Sources, effects and present perspectives of heavy metals contamination: soil, plants and human food chain

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Abstract

The poisoning of agricultural soils with heavy metals (HMs) is a severe threat to the worldwide food supply, human health, and plant life. The health and production of crops are negatively impacted when HM levels in agricultural soils reach hazardous levels. The major heavy metals are chromium (Cr), arsenic (As), nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg), zinc (Zn) and copper (Cu). These metals may be found everywhere in the environment, including in things like soil, food, water, and even air. These materials cause changes in the properties of soil and also harm plants, which reduces crop production. Crop type, growth conditions, elemental toxicity, developmental stage, soil chemical and physical properties, and the presence and bioavailability of HMs in the soil solution are all factors that affect how toxic HMs are to crops. By interfering with their normal function and structure in cellular components, HMs can hinder a variety of metabolic and developmental processes. Humans are susceptible to a wide range of serious diseases when they consume these affected plant products. The kidneys, brain, intestines, lungs, liver, and other organs in the human body are all negatively impacted by exposure to these metals. This review assesses (1) contamination of heavy metal in soils through different sources, like Anthropogenic and natural; (2) the effect on microorganisms and the chemical and physical properties of soil; (3) the effect on plants as well as crop production; and (4) entering the food chain and associated hazards to human health. Finally, we found some research gaps and indicated future work. The discharge of heavy metals into the environment must be strictly regulated if people are to feel secure in their surroundings.

Keywords: heavy metals; food chain; agricultural soil; plants; contamination.

1. Introduction

Heavy metals are a serious issue and a major cause of soil pollution because of their toxicity and persistence in the environment (Uchimiya et al., 2020). Rapid industrialization, air deposition, farmyard manure, sewage sludge, and extensive use of synthetic fertilizers are all factors that contribute to the presence of HMs in soils (Mehr et al., 2021; Xu et al., 2019). Over 20 million hectares (ha) of land are affected by HMs, which include zinc (Zn), lead (Pb), nickel (Ni), arsenic (As), mercury (Hg), copper (Cu), cadmium (Cd) and chromium (Cr) (Liu et al., 2018). The Agency for Harmful Substances and Disease Registry (ATSDR) states that the four HMs Hg, Pb, Cd, and As are extremely harmful to both plants and people (Mansoor et al., 2020). In general, they may enter plant systems and pollute the food chain, which is extremely dangerous for the safety of human health and the quality of food (Yang et al., 2021; Zheng et al., 2021).

HMs and metalloids are agricultural soil pollutants since they have the potential to harm crop health and production if they are present in the soil at high concentrations (Shahid et al., 2015; Rashid et al., 2023). HMs are resistant to degradation, and if plants do not absorb them or leach them out, they can accumulate in the soil and last for a very long time (Wuana et al., 2011; Ghori et al., 2019; Ali et al., 2019). Ni, Cd, Hg, Cu, Cr, As, Pb and Zn are among the elements that regularly pollute agricultural soils and have hazardous effects on plants at high concentrations (Wuana et al., 2011; Tóth et al., 2016). Among these, Cr Cd, Hg, As, and Pb are very toxic and harmful to plant life at practically all levels of pollution (Tiwari et al., 2018; Rai et al., 2019; Singh et al., 2016). The over-standard rate of soil contamination is 16.1%, while the over-standard rates of the HMs Cr, Cd, As, Pb, and Hg are 1.10%, 1.50%, 1.60%, 2.70% and 7.00%, respectively (Zhao et al., 2022).

The development and production of plants depend on several minerals. Mg, Cu, Mn, Zn, Fe, Ca, Mo, Ni, and B are among the examples. These elements can improve a variety of cellular processes in plants, including pigment biosynthesis, ion homeostasis, gene regulation, respiration, enzyme activity, sugar metabolism, photosynthesis, nitrogen fixation, etc., at relatively low concentrations (Tiwari et al., 2018; Bashir et al., 2016). These same critical components, however, can negatively impact plant growth, development, and reproduction when they are accumulated at concentrations over their optimal levels (Shahid et al., 2015; Rashid et al., 2023). On the other hand, they also cause signs of mineral insufficiency in plants if the concentration falls below specific threshold values (Bashir et al., 2016).

The soil has already absorbed the majority of these HMs. On the other hand, long-term exposure to heavy metals can cause lung cancer and bone fractures in people (Rai et al., 2019). Regarding the use of ordinary foodstuffs like fruits and vegetables that have been tainted with HMs, human health concerns have grown significantly over the past few decades. If ingested through tainted food, Pb, Ld, Cd and As offer significant health concerns. Since these substances are rapidly absorbed into the food chain, cadmium and lead pose serious health risks. Because these substances accumulate quickly in tissues and induce retardation in children as well as severe effects on the auditory system, cardiovascular system, and kidneys, children are more susceptible to these substances than adults (Hembrom et al., 2020). In light of this, the evaluation of pollution and remediation methods for polluted soil has received a great deal of attention both locally and internationally.

The main contributors to HM pollution in the environment at the moment appear to be unique geogenic and meteorological variables, special situations like growing urbanization, and rising industrial, municipal, agricultural, residential, medical, and technical applications. However, the issue is more pronounced in many developing nations, partially for the reasons listed above and perhaps a lack of sufficient understanding of the hazardous effects of these elements on both agricultural production and human health.

This review indicated the sources of HMs, including anthropogenic and natural. This review also highlighted their impact on soil microorganisms and how they affect the chemical and physical characteristics of the soils. We emphasized their impact on plants and human health. Finally, we identified several gaps in the literature and suggested further investigation.

2. Sources of HMs in contaminated soil and irrigation water

HMs are defined as metals having a high atomic weight and a density of at least 5 g/cm^3 (Zhang et al., 2019). According to certain studies (Zang et al., 2017; Fei et al., 2020), the accumulation of HMs in soil may result in a drop-in soil quality, a decrease in soil fertility and agricultural production, and even possibly be harmful to human and animal health. The ecosystem and general people are at risk from a variety of HMs in polluted soil, especially given how swiftly the economy and society are evolving (Min et al., 2018). In soil environments, HMs, including mercury (Hg), cadmium (Cd), copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), arsenic (As) and chromium (Cr) are a common contaminant. This type of pollution is pervasive in the soil environment, widely disseminated, and dangerous from a biological standpoint (Ma et al., 2013). There are 5 million places on the planet where the concentration of HMs in the soil is now higher than what is deemed safe (Li et al., 2019). The most dangerous metals in the environment, according to the Environmental Protection Agency (EPA), are mercury, lead, cadmium and arsenic (Goyer, R., 2004). Human production activities, such as the use of fertilizers in agriculture, the manufacture of chemicals, and mineral mining, are the primary contributors to the building of HMs in soil (Tang et al., 2019). When compared to anthropogenic activities, several studies have indicated that natural sources of HMs in the environment are frequently of modest relevance (Dixit et al., 2015).

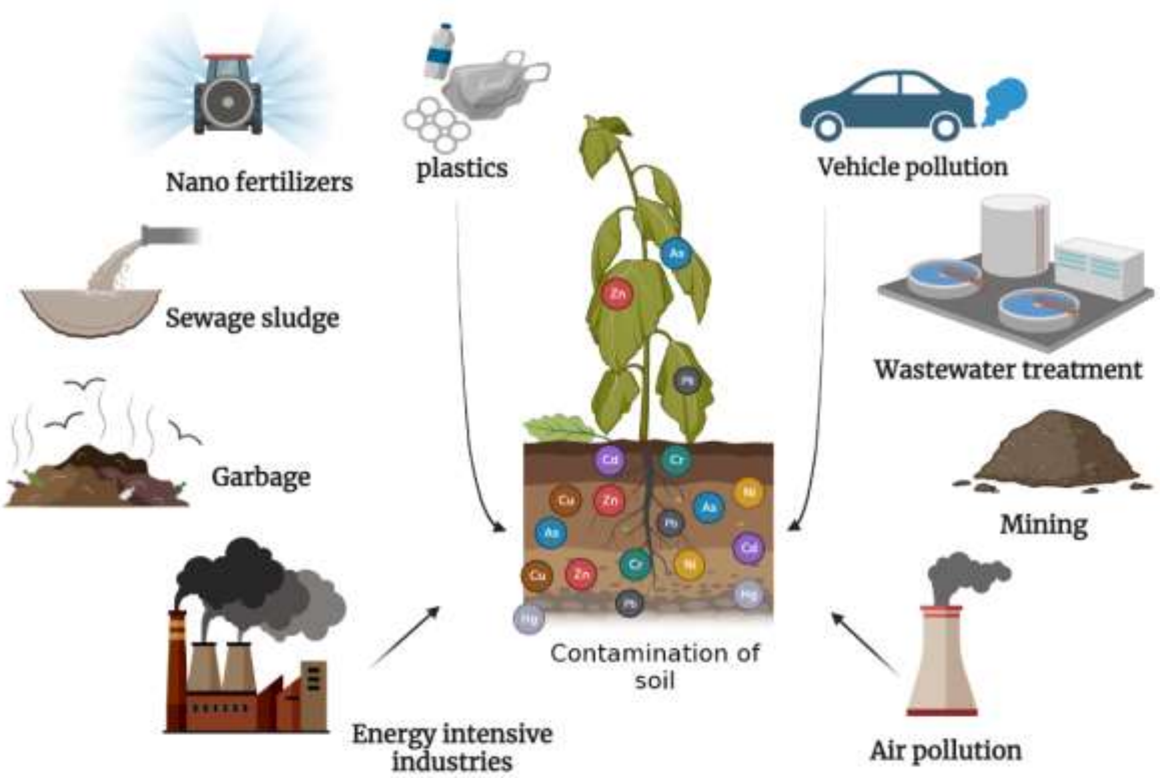

Figure 1. Different sources of HMs (vehicle, mining, garbage, sewage, plastics, nano-fertilizer, wastewater).

2.1 Natural

Igneous and sedimentary rocks are regarded to be the most common natural sources of heavy metals (Cannon et al., 2019). The parent material, from which they were originally derived, is the main source of HMs in soils. The Earth's crust is composed of sedimentary rocks to a little extent (approximately 5%) and 95% igneous rocks (Sarwar et al., 2016). Different concentrations of HMs are present in igneous and sedimentary rocks (Table 1).

Table 1: HM concentrations in igneous and sedimentary rocks, measured in parts per million (ppm).

HMs	Basaltic Igneous	Granite Igneous	Clays and Shales	Black Shales	Sandstone
Cu	48–240	5–140	18–180	34–1500	2–41
Zn	2–18	6–30	16–50	7–150	<1–31
Pb	30–160	4–30	18–120	20–200	-
Cd	0.006–0.6	.003–.18	0–11	<.3–8.4	-

Heavy metals naturally arise in the soil as a result of the weathering process because they originate in the Earth's crust. Natural activities, including meteoric, biological, terrestrial, and volcanic processes, erosion, leaching, and surface winds, can all result in HMs in rocks being released into the soil environment (Muradoglu et al., 2015).

2.2 Anthropogenic

Anthropogenic generally indicates sources that are manmade. Anthropogenic activities like mining and smelting (Chen et al., 2015), burning fossil fuels for energy (Muradoglu et al., 2015), dumping municipal waste (Khan et al., 2016), the use of pesticides, sewage irrigation, and fertilizer application (Sun et al., 2013) all increase the concentrations of HMs in the agricultural soil environment (Figure 1).

2.2.1 Industrial

Heavy metals are released into the environment as a result of rising human activity, such as industrial advancements. Eventually, these contaminants build up in the soil, especially in areas that are rapidly industrializing (Jin et al., 2019; Liu et al., 2020).

Some industrial sources of heavy metals are

Lead

Combustion of fossil fuel, paints and pigments, application of lead in gasoline, fertilizers, solid waste, incineration industrial waste, explosive, ceramics and dishware, solid waste combustion, paints and pigments, industrial dust and fumes, manufacturing of lead-acid batteries, pesticides, mining and metallurgy, some types of PVC, urban runoff.

Nickel

Industrial dust, electroplating, production of iron and steel, food processing industries, chemical industries, incineration of waste, fertilizers, industrial aerosols, mining and metallurgy, battery, and combustion of coal,

Chromium

Textile industry, metal plating, paints and pigments, rubber, photography, tanning, chemical industry, leather industry, industrial dust and fumes, fertilizers, mining and metallurgy.

Mercury

industrial wastewater, fossil fuel combustion, fluorescent bulbs, chlor-alkali, scientific instruments, production of chemicals, mercury arc lamps, industrial dust and fumes, incineration of municipal wastes, pesticides, fertilizers, solid waste combustion, smelting and metallurgy, electrical switches, explosive, rubber and plastics, mercury products (mercury amalgam, thermometers, batteries), cellulose, mining,

Copper

Textile industry, plating, paints and pigments, rayon, mining and metallurgy, pesticides, mining and metallurgy, explosives, electrical and electronics waste,

Arsenic

industrial dusts and waste, smelting of gold, lead, mining, smelting, medicinal, textile, pharmaceutical, wastewater, metal hardening, pesticides, paints, copper and nickel, production of steel and iron, phosphate fertilizers, combustion of fossil fuels.

Cadmium

PVC products, phosphate fertilizer, color pigments, electronics, industrial and incineration dust and fumes, pesticides, pigments and paints, batteries, mining and metallurgy and wastewater.

Zinc

Metal waste, fertilizers, electroplating, plating iron and steel, galvanization, mining and metallurgy

2.2.2 Agricultural

The agricultural sector has many potential sources, including fertilizer, pesticides, livestock dung, and wastewater (Li et al., 2013). Heavy metal pollution in agricultural soil and plants is caused by both industry and agriculture, especially in locations near cement and electroplating industries. That is to say, the soil's surface is an ideal location for accumulating heavy metals, which the plant can then take in through its roots and vascular system together with water (Xiao et al., 2017). Bioaccumulation of pesticides in food chains, caused by careless usage, poses a significant threat to mammals and other non-target species (Liu et al., 2016). Plant parts, soil, air, and water can all retain pesticide residues for long periods of time (Lefrancq et al., 2013).

2.2.2.1 Fertilizer

Both organic (natural) and inorganic (synthetic) fertilizers fall into this category. After the anaerobic digestion (AD) procedure, ammonium fertilizers (sulfate and nitrate) are created as organic or biofertilizers (Alengebawy et al., 2021). Chemically made or synthetic fertilizers are another name for inorganic fertilizers, which are composed of both inorganic and chemical components (Cai et al., 2019). The chemical designation of arsenic (As), a naturally occurring and abundant element of the Earth's crust, is a metalloid due to its metallic and nonmetallic qualities (Kesici, 2016). Both organic and inorganic forms of As are found in soil, with the latter being a very toxic form (Shrivastava et al., 2015). Bio-fertilizers, liming materials, and phosphate fertilizers are the most common inorganic fertilizer types responsible for HM release in agricultural soil and subsequent uptake by plants (Fan et al., 2018).

2.2.2.2 Pesticide

Pesticides are harmful substances that can be created synthetically or naturally. They can also be hazardous compound combinations. Insecticides, bactericides, and fungicides are frequently used in agricultural fields to control harmful weed, fungus, bacterial, and insect infestations (Khalek et al., 2018). In recent years, around 2 million tons of pesticides have been used globally, with 47.5% of those being used as herbicides, 17.5% as fungicides, 5.5% as other pesticides and 29.5% as insecticides (De et al., 2014; Sharma et al., 2019). Table 2. presents the four categories in order of increasing toxicity, from least to most hazardous, with a corresponding level of toxicity.

Table 2: categorization of pesticides in accordance with the WHO's standards for their toxicity.

Classifications	**Toxicity Level**	**LD 50 for the Rate (mgkg^{-1} Body Weight)**		**Examples**
		Dermal	**Oral**	
Type I(a)	Extremely hazardous	<50	<5	Parathion, Dieldrin
Type I(b)	Highly hazardous	50–200	5–50	Eldrin, Dichlorvos
Type II	Moderately hazardous	200–2000	50–2000	DDT, Chlordane
Type III	Slightly hazardous	>2000	>2000	Malathion

The use of Cu-based fungicides has sped up the buildup of Cu in citrus groves, vineyards, and other perennial crops. Due to the degradation of soil quality and phytotoxicity caused by Cu-contaminated soil, crop production potential is also decreased (Khanam et al., 2019). Because surface runoff or stormwater transports more Cu to recipient water bodies, it also contributes to water pollution (Kumar et al., 2018).

2.2.3. Others

The application of solid agricultural wastes, including biosolids and farm manures, has increased the buildup of hazardous metals in soils, while their availability in soils is unlikely to change much in the near future (Urra et al., 2019; Taghipour and Jalali, 2019). It has been noted that applying biosolids and agricultural manures repeatedly raises the amount of Ni, Cd, Zn, Cr, Cu, and Pb in soils (Epa, 2010).

3. Effects of HMs on soil

3.1 Effect on microorganisms in soil

HMs are toxic metallic elements like mercury, cadmium, chromium, nickel, lead and arsenic that are characterized by their high density and relatively high atomic weight. They can be found in the environment naturally and are later released into the soil, water and air due to human activities like industrial processes, mining, farming, and the use of certain products. Because of their toxic nature, they can accumulate in living organisms, which can pose significant risks to the environment. They harm soil microorganisms, which are crucial for soil fertility and ecosystem function. HMs have diverse and significant impacts on soil microorganisms, affecting the overall health and productivity of soil ecosystems.

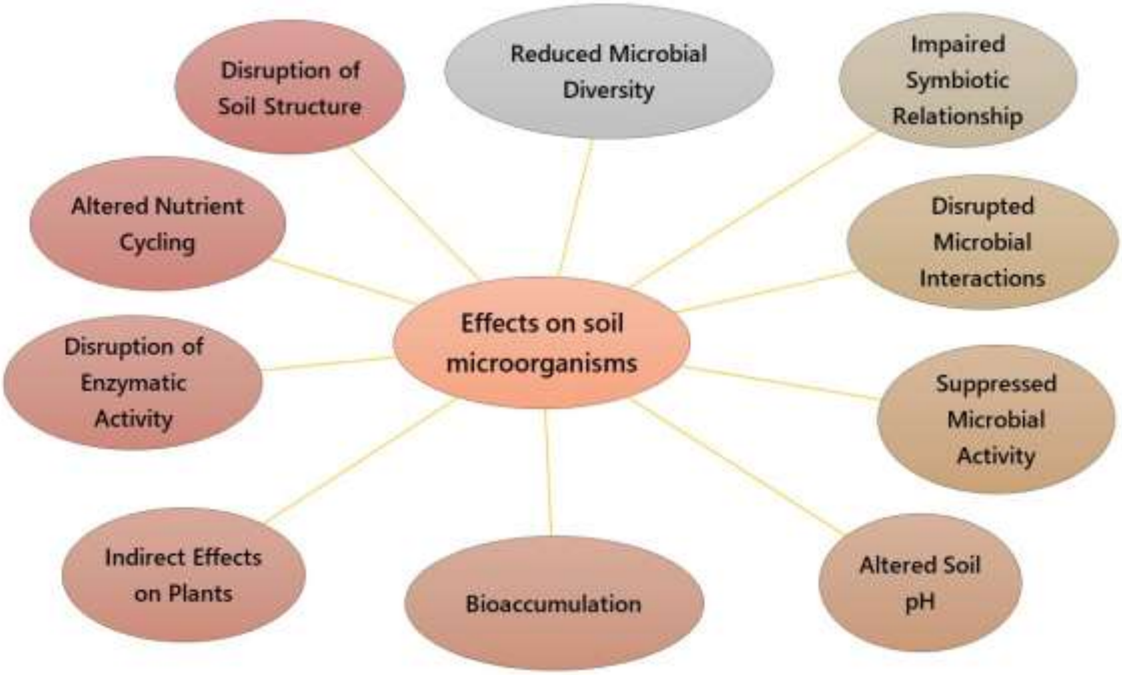

Figure 2. Effects of HMs on soil microorganisms.

The presence of HMs in the soil primarily inhibits the growth and development of the microbes as they damage the microbial cells, which in turn minimize the microbial population in the soil. This diminished microbial biomass can disrupt crucial processes like the decomposition of organic matter in the soil and alter the nutrient cycle such as nitrogen fixation, nitrification, and denitrification, impairing the overall nutrient availability in the soil and breaking down pollutants. Certain metals, such as lead, mercury and cadmium, are particularly toxic to microorganisms.

In addition to growth inhibition, these toxic heavy metals interfere with enzymatic activity, which is pivotal in carrying out the essential metabolic processes. These metabolic processes include the transformation of nutrients and the degradation of organic compounds into usable forms by flora. The presence of excessive HMs can imbalance these cycles and the availability of nutrients. This reduces the fertility status of the soil, reducing its productivity and the overall growth and development of the plants.

Soil microorganisms play an important role in ecological balance. It maintains the soil ecosystem's resilience and helps in providing various ecosystem processes like disease suppression, the formation of soil structure, and nutrient cycling (Figure 2). Certain microbial groups are highly sensitive to higher concentrations of HMs. It reduces population diversity and has negative implications for the stability and functioning of the ecosystem. Similarly, some groups of microorganisms may develop the tolerance to withstand heavy metal stress, known as bioaccumulation. As a result, they can accumulate in the microbes' tissue, increasing the concentration in their biomass, which affects the microbes themselves as well as the higher trophic levels of the food web (Kapahi & Sachdeva, 2019). They can also disrupt the symbiotic relationships between microorganisms, plants and mycorrhizal fungi. They also can impair nutrient acquisition and limit the growth and development of plants.

Soil Microbes also play an important role in maintaining the soil's pH (Figure 2). Too high or too low soil pH disturbs the microorganisms in the soil. HMs found in soil can cause shifts in soil pH. Certain heavy metals, like aluminum, have the potential to acidify the soil, resulting in a decrease in pH. This fluctuation in pH can have consequences for the viability and functioning of soil microorganisms, as different species have varying levels of tolerance to pH changes. Changes in soil pH can also affect the accessibility and movement of HMs within the soil, intensifying their impact on microorganisms. One of the studies shows that Contamination of Pb in soil results in soil acidification (Collin et al., 2022). Contamination with Lead inhibits nitrogen fixation and affects photosynthesis in plants (Porter & Sheridan, 1981). Similarly, it inhibits the activity of mycorrhizal fungi and soil enzymes. Short-term additions of N and P are sensitive to communities of soil microbes and enzymatic activities (Zi et al., 2022). Another study conducted on the effect of soil Amendments on trace elements indicates HMs like Cd have a toxic effect on microorganisms. Contamination with Cd reduces the soil pH, which has toxic effects on soil bacteria, fungi, and earthworms (Ukalska-Jaruga et al., 2022). This contamination affects Nitrogen cycling. Similarly, High levels of Cu and Zn in the soil increase the soil pH slightly, which disrupts microbial communities, especially bacterial communities involved in decomposition (Sazykin et al., 2023). Some microorganisms, such as arbuscular mycorrhizal fungi, can accumulate zinc (Begum et al., 2019). Even though Mercury contamination does not have a direct influence on soil pH, a toxic form of mercury, namely methylmercury, can be produced by certain soil bacteria and fungi, bioaccumulate in the food chain, and pose risks to higher organisms. This affects the marine food web as well (Harding et al., 2018). Additionally, Cr contamination does not significantly affect soil pH. High levels of chromium can be toxic to soil bacteria, fungi, and other microorganisms, inhibiting their growth and activity (Ali et al., 2023). However, the impact on soil pH and microorganisms can vary depending on factors such as the concentration of the heavy metal, soil type, duration of exposure, and the specific microorganisms present in the soil. Additionally, the tolerance and response of microorganisms to HMs can vary among species.

Similarly, Soil microorganisms play a pivotal role in maintaining the stability and structure of the soil (Wang et al., 2022). Soil aggregation is negatively impacted by the presence of HMs (Shen et al., 2022). It leads to compaction of the soil, which does not allow water infiltration, resulting in poor root growth. It affects the health of soils as well as the plants growing in them.

3.2 Effect on soil physical properties

One of the biggest issues in the modern world is HM poisoning of the soil. The physical characteristics of soil include its composition, porosity, bulk density, consistency, temperature, color, resistivity, and more. One of the main factors contributing to soil pollution is thought to be HMs. Several metals, including Cr, Cu, Pb, Zn, Cd, and Ni, are responsible for heavy metal pollution of the soil. HMs indirectly affect soil enzymatic activities by shifting the microbial community that synthesizes enzymes (Shun-hong et al., 2009).

HMs are elements with high atomic weights and densities that can have detrimental effects on soil's physical properties. These metals include As, Pb, Cr, Hg, and Cd. When present in excessive concentrations, they can negatively impact soil structure, texture, porosity, and water-holding capacity. Here are some ways in which HMs affect soil physical properties:

1. **Soil Structure Disruption:** HMs can alter soil structure by preventing soil aggregate production and stability. To maintain healthy soil structure, porosity, and water penetration capability, aggregates are crucial. According to studies, HMs including Cd, Pb, and Cu can destabilize aggregates and subsequently constrict soil (Alloway et al., 2013).

2. **Soil Texture Alteration:** Heavy metal accumulation in the soil matrix and altered particle size distribution can change soil texture. It has been noticed that metals like Ni and Zn have an impact on soil texture, changing the ratios of sand, silt, and clay particles (Pendias-Kabata, 2001).

3. Soil Porosity Reduction: Heavy metal contamination can reduce soil porosity, affecting the circulation of air, water, and nutrients. Metals including Cr, Cd, and Pb can clog soil pores, lowering the amount of water that percolates through and limiting the growth of roots (Adriano, 2001).

4. Water Holding Capacity: HMs can have an impact on the soil's capacity to hold water. High concentrations of HMs can reduce soil porosity and pore connectivity, leading to decreased water-holding capacity and increased water runoff (Bojórquez-Quintal et al., 2008). It has been discovered that a buildup of metals like Cu and Zn reduces the soil's capacity to retain water, increasing runoff and reducing the amount of water available to plants (Huang, Q., et al., 2016).

5. Soil Erosion: Heavy metal contamination can speed up soil erosion rates. HM buildup in the topsoil can weaken soil aggregate stability, increasing the likelihood of wind or water erosion (Zhang, Y., et al. 2016).

3.3 Effect on soil chemical properties

Heavy metals can have significant effects on soil chemical properties.

- **pH Alteration:** HMs can influence soil pH by either increasing or decreasing it. For example, metals such as cadmium and aluminum can lower soil pH, making it more acidic (Liu et al., 2013). On the other hand, metals like nickel and chromium can increase soil pH, making it more alkaline (Zhu et al., 2017). These changes in soil pH can impact nutrient availability, microbial activity, and overall soil health. The pH and organic content of the soil have the most effect on the accumulation and movement of HMs (Hu et al., 2018).
- **Nutrient Imbalance:** HMs can disrupt the balance of essential nutrients in the soil. Some metals, such as Ca, Pb, and Zn, can compete with and inhibit the uptake of essential nutrients like

magnesium, calcium, iron, and manganese by plants (Das et al., 2019; Kabata-Pendias and Mukherjee, 2007). This interference can lead to nutrient deficiencies in plants and affect their growth and productivity. One of the potentially harmful metals, Ld, affects microbial diversity, nutrient availability, and soil fertility (Dotaniya et al., 2020).

- **Soil Organic Matter (SOM) Degradation:** HM contamination can influence soil organic matter content and decomposition rates. High levels of HMs, such as Zn and Cu, can inhibit microbial activity responsible for organic matter decomposition (Li et al., 2018). This can result in the accumulation of organic matter in the soil, affecting nutrient cycling and soil fertility.
- **Redox Reactions:** HMs can influence redox reactions in the soil, altering the availability and mobility of nutrients. For example, metals like manganese and iron can undergo redox reactions, affecting the oxidation and reduction states of the soil (Alloway, 2013). These reactions can impact nutrient transformations, such as the conversion of nitrogen and sulfur compounds, and influence soil fertility.
- **Adsorption and Desorption:** HMs can undergo adsorption and desorption processes in the soil, affecting their mobility and availability. Soil properties, such as clay minerals and organic matter content, play a crucial role in heavy metal adsorption (Kabata-Pendias and Mukherjee, 2007). Some HMs, like lead and cadmium, have a high affinity for soil particles and can become strongly adsorbed, reducing their bioavailability to plants.

4. Effects on plants and crop production

The impact of HMs on plant and crop production is a significant issue that raises concerns regarding food safety, agricultural productivity and human health. Either naturally or artificially, due to human activity, HMs can accumulate in the soil. The harmful human activities include industrial pollution like oil refineries, adulteration from leaking septic schemes, oil spills, the proscribed dumping of chemicals from mining activities, and the use of contaminated inputs like irrigation water, pesticides, herbicides, insecticides, and fertilizers. This accumulation poses an impending menace to the environment and agricultural systems. The influence of toxic HMs on flora and crops can be inclusive and can ominously affect their growth, development, and overall productivity.

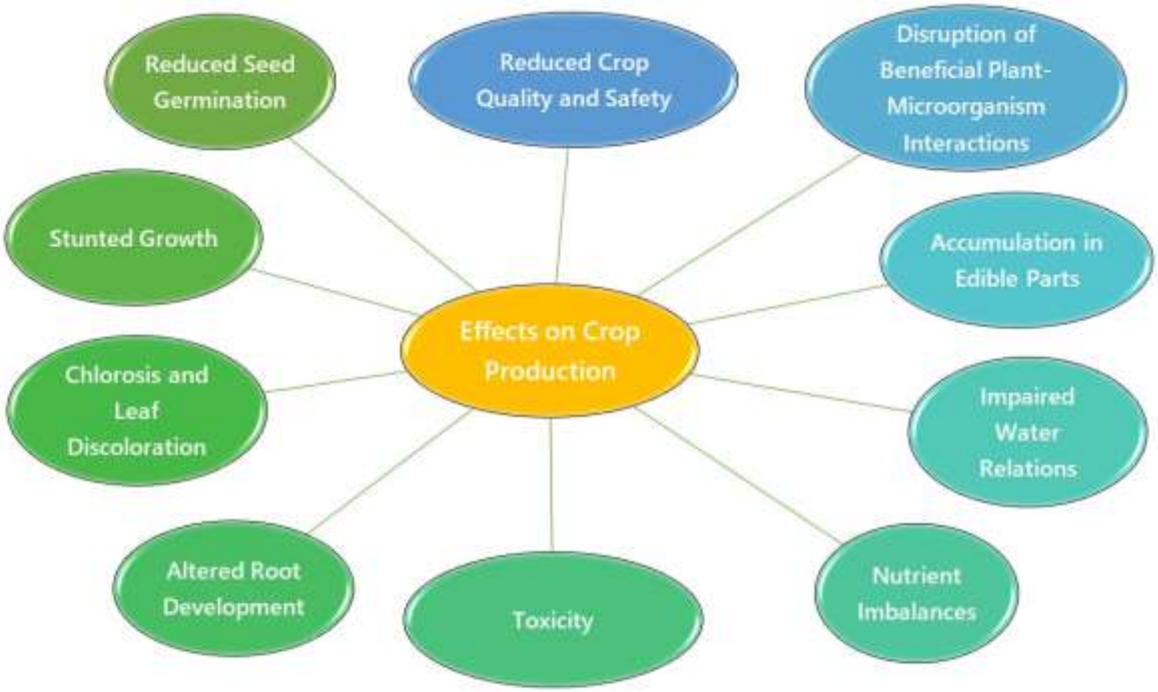

Figure 3. Effects of HMs on plant and crops production.

The content of HMs gets accumulated in the edible parts of plants like vegetables, grains and fruits (Najmi et al., 2023). Crops with higher concentrations may be unsuitable for consumption as they reduce the quality of harvested produce. In order to make the foods usable, extensive processing costs may be required, resulting in heavy economic drift and a potential risk to the well-being of human beings. Plants that are exposed to HMs may exhibit levels of essential nutrients for humans, like vitamins and minerals. Even after the extensive processing cost to make the food suitable for consumption, consumers may perceive crops with off-flavors or metallic tastes and can cause adverse health effects like organ damage, heavy metal poisoning, and chronic health effects if consumed over a prolonged period (Lebelo et al., 2021).

Additionally, its effect includes an increment in toxicity level (Figure 3). It affects the biochemical and physiological processes in plants, which affect the process of photosynthesis by reducing chlorophyll production, impairing enzymatic activities, and hindering the uptake of nutrients, which in turn results in stunted growth and development of plants and decreases crop yields (Ejaz et al., 2023). Additionally, HMs can cause oxidative stress in plants. They can engender reactive oxygen species (ROS) that can damage cellular structures, interrupt customary metabolic functions and damage aquatic organisms (Singh & Kalamdhad, 2011). Oxidative stress can lead to cell membrane damage, protein degradation, and DNA alterations, ultimately impacting plant growth and crop productivity.

HMs can also cause nutritional imbalances in plants (Table 3). Some HMs, such as lead and cadmium, have the aptitude to imitate essential nutrients and compete for uptake by plant roots. This competition can lead to nutrient deficits because they are preferentially taken up, resulting in insufficient nutrient uptake by crops. Nutrient deficiencies can harm plant growth, disrupt reproductive processes, and lower crop quality and output. HMs in the soil can also have an impact on the availability and drive of other vital nutrients. They can bind to soil particles or form insoluble compounds, reducing the availability of nutrients for plants. This can reduce nutrient availability for crop uptake and use, reducing plant development and production even further.

HMs show an indirect effect on plants by disrupting beneficial interactions between plants and soil microorganisms (Table 3) (Gladkov et al., 2023). Mycorrhizal fungi establish symbiotic associations with the roots of plants, which perform vital activities like nutrient and water uptake and retention, influencing the growth and development of the plant (Sazykin et al., 2023). This interference reduces nutrient acquisition by plants and impacts their ability to withstand environmental stresses. Water stress negatively impacts the physiological processes of plants like photosynthesis, especially in arid and semi-arid areas where the sources of water are limited (CHAVES et al., 2002).

Table 3: HMs in plant uptake and metabolism

HMs	Available form for plant Uptake	Plant metabolism	Plant effects	References
Cu	Cu^{2+}	● catalyst for redox processes in cells' cytoplasm, chloroplasts, and mitochondria. ● electron transporter in plant respiration	● cell lengthening ● photosynthesis ● thylakoid membrane structural changes ● seedling growth ● root lengthening and expansion Lipid peroxidation	(Nazir et al., 2019)
Pb	Pb^{2+} and lead-hydroxy complexes	● non-essential element	● seed germination ● chlorophyll synthesis ● plant growth	(Ghani et al., 2021; Yahaghi et al., 2019)
Zn	Zn^{2+}	● a component of zinc finger proteins, which are unique proteins that bind to DNA and RNA. ● constituents of enzymes (oxidoreductases, hydrolases and transferases) and ribosomes.	● necrotic spotting ● photosynthesis ● DNA regulation and stabilization ● genetic-related disorders ● plant growth	(Kaur & Garg, 2021)
Cd	Cd^{2+}	● non-essential element	● reactive oxygen species production ● photosynthesis ● nutrient uptake ● water uptake ● unregulated cellular growth ● necrotic cell death	(Huybrechts et al., 2021; Zhu et al., 2021)

As	As^{5+}	● non-essential element	● metabolism of phosphate	(Shri et al., 2019)
Ni	Ni^{2+}	● iron uptake ● seed germination ● important component in triggering the nitrogen-metabolic enzyme urease.	● seed germination and plant development by inhibiting amylase and protease activity. ● leaf area and plant height ● The prevention of new lateral roots from growing. ● breaks in the photosynthesis machinery. ● slows down root cell division during mitosis.	(Khan et al., 2023; Koza et al., 2022)
Cr	Cr^{3+} Cr^{6+}	● non-essential element	● dry matter of seedlings ● cell division ● Early plant growth stage: development of stems and leaves ● metabolic issues that affect seed germination ● roots and shoot elongation	(Madhu & Sadagopan, 2020)

5. Enter into the food chain and potential risks for human health

High heavy metal contents are reported in some developing countries like South Africa (Fonge et al., 2021), Pakistan (Alam et al., 2018), Ethiopia (Gebeyehu and Bayissa, 2020), Bangladesh (Islam et al., 2022) and Ghana (Ametepey et al., 2018), especially in urban areas of those countries, due to the main cause of rapid industrialization as well as wastewater irrigation and some other anthropogenic activities.

HMs are hazardous substances that are not biodegradable and are derived from natural sources of minerals or industrial discharges; they include lead, arsenic, chromium and cadmium (Qin et al. 2020). Some common foods, like fresh vegetables and fruits, have an abundance of HMs and pose dysfunction in the kidney, carcinogenesis, imbalance in the immune system, and sometimes even death-like human health risks due to their capacity for bioaccumulation and biomagnification (Ahmed et al. 2019; Shamsudduha et al. 2019). HMs are commonly found in agricultural products like vegetables, fish, rice, and fruits (Ahmed et al. 2019). Poisoning from HMs has been reported in groundwater along Bangladesh's coast and in drinking water, with possible dangers to both adults and children, including those related to cancer and other diseases (Islam et al. 2020).

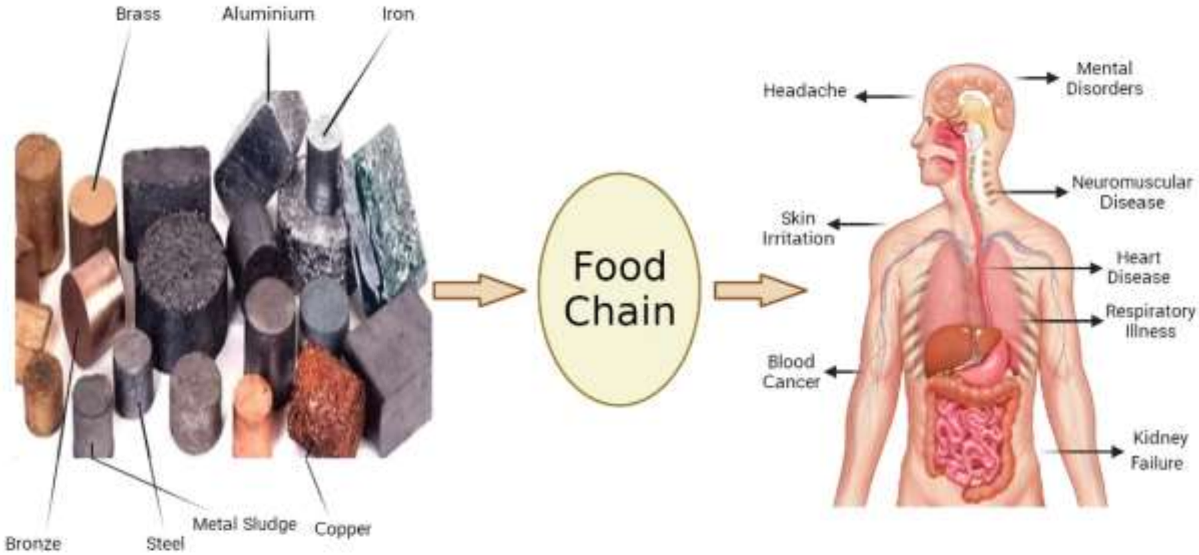

Figure 4. Effect of HMs on human body.

Many studies indicate that copper, chromium, cadmium, zinc, arsenic and lead are present at concentrations higher than the maximum tolerable limits (MTLs) parameter given by WHO (Islam et al. 2018). Poor management of industrial effluent, use of metal-rich irrigation water, wrong handling of trace metal additives in fish and poultry feed, and use of HM-containing fertilizer and pesticides all lead to a higher level of toxicity and transfer of HMs into the food chain (Zakir et al., 2020). This is called heavy metal contamination. Poor industrial effluent management, inadequate monitoring of entry routes, and a lack of awareness of regulatory requirements are the main causes of environmental and food contamination in Bangladesh (Shamsudduha et al. 2019; Zakir et al. 2020). Natural and anthropogenic activities are the main causes behind heavy metal contamination, and ecosystem components are being polluted (Ratul et al. 2018; Kumar et al. 2019). Primary sources of HMs include fertilizer or pesticide applications that contain HMs, improper industrial effluent disposal, mining, HMs release from poultry manure, trace metal rocks and minerals weathering, etc. (Kumar et al. 2019; Zakir et al. 2020).

Inappropriate arsenic ore mining and irrigation with arsenic-polluted groundwater both increase arsenic spread into the environment. It is widely proven that prolonged exposure to arsenic-contaminated water and foods poisons the human food web (Huq et al. 2020; Mihajlov et al. 2020). Tanneries that do not have environmental treatment release tannery effluents, including HMs, into the environment. About 200 tanneries in Dhaka City dump roughly 21,000 m3 of untreated effluents and 115 tons of solid debris into the natural ecosystem per day (Islam et al. 2022). Thus, HMs uptake by plants leads to toxicity in the food web through the intake of crops grown on polluted land, and in this case, there is a serious problem of trophic transfer of HMs from the primary sources to the human food chain. As a consequence, soils and groundwater contaminated with HMs serve as secondary sources. Heavy metal contamination is found in almost all rivers that are close to industrial cities. Some recent research conducted on aquatic species in South India shows dangerous levels of mercury and a great possible health hazard from exposure to humans (Subhavana et al. 2020).

A major concern for global food safety is the trophic transmission of HMs from primary sources to food webs and neighboring ecosystems (Ali and Khan 2019; Kumar et al. 2019). Further evidence that the biomagnification and HMs transfer to cow milk by grazing in contaminated fields pose a global hazard for newborns, kids, and adults comes from the discovery of HMs in raw cow milk (Boudebbouz et al. 2021; Haakonde et al. 2021). Additionally, it was shown that the Italian people were exposed to HMs through their food system (Filippini et al. 2019). As a result, the movement of HMs into the food chain is viewed as a potential threat to global food security.

Additionally, petrochemical operations cause more soil contamination and pose a threat to human health and the ecosystem (Sun et al., 2019). The use of gasoline leads to the accumulation of particular HMs such as Cu, Ni, Pb, Cd and Zn in plants from roadside soil (Zhai et al., 2021). Vegetables that are planted close to industries show higher HM concentrations than those grown far from such sites (Haque et al., 2021).

As the general population's awareness of health dangers expands, risk assessment related to heavy metal pollution has emerged as a global hot topic. Chronic heavy metal deposition in humans' liver, kidneys, and bones may develop from long-term exposure to high amounts of HMs through contaminated food, leading to renal, cardiovascular, neurological, and bone problems (Gupta et al., 2022).

Even trace amounts of HMs are very toxic to humans (Figure 4). Exposure to them adversely affects major organs like the brain, central nervous system, kidney, digestive system, and reproductive system. Children's physiology, such as the nervous system, brain, kidneys, and circulation, is also affected (Kumar et al. 2019). Both humans and animals face chronic or acute toxicity when lead, arsenic, mercury, or cadmium are consumed orally. This heavy metal poisoning causes vomiting, diarrhea, nausea, dysfunction in motor neurons, impairment in vision and hearing, heart and brain damage, hypertension, and other symptoms (Mari et al. 2018).

Additionally, internal and cellular toxicity can impair DNA structure, mitochondrial metabolic processes, such as ATP production and oxidative photophosphorylation, and nerve cell function (Kumar et al., 2019). According to a recent study, hazardous metalloids and HMs are bioavailable in the air's suspended particulate matter, and this poses a great threat to human health when inhaled (Ren et al., 2021). Due to frequent exposure to foods contaminated with toxic HMs, these serious consequences may potentially result in mortality in the global context.

6. Research gaps and future work

During our analysis, we found some research gaps. To promote future studies on HMs, we provided some potential recommendations that are mentioned below:

Plants are simultaneously exposed to numerous metals at once, and recent research has generally focused on the impacts of specific HMs. It may be possible to explore the cumulative toxicity of different HMs and their potential synergistic or antagonistic effects on plants by scrutinizing how they interact with each other and how they affect plants individually.

There has been very little research on crop genetic variation and adaptation mechanisms in crop plants. Different plant species and their individual genotypes may show different levels of sensitivity and tolerance to HMs. There is much scope for investigating the genetic variation and adaptations that enable some plants to thrive in metal-contaminated environments, which can provide important insights into plant resilience and help in the development of potential metal-tolerant plants.

Since HMs are capable of influencing several ecological interactions such as soil microbial communities, nanoparticles, microplastics and other metal ions, It can be investigated how they affect these interactions and it may have broad ecological implications such as effects on the function of the ecosystem, food chain contamination, biodiversity and ecological stability. Exploring these interactions helps to understand the fate and effects of emerging contaminants in the ecosystem.

Although mechanisms of HM uptake and transport in plant systems are fully understood, it is still ambiguous to us how heavy metal exposure in one generation of plants impacts their subsequent generations. Still, there is scope for investigation of the HMs movement pathway from generation to generation.

Recent research has mostly focused on the presence of microplastics in soil. But exploring how microplastics act as transport mechanisms for HMs and their distribution and bioavailability would be an interesting research area.

These research areas need interdisciplinary cooperation among the fields of plant biology, soil science and toxicology. Scientists can contribute to developing sustainable methods for suppressing heavy metal contamination and preserving healthy ecosystems and food security.

7. Conclusion

The pollution of soils with HMs poses an increasing risk to plant life and human health. As the industry expands rapidly, more heavy materials are required to produce a variety of goods; these include gasoline, explosives, film for cameras, pigments for batteries, paint for airplanes, coatings for cars, and steel. To address the worldwide food safety, plant, soil, and human health problems brought on by HM toxicity, we think that this review will make a significant contribution to the field of heavy metal research.

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