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Heavy Metals Sources and Impacts on Agricultural Soil, Plant Growth and Mitigations - A Review

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Abstract

Heavy metals are metallic elements that have a high density and are toxic to living organisms at certain concentrations. They can enter agricultural soil through various sources, including industrial activities, mining operations, and the use of contaminated fertilizers and pesticides. These heavy metals, such as lead, cadmium, mercury, and arsenic, can have detrimental effects on agricultural soil, plant growth, and ultimately human health. One of the major impacts of heavy metals on agricultural soil is their accumulation over time. Continuous exposure to heavy metals can lead to their build-up in the soil, making it unsuitable for plant growth. This accumulation can disrupt the soil's physical and chemical properties, affecting its fertility and nutrient availability. Additionally, heavy metals can alter the soil's pH, leading to imbalances in nutrient uptake by plants. The presence of heavy metals in agricultural soil can significantly impact plant growth and development. These metals can inhibit seed germination, reduce root growth, and impair nutrient absorption in plants. They can also interfere with essential physiological processes, such as photosynthesis and enzyme activity, leading to stunted growth and reduced crop yields. Furthermore, heavy metals can be taken up by plants and accumulate in their tissues, posing a risk to human health when consumed. To mitigate the impacts of heavy metals on agricultural soil and plant growth, several strategies can be employed. The approach Heavy metals mitigation and remediation techniques encompass a range of approaches, including soil stabilization, soil washing, phytoremediation, bioremediation, electrokinetic remediation, and thermal desorption. Soil stabilization involves the addition of amendments to immobilize heavy metals, reducing their mobility and bioavailability. Soil washing employs chemical solutions or water to remove heavy metals from contaminated soil. These plants, known as hyperaccumulators, can be used to extract heavy metals from contaminated soil, thereby reducing their concentration. Additionally, proper waste management and the use of organic fertilizers can help minimize heavy metal contamination in agricultural soil.

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Introduction

Heavy metals are naturally occurring elements that can be found in soil, but their concentration can be significantly increased through human activities. Industrial processes, mining operations, agricultural practices, and improper waste disposal are common sources of heavy metal contamination in soil. These activities release heavy metals such as lead, cadmium, mercury, arsenic, and chromium into the environment, leading to their accumulation in soil (Engwa *et al.*, 2019). Different types of heavy metals have varying impacts on soil and plant growth. Lead, for example, can inhibit plant growth by interfering with enzyme activity and nutrient uptake. Cadmium is toxic to plants and can accumulate in their tissues, leading to reduced growth and yield. Mercury can disrupt photosynthesis and impair plant metabolism. Arsenic is highly toxic and can cause severe damage to plant cells, affecting their growth and development. Chromium can also hinder plant growth and reduce seed germination (Saud *et al.*, 2022).

The impacts of heavy metal contamination on soil and plant growth are significant. Heavy metals can alter soil pH, disrupt soil structure, and reduce nutrient availability. This can lead to poor soil fertility and hinder plant growth. Heavy metals can also accumulate in plant tissues, affecting their physiological processes and reducing their productivity. Contaminated plants may exhibit stunted growth, chlorosis (yellowing of leaves), necrosis (tissue death), and reduced seed germination. In severe cases, heavy metal toxicity can lead to plant death (Asati *et al.*, 2016)

Furthermore, heavy metal contamination in soil can have cascading effects on the entire ecosystem. Contaminated plants can be consumed by animals, leading to the bioaccumulation of heavy metals in their tissues. This can result in the transfer of heavy metals through the food chain, posing risks to wildlife and human health. Heavy metals can also leach into groundwater, contaminating water sources and affecting aquatic ecosystems. The persistence of heavy metals in soil can lead to long-term environmental degradation and loss of biodiversity (Sonone *et al.*, 2020)

To mitigate the impacts of heavy metal contamination, various remediation techniques, such as soil stabilization, soil washing, phytoremediation, bioremediation, electrokinetic remediation, and thermal desorption, can be employed. These methods aim to reduce the mobility and bioavailability of heavy metals in soil, remove or transform the contaminants, and restore soil health. Proper management of industrial waste, improved agricultural practices and strict regulations on heavy metal emissions are also crucial in preventing further contamination and protecting soil and plant health (Awa and Hadibarata, 2020).

Sources of heavy metals

Soil contamination with heavy metals is a growing concern worldwide due to its potential impact on ecosystems and human health. Heavy metals can enter the soil through various natural and anthropogenic sources. Heavy metals are conventionally defined as elements with metallic properties (ductility, conductivity, stability as cations, ligand specificity, etc.) and atomic number >20. The most common heavy metal contaminants are: Cd, Cr, Cu, Hg, Pb, and Zn. Metals are natural components in soil. Contamination, however, has resulted from industrial activities, such as mining and smelting of metalliferous ores, electroplating, gas exhaust, energy and fuel production, fertilizer and pesticide application, and generation of municipal waste (Engwa *et al.*, 2019).

Soils

Rocks disintegrate into fine particles or soil by the influence of ice, water, temperature, etc. The soil matrix is a major reservoir or transporting media for heavy metals, because soil and heavy metals associations have rich and diverse binding characteristics. Metals do not biodegrade like organic pollutants, rather they bioaccumulate in the environment. Soil matrix may adsorb, oxidize, exchange, catalyze, reduce, or precipitate the metal ions. These processes depend on several factors such as pH, water content, temperature, particle size distribution, nature of metal, and the clay content. This composition will determine the mobility, solubility, and toxicity of heavy metals present in the soil. Generally, the minerals are dissolved by interacting with carbonic acid and water. The insoluble minerals are dispersed into fine particles. Soils are contaminated by metals and metalloids from metal wastes, gasoline, animal manure, sludge, waste water irrigation, atmospheric deposition, etc. (Khan *et al.*, 2008). The heavy metals present in the soil become contaminant due rapid generation via man made cycle, direct exposure of mine samples due to transportation from mines to environmental location and high metal disposes (Singh and Steinnes, 2020).

Water

Heavy metals in water refer to metallic elements that are present in aquatic environments, such as rivers, lakes, and oceans. These metals can originate from both natural and anthropogenic (human) sources. Metal composition in surface water like rivers, lakes, ponds, etc. is influenced by the type of soil, rock and water flow Metals present on the surface of soil are carried out from its path, which ends up in sewage and reservoirs. The rain water gets contaminated while passing through the atmosphere. Water sources get contaminated by the flow of various industrial effluents into it. Ground waters are contaminated from landfill leachates, deep well liquid disposal and industrial wastes. Factors such a temperature, pH, living organism, cation exchange, evaporation, absorption, etc., will also influence the metal composition in the water (Edelstein and Ben, 2018).

Atmosphere

Heavy metals in the atmosphere refer to metallic elements that are present in the air as particulate matter or in gaseous form. These metals can originate from both natural and anthropogenic (human) sources. Heavy metals are released into the atmosphere as gases and particulates by surface erosion and colloid loss. Sources of heavy metals in the atmosphere include mineral dusts, sea salt particles, volcanic eruption, and forest fires. Other than these natural sources, heavy metal air pollution can also originate from various industrial processes that involve the formation of dust particles, e.g., metal smelters and cement factories. Volatile metals such as Se, Hg, As, and Sb are transmitted in gaseous and particulate form in the atmosphere. Metals such as Cu, Pb, and Zn are transported as particulate form. The presence of heavy metal depends upon number of site-specific factors such as the quantity and characteristics of the industrial pollutants, environmental sensitivity, potential for environmental release and proximity of these heavy metals in humans and its effect on their health (Kacholi and Sahu, 2018).

Types of heavy metals

Lid (Pb)

The presence of a Pb lid can have significant effects on soil and plant growth. Firstly, the lead from the lid can leach into the soil, leading to soil contamination. Lead is a toxic heavy metal that can accumulate in the soil over time, disrupting its natural balance and fertility. This contamination can hinder the growth of plants by interfering with nutrient uptake and physiological processes. Secondly, plants can absorb lead from the contaminated soil through their roots. Once inside the plant, lead can disrupt essential processes such as photosynthesis, enzyme activity, and nutrient absorption. This can result in stunted growth, reduced yield, and overall poor plant health. Furthermore, lead can accumulate in edible plant parts, posing a risk to human health if consumed. Lastly, the presence of lead in the soil can alter its pH and nutrient availability. Lead contamination often leads to increased soil acidity, which can negatively impact the availability of essential nutrients for plant growth. Additionally, lead can compete with other vital elements, such as calcium, iron, and zinc, for uptake by plant roots. This competition can result in nutrient deficiencies in plants, further impairing their growth and development (Gurung *et al.*, 2018).

Zinc (Zn)

Zinc (Zn) is an essential micronutrient for plants, but excessive levels can have adverse effects on soil health and plant growth. Zinc is an essential micronutrient for plants, playing a crucial role in various physiological processes. However, when present in high concentrations, it can become toxic and negatively impact soil and plant health. Zinc contamination in soil can occur through various sources, including industrial activities, mining, and the use of zinc-containing fertilizers.

This contamination can disrupt soil microbial communities, affecting nutrient cycling and soil fertility (Khan *et al.*, 2019). High levels of zinc can also interfere with the uptake of other essential nutrients by plants, such as iron, manganese, and copper, leading to nutrient imbalances and impaired plant growth (Alloway, 2013). When plants are exposed to excessive zinc in the soil, it can inhibit root development and reduce water uptake.

Zinc toxicity can impair photosynthesis, leading to chlorosis (yellowing of leaves) and reduced crop yield (Alloway, 2013). Additionally, high levels of zinc can disrupt enzyme activity within plants, leading to metabolic imbalances and physiological disorders that further hinder plant growth and development (Khan *et al.*, 2019).

Cadmium (Cd)

Cadmium (Cd) is a highly toxic heavy metal that can have significant effects on soil and plant health. Research studies have shown that cadmium contamination in soil can lead to soil degradation and reduced soil fertility (Liu *et al.*, 2013). Cadmium can alter soil pH, disrupt nutrient cycling, and inhibit microbial activity, which can negatively impact plant growth (Khan *et al.*, 2019).

When plants are exposed to cadmium-contaminated soil, they can absorb the metal through their roots. Cadmium can interfere with various physiological processes in plants, including nutrient uptake, enzyme activity, and photosynthesis (Chen *et al.,* 2016). This can result in stunted growth, reduced yield, and overall poor plant health (Khan *et al.,* 2019). Additionally, cadmium can accumulate in edible plant parts, posing a risk to human health if consumed (Liu *et al.,* 2013).

Chromium (Cr)

Chromium can originate from both natural and anthropogenic sources. Naturally, it is found in the Earth's crust and can be released into the environment through weathering of chromium-containing minerals.

Anthropogenic sources include industrial activities, such as metal plating, leather tanning, and stainless steel production. When chromium enters the soil, its impact on plant growth depends on its oxidation state.

Trivalent chromium (chromium III) is essential in small amounts but can be harmful in excess. Hexavalent chromium (chromium VI) is highly toxic to plants, inhibiting growth, reducing seed germination, and causing leaf damage. The effects of chromium on soil and plant growth are influenced by factors like concentration, soil pH, organic matter content, and plant species (Gong *et al.,* 2020).

Copper (Cu)

Excessive levels of copper (Cu) in soil can have significant effects on soil health and plant growth. Copper is an essential micronutrient for plants, but when present in high concentrations, it can become toxic and negatively impact soil and plant health. Copper contamination in soil can occur through various sources, including agricultural practices, industrial activities, and the use of copper-based fungicides.

High copper levels in soil can disrupt soil microbial communities, affecting nutrient cycling and soil fertility (Khan *et al.,* 2019). Additionally, excessive copper can inhibit root growth and reduce water uptake in plants, leading to stunted growth and reduced crop yield (Alloway, 2013). Furthermore, copper toxicity can interfere with various physiological processes in plants.

It can disrupt enzyme activity, impair photosynthesis, and affect the balance of other essential nutrients, such as iron and zinc, in the soil (Khan *et al.,* 2019). These disruptions can result in nutrient imbalances, chlorosis (yellowing of leaves), and overall poor plant health (Alloway, 2013).

Effects of heavy metal

On soil

Pollution of soil by heavy metals s is a serious environmental problem, associated with industrial activities, land use patterns, local climatic conditions, socio-economic development issues, and elevated population densities. Heavy metals are metals and metalloids that have an atomic mass higher than 20 and an elemental density higher than 5 g cm-3. The most common heavy metals detected in the environment are cadmium, mercury, copper, arsenic, lead, chromium, uranium, and zinc. Heavy metals have adverse health effects when their concentrations exceed the permitted levels. Potentially toxic elements pose many risks to human beings and the environment. They have a long half-life and remain active in the environment for a long time without biodegrading. The mobility and availability of heavy metals in the soil is determined by the nature of heavy metals, as well as by the physical and chemical characteristics of the soil. The concentrations of heavy metals found in the soil may result from natural activities, mostly erosion of heavy metal containing rocks and volcanism. In addition, the soil concentrations of heavy metals may have an anthropogenic component. This pollution of soil by heavy metals is nowadays an emerging environmental problem. Soil pollution is gradually aggravated because of fast urbanization, rapid population growth, and increasing industrialization. Moreover, intensive anthropogenic activities, such as mining, smelting, and usage of various metal-containing substances and materials, as well as their degradation products, have a negative effect on soil quality (Budovich, 2021).

On Plant growth

The heavy metals that are available for plant uptake are those that are present as soluble components in the soil solution or those that are easily solubilized by root exudates. Although plants require certain heavy metals for their growth and upkeep, excessive amounts of these metals can become toxic to plants. The ability of plants to accumulate essential metals equally enables them to acquire other nonessential metals. Despite metals cannot be broken down, when concentrations within the plant exceed optimal levels, they adversely affect the plant both directly and indirectly. Plants exposure to the toxic levels of heavy metals causes the physiological and metabolic alterations. There are different sites of action for different heavy metals within the plant; however the most widespread evidence for the heavy metal toxicity is reduction of plant growth also causes leaf chlorosis, necrosis, turgor loss, reduction in seed germination and a damaged photosynthetic apparatus, finally resulting in the plant death. All these effects are responsible for molecular, ultrastructural and bio-chemical changes in the plant cells and tissues.

Heavy metals also affects homeostatic events such as water uptake, transport, transpiration and nutrient metabolism and also disturbs the uptake of Ca, Mg, K and P. High levels of the heavy metals also have direct effect on photosynthetic apparatus including thylakoids which decreases the rate of photosynthesis. Heavy metals also creates a barrier in the release of proteins, lipids, and eliminated components if thylakoid membranes, resulting in the damage to light-harvesting complexes and photosystem. Heavy metals also causes reduction in chlorophyll synthesis, which may be the cause of enzyme inhibition involved in the synthetic pathway. They also hinder carbon assimilation by inhibiting the enzyme which is involved in the fixation of carbon dioxide (Shah and Daverey, 2021).

Mitigation methods

Soil Stabilization

Soil stabilization is a remediation method used to address heavy metal-contaminated soil. It involves the addition of certain amendments or stabilizing agents to the soil to reduce the mobility and bioavailability of heavy metals. The primary goal of soil stabilization is to transform the contaminants into less toxic forms and prevent their uptake by plants or leaching into groundwater. One commonly used stabilizing agent is lime, which can raise the soil pH and promote the precipitation of heavy metals as less soluble forms. Lime also enhances the soil structure, reducing the mobility of contaminants. Another effective stabilizing agent is phosphate, which forms insoluble complexes with heavy metals, making them less available for plant uptake. Organic matter, such as compost or manure, can also be added to the soil to improve its structure and increase its ability to retain heavy metals. Soil stabilization is a cost-effective and environmentally friendly method for remediating heavy metal-contaminated soil.

It can be applied in situ, minimizing the need for soil excavation and transportation. However, the effectiveness of soil stabilization depends on factors such as the type and concentration of heavy metals, soil characteristics, and the specific stabilizing agents used. Therefore, a thorough site assessment and monitoring are crucial to ensure the success of the remediation process (Shah and Daverey, 2021).

Soil Washing

Soil washing is an effective remediation method used to mitigate heavy metal-contaminated soil. It involves the physical separation of contaminants from the soil particles through the use of water or chemical solutions. The process typically consists of several steps, including soil excavation, soil washing, and separation of the contaminants from the liquid phase. During soil washing, water or chemical solutions are applied to the contaminated soil, and the mixture is vigorously agitated to dislodge the heavy metals from the soil particles. The resulting slurry is then passed through a series of physical separation techniques, such as sedimentation, filtration, or centrifugation, to separate the soil from the liquid phase. The liquid phase, containing the extracted heavy metals, can be further treated or disposed of properly. Soil washing is advantageous because it can be applied on-site, reducing the need for soil transportation and disposal. It can effectively remove a significant portion of heavy metals from the soil, reducing their concentration to acceptable levels. However, it is important to note that soil washing may not completely eliminate all contaminants, and the extracted heavy metals need to be properly managed to prevent further environmental contamination. Additionally, the process requires careful monitoring and management of the wastewater generated during the washing process to ensure proper treatment and disposal (Liu *et al.,* 2021)

Phytoremediation

Phytoremediation is a sustainable and environmentally friendly method used to alleviate heavy metal-contaminated soil. It involves the use of specific plant species, known as hyperaccumulators, which have the ability to absorb and accumulate high concentrations of heavy metals in their tissues. These plants can be grown in contaminated areas, and through their natural processes, they can extract, stabilize, or degrade the heavy metals present in the soil. The roots of hyperaccumulator plants release certain compounds that enhance the availability and uptake of heavy metals from the soil. Once absorbed, the metals are transported and stored in the plant's above-ground tissues, such as leaves or stems. The plants can be harvested and properly disposed of, effectively removing the contaminants from the soil. Phytoremediation offers several advantages. It is a cost-effective method that can be applied in situ, reducing the need for soil excavation and transportation. It also has low energy requirements and can be used in conjunction with other remediation techniques. Additionally, phytoremediation can have aesthetic and ecological benefits, as the selected plants can enhance biodiversity and improve the overall environmental quality of the site. Despite, it is important to note that phytoremediation is a relatively slow process and may not be suitable for sites with high concentrations of heavy metals or time-sensitive remediation requirements (Emenike *et al.*, 2021).

Bioremediation

Bioremediation is a natural and sustainable method used to mitigate heavy metal-contaminated soil. It involves the use of microorganisms, such as bacteria or fungi, to degrade or transform the heavy metals present in the soil. These microorganisms have the ability to bind with the metals or convert them into less toxic forms, reducing their bioavailability and potential harm to the environment. In bioremediation, the microorganisms are introduced into the contaminated soil either through natural processes or by adding them as inoculants. The microorganisms then break down the heavy metals through various mechanisms, such as enzymatic reactions or metabolic processes. This can result in the immobilization or detoxification of the contaminants, making them less harmful. Bioremediation offers several advantages. It is a cost-effective and environmentally friendly method that can be applied in situ, minimizing the need for soil excavation and transportation. It can also be used for large-scale remediation projects. Additionally, bioremediation can be enhanced by adjusting environmental conditions, such as pH or temperature, or by adding nutrients to promote the growth and activity of the microorganisms. However, the effectiveness of bioremediation depends on factors such as the type and concentration of heavy metals, soil characteristics, and the specific microorganisms used (Rahman and Singh, 2020).

Electrokinetic Remediation

Electrokinetic remediation is an innovative technique used to mitigate heavy metal-contaminated soil. It involves the application of an electric field to the soil, which induces the movement of heavy metals towards specific electrodes. This method is particularly effective for soils with low permeability, where traditional remediation techniques may be less efficient. During electrokinetic remediation, electrodes are inserted into the contaminated soil, and a direct current is applied. The electric field causes the migration of heavy metal ions towards the oppositely charged electrodes. The metals can then be collected and treated separately, effectively removing them from the soil. Electrokinetic remediation offers several advantages.

It can be applied in situ, minimizing the need for soil excavation and transportation. It is also a relatively fast process compared to other remediation methods. Additionally, electrokinetic remediation can be combined with other techniques, such as soil washing or stabilization, to enhance the overall effectiveness of the remediation process. However, it is important to note that electrokinetic remediation requires careful monitoring and management of the electrolyte solution used, as well as proper handling and disposal of the collected heavy metals (Ayyanar and Thatikonda, 2021).

Thermal Desorption

Thermal desorption is a remediation method used to mitigate heavy metal-contaminated soil. It involves the application of heat to the soil to volatilize the contaminants, which can then be collected and treated separately. This technique is particularly effective for organic contaminants but can also be used for heavy metals. During thermal desorption, the contaminated soil is heated to a specific temperature, typically between 300 to 800 degrees Celsius, in a controlled environment. The heat causes the contaminants to vaporize, leaving behind clean soil. The vaporized contaminants are then collected and treated using various methods, such as condensation or filtration, to remove them from the air or gas stream. Thermal desorption offers several advantages. It can be applied on-site, reducing the need for soil excavation and transportation.

It is also a rapid process, capable of treating large volumes of soil in a relatively short period. Additionally, thermal desorption can be combined with other remediation techniques to address both organic and heavy metal contaminants simultaneously. However, it is important to note that thermal desorption requires careful monitoring and control of the heating process to prevent the release of harmful gases or the formation of secondary pollutants. Proper handling and disposal of the collected contaminants are also essential to prevent further environmental contamination (Wali and Ksibi, 2014).

Heavy metals are metallic elements that have a high density and are toxic to living organisms at certain concentrations. They can enter agricultural soil through various sources, including industrial activities, mining operations, and the use of contaminated fertilizers and pesticides. These heavy metals, such as lead, cadmium, and mercury, can have detrimental effects on agricultural soil and plant growth. When heavy metals accumulate in agricultural soil, they can disrupt the soil structure and reduce its fertility. This, in turn, affects plant growth and development. Heavy metals can inhibit nutrient uptake by plants, impair enzymatic activities, and interfere with metabolic processes. As a result, plants may exhibit stunted growth, reduced yields, and even show signs of toxicity. To mitigate the impacts of heavy metals on agricultural soil and plant growth, several methods can be employed such as Soil stabilization; soil washing phytoremediation, bioremediation electrokinetic remediation and thermal desorption involves heating the contaminated soil to vaporize the heavy metals, which can then be collected and treated. These mitigation methods can help restore the health and productivity of agricultural soil by reducing the concentration of heavy metals and minimizing their adverse effects on plant growth. However, the choice of method depends on various factors, including the type and concentration of heavy metals, soil characteristics, and site-specific conditions. Implementing a combination of these methods, tailored to the specific needs of each contaminated site, can provide effective and sustainable solutions for heavy metal contamination in agricultural soil.

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