Review Article

Impact of Heavy Metal Contamination on Soil and Crop Ecosystem with Advanced Techniques to Mitigate Them

Comment [MOU1]: As far as I have read, this article is good, it's just that other people's research articles related to this title are still lacking. add previous research to each article discussion

ABSTRACT

Heavy metal pollution in soils has become widespread globally due to both natural processes and human activities. Geologic and anthropogenic activities, such as mining, industrial processes, and agricultural practices, significantly contribute to heavy metal accumulation in soil, posing threats to both plant and animal health.These metals endure in the environment and build up in organisms because they resist breakdown or metabolism.They enter the food chain via primary producers and move up as higher trophic levels consume them.This contamination adversely affects the overall human health, plant growth, performance, and yield and also impacts the soil properties. To minimize this effect of heavy metal toxicity, bioremediation emerges as a highly effective method for treating such polluted soils, often conducted in situ, making it suitable for crop establishment or reestablishment. Bioremediation encompasses various techniques like bioventing, biostimulation,air sparging,natural attenuation, phytoremediation, vermistabilization, rhizofiltration, biosorption etc. Both microorganisms and plants play crucial roles in bioremediation, with the combined approach ensuring more efficient cleanup. However, the success of this method depends significantly on the specific species involved. Traditional physical and chemical remediation methods are often costly and fail to restore soil suitability for plant growth. In contrast, bioremediation offers a more environmentally friendly and economically viable solution, leveraging natural processes to encourage plant growth on contaminated soils.

Keywords: Bioremediation, biostimulation, environment, heavy metals, phytoremediation,

1. INTRODUCTION

Heavy metals are metallic elements characterized by high atomic weights and densities and often accumulate in the environment, posing risks to ecosystems and human health.A considerable number of heavy metals pose toxicity, contributing to environmental pollution. Due to their non-biodegradable and water-soluble properties, they easily permeate plants and human bodies, leading to negative consequences[1]. The term "heavy metal" denotes a metal or metalloid possessing an atomic density at least five times higher than that of water [2,3]. Common heavy metals present in the environment comprise cadmium (Cd), lead (Pb), nickel (Ni), silver (Ag), zinc (Zn), cobalt (Co), chromium (Cr), iron (Fe), arsenic (As), and mercury (Hg). The high concentration of heavy metals in water, air, and soil poses a threat to all living organisms [4]. While heavy metals naturally occur in soil, human activities, both geological and anthropogenic, escalate their concentrations to levels detrimental to plant and animal health. These activities comprise mining and metal smelting, fossil fuel combustion, agricultural use of fertilizers and pesticides, industrial production of batteries and metal goods, sewage sludge disposal, and municipal waste management. Recorded instances show that plants growing on soils contaminated with heavy metals experience growth reduction due to alterations in their physiological and biochemical processes [5,6,7]. Heavy metals predominantly exist in dispersed form within rock formations. The human impact of heavy metal presence in the biosphere has surged due to industrialization and urbanization. These metals are most abundant in soil and aquatic ecosystems, with a smaller presence in the atmosphere as particles or vapors. The toxicity of heavy metals to plants depends on various factors such as plant species, the particular metal involved, its concentration, chemical form, and soil properties including composition and pH. Interestingly, several heavy metals are essential for plant growth, and similarly, many serve as essential trace nutrients for animals and the human body [8].Similarly, numerous heavy metals play essential roles for plants by serving as cofactors, triggering enzyme reactions, exhibiting ductility and conductivity, and ensuring cation stability[9].Heavy metals enter the human body through different routes, including contaminated food, water, skin contact, and inhalation. Those absorbed through the intestine are typically water-soluble and travel to various organs via the circulatory system. Even at low concentrations, heavy metals impact the respiratory tract and various cell types such as endothelial and epithelial cells[10].

These heavy metals persist in the environment and accumulate in living organisms, as they are not easily broken down or metabolized. They enter the ecological food chain starting from primary producers and then move up through consumption at higher trophic levels. Plants, being stationary, primarily interact with heavy metal ions through their roots, while in aquatic systems, the entire plant body is exposed to these ions. Additionally, heavy metals can directly adhere to leaves through particles deposited on foliar surfaces. Human exposure to heavy metals occurs mainly through inhalation or ingestion, with ingestion being the primary route for the general population. However, urbanization, traffic, industrial and agricultural activities, waste incineration, and mining significantly contribute to heavy metal inhalation exposure. Metals like Cadmium (Cd), Nickel (Ni), Arsenic (As), and Chromium (Cr) present various hazards to human health and are potent carcinogens. Cadmium intake can lead to Itai-Itai disease, while mercury intake can result in Minamata disease. Arsenic and other heavy metals can cause poisoning through contamination of drinking water.

Numerous methods are available for remediating metal-polluted soils, encompassing a spectrum from physical and chemical approaches to biological ones. However, many physical and chemical methods, including encapsulation, solidification, stabilization, electrokinetics, vitrification, vapor extraction, soil washing, and flushing, tend to be costly and may not render the soil conducive to plant growth [11]. The biological approach, known as bioremediation, promotes the growth or re-growth of plants in polluted soils. It stands out for its environmental friendliness, as it relies on natural processes. Additionally, bioremediation proves to be a cost-effective technique compared to other remediation methods. This paper explores the characteristics of soils contaminated with heavy metals, evaluates plant growth and productivity in such soils, and emphasizes the utilization of biological methods for remediating heavy metal pollution.

2. SOURCES OF HEAVY METAL POLLUTION

2.1 NATURAL SOURCES

Heavy metals originating from rock materials constitute the "lithogenic" aspect. The concentration and composition of heavy metals formed in soil are primarily determined by the type of parent rock[12]. The main heavy metal pollutants contributed by parent rocks comprise Cobalt (Co), Chromium (Cr), Iron (Fe), Manganese (Mn), Nickel (Ni), and Zinc (Zn). The weathering process of igneous rocks, such as Augite, Olivine, and Hornblende, results in substantial amounts of heavy elements, whereas sedimentary rocks contribute only a minor portion [13].

In addition to rocks, natural sources of heavy metals include volcanoes, wind-blown dust and storms, wildfires, sea sprays, and aerosols (especially in coastal regions) [14]. Geothermal sources, along with volcanic eruptions, have also contributed significantly to atmospheric pollutants and toxic waste [15].

2.2 ANTHROPOGENIC SOURCES

2.2.1 **Agricultural sources:** Inorganic and organic fertilizers, manure, lime, pesticides, and other agricultural inputs contain varying levels of Chromium (Cr), Cadmium (Cd), Nickel (Ni), Zinc (Zn), Lead (Pb), and other heavy metals. Similarly, many widely used chemical pesticides such as Bordeaux mixture and lead arsenate contain Copper (Cu), Mercury (Hg), Manganese (Mn), Lead (Pb), or Zinc (Zn). Additionally, the utilization of municipal and industrial wastewater for irrigation serves as a significant source of heavy metal contamination in soil.

2.2.2 **Industrial Sources:**Industrial activities such as mining, smelting, and metal processing primarily produce Chromium (Cr) and Nickel (Ni), while Vanadium (V), Titanium (Ti), and Manganese (Mn) are predominantly derived from oil and coal-related operations [16]. Coal mining releases significant amounts of Arsenic (As), Cadmium (Cd), and Iron (Fe), while gold mining elevates Mercury (Hg) levels in the environment [17]. These heavy metals are typically emitted in particulate and vapor forms, which, upon interaction with atmospheric moisture, form aerosols. These aerosols can be dispersed by wind (dry deposition) or deposited through rainfall (wet deposition), leading to soil and water contamination [13]. Moreover, combustion processes involving coal, petroleum, and nuclear power stations release heavy metals such as Selenium (Se), Cadmium (Cd), Boron (B), Copper (Cu), Cesium (Cs), Zinc (Zn), and Nickel (Ni) into the atmosphere [18]. Additionally, activities like plastics processing, microelectronics manufacturing, wood preservation, textiles production, and paper processing also contribute to heavy metal pollution in the environment [3].

2.2.3 **Domestic Effluents:** The primary source of heavy metal pollution in water bodies is domestic effluents. These effluents encompass untreated wastewater, as well as substances that have been processed through biological treatment plants and discharged through sewage outfalls. Additionally, many commonly used enzymatic detergents contain small amounts of elements such as Iron (Fe), Chromium (Cr), Manganese (Mn), Zinc (Zn), Cobalt (Co), Strontium (Sr), and Boron (B), thereby adding to the burden of heavy metal pollution [19].

3. EFFECT OF HEAVY METAL CONTAMINATION IN SOIL

Heavy metals possess metallic characteristics like ductility, malleability, conductivity, cation stability, and ligand specificity. They are characterized by their high density and atomic weight, typically having an atomic number greater than 20. While some heavy metals like Cobalt (Co), Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Vanadium (V), and Zinc (Zn) are essential in small quantities for organisms, excessive amounts of these elements can be detrimental. On the other hand, heavy metals such as Lead (Pb), Cadmium (Cd), Mercury (Hg), and Arsenic (As) (considered a metalloid but often grouped with heavy metals) have no beneficial effects on organisms and are considered significant threats due to their harmful effects on both plants and animals. Metals can be found in soil either independently or in association with other soil constituents. These constituents encompass exchangeable ions adhered to the surfaces of inorganic solids, nonexchangeable ions, and insoluble inorganic metal compounds like carbonates and phosphates. Additionally, metals may exist as soluble compounds or free ions in the soil solution, as complexes with organic materials, or attached to silicate minerals [11]. Metals attached to silicate minerals constitute the inherent soil metal levels and typically do not pose contamination or pollution concerns, unlike metals found independently or in high concentrations within the other four components [20].

Various soil properties have distinct impacts on the availability of metals. Soil pH emerges as a crucial determinant of metal availability [21]. For example, the presence of Cadmium (Cd) and Zinc (Zn) for *Thlaspi caerulescens* roots diminishes with higher soil pH levels. Moreover, organic matter and hydrous ferric oxide have demonstrated the ability to reduce heavy metal availability by immobilizing these metals [22]. Additionally, notable positive associations have been observed between heavy metals and certain soil physical attributes such as moisture content and water holding capacity [23].

Metal availability in soil is influenced by several factors, including the density and charge type of soil colloids, the extent of complexation with ligands, and the relative surface area of the soil [11,24]. Soil colloids, with their extensive interface and specific surface areas, play a crucial role in regulating heavy metal concentrations in natural soils. Additionally, in polluted soils, soluble metal concentrations may be decreased by soil particles possessing high specific surface areas, although this effect may vary depending on the metal [11]. For example, the addition of amendments containing hydroxides with high reactive surface areas reduced the solubility of Arsenic (As), Cadmium (Cd), Copper (Cu), Molybdenum (Mo), and Lead (Pb), while the solubility of Nickel (Ni) and Zinc (Zn) remained unchanged [25]. Furthermore, soil aeration, microbial activity, and mineral composition have been demonstrated to impact heavy metal availability in soils [26]

On the other hand, heavy metals can alter soil properties, particularly biological aspects [27]. Monitoring changes in soil microbiological and biochemical properties post-contamination serves as a sensitive method for assessing soil pollution intensity, providing faster results compared to monitoring physical and chemical properties [28]. Heavy metals influence the abundance, diversity, and functions of soil microorganisms, with their toxicity dependent on various factors including soil temperature, pH, clay minerals, organic matter, inorganic ions, and chemical forms of the metal.

Studies examining the impact of heavy metals on soil biological properties yield varying results, with some showing negative effects while others find no significant relationship. Discrepancies likely stem from differences in experimental setups, including the use of artificially contaminated soils in labs versus naturally polluted soils in the field. Regardless of soil origin, further detailed research is needed to fully understand heavy metals' effects on soil ecosystems. It's advisable to employ multiple methods, such as assessing microbial biomass and enzymatic activities, to gain a comprehensive understanding. Additionally, heavy metals can influence each other's availability in soil, affecting plant uptake. Interactions like antagonism and synergy exist among heavy metals, as observed in various studies. For instance, the inhibitory effect of manganese on carbon mineralization can be countered by cadmium. Similarly, competition between copper and zinc, as well as nickel and cadmium, has been noted in plant membrane carriers. However, the relationship between metals can be complex, as copper has been found to enhance zinc toxicity in certain plants, highlighting the need for further investigation in this field. Furthermore, different species of the same metal can interact with each other. For instance, the presence of arsenite strongly inhibited the uptake of arsenate by rice plants growing in polluted soil[29].

4. EFFECT OF HEAVY METAL CONTAMINATION IN CROPS

The heavy metals accessible for plant uptake are either those existing as soluble components in the soil solution or those readily solubilized by root exudates. While plants require specific heavy metals for their growth and maintenance, excessive amounts of these metals can pose toxicity risks. Plants' ability to accumulate essential metals also facilitates their uptake of other nonessential metals.Metals found in elevated levels in the soil influence seed germination, plant growth, production, as well as physiological, biochemical, and genetic aspects of the plant system[30].

Elevated concentrations of heavy metals can cause various direct toxic effects, such as inhibiting cytoplasmic enzymes and damaging cell structures due to oxidative stress. An example of an indirect toxic effect is the displacement of essential nutrients at cation exchange sites in plants. Furthermore, heavy metals' detrimental impact on the growth and activities of soil microorganisms can indirectly affect plant growth. For instance, a decrease in the population of beneficial soil microorganisms due to high metal concentrations may lead to reduced organic matter decomposition, resulting in soil nutrient depletion. Additionally, heavy metal interference with soil microorganisms' activities can impede enzyme functions crucial for plant metabolism. These toxic effects, whether direct or indirect, ultimately contribute to a decline in plant growth and, in severe cases, may lead to plant death. Some of the common examples of heavy metal contamination on crops are as follows:

1. **Arsenic (As) toxicity:**
    - **Rice**: Reduced seed germination, decreased seedling height, reduced leaf area, and lower dry matter production.
    - **Tomato:** Decreased fruit yield and lower leaf fresh weight.
    - **Canola:** Stunted growth, chlorosis (yellowing of leaves), and wilting.
2. **Cadmium (Cd) toxicity:**
    - **Wheat:** Reduced seed germination, decreased plant nutrient content, and shorter shoot and root length.
    - **Garlic**: Reduced shoot growth and accumulation of Cd in the plant.
    - **Maize:** Reduced shoot growth and inhibition of root growth.
3. **Cobalt (Co) toxicity:**
    - **Tomato:** Reduction in plant nutrient content.
    - **Mung bean:** Reduced antioxidant enzyme activities, decreased plant sugar, starch, amino acids, and protein content.
    - **Radish:** Reduced shoot length, root length, and total leaf area; decreased chlorophyll content; reduced plant nutrient content, antioxidant enzyme activity, plant sugar, amino acid, and protein content.
4. **Chromium (Cr) toxicity:**
    - **Wheat**: Reduced shoot and root growth.
    - **Tomato:** Decreased plant nutrient acquisition.
    - **Onion:** Inhibition of germination process and reduction of plant biomass.
5. **Copper (Cu) toxicity:**
    - **Bean**: Accumulation of Cu in plant roots, root malformation, and reduction.
    - **Black bindweed:** Plant mortality, reduced biomass, and decreased seed production.
    - **Rhodes grass:** Reduced root growth.
6. **Mercury (Hg) toxicity:**
    - **Rice:** Decreased plant height, reduced tiller and panicle formation, yield reduction, and bioaccumulation in shoot and root of seedlings.
    - **Tomato:** Reduced germination percentage, decreased plant height, reduced flowering and fruit weight, and chlorosis.
7. **Manganese (Mn) toxicity:**
    - **Broad bean:** Mn accumulation in shoot and root, reduced shoot and root length, and chlorosis.
    - **Spearmint:** Decreased chlorophyll a and carotenoid content, and accumulation of Mn in plant roots.
    - **Pea:** Reduced chlorophylls a and b content, lower relative growth rate, reduced photosynthetic O2 evolution activity, and decreased photosystem II activity.
    - **Tomato:** Slower plant growth and decreased chlorophyll concentration.
8. **Nickel (Ni) toxicity:**
    - **Pigeon pea:** Decreased chlorophyll content, reduced stomatal conductance, and decreased enzyme activity affecting the Calvin cycle and CO_2 fixation.
    - **Rye grass:** Reduced plant nutrient acquisition, decreased shoot yield, and chlorosis.

  - **Wheat**: Reduced plant nutrient acquisition**.**
  - **Rice:** Inhibition of root growth.

9. **Lead (Pb) toxicity:**
   - **Maize:** Reduced germination percentage, suppressed growth, reduced plant biomass, and decreased plant protein content.
   - **Portia tree:** Reduced number of leaves and leaf area, decreased plant height, and reduced plant biomass.
   - **Oat:** Inhibition of enzyme activity affecting CO_2 fixation.
10. **Zinc (Zn) toxicity:**
    - **Cluster bean:** Reduced germination percentage, decreased plant height and biomass, and reduced chlorophyll, carotenoid, sugar, starch, and amino acid content.
    - **Pea:** Reduced chlorophyll content, altered chloroplast structure, decreased photosystem II activity, and reduced plant growth.
    - **Rye grass**: Accumulation of Zn in plant leaves, growth reduction, decreased plant nutrient content, and reduced efficiency of photosynthetic energy conversion.

Table 1.**Range of Toxic heavy metals in plants and crops [31]**

Heavy metals	**Range in soils (ppm d. wt.)**	**Range in crops (ppm d. wt.)**
Cadmium	0.01–0.7	0.2–0.8
Nickel	10–1000	1.0
Arsenic	0.1–40	0.01–5
Mercury	0.01–0.2	0.005–0.02
Lead	2–200	0.1–10

Table 2.Regulatory limits of some toxic heavy metals on humans [32]

Heavy metals	**Max. acceptable conc. (WHO)**	**Max. acceptable conc. in drinking water (EPA)**
Cadmium	0.003 ppm	0.005 ppm
Nickel	–	2–4.3 ppb
Arsenic	0.01 ppm	0.01 ppm
Mercury	0.001 ppm	2 ppb
Lead	0.01 ppm	50 ppb

5. APPROACHES TO MITIGATE HEAVY METAL TOXICITY

The biological approach, known as bioremediation, promotes the establishment or reestablishment of plants in polluted soils. It's considered environmentally friendly as it relies on natural processes for its implementation [33]. Bioremediation presents an opportunity to neutralize or eliminate various pollutants through natural biological processes. It relies on cost-effective, simple techniques that are generally well-received by the public and can often be conducted on-site. However, it may not always be feasible as it has limitations in its effectiveness against certain contaminants, operates on relatively lengthy timeframes, and may not always achieve desired levels of decontamination. While the methods involved are not overly complex, designing and executing a successful bioremediation program may necessitate significant expertise and experience to thoroughly evaluate site suitability and optimize conditions for optimal results.

Techniques involved in bioremediation are as follows:

1. **Bioventing:** Bioventing is an in-situ bioremediation technique that involves supplying oxygen to the unsaturated (vadose) zone of the subsurface to stimulate the aerobic biodegradation of contaminants by indigenous microorganisms. Air is delivered through injection or extraction wells, and the technique is primarily used for treating fuels, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), pesticides, and herbicides. It requires the presence of indigenous microbes capable of degrading the target contaminants and necessary nutrients for their growth. Bioventing is relatively inexpensive, low-maintenance, and enjoys public acceptance. However, it is less effective in treating high water table areas, low moisture soils, and sites with high concentrations of inorganic salts, heavy metals, or organic compounds that inhibit microbial growth.

2. Biostimulation: Biostimulation involves introducing water-based solutions containing nutrients, electron acceptors (e.g., oxygen, nitrate), or other amendments to stimulate the growth and activity of indigenous microorganisms capable of degrading contaminants in soil and groundwater. It is designed for treating fuels, non-halogenated VOCs, SVOCs, pesticides, and herbicides. While biostimulation can be applied to halogenated organics, it may be less effective. The technique requires the presence of indigenous degraders and bioavailability of contaminants. It is not suitable for sites with high levels of inorganic salts, heavy metals, or organic compounds that inhibit microbial growth. It can be relatively inexpensive compared to other remediation methods but may increase contaminant mobility, necessitating treatment of underlying groundwater.

3. Air sparging: Air sparging is an in-situ technique that involves injecting air below the water table to promote aerobic biodegradation of groundwater contaminants by indigenous microorganisms. It is primarily used for treating fuels, non-halogenated VOCs, SVOCs, pesticides, organics, and herbicides. Air sparging has also been demonstrated to be effective for remediating petroleum hydrocarbon-contaminated aquifers. Like other bioremediation techniques, it requires the presence of indigenous degraders, nutrients, and bioavailability of contaminants. Air sparging can be relatively inexpensive and low-maintenance but is not applicable in sites with high levels of inorganic salts, heavy metals, or organic compounds that inhibit microbial growth.

4. Natural attenuation: Natural attenuation, also known as passive remediation or intrinsic bioremediation, is a proactive approach that relies on monitoring and verifying natural remediation processes without active intervention. It is suitable for treating fuels, non-halogenated VOCs, SVOCs, pesticides, herbicides, and hydrophobic contaminants like high molecular weight PAHs that tend to sorb tightly to soil particles. Natural attenuation processes can be destructive (destroying the contaminant) or non-destructive (reducing contaminant concentrations). While relatively simple and low-cost, natural attenuation can be time-consuming, and contaminant plumes may migrate if attenuation rates are too slow. It requires long-term monitoring and may face public scepticism due to the perception of inaction.

5. Landfarming: Landfarming involves excavating contaminated soil and applying it to the soil surface, where it is periodically tilled to mix and aerate the material, promoting biodegradation, transformation, and immobilization of contaminants through biotic and abiotic reactions. It is primarily used for treating soil contaminated with fuels, PAHs, non-halogenated VOCs, SVOCs, pesticides, and herbicides. While simple and inexpensive, landfarming requires large areas and may sometimes result in contaminant volatilization rather than biodegradation. Liners or other methods may be used to control leachate.

6. Phytoremediation: Phytoremediation is the use of plants to remove, degrade, or immobilize contaminants in soil and groundwater. It can be used for remediating toxic heavy metals, radionuclides, organic contaminants like chlorinated solvents, BTEX compounds, non-aromatic petroleum hydrocarbons, nitrotoluene ammunition wastes, and excess nutrients. Plants facilitate remediation through direct uptake and incorporation of contaminants, immobilization (phytostabilization), release of enzymes that act on contaminants, and stimulation of microbially mediated degradation in the rhizosphere. Phytoremediation is a relatively low-cost and environmentally friendly approach but is limited by factors such as depth of contamination, time requirements, and the ability of the site to support plant growth. Types of phytoremediation techniques are as follows:

A. Phytoextraction: This technique utilizes plants that can accumulate and concentrate high levels of contaminants, especially heavy metals, in their biomass from the soil or water. The contaminated plant parts can then be harvested and disposed of safely. It is particularly useful for removing metals like lead, cadmium, zinc, nickel, and arsenic from contaminated sites. Key factors include selecting hyperaccumulator plants, enhancing metal bioavailability through soil amendments, and optimizing plant growth conditions.

B. Phytostabilization: In this approach, metal-tolerant plants are used to immobilize and reduce the mobility of contaminants, primarily heavy metals, in the soil. The plants help stabilize the contaminated soil, preventing erosion, leaching, and further spread of the contaminants. This technique is useful for stabilizing and revegetating metalliferous mine wastes, tailings, and other contaminated sites.

C. Phytodegradation: This involves the breakdown and degradation of organic contaminants, such as chlorinated solvents, herbicides, and ammunition wastes, by enzymes produced within the plant tissues after uptake. The contaminants are transformed into simpler, less toxic molecules that can be incorporated into the plant biomass or released into the environment.

D. Phytovolatilization: Plants and associated soil microbes are used to take up certain contaminants, like selenium, arsenic, and mercury, from the soil, transform them into volatile forms, and release them into the atmosphere. This technique is primarily employed for removing mercury and selenium from contaminated sites.

7. Composting: Composting is a controlled biological process in which organic materials are decomposed by microorganisms under aerobic conditions. The process involves several stages, including the mesophilic, thermophilic, and maturation phases. During composting, various factors such as temperature, moisture content, pH, aeration, and the carbon-to-nitrogen ratio are carefully controlled to optimize the degradation of organic contaminants. Successful application of composting for the bioremediation of polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons, phenol derivatives, polychlorinated biphenyls (PCBs), phthalic acid esters, and pesticides is possible. Several studies have demonstrated the ability of composting to reduce the concentrations of these contaminants through biodegradation, volatilization, and other mechanisms.

8. Vermistabilization: Vermistabilization, also known as vermicomposting, is a composting process that involves the use of earthworms to break down organic matter and facilitate the biodegradation of contaminants. Earthworms play a crucial role in aerating and bioturbating the soil, improving its nutritional status and fertility, and hindering the binding of organic contaminants to soil particles, thereby increasing their bioavailability.Earthworm species like *Eisenia fetida, Lumbricus terrestris*, and *Allobophora chlorotica* have been found to facilitate the removal of heavy metals, PAHs, PCBs, atrazine, and metamitron from contaminated soil during vermicomposting.

9. Rhizofiltration: It involves using plant roots to absorb, precipitate, and concentrate contaminants, primarily heavy metals, from contaminated water sources. The water is passed through a network of plant roots that can sorb or uptake the contaminants. The roots can then be harvested, processed to recover the metals, or disposed of safely. This technique is suitable for treating large volumes of water with low concentrations of metal contaminants.

10. Controlled solid-phase biotreatment: These processes involve the ex-situ treatment of contaminated soils in controlled environments, such as prepared treatment beds, biotreatment cells, and soil piles or biopiles. The contaminated soil is excavated and mixed with soil amendments, and parameters like moisture, heat, nutrients, oxygen, and pH are carefully controlled to enhance biodegradation. These techniques differ from traditional landfarming in that the treatment processes are often enclosed to control off-gases and leachate. They offer the advantage of containing toxic byproducts or metabolites formed during the biodegradation process.

11.Slurry-phase bioremediation: Slurry-phase bioremediation involves the treatment of excavated contaminated soils in a controlled bioreactor environment. The soil is processed to separate stones and rubble, then mixed with water to form a slurry, typically containing 10-40% solids. Electron acceptors, nutrients, and specialized microorganisms (if necessary) are added to the bioreactor, and parameters like pH and temperature are controlled to optimize biodegradation processes. This technique is favored over in-situ biological treatments for heterogeneous soils, low permeability soils, or when faster treatment times are required. It also has the advantage of containing toxic metabolites produced during biodegradation.

12. Biosorption: Biosorption is a highly promising bioremediation technique for removing heavy metal ions from aqueous solutions, particularly due to their extreme toxicity and persistence in the environment. This process involves the binding and concentration of contaminants by certain types of inactive or dead microbial biomass. One of its significant advantages is its cost-effectiveness, coupled with high efficiency and the potential for metal recovery. Unlike conventional treatment methods, biosorption minimizes the generation of chemical or biological sludge and allows for the regeneration of biosorbents. Recently, attention has shifted towards utilizing low-cost renewable organic materials, such as waste byproducts from industrial operations and agricultural residues, as effective biosorbents. These materials have shown remarkable abilities to accumulate heavy metals, including lead, cadmium, uranium, copper, zinc, and chromium, with some biosorbents capable of binding multiple metal types simultaneously. The choice of biomass for biosorption experiments depends on factors such as its origin, availability, and specificity towards certain metal ions. Various sorption processes, such as ion exchange, complexation, chelation, microprecipitation, and oxidation/reduction, contribute to the complex phenomenon of biosorption. Understanding the scientific principles, kinetics, thermodynamics, and equilibrium interactions of biosorption is crucial for optimizing this bioremediation technique, which has been extensively explored and documented in the scientific literature. Batch and continuous modes of operation are commonly employed in laboratory-scale biosorption processes, with factors like pH, temperature, ionic strength, biosorbent dosage, and agitation rate influencing bacterial batch biosorption. Overall, biosorption holds significant potential as a sustainable and effective approach for mitigating heavy metal pollution in water bodies and industrial effluents.

6. CONCLUSION

Heavy metal contamination poses significant threats to soil health and crop productivity. The accumulation of heavy metals in soil can lead to toxic effects on plants, including inhibition of enzyme activity, oxidative stress, and nutrient displacement. Consequently, this contamination jeopardizes crop quality and yield, posing risks to human health through food chain transfer. However, bioremediation offers a promising solution to mitigate these adverse effects. Through the use of microorganisms and plants, bioremediation processes can detoxify contaminated soil by immobilizing, degrading, or extracting heavy metals. This eco-friendly approach not only restores soil health but also helps in the restoration of ecosystem balance. By harnessing the natural processes of microbial and plant interactions, bioremediation presents a sustainable and cost-effective strategy to combat heavy metal contamination, safeguarding both soil fertility and crop productivity for future generations. Embracing bioremediation practices can lead us towards a healthier environment and more resilient agricultural systems.

7. FUTURE PROSPECTS

Looking ahead, the future prospects for bioremediation in addressing heavy metal contamination are promising. Continued research and technological advancements hold the potential to enhance the efficiency and scalability of bioremediation techniques. Furthermore, integrating bioremediation strategies with other sustainable agricultural practices could offer holistic solutions for managing heavy metal pollution while promoting soil health and crop productivity. Additionally, increasing awareness and adoption of bioremediation among farmers, policymakers, and industries can accelerate its implementation on a larger scale. By embracing bioremediation as a key component of environmental stewardship and sustainable agriculture, we can strive towards a cleaner, healthier, and more resilient future for our soil and crops.

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