Effect of Contamination of Heavy Metals in Soil and Its Mitigation Strategies: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Review Article

ABSTRACT

Rising soil pollution has recently emerged as a significant global issue due to increased industrialization, urbanization, and inadequate waste management. This review thoroughly examines the presence of common heavy elements in damaged soils, such as Pb, Cr, As, Zn, Cd, Cu, Hg, and Ni, utilizing publically available literature. It discusses the concepts of phytoremediation, soil cleaning, and immobilization, highlighting the advantages and drawbacks of each method. These techniques are widely recognized as effective means to remediate heavy metal-polluted soil, addressing associated risks, freeing up land for agriculture, bolstering food security, and resolving land tenure issues arising from changing land use patterns.

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1. INTRODUCTION

The primary sources of soil contamination by heavy metals include wastewater irrigation, waste disposal, sludge applications, vehicle emissions, and industrial processes. Crops cultivation in polluted soils often exhibit elevated levels of metal uptake. Wastewater is identified as a significant contributor, containing both harmful heavy metals and beneficial nutrients, presenting both opportunities and challenges for agriculture [1 and 2]. According to Muchuweti *et al.*, [3], the use of wastewater for soil irrigation results in the deposition of significant quantities of heavy metals, which negatively impact soil quality. Consequently, crops absorb these additional heavy metals, thereby compromising the safety and quality of the food produced. Heavy metals and metalloids are non-biodegradable in nature and can affect human health directly and indirectly [4]. The increasing accumulation of heavy metals in both soils and plants has raised concerns about potential risks to human health, particularly through the consumption of contaminated food. Food poisoning stands out as a predominant route for these hazardous chemicals to enter the human body. The evaluation of metal absorption by various plants relies on factors such as plant absorption or metal-to-plant transmission [5]. The extent of heavy metal accumulation in plants varies depending on the plant species.

The contamination of soils with heavy metals and metalloids, including lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), mercury (Hg), and nickel (Ni), can result from various human activities such as mine tailings, fertilizer application, sewage sludge disposal, pesticide use, animal manures, wastewater irrigation, coal combustion residues, petrochemical spills, and atmospheric deposition [6 and 7]. Additionally, lead, which is a hazardous metal, is commonly found in leaded gasoline and paint. These contaminants are frequently encountered in areas that have been affected by soil contamination. These metals represent a category of inorganic chemical hazards [8]. While many anthropogenic activities release heavy metals into the environment, soil tends to absorb these metals. Unlike organic pollutants that undergo microbial degradation to carbon (IV) oxide, most metals resist bacterial or chemical breakdown [9]. Even after several decades of use, the overall concentration of

metals in soils remains high [10]. However, the chemical forms (speciation) and bioavailability of these metals can vary. Notably, hazardous metals in soil have been shown to impede the degradation of organic pollutants significantly [11].

Soil contamination with heavy metals poses risks to both human health and the environment through various pathways: inhalation or direct contact with polluted soil, entering the food chain (from soil to plants to humans or animals and then to humans), consumption of contaminated groundwater, diminishing food quality due to phytotoxicity, limiting agricultural land usability leading to food insecurity, and giving rise to land tenure issues [12 and 13]. Identifying and addressing ecosystems with heavy metal contamination is essential for proper protection and recovery. This study explores the origins of pollution, underlying chemistry, and associated health and environmental threats related to priority heavy metals (Pb, Cr, As, Zn, Cd, Cu, Hg, and Ni). The aim is to provide insights into the mechanisms governing heavy metal speciation and bioavailability, leading to the selection of appropriate remedial strategies. The investigation covers techniques for immobilization, soil cleansing, and botanical remediation, delving into their principles, advantages, and drawbacks.

2. SOURCES OF HEAVY METALS IN SOILS

The natural occurrence of heavy metals in soil is a result of pedogenetic weathering processes acting on parent materials, leading to trace levels (up to 1000 mg kg^{-1}) and occasionally reaching hazardous concentrations [14 and 15]. Both rural and urban soils commonly have the capacity to accumulate one or more heavy metals beyond specified background levels, posing risks to human health, plants, animals, ecosystems, and other environmental components [16]. This situation arises due to human interventions disrupting nature's gradual geochemical metal cycle. The contamination of soil by heavy metals is primarily attributed to the following factors:

1. Their artificial cycle generation rates are faster than natural cycle generation rates.
2. They are moved from mines to areas where there is a higher risk of direct exposure.

3. Their concentrations in discarded products are higher than those in the receiving environment.
4. The chemical condition (species) of methane gas [16].

Anthropogenic heavy metals in soil tend to exhibit higher mobility and bioavailability compared to naturally occurring pedogenic or lithogenic heavy metals [17 and 18].

The presence of metal-laden solids in polluted areas can be attributed to various sources, such as land-applied fertilizer, animal manures, biosolids (sewage sludge), compost, insecticides, coal combustion residues, petrochemicals, and atmospheric deposition [6,7 and 19]. These diverse contributors are responsible for the contamination of soils with metals in polluted regions.

2.1 Inorganic Fertilizers as a Source of Heavy Metals

Apart from certain impoverished developing nations that use minimal fertilizer, macronutrient fertilizers are prevalent sources of heavy metal (loid) inputs into agricultural soils worldwide. The key macronutrients—nitrogen (N), phosphorus (P), and potassium (K)—are widely employed to enhance plant growth and yield. These nutrients are combined into compound fertilizers like NPK or NP, which are applied to the soil either individually based on specific needs or more commonly in various combinations. Calcium (Ca) is typically administered as lime (usually as $CaCO_3$) to amend the pH of acidic soils, and magnesium (Mg) may also be applied in dolomite for the same purpose. Secondary macronutrient fertilizers such as calcium, magnesium, and sulfur are also utilized.

Regularly fertilized arable soils, particularly those with high fertilizer contents, may accumulate elevated concentrations of certain heavy metals (loids) due to the contaminants present. For instance, cadmium (Cd) and lead (Pb) lack physiological benefits. Phosphatic fertilizers containing fluorine (F), mercury (Hg), and lead (Pb) inadvertently introduce cadmium and other potentially toxic elements into the soil [20].

2.2 Pesticides as a Source of Heavy Metals

Metal concentrations were found to be high in various traditional pesticides that were commonly used in horticulture and agriculture. For instance, copper (Cu), mercury (Hg), manganese (Mn), lead (Pb), and zinc (Zn) were detected in 10% of recently approved pesticides in the United Kingdom, particularly fungicides and insecticides. Lead arsenate, historically employed to control parasitic insects in apple orchards, and wood preservation treatments involving copper (Cu), chromium (Cr), and arsenic (As) have led to elevated soil concentrations of these elements in numerous abandoned areas, surpassing background levels. In regions like New Zealand and Australia, arsenic-containing pesticides were frequently utilized to manage livestock ticks and banana pests. The resulting contamination poses potential hazards, particularly when these areas are repurposed for non-agricultural uses. However, compared to fertilizers, the use of such products has been more restricted, targeting specific regions or crop types [21].

Fig. 1. Sources of heavy metals in soil

2.3 Biosolids and Manures

The unintentional buildup of heavy metal pollutants in soil arises from the application of various biosolids to land, including livestock manures, composts, and municipal sewage sludge [19]. Agricultural wastes such as chicken, cattle, and pig dung are commonly utilized as solids or slurries for crops and pastures [22]. Copper (Cu) and zinc (Zn) are frequently used in the pig and poultry industries, and the presence of these metals in chicken feed has been associated with soil contamination [22 and 23]. Manure from animals on such diets contains elevated levels of arsenic (As), copper (Cu), and zinc (Zn). The regular application of this manure in confined land areas can lead to the gradual accumulation of significant quantities of these metals in the soil.

Biosolids, also known as sewage sludge, primarily consist of organic solid components recycled for environmental purposes following wastewater treatment operations [24]. Many countries permitting the reuse of biosolids from urban populations routinely apply these materials to the land [25]. Although "sewage sludge" is a commonly used term with a legally defined meaning, "biosolids" is gaining popularity for its more accurate portrayal of the positive properties of sewage sludge [26]. Major Australian cities generate approximately 175,000 metric tonnes of dry biosolids annually, predominantly used in arable cropping scenarios where they can be integrated into the soil [21].

2.4 Wastewater as a Source of Heavy Metals

Over the past four centuries, municipal, industrial, and related effluents have been applied to land for various purposes [27]. Globally, 20 million hectares of agricultural land are irrigated with water, with wastewater irrigation accounting for 50% of vegetables consumed in Asian and African urban areas, as noted by Bjuhr, [28]. Farmers often prioritize increasing yields and profits over considering environmental advantages or risks. The accumulation of heavy metals in the soil can occur when wastewater effluent, despite having low metal concentrations, is used for prolonged irrigation. This process leads to significant metal deposition over time.

2.5 Metal Mining and Milling Processes and Industrial Wastes

The impact of industrialization is evident in soil pollution caused by metal ore mining and processing, leaving a lasting impact in numerous countries. Elevated concentrations of pollutants result when larger, denser tailings, which accumulate at the bottom of flotation cells during mining, are directly deposited into natural depressions, such as onsite wetlands [29]. The widespread mining and smelting of lead and zinc ore pose environmental and public health risks. Soil reclamation methods employed in these areas are often costly, time-consuming, and their effectiveness in enhancing soil productivity is subject to debate. The bioavailability of heavy metals in soil plays a crucial role in determining human environmental risk. Various industries, including textiles, tanning, pesticides, pharmaceuticals, and petrochemicals (resulting from unintentional oil spills or the use of petroleum-based products), contribute to soil pollution. While some of these components are occasionally dumped on land, only a small percentage is beneficial for forestry or agriculture. Additionally, some substances, containing heavy metals such as chromium (Cr), lead (Pb), and zinc (Zn), or toxic organic compounds, are rarely or never used on land, posing hazards. Certain substances lack both soil conditioning properties and plant nutrition [22].

2.6 Air-Borne Sources of Heavy Metals

Metals can be introduced into the atmosphere through fugitive emissions, such as dust from landfills or storage facilities, as well as emissions from stacks or ducts handling air, gas, or vapor streams. Airborne sources of metals often release particles into the gas stream, and certain metals like arsenic (As), cadmium (Cd), and lead (Pb) can undergo volatilization at high temperatures. In the absence of a reducing environment, these metals oxidize and condense into fine particles [30].

The dispersion of stack emissions in the air via natural air movements continues until they are eventually eliminated from the gas stream using dry or wet precipitation methods. Fugitive emissions, originating closer to the ground, typically cover a smaller area, with pollutant levels usually lower than those in stack emissions. The types and concentrations of metals emitted by these sources vary depending on surrounding conditions. Solid particles released in industrial chimney smoke eventually settle on land or water. Heavy metal contamination in fossil fuels has been widespread since the industrial revolution,

leading to elevated levels of cadmium (Cd), lead (Pb), and zinc (Zn) in plants and soils near smelting activities. The burning of tetraethyl lead-containing fuel releases lead into the environment, contributing to soil contamination and significantly increasing lead content in urban soil and dirt near major highways.

3. BASIC SOIL CHEMISTRY AND POTENTIAL RISKS OF HEAVY METALS

According to the USEPA [31], the most abundant heavy metals found in contaminated sites, ranked in decreasing order, are lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), and mercury (Hg). These metals are significant due to their potential to accumulate in organisms and magnify in the food chain, thereby impacting agricultural production and posing risks to surface and groundwater pollution. To understand their speciation, bioavailability, and develop effective remediation strategies, it is crucial to have a comprehensive understanding of the fundamental chemistry, environmental impact, and effects on human health associated with these heavy metals.

Levy et al., [32] state that the chemical form and speciation of heavy metals have a significant influence on their movement and fate in the soil. The adsorption of heavy metals occurs through rapid initial reactions and delayed adsorption processes, resulting in diverse chemical forms with varied bioavailability, mobility, and toxicity. This distribution affects various heavy metal reactions in soils, such as mineral precipitation and dissolution, ion exchange, adsorption and desorption, aqueous complexation, biological immobilization and mobilization, and plant absorption.

3.1 Lead

Lead is positioned in the 6th period and 4th group of the periodic table, displaying a density of 11.4 g/cm³, an atomic mass of 207.2, a melting point of 327.4°C as well as a boiling point of 1725°C. It forms crystals with other elements such as sulfur (PbS, $PbSO_4$) and oxygen ($PbCO_3$). Lead is the sixth most abundant industrial metal, following iron, copper, aluminum, and zinc, and about half of America's lead consumption is dedicated to the production of lead storage batteries. Although lead is highly utilized in industry, it can pose serious health

risks such as impaired brain functioning, developmental delays, and behavioral issues if high concentrations are present. Thus, measures to reduce lead exposure are vital to public health and safety.

The prominent forms of lead that are commonly found in soil, groundwater, and surface waters comprise ionic lead (Pb (II)), lead oxides, hydroxides, and lead metal oxyanion complexes. Among these, the most stable oxidation states of lead are lead (II) and lead-hydroxy complexes. Lead (II) is particularly reactive and can give rise to mono- and polynuclear hydroxides and oxides [8]. Insoluble lead compounds that are frequently encountered include lead hydroxides, carbonates, and phosphates, where lead carbonates tend to exist at pH levels exceeding 6. Under reducing conditions with higher sulfide concentrations, lead sulfide (PbS) forms as the most stable solid form in the soil matrix [33].

Under conditions where there is no oxygen, microbial alkylation can produce organo lead (tetramethyl lead), as stated by GWRTAC [8]. The consumption of food grown in gardens that contain soil levels below 300 parts per million of lead is widely recognized as safe. However, if the lead levels in the soil exceed this limit, the danger of lead poisoning in the food chain is heightened. Furthermore, as per Rosen's [34] research, the deposition of dust or soil onto plants presents a more significant risk of lead exposure than actual lead uptake by the plants, especially when soil concentrations go beyond 300 ppm.

3.2 Chromium

Chromium, a transition metal in the first row of the d-block of Group VIB on the periodic table, possesses the following physical characteristics: atomic mass of 52, atomic number 24, density of 7.19 g/cm₃, melting point of 1875°C, and boiling point of 2665°C. Unlike some elements, chromium is less commonly found in its elemental form and is primarily encountered in compound states in nature. A significant mining ore product associated with chromium is the chromite mineral, $FeCr_2O_4$.

The sources of chromium contamination are mainly attributed to waste disposal and electroplating processes [30]. If sites are contaminated, chromium (VI) is generally present, while the existence of chromium (III) is dependent on pH and redox conditions. Cr (VI) is

typically found in aerobic shallow aquifers, but its conversion to Cr (III) can occur in deeper groundwater under anaerobic conditions through interactions with iron ions, soil organic matter, and S^{-2} ions. In the presence of metal cations like Pb^{+2}, Ba^{2+}, and Ag, the primary Cr (VI) species, chromate and dichromate, can easily precipitate. Chromate and dichromate generally adsorb onto soil surfaces, predominantly aluminum and iron oxides. Chromium (III) generally transforms into Cr^{3+} under lower pH levels (approximately 4), and it forms soluble organic ligand solutions such as SO_4^{-2}, F, CN, Cl, OH, and NH_3.

3.3 Arsenic

As_2O_3, a metalloid belonging to Group VA of the periodic table, is commonly found in ores containing Ag, Au, Pb, Zn, and Cu, as well as coal combustion ash. Arsenic has an atomic mass of 75, an atomic number of 33, a melting point of 817°C, and a boiling point of 613°C. Its chemical makeup is complex and can exist in various oxidation states [30].

Under aerobic conditions, As (V) is the prevalent species and usually occurs as arsenate in three protonation states: H_3AsO_4, H_2AsO_4, or both. When metal cations are present, arsenate and other arsenic anionic forms can precipitate and exhibit chelating activity [35]. Stability of metal arsenate complexes is limited, but iron oxyhydroxides can coprecipitate with or adsorb arsenic (V) in acidic, mildly reducing environments. In such conditions, coprecipitates are stationary, but as pH increases, arsenic becomes more mobile [30]. Elevated levels of zinc in industrial wastewater contribute to water pollution, leading to the deposition of zinc-contaminated sediment along riverbanks. Water acidity may also increase due to zinc, potentially resulting in groundwater pollution.

3.4 Cadmium

Cadmium, situated at the end of the second row of transition elements, has an atomic weight of 112.4, a density of 8.65 g cm^{-3}, and melting and boiling points of 320.9°C and 765°C, respectively. With an atomic number of 48, cadmium does not have any recognized essential biological functions but is classified as one of the three primary heavy metal toxins, alongside Pb and Hg. In its compounds, cadmium typically takes the form of the divalent cadmium (II) ion. Found most in Ni/Cd batteries,

cadmium is often present in rechargeable power sources known for their high output, extended life, low maintenance, and tolerance to physical and electrical stress. The mobility of cadmium in geochemistry has increased due to acid rain and the consequential acidification of soil and surface water. Under such circumstances, surface-water concentrations of cadmium rise when lake water pH declines [36]. The most well-known and severe case of cadmium poisoning happened to people who ate food contaminated with the metal while living in the Jintsu River Valley, close to Fuchu, Japan. Itai-Itai sickness, which is pronounced "ouch, ouch" in Japanese, was the cause of the sufferers' illness. Painful osteomalacia (a bone disease) and kidney dysfunction combine to cause the symptoms. Irrigated rice that was tainted by Pb, Zn, and Cd from an upstream mine was to blame for the cadmium poisoning that occurred in the Jintsu River Valley. Chronic buildup in the kidneys that causes renal disease is the main hazard to human health. The two primary ways that Cd enters the body are through eating and smoking cigarettes [37].

3.5 Copper

Copper, located in Group IB of Period 4 of the periodic table, is a transition metal with an atomic number of 29, an atomic weight of 63.5, a density of 8.96 g cm^{-3}, a melting point of 1083 °C, and a boiling point of 2595 °C. According to VCI [38], it is the third most widely utilized metal worldwide. Copper is also essential for the growth of both plants and animals as it assists in the production of hemoglobin in the blood. Despite its complexity in environmental interactions, most discharged copper appears stable or transforms into non-threatening forms, demonstrating minimal bioaccumulation. Copper's solubility in soil is influenced by its tendency to complex with organic compounds, with pH playing a crucial role. The relationship between plant metal absorption, soil and water pollution, and various influencing factors necessitates an understanding for sustainable agricultural practices [39 and 40].

3.6 Mercury

Belonging to Group 12 of the periodic table along with copper and zinc, mercury is the only metallic element that is liquid at standard temperature and pressure (STP). With an atomic weight of 200.6, a density of 13.6 g/cm^{-3}, a melting point of

-38.83 °C, and a boiling point of 356.73 °C, mercury is often a byproduct of mining activities and a significant pollutant resulting from coal combustion. The stability of mercury forms depends on pH and redox potential, with alkylated forms being the most hazardous. The sorption of mercury in sediments and soils is crucial, with microbial activity influencing the transformation of mercury into various forms. Mercury exposure is associated with kidney disease [30 and 41].

3.7 Nickel

Nickel, a transition element with an atomic weight of 58.69 and atomic number 28, exhibits different forms in varying environmental conditions. Nickelous ion (Ni^{2+}) predominates in low pH environments, forming stable chemical nickelous hydroxide $(NiOH)_2$. Nickel sources include mining, electroplating, metal plating industries, and fossil fuel combustion [42]. Nickel contamination can impact animals near refineries, leading to various cancers. While nickel is an essential nutrient in trace amounts, exceeding tolerable levels can pose risks. Nickel mobility is influenced by soil acidity, with potential groundwater contamination in acidic conditions [43].

4. SOIL METAL CONCENTRATIONS AND REGULATORY STANDARDS

The soil sample is contaminated by metals depending on the local activities and methods of waste disposal employed at the site. Additionally, environmental factors like soil and groundwater chemistry, local transportation systems, and other variables impact the type, quantity, and distribution of metal pollutants present [8]. The spatial characteristics were caused by many factors such as soil parent material, agricultural activities and industrial activities [44]. Metals can exist in various phases in soils—liquid, gaseous, or solid—posing challenges for analysis and interpretation. Total elemental analysis, employing methods like USEPA Method 3050, is commonly used to estimate metal concentrations in soil. This method involves subjecting the solid to sequential extractant solutions, each designed to dissolve a distinct percentage of the associated metal, offering insights into different types of metal contamination. Contaminated water with metal pollutants can undergo direct testing. Protocols for remediating metal-contaminated land have been developed by DRP-EGASPIN [45] and Riley *et al.*, [46], based on interim intervention values and target values until definitive parameters are established.
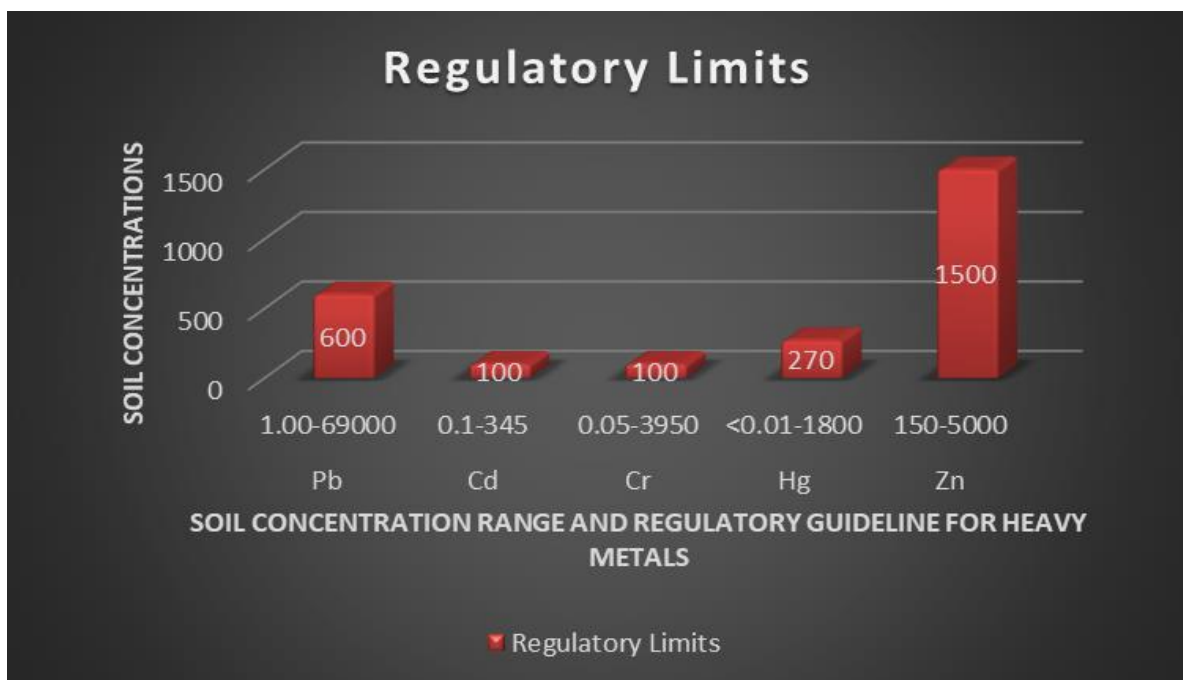

Fig. 2. Ranges of soil concentrations and regulatory recommendations for specific heavy metals
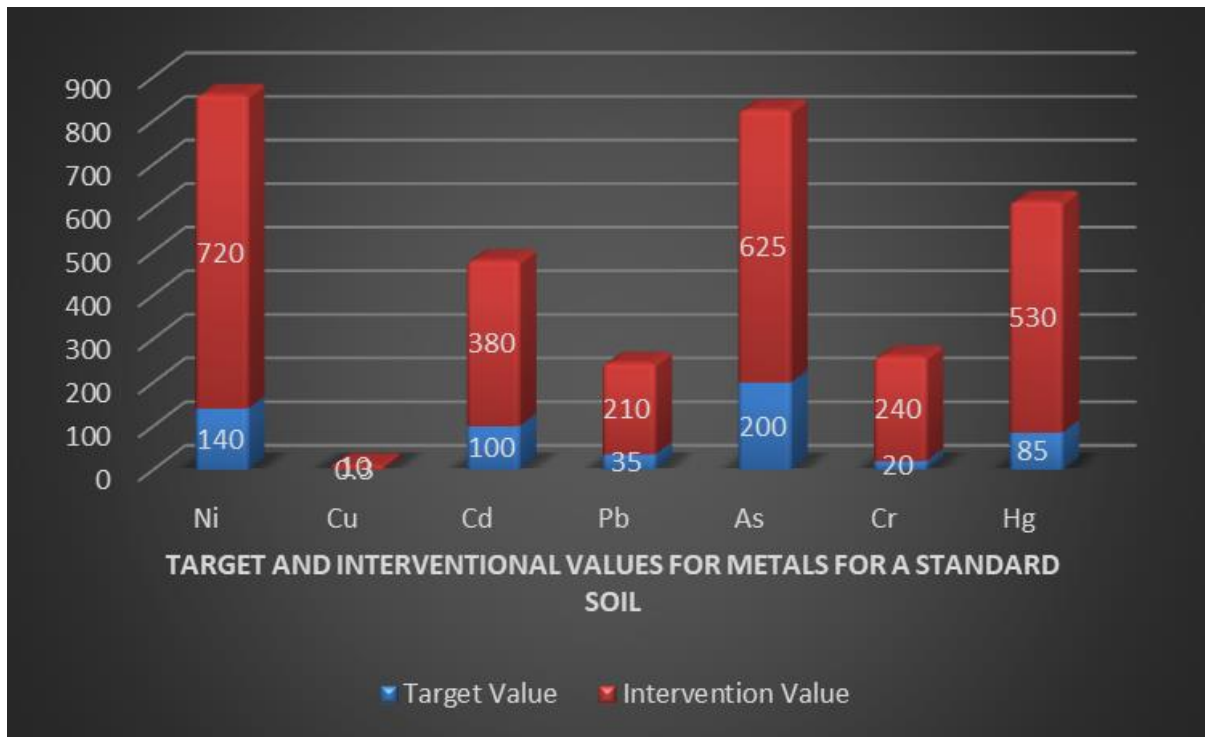*(Source: Riley, 1992)*

Fig. 3. Target and intervention values for some metals for a standard soil
(Source: DPR-EGASPIN, 2002)

Intervention values signify the extent to which the soil's capacity to support life—plants, animals, and humans—has been significantly impaired or is at serious risk. Concentrations surpassing intervention thresholds indicate severe contamination. Target values, on the other hand, represent the complete restoration of soil capacity to sustain biotic, abiotic, and microbiological life, ensuring soil quality for sustainability. Hence, target values reflect the highest levels of ideal soil quality in the context of remedial policies.

5. REMEDIATION APPROACHES FOR HEAVY METAL-CONTAMINATED SOILS

The primary objectives of any soil remediation plan should revolve around safeguarding the environment and public health [47]. When statutory requirements are absent or advisory standards are in place, remedial actions may be guided by assessments of environmental and public health risks. Compliance with legal standards is typically mandatory for remediation, and regulatory agencies generally disapprove of strategies that aim to reduce metal bioavailability unless a clear correlation between decreased bioavailability and reduced risk is established, or if the decrease is proven to be long-lasting [47].

The choice of the most effective remediation treatment for heavy metal-contaminated soils largely depends on the specific physical and chemical forms of the metal pollutants present. Obtaining information on the physical contamination at the site is crucial for a comprehensive analysis of pollution and the consideration of potential remedial approaches. Defining soil pollution involves determining the nature, quantity, and distribution of heavy metals in the soil. In addition, enterprises should upgrade their production processes and strengthen existing environmental protection measures to reduce the total amount of heavy metal emissions. It is an effective measure to protect soil environmental quality to strengthen the standardized treatment of pollutants discharged by enterprises in cities with heavy metal industries [44 and 48]. After the contaminated site has been evaluated, it is crucial to determine the desired concentration of each metal. This can be achieved by performing site-specific risk evaluations or comparing measured levels of heavy metal with soil quality thresholds within a specific regulatory zone. Remediation objectives may concentrate on total metal concentrations, the amount of extractable metals present in the soil, or both. As previously mentioned, among the most promising treatment

methods for areas polluted with heavy metals are soil washing, phytoremediation, and immobilization techniques known as Best Demonstrated Available Technologies (BDATs).

5.1 Immobilization Methods

Effective strategies for addressing metal-contaminated soils involve both in situ and ex-situ immobilization techniques. The ex-situ approach is employed when highly contaminated soil poses significant ecological risks upon excavation. While ex-situ methods offer quick and cost-effective applications, they come with drawbacks, including environmental invasiveness, substantial waste generation, and the need for specific landfill disposal. In contrast, the in-situ method treats the unexcavated soil with fixing agents and amendments, boasting advantages such as minimal invasiveness, rapid application, cost-effectiveness, low waste generation, public acceptability, and coverage of various inorganic pollutants. However, in situ immobilization has limitations, serving as a temporary solution and posing risks of reactivating pollutants with changes in soil characteristics. Inactivation treatments that utilize inorganic and organic amendments are considered effective at decreasing the mobility and toxicity of metals present in soil. By using processes like complexation, precipitation, and

sorption, immobilization methods facilitate the reduction of metal mobility and toxicity [49].

5.1.1 Solidification/Stabilization (S/S)

To enhance physical and dimensional stability, restrict external accessibility, and encapsulate contaminants, solidification/stabilization utilizes binding agents added to contaminated substances. During the stabilization process, chemicals are added also to develop more stable chemical constituents Although conventional S/S is recognized worldwide as a hazardous waste treatment, it is also employed as a remediation strategy for contaminated soils. Stabilization materials, including organic stabilizers like bitumen and inorganic binders such as clay and cement, are mixed or injected into the soil. Additives like sand or clay may be introduced to achieve specific properties of vitrified waste, which can be recycled for various purposesm [30].

5.1.2 Vitrification

Vitrification involves applying high heat to contaminated areas, forming vitreous material that reduces the mobility of metal contaminants. This method is effective for treating organic and inorganic pollutants, and both in situ and ex-situ technologies can be utilized. The ex-situ

Fig. 4. Remediation strategies for heavy metals

vitrification process includes excavation, preparation, mixing, melting, off-gas treatment, and shaping the melted result. The energy costs for ex-situ vitrification are influenced by the required melting energy, and various energy sources can be employed based on regional cost considerations. Recycling options for vitrified waste include reusing it as clean fill, aggregate, or other recyclable materials [30].

5.2 Soil Washing

Soil washing aims to reduce volume and waste by eliminating metal pollutants from soils through ex-situ methods. Physical separation, chemical extraction, and recovery from solution on a solid substrate are employed to remove contaminants from bulk soil fractions. Additional chemical, thermal, or biological treatment may be applied to isolated pollutants, and the remaining soil can often be used as inert backfill or disposed of inexpensively. Acid washing and chelator dirt cleansing are common soil washing techniques [50].

5.3 Phytoremediation

Phytoremediation is a technique that takes place on-site, utilizing soil amendments, agricultural methods, plant life, and the associated microbiota to get rid of, contain, or neutralize environmental pollutants. Proposed in 1983, the concept of using metal-accumulating plants for this purpose has roots dating back three centuries. Plants can stabilize and remove both organic and metal contaminants. Phytoremediation techniques are similar for sites contaminated with organic or metal pollutants.

6. CONCLUSION

To conclude, a detailed knowledge of the chemical properties, potential hazards, and sources of toxic heavy metals in polluted soils is essential when selecting appropriate remediation methods. The cleanup of heavy metal-contaminated soils is critical in reducing associated risks, making room for agricultural development, improving food security, and addressing land ownership concerns. Immobilization, soil washing, and phytoremediation are widely recognized as the most effective solutions for restoring such soils. These techniques are particularly valuable in developing countries experiencing environmental deterioration due to urbanization, agriculture, and industry.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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