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Effects of Heavy-Metal Pollution on Soil Microbial Community, Plants, and Human Health

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Abstract

Heavy metals are among the most important sources of contamination in soil, and are considered among the most dangerous matters due to their toxicity, persistence, and resistance to biological degradation. They may cause serious health problems for many forms of life. Heavy metals exhibit toxic effects towards soil biota by affecting key microbial processes and decreasing the number and activity of soil microorganisms. Crops grown on contaminated soils can potentially lead to the uptake and accumulation of trace metals in the edible plant parts. The uptake of heavy metals by plants and their subsequent accumulation along the food chain pose potential threats to animal and human health.

Keywords: Heavy metals, environment, soil, plants, microorganisms, human health.

1. Introduction

In the recent years, the world has witnessed various kinds of pollution which threatens human life and over time makes many environments inhabitable (Panigrahi et al., 2019). Rapid growth of industrialization and urban population have affected the quality of soil (Bulgariu and Gavrilescu, 2015). Heavy metals are among the most important soil contaminants (Tangahu et al., 2011) due to their toxicity, persistence, resistance to biological degradation and long-term accumulation in the food chain; thus, causing serious health problems for many forms of life (Bulgariu and Gavrilescu, 2015).

Metals are present naturally at various levels in the earth's crust. The burning of fossil fuels, mining of metalliferous ores, wastes of municipal areas, and excessive use of pesticides and fertilizers lead to an accelerated release of metals and metalloids into various components of ecosystems (Kumar et al., 2016). Heavy metals are defined as metals and metalloids having densities greater than > 5 g cm-3 (Oves et al., 2016).

Soil contamination by heavy metals is one of the most formidable threats throughout the industrialized world. Heavy-metal pollution not only results in adverse effects on various parameters relating to plant quality and yield but also causes changes in the size, composition, and activity of the microbial community (Singh et al., 2011). The consumption of plants grown in contaminated areas, as well as the ingestion or inhalation of contaminated particles are two principal factors contributing to human exposure to metals (Zhuang et al., 2009). Also, the cultivation of crops for human or livestock consumption on contaminated soil can potentially lead to the uptake and accumulation of trace metals in the edible plant parts with a resulting risk to human and animal health (Zhuang et al., 2009).

Heavy metals do not all pose the same risks because of their effects on organisms, chemical, physicochemical and biological properties. Their toxicity is variable and their impact on the environment varies widely. Therefore, the objective of this paper is to discuss the effects of heavy metals on the soil, plants and human health.

2. Heavy Metals' Origins

Heavy metals (HM) are naturally present in earth crust and rocks in the form of sulphides and oxide ores such as sulphides of lead, iron, mercury, cadmium, arsenic or cobalt (Verma and Kaur, 2016).

HM in the environment can vary across different regions resulting in spatial variations of background concentrations. The distribution of metals in the environment is governed by the properties of the metal and influences of environmental factors (Morais et al., 2012). HM and their compounds are characterized by relatively high stability, solubility in atmospheric precipitation, and the ability to be absorbed by soil and plants. They are accumulated in organisms, and are toxic in any state for humans and animals with a wide spectrum and variety of harmful effects (Dzyadevych and Jaffrezic-Renault, 2014). HM occur naturally in the soil environment from the pedogenetic processes of the weathering of parent materials at levels that are trace (<1000 mg kg^{-1}) and are rarely toxic (Wuana and Okieimen, 2011).

Natural sources of HM such as volcanic emissions, transport of continental dusts, and weathering of metal-enriched rocks due to long exposure to air, greatly add higher amounts of HM to soils (Oves et al., 2016). However, the major source of contamination is of anthropogenic origin (Table 1); such human activities responsible for the increase of metal flows are: the exploitation of mines and smelters,

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the application of metal-based pesticides and metal-enriched sewage sludge in agriculture, the combustion of fossil fuel, metallurgical industries, and electronics, and military training and weapons (Oves et al., 2016; Villanneau et al., 2008).

Table 1. Anthropogenic sources and usage of heavy metals, through which they can be introduced into the environment (Bradl, 2005).

Metal	Sources
Arsenic (As)	Additive to animal feed, wood preservative, ceramics, pesticides, electronic components, metallurgy, textile, pigments.
Beryllium (Be)	Electrical insulators in power transistors, moderator or neutron deflectors in nuclear reactors.
Cadmium (Cd)	Ni/Cd batteries, pigments, anti-corrosive metal coatings, plastic stabilizers, alloys, coal combustion.
Cobalt (Co)	Metallurgy, ceramics, glasses, paints.
Chromium (Cr)	Manufacturing of ferro-alloys, plating, pigments, textile, passivation of corrosion of cooling circuits, wood treatment.
Copper (Cu)	Good conductor of heat and electricity, water pipes, roofing, kitchenware, chemicals and pharmaceutical equipment, pigments, alloys.
Iron (Fe)	Cast iron, wrought iron, steel, alloys, construction, transportation, machine manufacturing.
Mercury (Hg)	Extracting of metals by amalgamation, electrical and measuring apparatus, fungicides, catalysts, pharmaceuticals, dental fillings, scientific instruments.
Nickel (Ni)	As an alloy in the stell industry,arc-welding, rods, pigments for paints and ceramics, surgical and dental prostheses, computer components, catalysts.
Lead (Pb)	Antiknock agents, lead-acid batteries, pigments, glassware, ceramics, plastic, in alloys, sheets, cable sheathings, solder, pipes or tubing.
Titanium (Ti)	For white pigments (TiO2), as a UV-filtering agents (sun cream), nucleation Agent for glass ceramics, as Ti alloy in aeronautics.
Zinc (Zn)	Zinc alloys (bronze, brass), anti-corrosion coating, batteries, cans, in medicines and chemicals, rubber industry, paints, soldering and welding fluxes.

High concentrations of heavy metals have deleterious effects on the environment (Mustapha and Halimoon, 2015). They cannot be destroyed biologically, but can be accumulated in living organisms, and their toxicity can last for a long time in nature. Some HM, such as mercury, can even be transformed from relevant low toxic species into more toxic forms in a certain environment (Alkorta et al., 2004) and cause various diseases and disorders even at relatively lower concentrations (Tangahu et al., 2011).

3. Heavy Metals effects

3.1 Aquatic Environment

In natural aquatic ecosystems, metals occur in low concentrations, normally at the nanogram to microgram per liter level. Recently, the occurrence of metal contaminant, especially the heavy metals in excess of natural loads, has become a problem raising increasing concerns (Biney et al., 1994).

Anthropogenic inputs, geochemical structure, and the mining of metals create potential sources of heavy-metal pollution in the aquatic environment. Heavy metals are natural constituents of rocks and soils and can enter the environment because of weathering and erosion (Yahya et al., 2018). The agricultural sector also contributes to contamination through some wastes containing metals. For example, Cu from piggery wastes has been correlated to contamination of sediments and molluscs (Shazili et al., 2006).

Through toxicity and accumulation in the environment, HM discharged into the marine environment can impact species diversity as well as entire marine ecosystems (Gu et al., 2015). Among animal species, fishes are the inhabitants that cannot escape from the detrimental effects of these pollutants. Directly acting or synergistically acting metals such as Fe, Zn, Pb, Cd, Cu, and Mn are common toxic pollutants for fish (Joseph et al., 2010).

In biological systems, HM have been reported to affect cellular organelles and components such as cell membrane, mitochondrial, lysosome, endoplasmic reticulum, nuclei, and some enzymes involved in metabolism, detoxification, and damage repair at the cellular level (Yahya et al., 2018).

3.2 Soil Microbial Dynamic

Metals play an integral role in the life processes of microorganisms. Some metals, such as Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, and Zn are required nutrients and are essential. Others have no biological role (Ag, Al, Cd, Au, Pb, and Hg) and are nonessential (Bruins et al., 2000). However, heavy metals' excess causes morphological and physiological changes, and affects the reproduction of microorganism (Scott-Fordsmand, 1997).

The effects of HM on microorganisms have been studied at several levels of experimental complexity. Such studies have determined the concentrations of HM that reduce or completely inhibit the growth of microbes in synthetic media and, to a lesser extent, in samples from natural environments (Babich and Stotzky, 1983) that affect the respiratory activity and the enzymatic machinery of soil organisms (Moreno et al., 2003; Singh and Kalamdhad, 2011). The mode of action of heavy metals varies from one enzyme to another, and the effects on enzymes depend on the type of heavy metal and their concentration (Moreno et al., 2003). Moreover, members of the same species in the microbial community would show considerable differences in their sensitivity to metal toxicity (Gillera et al., 1998). Metals either act on the cell membrane or interfere with cytoplasmic or nuclear functions after entry into the cell (Madoni, 2000) (Figure 1).

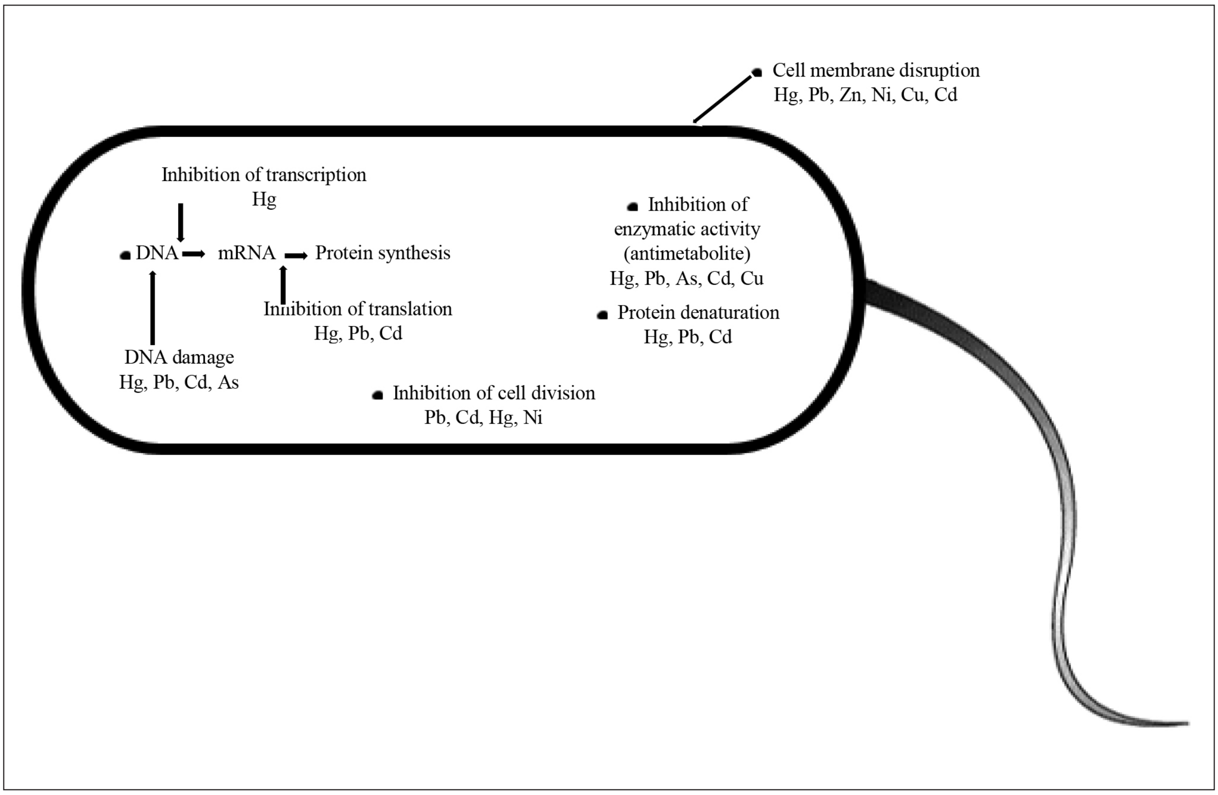

Figure 1. Various toxic influences of metals on the microbial cell. Adapted from Timberley et al. (2015).

For example, Ni is proposed to affect cell surface membranes, DNA replication, transcription, and translation, as well as other metabolic activities, including photosynthesis, nitrogen fixation, respiration, and fermentation (Babich and Stotzky, 1983). Excess of Ni causes a perturbation of protein function and is toxic for eukaryotic cells and bacteria (Lusi et al., 2017). Similarly, Cd toxicity can be identified by a number of cellular effects that include growth inhibition, enzyme inactivation, proteins and DNA oxidation, nucleotide conformation changes, and ultrastructural changes that can cause cell-membrane damage and destroy the transport of nutrients (Scott-Fordsmand, 1997). Furthermore, it is reported that copper oxide sorption on biomass is strong and rapid, which in turn caused a rapid loss of membrane integrity (Wang et al., 2010).

At the level of the fauna, these effects can be manifested by a loss of weight, an inhibition of the growth, an appearance of behavioural or physiological disorders at all reproduction stages. At the level of the ecosystem, heavy metals can generate loss of diversity, loss of biological activity (decomposition, mineralization, aeration of the soil) and change in the structure of the specific community (Forneris, 2002).

3.3 Plants

In many parts of the world, agricultural soils are slightly to moderately contaminated by heavy-metal toxicity and have become a critical environmental concern due to their potential adverse ecological effects. Such toxic elements are considered as soil pollutants due to their widespread occurrence, and their acute and chronic toxic effect on plants grown of such soils (Yadav, 2010).

HM are available to plants through mining activities (smelting, river dredging, mine spoils and tailings, and metal industries), industries (plastics, textiles, microelectronics, wood preservatives, and refineries), atmospheric deposition (urban refuse disposal, pyrometallurgical industries, automobile exhausts, and fossil fuel combustion), excessive use of agrochemicals (fertilizers and pesticides) and waste disposal (sewage sludge and leachate when the former is used as landfill) (Prasad and Strzalka, 1999).

Some heavy metals are required for normal growth and metabolism of plants (Table 2), but if large amounts are accumulated in the plants, they will adversely affect the absorption and transport of essential elements, disturb the metabolism, and have an impact on growth and reproduction (Cheng, 2003). HM accumulation in plants depends upon plant species and the different growth stages (Cheng, 2003); the efficiency of different plants to absorb metals is evaluated by either plant uptake or soil to plant transfer factors of the metals (Chaudhary et al., 2018). After prolonged metal exposure, sensitive plants develop visible symptoms of toxicity such as chlorosis, necrotic lesions as well as disorders and growth inhibition (Dietz et al., 1999; Peralta et al., 2001).

Table 2. Range of a few environmentally important heavy metals in plants (Nagajyoti et al., 2010).

Elements	Land plants (ug g-1 dray wt)
As	0.02-7
Cd	0.1-2.4
Hg	0.005-0.02
Pb	1-13
Sb	0.02-0.06
Co	0.05-0.5
Cr	0.2-1
Cu	4.15
Fe	140
Mn	15-100
Mo	1-10
Ni	1
Sr	0.30
Zn	8-100

Photosynthesis is considered as one of the most sensitive metabolic processes to lead to toxicity. The Pb-induced reduction in the photosynthesis may be due to stomatal closure, damage to chloroplast ultrastructural organization, alteration in the metabolites of photosynthesis, replacement of ions like Mg, Mn, by Pb in the chloroplast and inhibited synthesis or degradation of the photosynthetic pigments (Islam et al., 2008). High levels of Pb also cause the inhibition of enzyme activities, water imbalance, alterations in membrane permeability, and disturb mineral nutrition (Yadav, 2010).

An excessive supply of Zn affects both root and shoot growth. Shoots become stunted and chlorotic. Further, the epidermis of roots may become lignified (Balsberg Påhlsson, 1989).

Cr has no essential role in plant metabolism, and is poorly translocated within plants. This is likely due to chromium (III) oxide binding to cell walls, leading to increased concentrations of Cr in the roots. Deleterious effects, including restricted root growth, biomass reduction, and distortion of leaf appearance, have been recorded in plants grown in media with excess of Cr (III) and Cr (VI) (Hamilton et al., 2018).

Generally, visible symptoms of copper toxicity include having small chlorotic leaves and early leaf fall. Furthermore, plant growth is stunted and the initiation of roots and the development of lateral roots become poor. The reduced root development may result in a lowered water and nutrient uptake, leading to disturbances in the metabolism and growth retardations (Balsberg Påhlsson, 1989).

The toxic effects of higher concentration of Ni are observed at multiple levels. These include the inhibition of mitotic activities, reduction in plant growth, plant water relation and photosynthesis, inhibition of enzymatic activities as well as nitrogen metabolism, interference with the uptake of other essential metal ions, and induction of oxidative stress (Yusuf et al., 2011). The decrease in water uptake is used as an indicator of the progression of Ni^{2+} toxicity in plants (Yadav, 2010).

Analysis with scanning electron microscopy shows that plant exposure to Hg resulted in loss of cell shape, decrease in intercellular spaces, and vascular abnormality in leaves of Boston fern (Nephrolepis exaltata) and Indian mustard (Brassica juncea). Mercury treatment was found to reduce the amount of chlorophyll, and resulted in breakdown of thylakoid. Furthermore, Hg stress inhibited the activity of NADPH: protochlorophyllide oxidoreductase, which is responsible for the biosynthesis of chlorophyll (Chen and Yang, 2012).

HM affects the cell division of plants. The effects are different, and depend on the concentration. The genotoxicity influences the synthesis, and the duplication of DNA and chromosomes both directly or indirectly, and induces chromosomal aberration (Cheng, 2003).

3.4 Human Health

People may be exposed to heavy metals over the course of their lifetime. HM in the environment can affect human health through various absorption pathways such as direct ingestion, consumption of foods, beverages, dermal contact, inhalation of soil dust particulates, airborne particles, and vaporized metals (Mudgal et al., 2010; Singh et al., 2011). Chronic intakes of HM have damaging effects on human beings as well as other life forms (Liu et al., 2013).

The absorption, accumulation and distribution of HM in different food crops such as rice, wheat, barley, maize and potato, oil seed crops and forage crops have been documented. Mostly, edible parts of plants are the major source of heavy-metal intake for humans through consumption, which have long-term detrimental effects on human health (Sharma and Agrawal, 2005).

HM pose hazards to human health because these are persistent in nature and have accumulation tendency in biological systems (Sharma and Agrawal, 2005). They can disturb important biochemical processes. Toxicity level depends on the type of metal, its biological role, and the type of organisms that are exposed to it (Mohod and Dhote, 2013).

Cd is a heavy metal posing severe risks to human health. Up to this day, it could not be shown that Cd has any physiological function within the human body (Suwazono et al., 2006). Cd is efficiently retained in the organism in which it accumulates throughout life (Bernard and Lauwerys, 1986). For chronic dietary exposure, the kidneys constitute the target organ. Cadmium-induced renal damage is characterized by proximal tubular absorptive dysfunction (Järup and Åkesson, 2009). The first sign of renal effects is tubular damage, characterized by increased urinary excretion of low-molecular-weight proteins or intracellular tubular enzymes. More important, in succession to the tubular effects, Cd may affect the glomerular function (Suwazono et al., 2006).

Cd interferes with calcium metabolism, leading to a reduction in calcium levels and thus reducing the density and strength of bones, often causing the weakened bones to break (Huff et al., 2007). The Itai-itai disease is a bone disease causing fractures and severe pain. It was common after World War II in Fuchu, Toyama prefecture, Japan (Nordberg, 2009). The main features of the Itai-itai disease are pseudo fractures of the bones, osteomalacia with eventual osteoporosis, and renal dysfunction (Bernard and Lauwerys, 1986). Anemia and gastrointestinal and renal dysfunction were other less prominent findings. Elevated levels of Cd in urine were found, and in 1968, the disease was declared by the Japanese Government to be a disease related to environmental pollution (Nordberg, 2009). Acute Cd exposure via inhalation results in pulmonary edema and respiratory tract irritation (Liu et al., 2009), recent studies have also reported increasing cancer risks at low-level environmental exposure (Järup and Åkesson, 2009).

Chronic arsenic toxicity is mostly manifested in weight loss, capricious appetite, conjunctive and mucosal erythematic lesions including mouth ulceration, and reduced milk yields (Raikwar et al., 2008). The cardiovascular, gastrointestinal and urinary systems were some of the other systems most affected in humans (Kapaj et al., 2007). Similar to a protoplastic poison, it affects primarily the sulphydryl group of cells causing malfunctioning of cell respiration, cell enzymes, and mitosis (Jaishankar et al., 2014). It does cause gene amplification and chromosomal damage at lower doses, and can enhance mutagenesis by other agents, apparently by inhibiting DNA repair (Abernathy et al., 1999). The International Agency for Research on Cancer has listed arsenics as a human carcinogen since 1980. It is associated with cancers of skin and internal organs, as well as with vascular diseases (Kapaj et al., 2007).

Ni is normally present in human tissues under conditions of high exposure; these levels may increase significantly (Cempel and Nikel, 2006). The adverse health effects of Ni depend on the route of exposure (inhalation, oral, dermal), and can be classified according to systemic, immunologic, neurologic, reproductive, developmental, or carcinogenic effects (Das and Büchner, 2007). It is responsible for allergic skin reactions, and has been reported to be one of the most common causes of allergic contact dermatitis (Cempel and Nikel, 2006). The toxic effects of Ni result from its ability to replace other metal ions in enzymes, proteins or bind to cellular compounds, and among animals, micro-organisms and plants (Iyaka, 2011), it plays an important role in the suppression or silencing of genes and binds to DNA in different positions (Mishra et al., 2010).

4. Conclusion

This review is an attempt to discuss the effects of some heavy metals on soil, plants and human health. Heavy metals cannot be biodegraded, so they accumulate in living organisms. They inhibit the growth of microbes that affect the respiratory and enzymatic activity of soils, growth as well as the reproduction of plants. The uptake of heavy metals by plants and their subsequent accumulation along the food chain pose potential threats to animal and human health. Soils contaminated with heavy metals constitute a serious threat to ecosystems and consequently to human health.

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