https://doi.org/10.33451/florafauna.v28i2pp315-327
FLORA AND FAUNA ISSN 2456 - 9364 (Online)
2022 Vol. 28 No. 2 PP 315-327 ISSN 0971 - 6920 (Print)

Environmental Hazards of Heavy Metal Pollution and Toxicity: A Review

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Received **:** 27.08.2022; ***Accepted*** : 28.09.2022

ABSTRACT

Metals and especially heavy metals are one of the major constituents of environmental pollution. The sources of heavy metal pollution can be geogenic or anthropogenic. The man-made sources include fumes, metal laden dust or food components. Although, many metals are essential for animal metabolism but a dose exceeding the required concentration is often deleterious. The hazardous nature of these heavy metals has been extensively studied in human, animal and plants showing various toxicological impacts of toxic metals. The acute or chronic exposure of heavy metals to animals and human can result in severe injury to the structure and function of vital organs as liver, kidney, brain along with systemic disease conditions. The growth of plants is also severely affected by the intake of metallic compounds through the mineral and water absorption route. The deleterious effects on plants range from symptoms of injury to metabolic, enzymatic, and growth inhibition. The study of heavy metal pollution and the subsequent impact to flora and fauna can contribute in spreading public awareness and sensitizing policy makers to develop strategic planning in order to reduce the pollution and implement biological protection strategies.

Figures : 05 References : 76 Tables: 03
KEY WORDS : Acute, Anthropogenic, Chronic, Exposure, Geogenic, Heavy metals, Toxicological effects

Introduction

The excessive heavy metal pollution in the environmental components such as air, water and soil has raised great public health concern in recent times due to their inherent toxicity to the biological systems. The use of heavy metals by human civilization has been witnessed throughout the human developmental history, which has been demarcated in ages of about 10 million years as copper age, bronze age and iron age[38]. For example, high concentrations of metabolic lead have been found in buried bones of ancient man with the 5000 year of lead smelting history[54]. The metallurgy of eight metals as copper, gold, silver, iron, lead, zinc, tin and mercury has developed with the development of humans. But the last two centuries have witnessed excessive industrial development which has explicitly elevated the levels of heavy metals in the environmental components resulting in toxicological repercussions on flora and fauna.

Metals with higher (> 23) atomic mass and greater (>20) atomic number[36] with specific gravity higher than 5 g/cm^3 are termed as “heavy metals” although some workers consider all the metals and metalloids with specific gravity higher than 4 g/cm^3 broadly as heavy metals[43].

These toxic metals are introduced into the environment due to geogenic and anthropogenic sources[70]. The geogenic sources include volcanic activities, dissolution and weathering of bedrocks *etc.* The anthropogenic sources include the waste generated from glass manufacturing, chemical and textile industries, field application and subsequent spread through rains and air of metal laden fertilizers and pesticides, leachate from mining activities, automobile exhausts, combustion of fossil fuels and waste disposal, *etc.*[3,4]

These metals take entry into the biological system

ACKNOWLEDGEMENT : The authors like to thank Mr. Daksh Sharma for designing the figures 1,2 and 3.

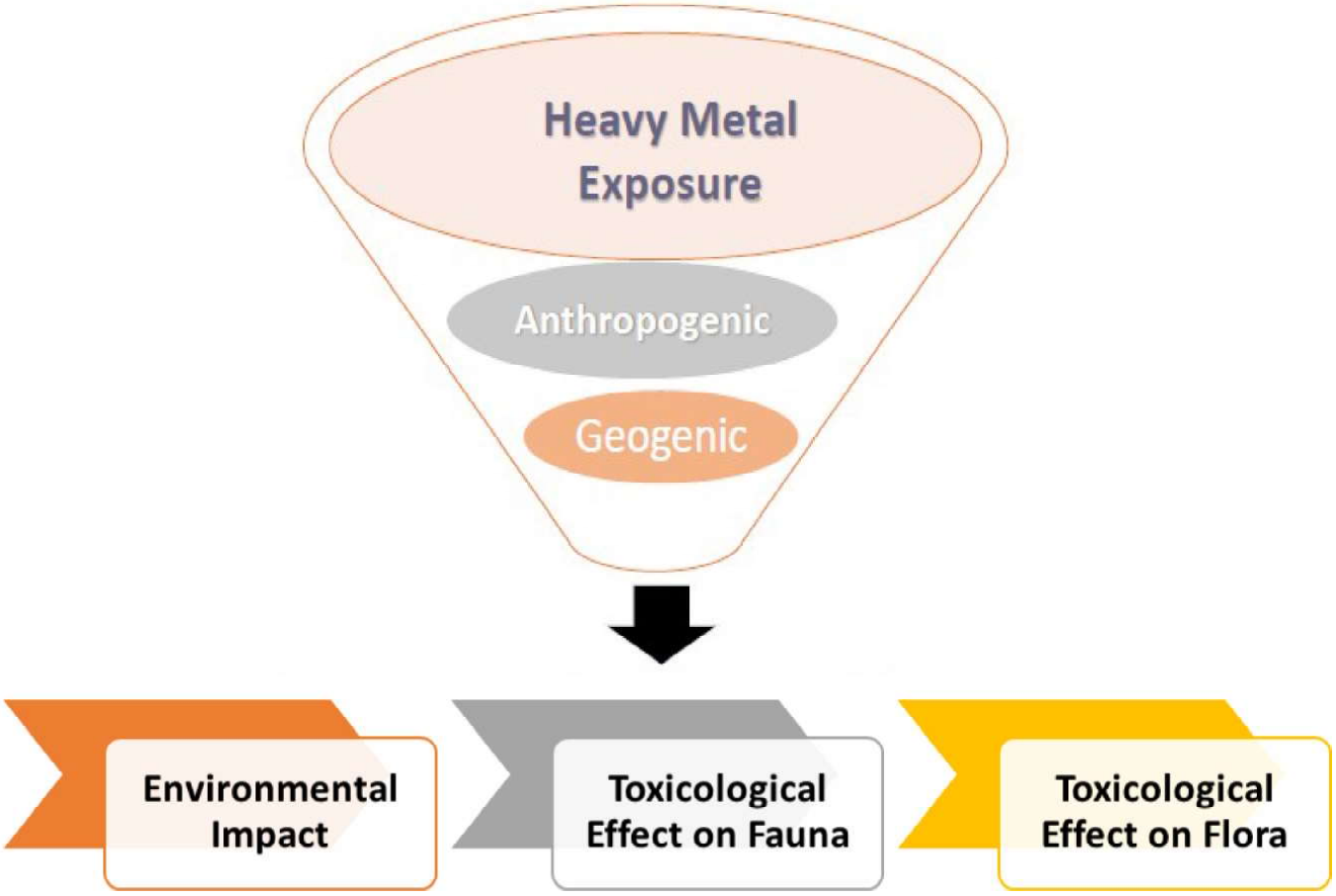

Fig. 1 : Graphical Abstract

through intake of contaminated food and water and subsequently get accumulated in the food chains, this leads to a variety of problems to plants, animals as well as human health. Metal toxicity is also witnessed in plants as these get absorbed in plant tissues through the soil. This causes negative influence on plant physiological activities like photosynthesis, gaseous exchange, nutrient absorption, that leads to reduction in plant growth and yield[48]. Heavy metals negatively affect human physiology and biological systems[6,35]. They may promote the formation of free radicals and reactive oxygen species, which may cause oxidative stress in cells[17]. Metals may also cause a wide variety of developmental and reproductive effects on living organisms. This includes reduced fertility, abortions, retarded development of nervous system, malformations, skeletal deformities, *etc.*[21]

The heavy metal pollutants present in the environmental components do not get degraded naturally and tend to accrue to the body tissues of the exposed animals by a process known as bioconcentration[6,35]. The severity of the metal generated effects increase with rise in trophic level by the phenomenon known as biomagnification as is the case of Mercury, although other metals are generally excreted from body to varying extent[24,69]. Many metals like chromium, nickel, iron, zinc, cobalt, manganese, *etc.* are required in the living systems in trace amounts and are known as 'trace elements'[45].For example, Cr (III) is considered as a micronutrient and required for proper sugar and lipid metabolism and can also promote plant growth at low doses[53,56]. However, some heavy metals like arsenic cadmium, mercury, lead, *etc.* are not essential as they have no biological role and are detrimental to the organism even at low dose[57].

The US-Agency of Toxic Substances and Disease Registry (ATSDR)[1] has listed 20 heavy metals, which exhibit a high level of toxicity. Among these 20 metals, four metals *viz.* arsenic (As), lead (Pb), cadmium (Cd) and mercury (Hg) are of major concern to human health. Arsenic has been placed on the top in this list[21].

The concentration of pollutant in the environment influences the population of microbes by affecting their growth, morphology, biochemical activities, *etc.* that results in decrease in biomass and diversity[59]. Heavy metals can damage cell membranes and disrupt cellular functions. They can even alter enzyme specificity as well

TABLE-1: Sources of metal pollution in environment

S.No.	Metal	Natural Sources	Anthropogenic sources
1.	Arsenic (As)	Natural levels are high in ground water and soil due to dissolution from rocks. Volcanic activities further increases its levels.	Mining activities, use of pesticides and insecticides, combustion of fuel, use of textile dyes.
2.	Cadmium (Cd)	Volcanic activities, weathering of rocks.	Ore processing and smelting industries, electroplating, stabilizers or pigments in plastic, alkaline batteries, alloys, steel industries, waste incineration, cigarette smoking .
3.	Chromium (Cr)	weathering of Cr containing rocks	Plating, Pigments, leather tanning, corrosion control, production of various chemicals ceramic glazes, refractory bricks, and pressure-treated lumber[4].
4.	Mercury (Hg)	Volcanic eruptions, forest fires, leachate from ore (cinnabar), consumption of fossil fuel (coal and petroleum)	Thermal power plant, hospital wastes (in thermometer, barometer, sphygmomanometer), electrical appliances, mining operations[76].
5.	Beryllium (Be)	Beryllium is present in rocks, coal and oil, soil and volcanic dust[1]	Occupational exposure in mining, extraction, and in the processing of alloy metals containing beryllium.
6.	Lead (Pb)	Volcanic explosions and forest fires	Lead batteries, Rubber industries, paints, smelting, ceramics, thermal power plants.

as can lead to DNA damage[10,22].

In general, heavy metals impose toxicity by forming complexes or ligands with organic compounds. These modified biological molecules (products) lose their ability to function properly and result in malfunctioning or death of the affected cells. The most common elements that are involved in ligand formation are oxygen, nitrogen and sulfur. When these toxic metals bind to these ligand groups, they may inactivate important enzyme systems or can affect protein structure[28,34].

The present review aims to showcase the major research on the threats of heavy metals exposure and the consequent debilitating impact on the ecosystem along with the overview of the heavy metal toxicological studies on flora and fauna.

Sources of metal pollution: Geogenic and anthropogenic

In their standard state, the 'heavy metals' are of great concern in today's era because of their natural distribution and widespread use by humans. Excessive use of heavy metals in routine by humans has led to a major problem of the present time that is pollution. Pollution is increasing globally at a very high pace due to natural causes (Fig. 2) as well as anthropogenic activities (Fig. 3) leading to contamination of terrestrial and aquatic ecosystems with excessive quantities of metals, non-metals, organic -inorganic compounds xenobiotics *etc.*[37,66].

The heavy metals cover a diverse and a wide range of elements with their great reactivity constitute a set of pollutants that has received the attention of researchers all over the world due to their toxic effects. Presence of toxic heavy metals in the environment even in traces can be detrimental to both flora and fauna. The diverse sources of these metallic pollutants in environmental components are summarized (Table-1 and Figs. 2 & 3).

TABLE-2: Toxicological impacts of heavy metals on fauna

Metal	Acute metal poisoning	Chronic metal poisoning
Arsenic (As)	Gastrointestinal unrest and severe diarrhoea. Encephalopathy and peripheral neuropathy.[60]	Skin pigmentation, keratosis, carcinoma affects kidneys and central nervous system. Multiple system disease.[42,74].
Cadmium (Cd)	Inhalation of cadmium oxide fumes may cause inhalation fevers or chemical pneumonitis.[2]	Adverse effect on kidney (renal tubulopathy), liver and gastrointestinal tract, Osteomalacia and diffuse osteoporosis.[2,8]
Chromium (Cr)	Respiratory distress, irritation, decrease in body weight.[23]	Chronic exposure of Cr (VI) can cause cancer risk of death due to non-cancer respiratory disease.[65]
Mercury (Hg)	Elemental mercury is most toxic and can result in death with few microlitre exposure on skin.	Permanent damage of nervous system and kidney.[8]
Beryllium (Be)	Acute berylliosis, respiratory disease and death.[1]	Sensitization, lung and skin disease[15]. Lung-fibroid, granulomata, cancer.[5,59]
Lead (Pb)	Anaemia, fatigue, sleep disturbances, anorexia.[20]	Mental lapse, risk of Parkinson's disease[71], teeth loss or enamel damage.[12]

The metals are extracted from ores after the process of mining and subjected to metallurgical separation of metals with varied grade of purity. With the increasing demand of the society the pressure on mining extraction and processing has increased many folds. This pressure creates excessive processing of various metals to prepare goods. During this process a great portion of metals gets washed away and subsequently released in surface water, soil or land environment. This can reach far away and gets deposited on vegetation, ice peaks, glaciers and can even get drained in rivers and finally into sea.

The excessive heavy metal pollution throughout the ecosystem is due to the uncontrolled anthropogenic activities besides the natural factors (Table-1). Increasing industrialization like petrochemicals, metallurgy, textile, chemical and pharmaceutical industries in urban as well as rural areas has led to the elevation of the natural levels of the heavy metal concentration[75] .Effluents from these industries, poor disposal of metallic waste, combustion of fuels and petroleum, use of metal containing pesticides and insecticides and use of metallic dyes directs the distribution of these heavy metals in soil, agricultural fields and water bodies and thereafter the whole ecosystem[38,40].

Environmental Impact of heavy metal pollution

Heavy metal pollution involves the whole population with respect to all the environmental components *i.e.*, Water, Soil and Air. The introduction of the these pollutants in the environment imposes negative impact on all the organisms and disturbs the ecological balance. The chemistry of metals in the environment is very complex as these form different compounds and chemical species having unique chemical and physical properties. The presence of different metal species in the abiotic and biotic components of the environment strongly influences the bioavailability and its toxicity to the receptor organisms[67].

One of the major problems associated with heavy metal pollution is its contamination in soil, surface water and sediments in high concentration is bioconcentration. Consequently, it enters the food chain, leading to the bioaccumulation and biomagnification in each stratum of the food chain, which affects all the living organisms.

The soil system in the vicinity of industrial or agricultural areas mainly receives an exceedingly high heavy metal load either directly by improper discharge of

TABLE-3: Toxicological effects of few heavy metals on plants

Heavy metals	Toxicological effects on plants
Cadmium (Cd)	Reduction in the rate of ❑ Photosynthesis ❑ Absorbance of nutrients and water Injury in terms of- ❑ Chlorosis ❑ Reduction in growth ❑ Browning of root margins ❑ Can be fatal
Zinc(Zn)	Inhibition of metabolic functions resulting in; ❑ Growth retardation ❑ Cellular death Injury in terms of chlorosis
Mercury(Hg)	Physical obstruction in water channel. Induction of oxidative stress ROS induces lipid peroxidation Disruption of; ❑ Lipids in biological membrane ❑ Cellular metabolism
Chromium(Cr)	Injury in terms of; ❑ Chlorosis in young leaves ❑ Nutrient imbalance ❑ Wilting of tops ❑ Root injury Inhibition of; ❑ Chlorophyll biosynthesis ❑ Plant growth Alteration in rate of; ❑ Germination ❑ Growth of root, stem and leaves Deleterious effect on; ❑ Metabolic activity ❑ Photosynthesis Generation of ROS
Lead (Pb)	Adverse effect on; ❑ Morphology ❑ Growth and development ❑ Photosynthesis Alteration of; ❑ Enzyme activities ❑ Water and mineral balance ❑ Membrane permeability Generation of ROS
Cobalt (Co)	Adverse effect on; ❑ Shoot growth ❑ Biomass ❑ Catalase activity ❑ Chlorophyll content Decrease in transpiration rate Alteration in rate of translocation of S, P, Mn and zinc from roots to the shoot.

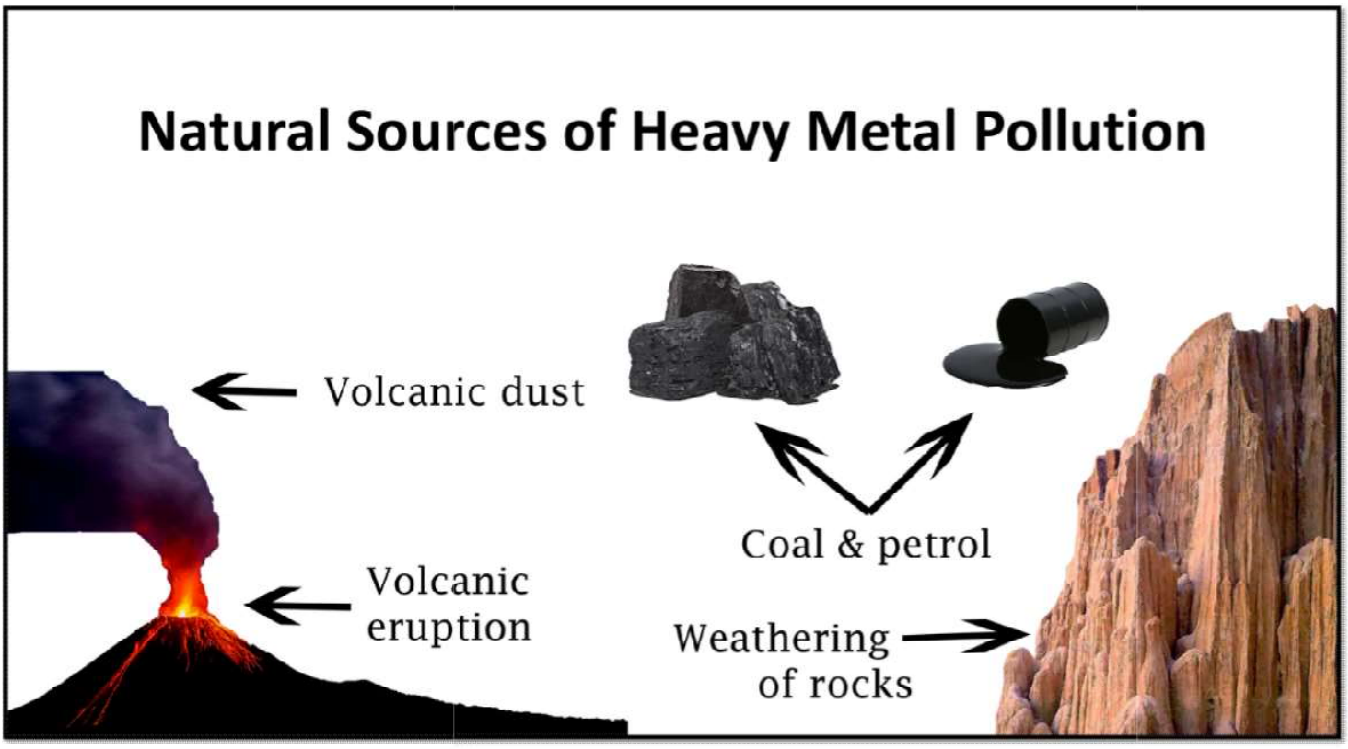

Fig. 2 : Pictorial depiction of some of the natural sources of heavy metal pollution

untreated waste or by the precipitation of airborne aerosols. Wastes from the petroleum and paint industry, animal manures, mine tailings, coal combustion, fertilizers, pesticides contaminate the soil with major heavy metals like chromium (Cr), lead (Pb), Arsenic (As), Mercury (Hg), Nickel (Ni),Copper (Cu), Zinc (Zn), Cadmium (Cd), Molybdenum (Mo), Selenium (Se) *etc.*[7,30,33] .As these contaminants are generally odorless and colorless, the deterioration of soil quality gets unnoticed for long and natural remediation cannot run with the pace of contamination.

The loads of heavy metals in the atmosphere can be mainly through the direct emission mode like combustion of petrochemicals, automobiles and industrial exhausts or by natural means like resuspension of roadside dust, volcanic emissions and even by bursting of bubbles in water bodies. The atmospheric load of heavy metals is chiefly in the form of aerosols of variable sizes and their seasonal and diurnal as well as geographical distribution depends on the natural or anthropogenic sources of heavy metals[26]. On the basis of emission data, the main sources of heavy metals contamination are the anthropogenic sources with largest source including coal combustion and non-ferrous metal industry[52].The deposition of metals in the atmosphere depends on its residence time and solubility. Thus, metals like lead, arsenic, cadmium and mercury with long residence times are found considerably far from the source[52]. These atmospheric heavy metals contaminants pose serious health issues due to respiratory exposure or even pollute the soil once it precipitates with rains.

The water bodies generally become the ultimate dump yards of all the wastes as sewage, industrial or agronomical waste. Thus, all the water bodies seem variably contaminated with waste including the heavy metals. This contamination not only hampers the quality of water but also negatively impacts the flora and fauna inside. The negative impacts on aquaculture due to metal contamination and subsequent bioaccumulation into aquatic flora and fauna have been documented. In a study on aquaculture fish *Tilapia* exposed to heavy metals in water as well as sediments in southwestern region of Taiwan with kidneys accumulating highest metal concentrations of mercury, cadmium, copper, zinc, nickel. The consumption of such contaminated aquaculture products is also increasingly risky[32]. In another study conducted in the Tibetan autonomous region of China using Carps and Tilapia. The accumulation of heavy metal in tissues was estimated by the total concentration of metal by inductively coupled Plasma mass spectrophotometry the metals like chromium, Barium, Cobalt, Manganese easily accumulated in gills, Copper accumulated in heart, the toxic metals like lead, arsenic and cadmium are accumulated in liver [29].

The physical and chemical state of these metals also depends upon the chemical properties of the soil

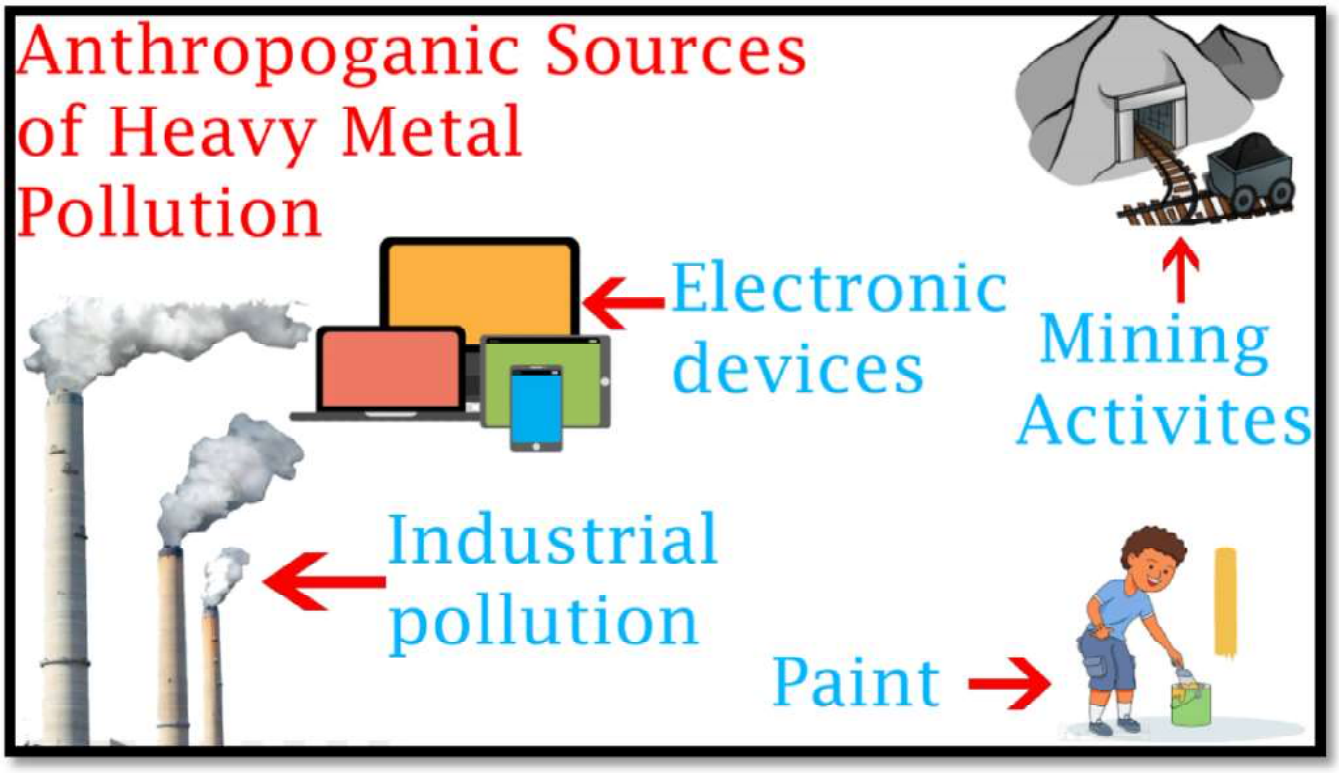

Fig. 3 : Showing various anthropogenic sources of metal pollution in the environment

which in turn influences its solubility and subsequent mobility with the runoff. The soil microbial community also plays an important role in biogeochemical cycling of the metals. Some of these bacteria convert the toxic form of metals to less toxic state while deriving energy (chemo lithotrophic), others avoid its toxicity by the process of exclusion from the cell. The detoxification mechanisms involve various modes as entrapment in extracellular polymeric substance, volatilization, precipitation[16]or by chemical conversion to less toxic forms as in the case of arsenite oxidizing bacteria which can oxidize the most toxic form of Arsenic (AsIII) to less toxic form (As V)[55]. The bacteria mediated volatilization of Mercury has been known since long by many bacteria[44]. The mercury resistant bacteria like *Azotobacter chroococcum* possess enzymes like mercuric reductase and organomercurial lyase which aid in the detoxification process. Bacteria such as *Alcaligenes faecalis, Pseudomonas* and *Brevibacterium* have been studied for detoxification of mercury, cadmium and lead by extracellular entrapment in extracellular polymeric substances and precipitation of lead in sulfide form [16].

Heavy metal toxicological studies on Flora and Fauna

The excessive level of heavy metals causes toxicity due to range of interaction at the cellular and molecular levels.

Heavy metals like iron, molybdenum, manganese are classified to have low toxicity; zinc, copper, nickel, vanadium, cobalt, tungsten, chromium are categorized to have average toxicity, while arsenic, silver, antimony, cadmium, mercury, lead and uranium are grouped as highly toxic heavy metals[50]. The exposure to heavy metals and metalloids like lead, mercury, cadmium and arsenic are extremely toxic even at low concentrations.

This toxicity is due to the relative accessibility of these heavy metals to biological systems as these can be complex with biological macromolecules as protein and lipid molecules and thus pose disturbance or alteration in their function. The metals can also generate oxidative stress by generating free radicals resulting in reduced enzyme activity and disruption of lipid bilayer and DNA in the tissues. The reactive oxygen species have strong oxidizing activities and it may attack many cellular macromolecules such as nucleic acids, proteins, lipids.

Heavy metal exposure is a serious threat to human beings due to their neurotoxicological[49]and geno-toxicological effects[75] as well as effects on the reproductive system[72]. These metals get sequestered in various tissues and exhibit numerous adverse effects on vital functioning of the body . In body cells, heavy metals binds with nucleic acid, destroying these macromolecules

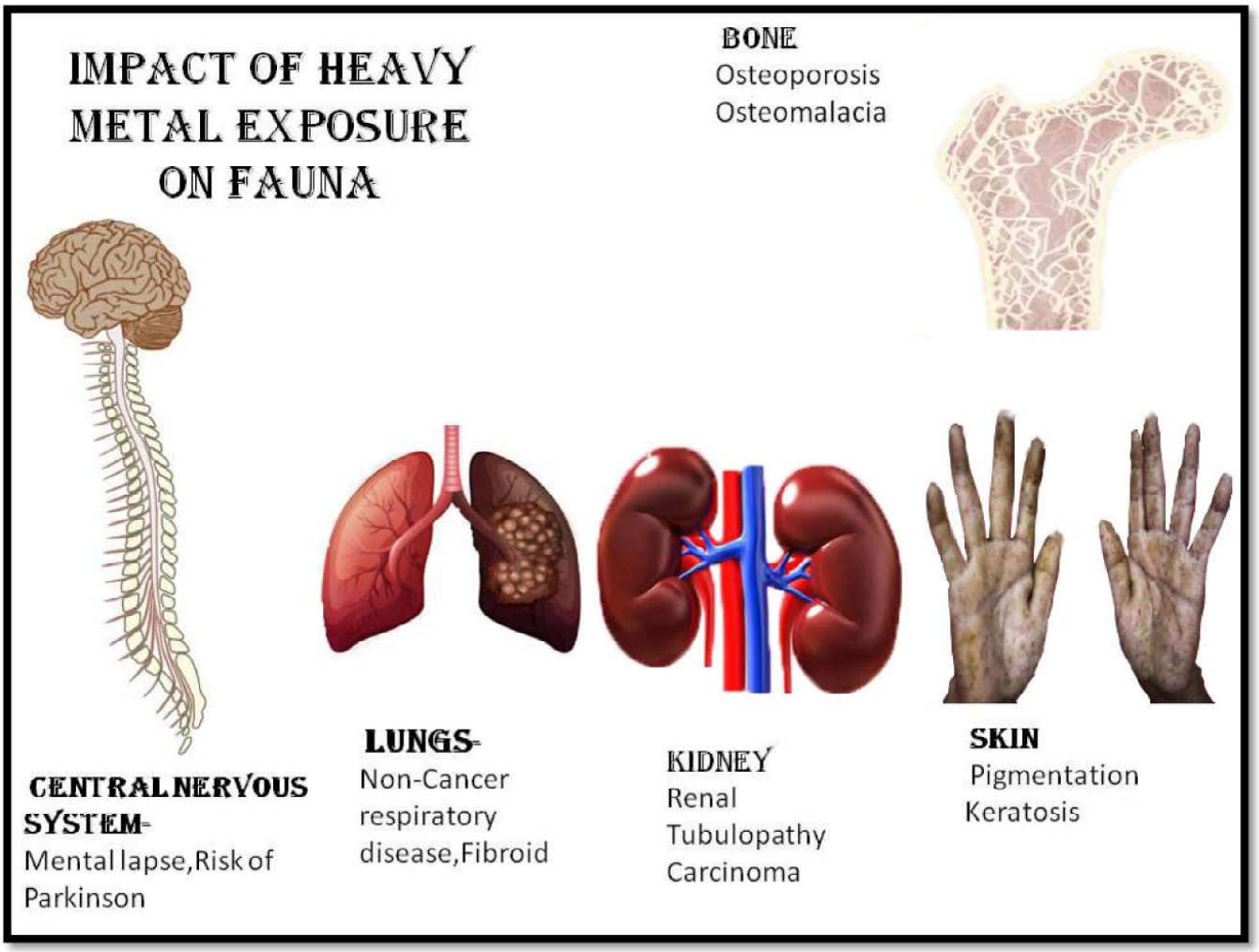

Fig. 4 : Showing the negative impacts of Heavy metal pollution on the Central Nervous System, Lungs, Kidney, Bone and Skin of animals

which in turn hinders their biological functions [28].

Heavy metals negatively affect human physiology and biological systems and show a number of toxic effects as neurotoxicological effects, adverse reproductive effects, developmental defects and geno-toxicological effects resulting in later development of cancers. The effect on metabolic functions is basically in two ways. At first, these get accumulated in the vital organs like heart, brain, kidney, liver and bones thereby disrupting their functions and secondly, they displace the nutritional elements from their native place and hinder the biological functions (Fig. 4).

Beryllium is widely used in nuclear facilities, parts of air craft, ceramics, electronics *etc.* thus the occupational exposure is very common. It gets deposited in lungs, spleen and a portion of beryllium is also excreted through kidneys. In case of acute exposure symptoms like pneumonitis, chest pain, cough, dyspnea are observed. Long term exposure and subsequent accumulation can result in formation of fibroid, granulomata or even cancer in lungs[5,39]

Bioaccumulation and bioconcentration are other causes of concern with heavy metals as these can enter the food chain and bio-magnify to many folds in animals of higher trophic levels. For instance, lead is a persistent toxin which gets accumulated with the food chain. Once this metal takes entry into the body it gets distributed throughout the body in all body tissues including the soft tissues and bones. Thereafter it manifests its harmful effects which are more in young developing children as compared to adults causing developmental, neurological, reproductive toxicity. Lead poisoning is observed in children even at low doses resulting in low IQ (intelligent quotient), poor hand eye coordination, poor performance, cognitive and learning deficits *etc.*

Long term exposure of lead in case of occupational circumstances can pose risk of Parkinson's disease[71], teeth loss or enamel damage[12]. The occupational human cadmium exposure is mainly through the cadmium laden fumes and food. About 10-50% of the inhaled or ingested

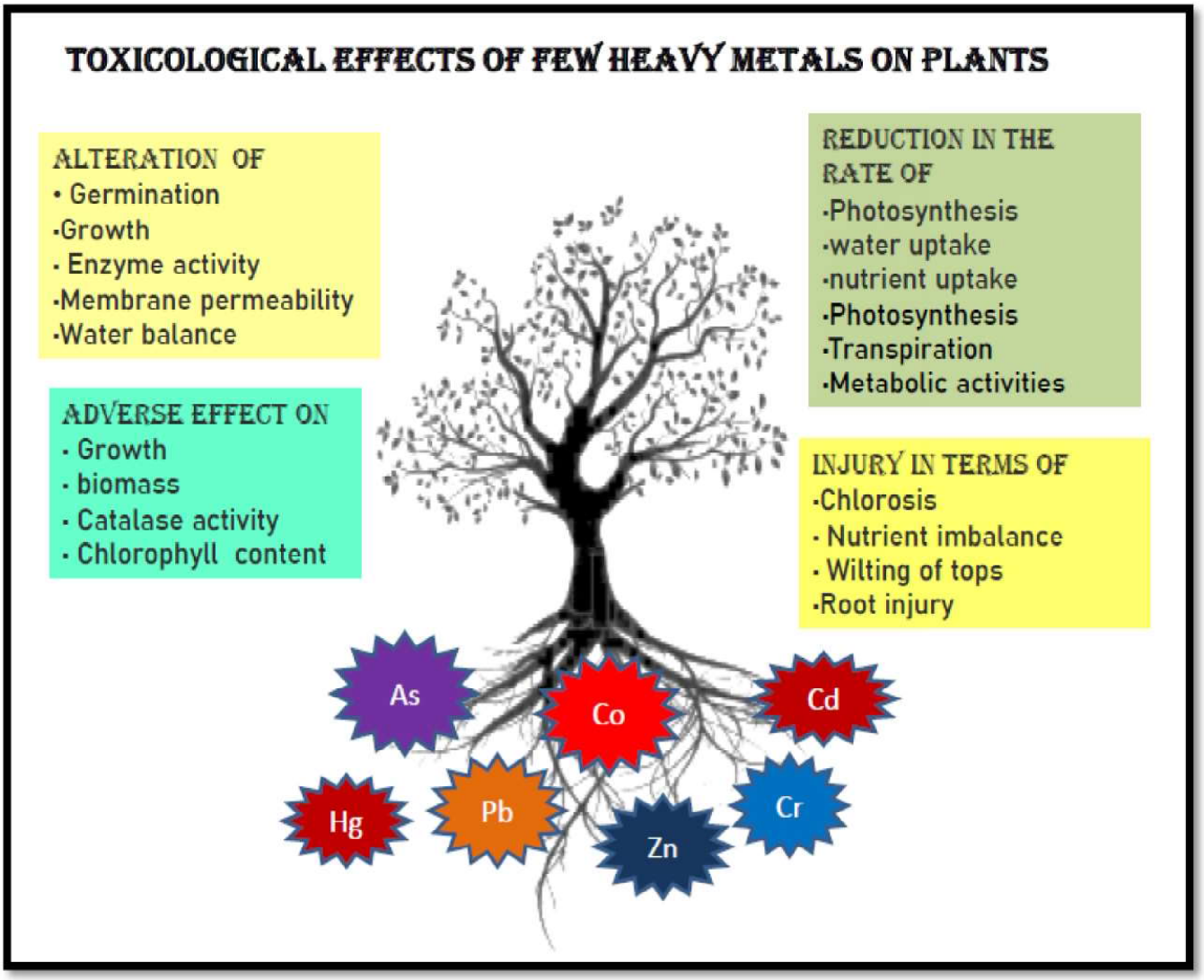

Fig.5 : Showing the negative impacts on plants after heavy metal exposure and accumulation

cadmium is absorbed or accumulated in liver and kidney. Mercuric salts tend to accumulate in body tissue (GI tract) with half-life of about 40 days[14,44].

Heavy metal induced toxicological effects on plants

The agricultural crops as well as the general plant biodiversity is widely subjected to either heavy metal contaminated soil or is irrigated with water containing heavy metals. These plants show numerous stress symptoms like inhibition of photosynthesis, chlorosis, reduced growth, germination or flowering, inhibition of enzyme synthesis and activity *etc.* Heavy metal toxicity is mainly because of oxidative stress which is evident in form of elevated ROS levels. This stress condition is generally evaluated in terms of elevated membrane lipid peroxidation levels. Thus, the antioxidant enzyme glutathione acts as a limiting factor in plant metal tolerance.

The lead polluted ecosystem poses harmful effects on plants which exhibit lead toxicity in terms of reduced growth, reduced pollen germination and seed viability.

High doses of chromium adversely impacts germination,growth, photosynthesis,uptake of nutrients,enzymatic functioning and cause oxidative imbalances and mutagenesis in plants[51]. The toxicological impacts of various heavy metals are summarized in the Table-3 and Fig. 5.

Conclusion

The effects of heavy metals on flora and fauna are frequently reviewed by World Health Organization (WHO). The main threats to human health are associated with either direct exposure to heavy metals or by ingestion of food containing metal contaminants. Once inside the body the reactivity, assimilation, excretion, detoxification depend upon the metal form and its reactivity with tissues. The excessive dose exposure can be deleterious for the

survival of animals or plants. Thus, measures need to be taken to control the excessive metal pollution in the environment along with strategies for safe disposal of metal containing waste.

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