and 1.05-2.35mg/kg in the wool hair of sheep. In poultry animals, lead is accumulated in the kidneys, liver, reproductive organs, and lungs, as reported by Aljohani (2023). These metals adversely affect multiple physiological systems, including the hematopoietic, vascular, nervous, renal, immune, and reproductive systems and disrupt the enzyme systems in animals (Afzal and Mahreen, 2024; Mukherjee et al., 2022). These metals also cause severe neurological damage and disrupt endocrine functioning. In vertebrates, excessive generation of reactive oxygen species (ROS) due to mercury and lead accumulation causes lipid peroxidation, protein oxidation, DNA damage, mitochondrial dysfunction, and apoptosis. Accumulation of these metals in animals, including birds, causes anemia, lethargy, tremors, impaired senses, muscle wastage, loss of fat reserves, green diarrhea staining the vent, wing droop, loss of balance and coordination, leg paralysis or convulsions (Sun et al., 2022). In terrestrial animals, lead predominantly accumulates in the kidney and liver, causing nephrotoxicity and hepatotoxicity, whereas mercury accumulates in the brain, lungs, heart, kidneys and liver (Hailu & Mulugeta, 2026). Kumar et al. (2023) reported ocular abnormalities, cleft palate, neurobehavioural changes and underweight offspring in wild monk and Greenlandic polar bears due to accumulation of mercury. Malnutrition, muscle loss, opaque hair, ataxia, anemia, paresis of the hypoglossal nerve, convulsions, reproductive impairment and aberrant fetal development are observed in cattle when lead accumulates in their body (Das et al., 2023; Tahir & Alkheraije, 2023; Roy & Edwards, 2022**).**

Due to impairing growth, reproduction, neurological function, immune competence, and survival, mercury and lead pose a significant threat to terrestrial animals by reducing livestock productivity and adversely impacting wildlife conservation.

7. Impact of mercury and lead on Humans:

7.1 Mercury toxicity

Human exposure to mercury that has no known positive functionality in the human body occurs in the metallic, inorganic and organic forms primarily via contaminated food, drinking water, and air. Mercury exposure adversely affects almost every organ system of the human body. Accumulation of mercury in the human body causes disorders in the central nervous system, respiratory (reduces lung functioning), cardiovascular system, digestive, reproductive, immune, endocrine, renal, hepatic, skeletal, blood vessels and adversely affects formation and function of the immune cell (WHO, 2024; Feiler et al., 2024; Philibert et al., 2022). Several neurological and behavioral disorders like memory loss, tremor, anxiety, depression, hallucinations, cognitive and motor disturbances, disruption in sensory systems (retinopathy, loss of hearing/vision), ASD (autism spectrum disorder), neurodegenerative diseases (Parkinson's and Alzheimer's disease), neuronal degeneration and Minamata-byo diseases were observed by Kort et al. (2024), Ogundare and Obeng-Gyasi, (2024), WHO (2024), Miao et al (2023) and Bjorklund et al. (2022). Reproductive health in both sexes of humans is negatively impacted on exposure to mercury, reduced testicular weight; inferior sperm quality and erectile dysfunction in males and ovarian dysfunction, menstrual irregularities, premature menopause, spontaneous abortion and infertility in females were observed by Dutta & Ruden (2024) and Nyanza et al. (2020). Cardiovascular toxicity such as endothelial dysfunction, hypertension, myocardial infarction, cardiac muscle injury, arrhythmias, and increased risk of cardiovascular diseases are reported due to mercury exposure by Ijomone et al. (2025), Kim et al. (2022) and Pavan et al. (2022). Vascular dysfunction is also reported due to oxidative stress caused by mercury. Mercury accumulation causes kidney diseases, viz., high protein content in urine, elevated urinary biomarkers such as gamma-glutamyltransferase, oxidative stress, and progressive renal dysfunction. Mercury also adversely impacts liver functioning, pancreas functioning and disrupts glucose metabolism, resulting to metabolic disorders (Adetunj and Obeng-Gyasi, 2024; Tian et al., 2023). Li et al. (2024) observed that mercury accumulation accelerates osteoporosis, osteoarthritis, and rheumatoid arthritis. Mercury exposure also negatively affects skin (causes skin rashes, scarring, and skin discoloration and reduces the skin resistance to microbial infections), as observed by Manful et al. (2024) and Podgorska et al. (2021). The literature data suggests that chronic mercury exposure contributes to mitochondrial dysfunction, oxidative DNA damage, epigenetic and gene sequence alteration, resulting in the increasing the risk of liver, kidney, thyroid, gall bladder, colon, prostate, lung, breast, skin cancer, as well as hematological malignancies such as leukemia (Hodgkin disease) (Wu et al., 2024; Li et al., 2024**)**

Human systems negatively impacted by Mercury exposure:

- Respiratory system
- Reproductive and endocrine system
- Metabolic system
- Liver and kidneys
- Skin and hair
- Skeletal system

- Immune system
- Cardiovascular and Circulatory system
- Nervous and Neurological systems
- Digestive system
- Cancer development and progression

7.2 Lead toxicity:

Accumulation of lead in the human body adversely affects nearly every organ and biological system **(**Generalova et al., 2025). The toxicity of lead is due to oxidative stress caused by excessive generation of reactive oxygen species (ROS), which damages DNA, disrupts protein folding, causes lipid peroxidation and cell membrane damage, and causes mitochondrial dysfunction (Generalova et al., 2025; Scutarasu and Trinca, 2023). Lead in the human body causes disorders in the nervous, pulmonary, hepatic, cardiovascular, gastrointestinal, reproductive, skeletal, hematological, immune, endocrine systems and dermatological systems. Prolonged lead accumulation causes proximal tubular dysfunction, renal hyperplasia, progressive chronic kidney diseases, renal failure, interstitial fibrosis and glomerulonephritis (Liang et al., 2025; Upadhyay et al., 2024; WHO, 2024). Cardiovascular toxicity is also caused by lead exposure. Rosengren et al. (2024) reported that prolonged exposure to lead increases the risk of cardiovascular diseases (CVD) (hypertension, peripheral arterial disease, ischemic heart disease, and stroke); they also reported that approximately 5.5 million deaths are due to CVD. Lead in blood is bound to red blood cells (erythrocytes) which increase the blood pressure and vascular dysfunction (Nucera et al., 2024; Dang et al., 2024). In humans 2ug/dL lead in blood increases the risk of hypertension and peripheral arterial disease according to the findings of Nucera et al. (2024). Significant immunological alterations were reported in humans, particularly in children, when exposed to lead. Exposure increases susceptibility to allergic responses and infectious diseases and promotes autoimmune disorders (Hong et al., 2025; Zhang et al., 2024). Lead exposure in younger individuals causes reproductive problems in both males and females. Lead exposure delays sexual maturation, reduces reproductive capabilities, disrupts sex hormonal secretions, reduces sperm quality, and adversely affects pregnancy outcomes (Aliche et al., 2025; Shan et al., 2023). Alcala et al. (2025) found that in children aged 5-14 years, lead exposure causes bronchial asthma, higher frequencies of eosinophilia and increased serum IgE levels. Lead exposure in humans also impacts bone health as lead replaces calcium within the bone matrix, retards vitamin D metabolism and dietary calcium uptake (Battistini et al., 2024; Wang et al., 2024). Zabihi et al. (2025) and Wang et al. (2024**)** found a significant negative correlation between lead accumulation and bone mineral density, increasing the risk of osteoporosis and skeletal abnormalities. In the human body approximately 33% of soft tissue lead is stored in liver, where it alters serum liver enzymes activities, including lactate dehydrogenase (LDH), aspartate aminotransferase (AST), alkaline phosphatase (ALP), and alanine aminotransferase (ALT), (viz., LDH, AST, ALK, ALT) and decreases total serum protein concentrations (Firoozichahak et al., 2022). Lead exposure also alters the composition and metabolic activity of the gut microbiota, causing gastrointestinal dysfunction (Renu et al., 2021; Yu et al., 2021). Lead, a well-established neurotoxin, upon accumulation, negatively impacts the neuronal networks and alters the ionic mechanisms of neurotransmitters. Prenatal and postnatal exposure to lead alters CNS structure and function, resulting in reduced intelligence quotient (IQ), poor academic performance, behavioral disorders and may cause paralysis, coma, or even death (Zhang et al., 2024; Alva et al., 2024; Collin et al., 2022).

Human organ toxicity caused by Lead exposure

- Reproductive system
- Blood and Circulatory system
- Nervous and Neurological system
- Cardiovascular system

- Immune system
- Endocrine and metabolic systems
- Respiratory system
- Bones & Skeletal system
- Ophthalmological (visual system
- Liver and Kidneys
- Gastrointestinal system

8. Current Gaps

- For effective environmental management and the protection of animal and public health, timely studies regarding the sources of lead and mercury, environmental fate, their chemical behavior, i.e. mobility, toxicity, and bioaccumulation are a key necessity.
- The impact of climate change on the environmental release, transport, and transformation of mercury and lead and global methylmercury production remains insufficiently investigated.
- There are very limited studies on the combined effects of mixtures of potentially toxic metals and other environmental stressors such as Microplastics, antibiotics, and pesticides on ecosystems, animals and humans.
- Very efficient laboratory experiments regarding the removal of these metals are not so effective in the field or on an industrial scale in the natural environment.
- In many developing countries, long-term monitoring data on mercury and lead contamination in terrestrial ecosystems, agricultural soils, food chains, and wildlife are still inadequate.

9. Future Strategies:

- Future research studies must be focused on reducing the global release and environmental emissions of mercury and lead by applying cleaner industrial technologies, sustainable mining practices, and strict regulatory measures.
- Studies must be conducted to identify and develop microbes and plants that can bioremediate and phytoremediate these metals from water and soils without disturbing ecosystem functions.
- Advanced water treatment methods such as activated carbon injection, membrane filtration, and electrochemical treatment, thermal desorption method, ion exchange, nanotechnology-based adsorbents, and advanced oxidation processes must be adopted to remove these metals from industrial effluents and domestic discharge.
- To characterize and mitigate risks of mercury and lead, there is a need to promote interdisciplinary and trans-disciplinary research to integrate toxicology, ecology, climatology, environmental chemistry, molecular biology, and public health.
- Public awareness programs based on scientific data through local communities on the negative impacts of these metals and their accumulation in seafood, fish, agricultural products, and medicinal plants are necessary to minimize human exposure.

- Methods such as remote sensing and artificial intelligence-based environmental surveillance must be developed for the early detection and continuous monitoring of mercury and lead contamination.
- International cooperation should be strengthened to ensure effective implementation of environmental regulations.

10. Conclusion:

The data of the present review demonstrate that mercury and lead, hazardous non-essential toxic metals, are contaminating water, the food chain, and air due to industrial and other anthropogenic activities. These metals, via shared exposure pathways and toxicological mechanisms, are present in the environment, livestock, wildlife, and human populations worldwide. These metals are transported by air and water thousands of kilometers away from the emission source. Excessive or prolonged exposure to mercury and lead in plants adversely affects plant growth, biomass accumulation, crop yield, and deteriorates the agricultural productivity and food quality. As the aquatic food webs efficiently bioaccumulate and biomagnify these toxic metals, they act as a link between environmental contamination and health impacts on wildlife and humans. In wildlife, domestic animals, and humans, mercury and lead accumulation induce oxidative stress through excessive generation of reactive oxygen species (ROS), impair antioxidant defense systems, inhibit essential enzymatic activities, disrupt mitochondrial function, damage DNA, and alter epigenetic regulation and gene expression. These metals also interfere with endocrine, reproductive, neurological, cardiovascular, renal, hepatic, and immune functions. Chronic exposure has been associated with cancer.

To minimize the negative health effects on livestock, wildlife and humans, continuous environmental monitoring, stricter pollution control measures, advanced remediation technologies, international regulatory cooperation, and public awareness are essential.

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Declaration

No original data have been used in this review; all information is accessed from published work.

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