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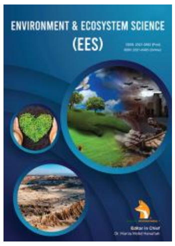

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REVIEW ARTICLE

THE IMPACT OF HEAVY METAL CONTAMINATION ON AGRICULTURAL ECOSYSTEM: A REVIEW

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ABSTRACT

Rapid industrialization over the past few decades has led to significant environmental pollution, with heavy metals being among the most hazardous contaminants due to their high toxicity and abundance. These metals, including Manganese, Magnesium, Copper, Iron, and Zinc are essential for plant growth in specific amounts but can be detrimental in excess, causing disruptions in photosynthesis and other physiological processes. Heavy metals like Cadmium and Lead are particularly harmful, affecting plant growth and enzymatic activities, leading to reduced crop yields. Soil ecosystems and plant growth are disrupted by heavy metal deposition, impacting the food supply and soil performance. This study aims to examine various types of heavy metals, their sources, significance in agriculture, mitigation activities, and recommendations for their control. Heavy metals are classified into essential and non-essential categories, both of which can be toxic at high concentrations. Sources of contamination include both natural processes and anthropogenic activities such as industrial processes, waste disposal, and the use of pesticides and fertilizers. The accumulation of heavy metals in soils affects soil microbial communities and enzyme activities, leading to soil degradation and reduced plant productivity. Understanding the sources, effects, and mitigation strategies for heavy metal contamination is crucial for sustainable agricultural practices and environmental health.

KEYWORDS

Agriculture, Contamination, Ecosystem, Heavy metals, Mitigation

1. Introduction

The rapid pace of industrialization worldwide over the past few decades has resulted in a global environmental pollution crisis (Gautam et al., 2016). Heavy metals are considered some of the most hazardous contaminants due to their high toxicity and the significant amounts released into the environment through both natural and human activities (Wang et al., 2014). The deposition of heavy metals in soil disrupts the normal functioning of soil ecosystems and hampers plant growth (Khan et al., 2008). When present in soil or irrigation water, various heavy metals are absorbed by plants (Fusconi et al., 2006).

Metals such as manganese (Mn), magnesium (Mg), copper (Cu), and iron (Fe) are essential elements for plants. These metals are required in specific quantities, and both deficiencies and excesses can negatively affect plant health, leading to reduced productivity. For instance, Mn plays a key role in splitting water molecules during photosynthesis, while Mg deficiency causes chlorosis in leaves and oxidative stress in plants (Wang et al., 2009). Although zinc (Zn) is vital for plant growth, excessive levels can harm plants by reducing chlorophyll production, leading to chlorosis. Additionally, toxic metals such as cadmium (Cd) and lead (Pb) have been shown to adversely affect plant growth, particularly by impairing leaf and root development and inhibiting enzymatic activities, ultimately reducing crop yield (Lai et al., 2012).

The current global increase in soil degradation and contamination has made heavy metal stress one of the most harmful factors for major food crops. These metals can displace essential elements in pigments or enzymes, thereby disrupting their functionality. Accumulation of heavy metals in soil can degrade soil performance, harm plant health, and contaminate the food supply (Wu et al., 2010).

Heavy metals also negatively affect plant cell division and can cause various chromosomal abnormalities depending on the concentration and duration of exposure (Jaiswal et al., 2021). The absorption and accumulation of excessive metals can alter the ultrastructure and anatomy of plant cells, disrupting vital physiological processes such as pollination, seed germination, nutrient uptake, enzyme activity, nitrogen fixation, and photosynthesis. The presence of heavy metals in seeds also reduces their nutritional value.

This study, therefore, seeks to explore the different types of heavy metals, their sources, their significance in agriculture, mitigation measures, and recommendations for controlling heavy metal contamination in the environment.

2. Heavy Metals

Heavy metals are defined as metals with a specific density greater than 5 g/cm^3 that have harmful effects on the environment and living organisms (Jarup, 2013). A heavy metal becomes toxic when it reaches a certain concentration in plants and animals. Trace elements, also known as micronutrients, are essential for the cellular function of both plants and

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animals. Elements such as Co, Cu, Fe, Mn, Mo, Ni, and Zn are only classified as "heavy metals" when they accumulate to a hazardous level (Klaus, 2020). Metals are only available to plants in solution once their oxidation states have changed due to chemical reactions, and the density of the metal does not influence the formation of chemical compounds.

Metals are generally identified by their physical properties, such as their ability to conduct heat, the variation of their electrical resistance with temperature, malleability, ductility, and luster (Housecroft et al., 2008; Muller, 2007). These characteristics help distinguish metals from non-metals and metalloids. However, when metals undergo chemical changes and form molecules available to plants, these physical traits are lost (Shaw et al., 2004).

Metals with an atomic weight higher than iron are often referred to as "heavy metals" (Sood *et al*., 2019). Additionally, metals with a density exceeding 5 g/cm^3 are classified as heavy metals (Sani, 2011). Heavy metals, including As, Pb, Cd, Hg, and Cr, are metallic elements with a high density that can be toxic at low concentrations (Appenroth, 2010). A study in 2012 categorizes heavy metals into two groups, both of which are non-biodegradable in nature. The first group includes harmful metals like Pb, Cd, and As, which are toxic at any dose and have no biological function. The second group comprises essential metals such as Cu, Zn, Mn, Fe, Ni, and Cr, which are beneficial to human health and plants in small amounts but become toxic in higher concentrations (Chen, 2012). Also, heavy metals are a loosely defined group of elements with metallic properties, including transition metals, metalloids, and other elements used in industrial applications like insecticides and landslides (Singh et al., 2011). From a chemical perspective, heavy metals are defined as metals and metalloids with an atomic mass above 20 and a specific gravity exceeding 5, such as Cd, Hg, Cu, As, Pb, Cr, Ni, and Zn. However, biologically, the term "heavy" refers to a variety of metals, including certain metalloids that are toxic to plants and animals even at low concentrations (Rascio et al., 2011).

2.1 Classification of heavy metals

2.1.1 Essential heavy metals

Essential metals like iron, cobalt, copper, chromium, zinc-nickel, and cobalt are needed at the ideal levels for all bodily functions. In addition, inadequate amounts otherwise result in deficiency disorders and high levels of intoxication (Sivaperumal et al., 2007; Abadi et al., 2014).

2.1.2 Non-essential heavy metals

These substances, often referred to as xenobiotics, lack biological functions. Elements such as aluminum, mercury, lead, cadmium, and others exhibit toxic effects on tissues when their concentrations increase (Sfakianakis et al., 2015). The bioaccumulation of heavy metals in both plants and animals leads to numerous harmful consequences.

2.2 Heavy metal contamination

There are many ways that metals can contaminate the environment. They can enter environmental compartments many years after initial deposition because of their stability. The weathering of discarded materials has the potential to contaminate land and water systems (Nordberg et al., 2015). Major environmental contamination problems include the deposition of heavy metals from both natural and anthropogenic sources in plants and soil, as well as the effects. Food safety concerns and associated health risks rank among the top environmental worries (Cui et al., 2004). Xenobiotic chemicals or other alterations in the natural soil ecosystem are what create soil contamination or pollution.

Heavy metal exposure can occur through contaminated drinking water from lead pipes, elevated air concentrations near heavy metal emission sources, or ingestion via the food chain (Alloway, 2001). The sources of heavy metals in soils include both the soil's parent material and a range of anthropogenic activities, many of which contribute multiple metals. In urban and agricultural soils, there are numerous anthropogenic sources of heavy metal pollution. In regions with lax emission regulations and soil quality standards, localized contamination from a single source, such as a metal smelter, can significantly impact soil, plant life, and potentially human health in surrounding areas. Generally, the type of heavy metal pollution found in industrial site soils depends on the specific industries, raw materials, and products involved. In urban soils, heavy metals like lead (Pb), zinc (Zn), cadmium (Cd), and copper (Cu) are often present due to traffic, paint, and other common urban sources. While the parent material has a greater influence on the heavy metal content of agricultural soils, additional factors such as the application of inorganic materials, contaminants in fertilizers, and long-range transport of aerosol particles from the combustion of fossil fuels can also play a significant role.

In many countries, efforts to reduce heavy metal contamination such as removing lead from paints and gasoline, changes in industrial practices, and stringent regulations on wastewater and atmospheric emissions have led to a decline in metal concentrations in soils. However, historical contamination continues to affect soils in various regions, with long-term consequences (Sutkowska et al., 2013). Some heavy metals, including copper, zinc, manganese, cobalt, and molybdenum, serve as essential micronutrients for human and animal growth when present in trace amounts, while others, such as cadmium, arsenic, and chromium, are carcinogenic (Trichopoulos et al., 2017). At the biochemical level, excessive levels of heavy metals can lead to various negative effects, such as competing with essential metabolites, replacing vital ions, interacting with -SH groups, disrupting cell membranes, and reacting with phosphate groups (Bharti and Sharma, 2022).

2.3 Sources of heavy metals

Both natural and anthropogenic processes contribute to the presence of heavy metals in agro-ecosystems. While natural sources of heavy metals in the environment generally have limited significance compared to anthropogenic sources, some soils can accumulate these metals from parent materials that contain high levels of naturally occurring heavy metals (Dixit et al., 2015). This inheritance can be detrimental to plants and other organisms due to the elevated concentrations of these metals. There are two primary categories of sources that release heavy metals into various environmental media, including soil, air, and water: anthropogenic and natural sources (El-Kady et al., 2018). The parent material, from which these metals originated, serves as the primary source of heavy metals in soils. The Earth's crust is made up of approximately 5% sedimentary rocks and 95% igneous rocks (Sarwar et al., 2017). As a rule, shales are rich in Pb, Cu, Zn, manganese (Mn), and Cd, while basaltic intelligent rocks are typically rich in heavy metals including Cu, Cd, Ni, and cobalt (Co). Through natural processes like meteoric, biological, terrestrial, and volcanic processes, as well as erosion, leaching, and surface winds, heavy metals stored in rocks can infiltrate the environment of the soil (Muradoglu et al., 2015).

The earth's natural processes include volcanic eruptions, sea-salt sprays, forest fires, rock weathering, biogenic sources, and soil carried by the wind. The anthropogenic sources include industrial, processes, waste water discharge, mining and metallurgical processes, motor discharge and chimney emissions.

The primary sources of metals include pesticides, paint production, textile printing, the earth's crust, hair dyes, and polyvinyl chloride (PVC) pipes for lead (Pb); rechargeable batteries, tobacco, phosphate fertilizers, pigments, industrial waste, and agrochemical waste for cadmium (Cd); stainless steel, alloy production, wood preservation, textile dyes, leather tanning, and electroplating for chromium (Cr); kitchen utensils, machine components, batteries, the earth's crust, cigarettes, and stainless steel for nickel (Ni); volcanic activity, biomass pyrolysis, mining, ship painting, wastewater discharges, and forest fires for mercury (Hg); and volcanic activity, disposal of arsenical chemicals, gold and copper mining, arsenical pesticides, smelting, and fertilizers for arsenic (As).

Anthropogenic processes disrupt the naturally occurring, slowly revolving cycle of heavy metals in the geochemical system, which leads to the buildup of one or more heavy metals in the soil (Dixit et al., 2015). Increased soil heavy metal contamination is mostly a result of recent improvements in the agricultural sector, industrialization, and urbanization. Anthropogenic activities such as mining and smelting, fossil fuel combustion for refining, municipal waste disposal, pesticide application, sewage irrigation, and fertilizer application all contribute to increasing heavy metal concentrations in agricultural soils (Chen et al., 2015; Muradoglu et al., 2015; Khan et al., 2016; Ogunlade et al., 2011; Sun et al., 2013; Atafar et al., 2010).

Table 1: Sources of various heavy metal contaminations in the environment

Heavy Metals	Sources
Cd	Geogenic sources, human activities, metal smelting and refining, fossil fuel combustion, the use of phosphate fertilizers, and sewage sludge.
As	Semiconductors, wood preservatives, mining and smelting operations, coal-fired power plants, herbicides, volcanic activity, petroleum refining, and animal feed additives.
Pb	Mining and smelting of metal ores, combustion of leaded gasoline, municipal sewage, industrial waste containing Pb, and paints.
Cr	Electroplating industry, sludge, solid waste, and tanneries.
Hg	Volcanic eruptions, forest fires, emissions from industries that produce caustic soda, as well as burning coal, peat, and wood.
Cu	Electroplating industry, mining, biosolids, and smelting and refining processes.
Ni	Volcanic eruptions, landfills, forest fires, bubble bursting and gas exchange in oceans, weathering of soils and geological materials, industrial effluents, kitchen appliances, surgical instruments, steel alloys, and automobile batteries.
Zn	Electroplating industry, smelting and refining, mining, and biosolids.

Source: (Lone et al., 2008)

3. Effect of Heavy Metals on Agricultural Soils

Soil pollution due to heavy metals is a significant concern in industrialized regions of the world (Hinojosa et al., 2004). In addition to impacting plant yield and quality, heavy metal contamination also affects the composition, size, and activity of the microbial community (Yao et al., 2003). Consequently, these metals are considered a primary contributor to soil degradation. The main culprits of soil pollution include Ni, Cu, Cd, Cr, Zn, and Pb (Hinojosa *et al*., 2004), which substantially influence organic matter, pH, clay content, soil biology, and soil biochemistry. These metals disrupt the microbial community that is essential for enzyme production, ultimately affecting the functionality of soil enzymes (Huang et al., 2009). Additionally, they harm the soil biota by altering key microbial activities and reducing both biotic activity and population sizes. One of the long-term effects is an increased tolerance among bacterial and fungal populations. For example, arbuscular mycorrhizal (AM) fungi play a vital role in the restoration of damaged ecosystems (de Mora et al., 2005).

Due to heavy metals, bacterial species have decreased, whereas actinomycetes have grown in proportion. Additionally, bacterial community diversity and biomass have decreased in contaminated soils (Chen et al., 2010). Due to certain chemical affinities in the soil system, certain metals might impact enzymes (Karaca et al., 2010). Pb has a lower mobility than cadmium and a higher binding affinity for soil colloids, making it less hazardous to enzymes than cadmium. More so than cellulose activity, it inhibits the activity of b-glucosidase. Catalase, urease, acid phosphatase, and invertase are all greatly decreased by Pb. Arsenic inhibits phosphatase and sulfatase but not urease. Urease, alkaline phosphatase, protease, and arylsulfatase activity are all negatively impacted by Cr, although invertase activity is only marginally affected. Enzymes from soil exhibit different levels of susceptibility to heavy metals. Inhibitors of urease activity include Cr, Cd, Zn, Mn, and Pb in decreasing order *(*Jaiswal et al., 2018).

To recycle plant nutrients, maintain soil structure, detoxify hazardous substances, and manage pests, soil bacteria are crucial. Analysis of soil organisms in ecosystems subjected to chronic heavy metal contamination is required *(*Wang et al., 2009). The two forms of chromium that are often found in soil, Cr (III) and Cr (VI), are separated by different chemical characteristics and toxicities. While Cr (VI) is highly poisonous due to its powerful oxidizing properties, Cr (III) is a nonhazardous micronutrient that is 10 to 100 times less harmful *(*Garnier et al., 2006). At high concentrations, Cr (VI) is thought to have significant impacts on microbial cell metabolism and is known to change how soil microbial communities are organized (Huang et al., 2009*)*. The population size, variety, and general activity of soil microorganisms are all altered as a result of these harmful impacts. Microbe metabolism is impacted by Cr, Zn, and Cd. High concentrations negatively impact enzyme activity and respiration rate and are reliable signs of soil contamination. Pb, on the other hand, barely changes the microbial profile at all *(*Ashraf and Ali, 2007*)*.

4. Effects of Heavy Metals on Plant

The discharge of pollutants into the environment has markedly increased over the last few decades due to rising urbanization, industrialization, and changes in agricultural practices (Hasan et al., 2017). Heavy metals such as As, Cd, Pb, Hg, and Se do not modify the physiological composition of plants, making them non-essential for plant growth. In contrast, metals like Co, Fe, Mn, Cu, Mo, Zn, and Ni are crucial for normal metabolism and growth but can become toxic when their concentrations exceed acceptable limits (Rascio et al., 2011). As heavy metals accumulate in the food chain, they pose significant risks to both animal and human health (Jordao et al., 2006). Plants absorb heavy metals through their roots, and factors such as nutrient availability, organic matter content, moisture levels, and pH influence the uptake and accumulation of these substances in plant tissues (Sprynskyy et al., 2007).

For example, in *Beta vulgaris* (spinach), metals like Cd, Cr, Zn, and Mn are more likely to accumulate during the summer, whereas Ni, Cu, and Pb are more prevalent in the winter. The faster decomposition of organic matter in summer releases heavy metals into the soil, which are subsequently absorbed by plants. Increased ambient temperatures and lower humidity during summer can lead to higher rates of Cd, Mn, Zn, and Cr uptake due to enhanced transpiration compared to winter (Sharma et al., 2007).

The amount of heavy metals that accumulate in plants is influenced by plant species and their absorption efficiency, determined by either plant consumption or soil-to-plant transfer mechanisms (Hinojosa et al., 2004). Elevated levels of Pb in soils can result in dark green leaves, drooping older leaves, reduced foliage, and short brown roots in plants (Bhattacharyya et al., 2008). Conversely, low concentrations can promote essential plant functions such as photosynthesis, mitosis, and water uptake. Phytotoxicity can lead to poor plant development, chlorosis, decreased yield, impaired nutrient uptake, and the failure of leguminous plants to fix atmospheric nitrogen, as well as metabolic disorders (Guala et al., 2010). High Pb levels ultimately impede seed germination. The detrimental effects of prolonged exposure, such as chelation, leaching, metal binding, and Pb accumulation by microorganisms, can be mitigated (Ashraf et al., 2007).

5. Common Heavy Metals Found in Agricultural Soils

5.1 Arsenic (As)

A metalloid called arsenic can be recovered from ores that are mostly composed of Cu, Pb, Zn, Ag, and Au. It can also be found in the ashes after burning coal. In aerobic conditions, As (V) predominates, primarily in the form of arsenate in various protonation stages. Arsenate and other anionic forms of arsenic act as chelates when metal cations are present and can precipitate *(*Silva *et al.,* 2014). Since arsenic is frequently present in anionic form, it does not combine with simple anions like chlorine ions (Cl-) and sulfur oxides (SO4 2-). The arsenic speciation also includes organometallic forms of arsenic such as methyl arsinic acid (CH3) AsO2H2). Many arsenic compounds securely attach to soils; thus, groundwater and surface water are limited in how far they can go *(*Requejo et al., 2015).

5.2 Cadmium (Cd)

The transition metal cadmium (Cd), which is poisonous and not necessary, is harmful to both people and animals. It is a contaminant that originates from industrial and agricultural sources and occurs naturally in the environment *(*Genchi et al., 2020). Low amounts of cadmium can be found in nature, especially in the zinc, lead, and copper sulfide ores. Although there aren't many cadmium ores, due to its isomorphic replacement to zinc, cadmium can be found in most zinc ores. Cadmium is present in food, drink, and breath in detectable concentrations due to its widespread occurrence (Sinicropi et al., 2010*)*.

Environmental cadmium pollution results from human activities such as fossil fuel combustion, landfill leachate, agricultural practices, and mining waste, particularly from zinc and lead mines (Thompson et al., 2008). Cadmium is used as a pigment, stabilizer for PVC and alloys, and in the electroplating process to prevent steel corrosion (Hayat et al., 2019). As one of the most toxic heavy metals, cadmium poses hazards in various ways. It has a strong affinity for biological structures like cysteine, glutathione (GSH), and disulfide -S-S- groups (cystine and reduced glutathione GS-SG), disrupting their functions. While cadmium itself does not produce free radicals, exposure leads to an increase in reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide, and hydroxyl radicals. Cadmium induces oxidative stress and ROS generation, which are typically counteracted by enzymatic (SOD, CAT, GPx) and non-enzymatic (GSH, vitamin C, vitamin E) antioxidant defenses (Matovi et al., 2015; Al-Gnami, 2014; Amamou et al., 2015).

5.3 Copper (Cu)

Copper is a vital component for many metalloproteins and takes part in many physiological processes; nevertheless, excess copper in cells can cause issues. Plant development is impeded by excessive copper, which also disrupts critical cellular functions such as photosynthetic electron transport. Despite the possibility of toxicity, copper is a necessary metal for healthy plant growth and development. (Yruela, 2005).

5.4 Lead (Pb)

Lead derived from the Latin plumbum, represents the chemical element lead, which has an atomic number of 82. It is a hefty metal, denser than the majority of everyday materials. Lead has a relatively low melting point and is soft and flexible. Lead has a blue tinge and is lustrous and grey when it is first cut. When it comes into contact with air, it turns a dismal grey colour. Out of all stable elements, lead has the greatest atomic number. Three of its isotopes are important nuclear decay endpoints of heavier elements. Even in small quantities, lead is hazardous, especially to young people. Nonetheless, natural processes such as igneous activity, radioactive decay, and rock weathering release trace amounts of lead into the environment. Lead concentrations in soil and water are now many orders of magnitude higher than naturally occurring concentrations due to anthropogenic lead emissions (Pattee and Pain, 2002).

5.5 Zinc (Zn)

Zinc, represented by the symbol Zn and atomic number 30, is a chemical element. At room temperature, it is a slightly brittle metal with a shiny, greyish appearance when free of oxidation. As an essential micronutrient, zinc is involved in various plant physiological functions and positively influences plant growth, development, and yield. It plays a crucial role in cellular processes across all living organisms. However, heavy metal concentrations, including zinc, are rising in agricultural soils due to various human activities (Hassan et al., 2017).

5.6 Chromium (Cr)

Chromium is a hard, lustrous, steel-gray metallic element known for its rust resistance and resistance to tarnishing. It is commonly used for plating other metals, hardening steel, and producing stainless steel and various alloys. Chromium is distinctive among regulated toxic elements in the environment because its different species, particularly chromium (III) and chromium (VI), are subject to separate regulatory measures, unlike other toxic elements where the oxidation state is not differentiated (Bhattacharyya et al., 2008).

5.7 Iron (Fe)

Iron (Fe) is a vital micronutrient necessary for proper erythropoiesis, oxidative metabolism, and cellular immune responses. It is found abundantly in most rocks of the Earth's crust. The formation of various iron oxides in soils can be understood by examining the pedoenvironmental conditions under which a specific phase or combination of phases is present in a given soil or soil sequence (Schwertmann and Taylor, 1989).

6. Negative Impact of Heavy Metals on Agricultural Crops

Heavy metal accumulation in waste disposal sites remains at environmentally hazardous levels. These metals are resistant to degradation and have a global environmental impact. Heavy metals are among the most common pollutants found on the surfaces and in the tissues of fresh vegetables (Balkhair et al., 2016). Depending on their environmental concentration, some heavy metals can function as plant nutrients, while others such as mercury, lead, cadmium, silver, and chromium are introduced through human activities and pose harmful effects even at low concentrations (Opaluwa et al., 2012). This leads to unhealthy conditions and environmental issues due to the toxic effects of heavy metals in plants, with potential health risks for humans and animals consuming these vegetables (Agbemafle et al., 2020). Once introduced into the soil, heavy metals are not degradable through biological or chemical processes, allowing them to persist in the environment for extended periods. This causes significant environmental pollution and detrimental effects on ecosystems, including bioaccumulation (Hoornweg et al., 2012). There is growing concern about soil contamination leading to the introduction of harmful elements into food chains via plant uptake, which threatens food safety. Heavy metal accumulation in soils and plants negatively impacts plant physiological activities such as photosynthesis, gas exchange, and nutrient absorption, ultimately reducing plant growth and dry matter accumulation (Gebre et al., 2015; Ozcan, 2016).

Lead (Pb) has been shown to disrupt plant metabolism, alter morpho-physiological traits, and impair plant growth and productivity. It reduces soil fertility (Kumar and Prasad et al., 2019) and delays seed germination (Singh et al., 2011). Additionally, lead contributes to malformed plant cellular structures, hormonal imbalances, reduced chlorophyll biosynthesis, and an excess of reactive oxygen species (ROS), which can induce oxidative stress in plant cells. This stress targets biological structures and biomolecules, leading to metabolic dysfunction (Tang et al., 2017).

Cadmium (Cd) has been linked to numerous defects in various plant parts, including roots, shoots, leaves, and fruits, along with an increased dry-to-fresh mass ratio (DM/FM) in all organs (Singh et al., 2020). It can adversely affect the sugar and amino acid content in some plants by increasing their concentrations, indicating suppressed starch hydrolysis (Singh et al., 2020). When Cd interacts with photosynthetic complexes, it reduces photosynthetic carbon assimilation. Moreover, Cd disrupts guard cell regulation, impairing the plant's water status and causing soil toxicity. This toxicity hampers phytochelatin production by blocking transporters/channels for loading other elements, resulting in nutrient imbalances (Bakshi et al., 2018).

Zinc's phytotoxicity directly impacts crop productivity (Balkhair and Ashraf, 2016), as it decreases the availability of nitrogen and sulfur in the soil, essential for crop growth. Similarly, copper reduces nitrogen and sulfur availability and more significantly inhibits the activity of β-glycosidase compared to cellulose (Bakshi et al., 2018).

7. Control of Heavy Metals in Soil and Agricultural Crops

Heavy metals are persistent in the environment, and once introduced into the soil, they remain for extended periods. Soil, being a biochemically and geochemically heterogeneous complex material (Alloway et al., 2019), retains heavy metals for longer durations compared to air and water (Kamari, 2011). Several methods are available to remediate soil contaminated with heavy metals, typically involving physical, chemical, or biological processes.

7.1 Engineering remediation

The process of replacing contaminated soil involves applying a significant quantity of clean soil either to cover or blend with the polluted soil's surface (Su et al., 2014; Kamari, 2011). Another approach, known as soil extraction and isolation, is a type of engineering remediation that entails physically removing the contaminated soil and replacing it with uncontaminated soil. This method is typically necessary for highly polluted soils in confined areas.

7.2 Electrokinetic remediation

This method utilizes the principle of DC voltage to create an electric field gradient on both sides of an electrolytic tank containing polluted soil. Pollutants within the soil are transported to the processing chambers situated at the two poles of the electrolytic cell, where processes such as electric migration, electro-osmosis, or electrophoresis help reduce pollution. This technique is particularly effective in low-permeability soils (Su et al., 2014; Kamari, 2011; Hanson and David, 1992). Another variation of this remediation method is soil leaching, which involves treating contaminated soil with specific chemicals to extract heavy metal complexes and dissolved iron adhered to solid particles. These heavy metals are subsequently recovered from the extraction solution (Su et al., 2014). Additional methods include adsorption fixation and adsorption using clay minerals such as bentonite and zeolite (Wang and Zhou, 2004).

7.3 Bioremediation

A form of this remediation method is Phytoremediation which involves planting specific plants in contaminated soil, such as Cruciferae, *Brassica* and Alyssum (Su et al., 2014; Kamari 2011; Xin et al., 2003).

Another is microbial remediation which uses microorganisms (bacteria, archaea, and fungus) to absorb, depose, oxidize, and reduce heavy metals in soil (Su et al., 2014; Kamari 2011; Fred et al., 2001).

8. Conclusion

The desk review highlights the significant impact of heavy metals on the environment and agriculture. Industrialization has increased the release of toxic heavy metals, becoming a major global issue. Contaminants like Mn, Mg, Cu, Fe, Cd, and Pb disrupt soil ecosystems and impair plant growth. While essential metals are beneficial in trace amounts, they are harmful in excess while non-essential metals are always toxic.

Heavy metals hinder plant physiological processes, reducing crop productivity and soil health by altering microbial communities and enzyme activities. Both natural and human activities, such as industrial emissions, mining, and agricultural practices, contribute to soil contamination. This accumulation poses severe risks to food safety and human health as these metals can enter the food chain and cause health issues.

Effective mitigation strategies, including stricter industrial emission regulations, cleaner technologies, and soil remediation techniques should be put in place. Understanding the specific sources and effects of different heavy metals is crucial for developing targeted interventions to protect agricultural productivity and environmental sustainability.

This study emphasizes the urgent need for comprehensive efforts to mitigate heavy metal contamination in agriculture to safeguard human health and promote sustainable practices.

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