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Current state of heavy metals accumulation and its remediation strategies in Indian soils

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Abstract

Environment pollution is continuously escalating at an alarming rate around the globe, particularly concerning the contamination of soils by heavy metals accumulation, particularly Pb, Cr, Ni, Cd and Hg. These metals are non-essential and highly toxic, pose high degrees of threat to plants, animals and humans. The situation has worsened more since the last 3 decades due to continuous increase of anthropogenic activities like mining, industrial processes and faulty agricultural practices *i.e.* extensive use of pesticides, fungicides and synthetic fertilizers. These activities release various harmful heavy metals into soil, water and air which subsequently infiltrates inside the plant system through physiological mechanisms and, therefore, adversely affecting the plant growth and development. For instance, excessive amounts of heavy metals disrupt the photosynthesis, nutrient uptake and absorption in plants, and thus resulting in stunted growth, chlorosis and even severe plant death. The environment and health risks associated with heavy metal pollution are further exacerbated by their persistence in the environment. Unlike organic pollutants, heavy metals do not degrade over time and can remain in the soil for decades, continuously posing risks to ecosystem and human populations. The bioaccumulation and bio-magnification of these metals through the food chain amplify their toxic effects, making it crucial to address and mitigate their presence in the environment. Efforts to manage and remediate heavy metal contamination involve a combination of strategies including phytoremediation, soil washing and use of amendments to immobilize heavy metals in the soil. Therefore the present study delves into the current status and effects of heavy metals on crops and soils, and further identifying and implementing suitable and effective remediation strategies.

Keywords: Phytoremediation, trace metals, environmental aspect, agriculture, soils, ecological balance

Introduction

Heavy metal encompasses the nature of metalloids, transition metals, basic metals, lanthanides and actinides. Among these, the primary elements which are identified as heavy metals include chromium (Cr), manganese (Mn), cobalt (Co), copper (Cu), zinc (Zn), molybdenum (Mo), mercury (Hg), nickel (Ni), tin (Sn), lead (Pb), cadmium (Cd) and antimony (Sb). Heavy metals of concern can be categorized into three main types: toxic metals, precious metals, and radio nuclides. Toxic metals, such as mercury (Hg), chromium (Cr), lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), arsenic (As), cobalt (Co) and tin (Sn) poses significant environmental threats and health risks. Precious metals like palladium (Pd), Platinum (Pt), silver (Ag), gold (Au) and ruthenium (Ru) have high economic value and are specialized for the industrial uses. Radionuclides such as uranium (U), thorium (Th), radium (Ra) and americium (Am) are general radioactive elements which are present in both environmental and hazards. Among these lead, mercury, cadmium and chromium are particularly notorious for their high toxicity levels. Moreover, lead, mercury, and cadmium are often referred to as ‘the big three elements which are especially prominent due to their substantial environmental impact and associated health risks (Adhikari and Ajay, 2012; Sharma *et al.*, 2023) [1, 28]. These metals imparts a range of adverse effects from neurological damage to organ failure, and thus their persistence in the environment makes them challenging to manage. Consequently, addressing the contamination and impact of these heavy metals is crucial for environmental protection and public health. In general, a heavy metal is considered toxic when it is a relatively dense metal or metalloid known for its potential to cause harm, particularly in environment settings (Ahemad, 2015) [4]. Heavy metal toxicity occurs when these elements, either in excess of the required concentrations and accumulate in the environment due to numerous anthropogenic activities. These metals can become concentrated and enter into the tissue of plants, animals, and humans through inhalation, ingestion and physical contact. Once getting inside the body, they bind and disrupt the functioning of essential cellular components and thus leading to numerous health related issues (Adhikari *et al.,* 2010) [2].

The abundance and presence of heavy metals in the environment is often the result of various human induced activities *i.e.* industrial processes, mining and faulty or non-scientific agricultural practices. These activities can lead to the release of these metals into the soil, water, and air where they can persist and accumulate over the time. Several metals including zinc (Zn), manganese (Mn), nickel (Ni) and copper (Cu) are regarded as essential micronutrients for the plant's growth. In typical non-accumulator plants, the accumulation of these micronutrients does not surpass their metabolic requirements, and therefore, maintaining the levels below 10 parts per million (ppm) (Aljerf and AlMarsi, 2018) [6]. However, in metal hyperaccumulator plants, the situation is markedly different. These plants have the remarkable ability to accumulate extraordinarily high concentrations of metals which often reach to thousands of ppm's. The process of metal accumulation in plants is inherently energy-intensive, which raises questions like what evolutionary benefits metal hyper-accumulation might provide to these species (Aguilar *et al.,* 2013) [3].

Researchers have shedded light on this intriguing phenomenon and suggest that the accumulation of metals in the foliage of hyper-accumulator plants offers significant adaptive advantages. One of the primary benefits is enhanced defense against various predators and pathogens. The ability to accumulate the metals also has implications for the ecological interactions of hyper-accumulator plants (Alloway *et al.,* 2013; Shubham *et al.,* 2023) [7, 30]. By reducing herbivory and disease, these plants can allocate more resources to growth and reproduction, and thus, can potentially increase their competitive edge over non-accumulator species. This can lead to greater success in colonizing and thriving in metal-rich environments, where other plants might struggle to survive. Moreover, the presence of metal hyper-accumulator plants in the ecosystem can influence the distribution and behavior of herbivores and pathogens. Herbivores may avoid areas with high densities of these plants, while pathogens might be less prevalent in such environments. This can create a non-stable and resilient plant community with hyper-accumulators playing a vital role in shaping the ecological dynamics (Khan *et al.,* 2008) [16].

Impact of heavy metals accumulations on soils

Heavy metals can be introduced into the soils through various sources including atmospheric deposition of metal-laden particles, application of sewage sludge, wastewater irrigation, phosphate fertilizers, pesticides and pig slurry. These metals exist in several chemical forms and their accumulation in agricultural soils has emerged as a significant environmental issue (Guala *et al.,* 2010; Shubham and Dixit, 2021) [14, 29]. The excessive build-up of heavy metals in soils through wastewater irrigation can lead to soil contamination and increased metal uptake by crops, consequently affecting the food quality. Heavy metals contamination in soils and plants is becoming an increasing concern due to the potential health risk to humans through the soil-crop food chain transfer.

Toxic metals can be accumulated in the edible parts of crops grown in contaminated soils, and thus, posing a direct threat to food safety. Various crops including rice, soybean, wheat, maize and vegetables have been reported to exhibit significant levels of heavy metals in their edible parts when cultivated under the contaminated soils. This accumulation can adversely affect plant growth, leading to reduced crop yields due to the inhibition of essential plant metabolic processes. The introduction of heavy metals into agricultural soils occurs through multiple channels. Like atmospheric emissions and vehicular exhausts. This form of pollution contributes to the gradual build-up of metals. Wastewater irrigation is another major source of heavy metal contamination IN soils. Wastewater from industrial processes and urban areas often contains various heavy metals which when used for irrigation lead to the direct deposition of these metals into the soil. Similarly, phosphate fertilizers pesticides which are widely used in agricultural practices can contain heavy metals as impurities. The use of pig slurry, as a by-product of livestock farming also contributes to soil contamination with heavy metals. The impact of heavy metal accumulation on agricultural soils is profound. Soil contamination with heavy metals not only affects the immediate environment but also has far-reaching implications for human health. When crops absorb these metals from contaminated soils, they become part of the human food chain. Consumption of food products with high levels of heavy metals can lead to numerous health problems, including neurological disorders, kidney damage and even cancer. Moreover, the presence of heavy metals in the soil can adversely affect the plant health. High concentration of metals can inhibit crucial metabolic processes in plants, leading to stunted growth and reduced crop yields. Addressing the issue of heavy metal contamination in agricultural soils requires a multifaceted approach. Moreover, regular monitoring of soil and crop metal levels is essential to identify and mitigate the contamination sources. Implementing practices that reduce the use of contaminated water and fertilizers, as well as exploring alternatives like organic farming, can be helpful for minimizing the heavy metals accumulation. Additionally, developing and applying remediation techniques to contaminated soils can help restore soil health and ensure the safety of food crops.

Impact of heavy metals accumulation in soils on crops

Heavy metals available for plant uptake are those which are present as soluble components in the soil solution or solubilized by the root exudates. While plants require certain heavy metals for their growth and maintenance, but excessive amounts can be toxic to plants. The ability of plants to accumulate the essential metals also enables them to take up non-essential metals. Since, metals cannot be degraded, and their accumulation beyond optimal levels can have detrimental effects on plants both directly and indirectly. Direct toxic effects of high metal concentrations include the inhibition of cytoplasmic enzymes and damage to cell structures caused by indirect oxidative stress. Toxic effects can occur when the concentration of essential nutrients are displaced at cations exchange sites in plants. The negative impact of heavy metals extends to soil microorganisms, which are crucial for plant health. High metal concentrations reduce the population of beneficial soil microorganisms, impairing organic matter decomposition and further decreasing the soil fertility. Enzyme activities which are vital for plant metabolism are also hindered due to interference of heavy metals with soil microorganism (Katare *et al.,* 2015) [15]. These toxic effects both directly and indirectly, lead to reduced plant growth and can ultimately result in plant death. Direct effects include enzyme inhibition and oxidative damage, while indirect effects involve nutrient displacement and a decrease in beneficial soil microorganisms, resulting in lower soil fertility and impaired plant growth. The cumulative impact of these toxic effects can significantly reduce the plant growth.

Basics of heavy metals in agricultural sector

a) Nature of heavy or trace metals

Heavy metals are the natural elements which cannot be biologically degraded or destroyed. The term "trace element" refers to elements present in small concentration in natural biological systems. Environmental concerns have highlighted the importance of understanding these trace elements. The basic components of plants, animal and human life can be classified into major and trace elements. Trace elements include both essential and non-essential elements. Essential trace elements, such as iron, zinc and copper are crucial for various biological processes (Katare *et al.*, 2015) [15]. They are required in minute amounts for the proper functioning of enzymatic reactions, hormone production and overall cellular health. Non-essential trace elements, on the other hand, are not required for biological processes and can be toxic if accumulated in significant amounts. The significance of trace elements lies in their dual nature. While, essential trace elements are vital for life and their deficiencies or excess can lead to numerous health issues (Pichhode *et al.*, 2015) [23]. For instance, iron is necessary for oxygen transport in the blood, but too much iron can cause oxidative damage. Similarly, zinc is crucial for immune function, but an excess can impair the copper absorption and can lead to severe deficiency. Thus, maintaining a balance of these elements is critical for health. For example, lead exposure can cause neurological damage, mercury can affect the nervous system and cadmium can lead to kidney damage and bone demineralization. The presence of heavy metals in the environment is a growing concern due to their persistence and potential for bioaccumulation. They can accumulate in soil, water and air, leading to contamination of natural resources (Nematshahi *et al.*, 2012; Shubham *et al.*, 2023) [21, 28]. This contamination can have far-reaching effects on ecosystems and human health. Plants can absorb heavy metals from contaminated soils, which then enter the food chain when these plants are consumed by animals and animals. The long-term exposure to heavy metals can lead to chronic health issues and environmental degradation.

Essential heavy metals in agriculture

Some heavy metals such as iron (Fe), copper (Cu) and zinc (Zn) are regarded as essential for the growth and development of plants and animals. These metals, along with others like manganese (Mn), molybdenum (Mo), nickel (Ni) and cobalt (Co) are considered as essential micronutrients. Their availability in the environment varies, and while they are necessary in small amounts for various physiological functions, their uptake in quantities exceeding plant requirements can lead to toxic effects (Guala *et al.*, 2010) [14]. The concentration ranges of several important heavy metals in land plants, measured in micrograms per gram of dry weight, provide insight into their typical levels and potential toxicity. For instance, arsenic (As) typically ranges from 0.02 ug/g to 7ug/g, cadmium (Cd) from 0.1 to 2.4ug/g, mercury (Hg) from 0.005 to 0.02 ug/g, and lead (Pb) from 1 to 13 ug/g. Other metals like antimony (Sb) are found in concentrations of 0.02 to 0.06 ug/g, cobalt (Co) from 0.05 to 0.5 ug/g, chromium (Cr) from 0.2 to 1 ug/g and copper (Cu) around 4 to 15 ug/g. Iron (Fe) concentrations are notably higher, averaging around 140 ug/g, while manganese (Mn) ranges from 15 to 100 ug/g, molybdenum (Mo) from 1 to 10 ug/g, nickel (Ni) around 1 ug/g, strontium (Sr) approximately 0.30 ug/g, and zinc (Zn) between 8 to 100 ug/g (Khan, 2021) [17]. These metals are integral to various biological processes. For example, iron is crucial for chlorophyll synthesis and enzyme function, while copper plays a role in photosynthesis, respiration and the formation of lignin in plant cell walls. Zinc is involved in enzyme activation, protein synthesis and growth regulation. Manganese is necessary for photosynthesis and nitrogen metabolism, molybdenum is a key component of nitrate reductase enzymes and nickel is essential for urease activity. Cobalt although needed in trace amounts, is important for nitrogen fixation in legumes (Ramana *et al.*, 2012[a]) [25]. Understanding the optimal and toxic concentration ranges of these metals is crucial for managing soil and plant health. Excessive accumulation of heavy metals in plants not only affects their growth and yield but also poses risks to the food chain and human health. Monitoring and regulating the levels of these metals in agricultural soils using appropriate fertilization practices and employing phytoremediation techniques can help to mitigate the adverse effects of heavy metal toxicity (Ashraf and Ali, 2007) [9].

Phyto-remediation of heavy metals in agriculture

Phyto-remediation as defined by Cunningham and Lee (1995), refers to the use of green plants to extract, contain or naturalize environmental contaminants. This definition encompasses a variety of biological, microbial, chemical, and physical influences by plants that contribute to the cleanup of polluted sites. Often termed green technology, phyto-remediation stands out for its environmental friendliness and aesthetic appeal when properly implemented (Pichhode and Nikhil, 2015; Shubham *et al.*, 2023) [23, 28]. Unlike other remediation techniques, it does not demand expensive equipment or highly specialized personnel, making it relatively straightforward to execute. Additionally, phyto-remediation is capable of permanently addressing a broad spectrum of contaminants across diverse environments. Therefore, it offers an environmentally sustainable, cost-effective and carbon neutral method for the cleanup of toxic pollutants. Plants that can hyper-accumulate, accumulate, exclude or indicate heavy metals play a crucial role in environmental remediation. Much of the research in phyto-remediation focuses on inorganic pollutants (Kumar *et al.*, 2012) [18]. One such method is phyto-extraction, which involves the use of metal accumulating plants to transfer and concentrate metals from soil into their roots and above-ground biomass. Another method is rhizofiltration, which employs plant roots to absorb, precipitate and concentrate toxic metals from polluted effluents. Phyto-stabilization uses plants to immobilize metals, thereby, reducing their mobility and preventing further environmental contaminations. Phyto-remediation harnesses the natural processes of plants to address contamination. For instance, in phyto-extraction, certain plants known as hyper-accumulators draw up heavy metals from the soil through their roots and store them in their stems and leaves (Ahemad, 2015) [4]. Over time, these plants can be harvested and disposed of safely, effectively removing contaminants from the soil. This process is particularly advantageous for soils contaminated with heavy metals such as lead, cadmium and arsenic. The plants used in phyto-extraction not only clean the soils, but also, prevents the spread of contaminants through wind or water erosion. Rhizofiltration is another significant phyto-remediation technique where plant roots filter contaminants from water.

This method is especially useful for treating polluted groundwater or industrial effluents. Plants like sunflower and Indian mustard have been found effective in Rhizofiltration, as their roots can absorb large amounts of heavy metals and other pollutants. This technique not only cleanses the water but also provides a cost-effective and sustainable solution to water pollution (Nematshahi *et al*., 2012) [21].

Phyto-stabilization unlike phyto-extraction and rhizofiltration, does not remove contaminants from the environment but stabilizes them. Plants used in this process secrete substances that precipitate heavy metals in the soil, reducing their mobility and bioavailability. This prevents the spread of contaminants to other areas and reduces the risk of exposure to human and wildlife. Phyto-stabilization is particularly useful in areas where contaminant removal is not feasible or where soil erosion needs to be controlled Ali *et al*., (1999) [5]. One of the most significant advantages of phytoremediation is its environmental friendliness. Traditional remediation methods often involve the use of chemicals or extensive excavation, which can further harm the environment. In contrast, phyto-remediation uses natural processes that enhance soil health and biodiversity. Moreover, the use of plants can improve the aesthetics of contaminated sites, making them more acceptable to the public and increasing their potential for redevelopment. Phyto-remediation is also cost-effective Mahimairaja *et al*. (2011) [19]. Traditional remediation methods can be prohibitively expensive, requiring significant financial investment in equipment, labor and disposal of contaminated materials. Phyto-remediation relies on the natural growth of plants which can be cultivated and managed with relatively low costs. This makes it an attractive option for developing countries or regions with limited financial resources for environmental cleanup.

Phyto-remediation status of heavy metals in India

There are very less reports present on the implication of phyto-remediation under field conditions in India, as most of the existing studies basically focusing on water bodies' remediation. In India, phyto-remediation technology has been implemented only in specific areas, such as re-vegetation of mine spoils. In these efforts, plant species of both ecological and economic significance were planted on mine spoil dumps using an appropriate mixture of organic waste combined with site-specific bio-fertilizers. However, there is a noticeable lack of scientific studies on the phyto-remediation of heavy metal contaminated soils in India. Despite its potential, phyto-remediation has not been widely explored in India, particularly in field applications. The majority of the research has been limited to aquatic systems leaving a significant gap in the understanding and implementation of phyto-remediation for soil contamination. In the few instances where phyto-remediation has been applied, such as in the reclamation of mine spoils, the focus has been on planting species with ecological and economic benefits. These plants are grown on mine spoil dumps with the addition of the organic waste and tailored biofertilizers to support growth and remediate efforts.

Contamination of water bodies has reached a critical level due to human activities. Natural groundwater contamination arises from the excessive weathering of minerals from rocks or the displacement of minerals from groundwater or subsurface soil layers. Major contributors to this pollution include increasing urbanization, intensive agricultural practices and industrial developments. In recent years, urbanization has led to the utilization of marginal lands, aquatic plants are being increasingly cultivated in ponds unsuitable for traditional agriculture. Despite exploiting these aquatic resources to meet the rising demand for food contamination with toxic metals has become a common occurrence. Research by Ali *et al*., (1999) [5] indicated that *S. acmophylla* could serve as a bio-monitoring tool for detecting metal contamination in soil and water bodies and is highly suitable for the phyto-remediation of metal contamination in lakes and soils. Kumar *et al*. (2008) studied heavy metal accumulation in various aquatic macro-phytes used as biomonitors, comparing them with water and sediments for phyto-remediators. Their study revealed that *Nelumbo nucifera* had a greater capacity for accumulating heavy metals compared to *echinichloa colonum*, which had a poor capacity for metal accumulation. Ghosh (2010) reported that the aquatic plant *Hydrilla verticillata* has a strong appetite for arsenic (As) and cadmium (Cd) and less for lead (Pb), making it an effective accumulator of As and Cd but less effective for extracting Pb from contaminated water. Similarly, *Ipomoea aquatica* was identified as a potential accumulator of Cd and a slightly less effective accumulator of *Pb.* Rai (2008) examined the phytoremediation capabilities of a small water fern, *Azolla pinnata*, for heavy metals. The study found that *Azolla pinnata* experienced growth inhibition of 27.0-33.9%, with the highest inhibition in the presence of Hg (II) ions at 0.5 mg/L compared to the control. After 13 days, metal contents in the solution decreased by 70-94%. Adhikari *et al.* (2010) [2] evaluated the phytoextraction potential of Pb by two wetland plant species, *Typha angustifolia L.* of the Typhaceae family and the behaya plant (*Ipomoea carnea* L.) of the convolvulaceae family. Both plants showed promise for removing Pb from contaminated wastewater. Chandra and Yadav, (2010) also evaluated *Typha angustifolia* for its phytoremediation potential of various heavy metals (Cu, Pb, Ni, Fe, Mn, and Zn) and concluded that this plant could be a potential phytoremediator for heavy metals in industrial wastewater containing metals, melanoidins and phenols under optimized conditions.

Unnikannan *et al*. (2013) assessed the phytotoxicity of chromium (Cr) in some aquatic weeds (*Salvinia natans*, *Pistia stratiotes* and *Eichhornia crassipes*) and found that these plants accumulated significant concentrations of Cr in their tissues, classifying them as hyperaccumulators for Cr. Kumar *et al.* (2012) [18] evaluated the phytoremediation of heavy metal-contaminated soil using five native macrophytes: *Bacopa monnieri*, *Eichhornia crassipes*, *Hydrilla verticillata*, *Ipomoea aquatica* and *Marsilea minuta*. Their research suggested that *E. crassipes* can be used for phytoremediation of Cu and Ni, while *M. minuta* and *H. verticillata* are effective for removing Cr and Pb, respectively, from contaminated water bodies. Susselan *et al.* (2006) identified the potential of *Mimosa pudica* for rhizofiltration of Cd, Hg, U, and Zn. Their study highlighted the utility of *Mimosa pudica* in accumulating these metals from contaminated environments emphasizing its role in phyto-remediation efforts.

Phyto-remediation of soils contaminated with heavy metals

The hyper-accumulation of heavy metals by higher plants involves several critical steps: (a) the transport of metals across the plasma membrane of riot cells, (b) loading and translocation within the xylem, (c) the detoxification and sequestration of metals at both the whole plant and cellular levels. Till date, more than 400 plant species have been identified as hyper-accumulators of metals. Das *et al.* (2005) investigated the phytoremediation of arsenic contaminated soils using several weed species (*Ludwigia parviflora*, *Elusine indica*, *Ageratum conyzoides*, *Vitis trifolia*, *Carton sparsiflorus*) and discovered that these plants above ground parts showed increased arsenic accumulation when grown in soils containing 2-14 mg As/kg. The finding suggests these species have great potential as hyper-accumulation of arsenic. Mandal *et al.* (2012[a]) [20] reported that two successive harvests with DAP as the phosphate fertilizer were an effective strategy for ameliorating arsenic contaminated soils in West Bengal, using phytoextraction by *Pteris vittata*. Dheri *et al.* (2007) [13] explored the potential of fenugreek (*Trigonella foenumgraecum* L.), spinach and rye for cleaning up chromium contaminated silty loam and sandy soils. Their findings indicated that the *cruciferae* family was the most tolerant to chromium toxicity, followed by *chenopodiaceae* and *leguminosae*. Anadhkumar (1998) [2], examined the level of chromium accumulation in flower plants including *Jasminum sambac* (Gundumallli), *Jasminum greandiflorun* (Jathimalli), *Nerium oleander* (Nerium) and found considerable chromium accumulation in these flower crops due to irrigation with tannery effluent. Mahimairaja *et al.* (2011) [19] assessed the phytoremediation potential of some floriculture plants for remediating chromium contaminated soils, findings that Jasminum species exhibited a high degree of tolerance to soil chromium. Among field crops, mustard could not survive under high soil chromium levels, while sunflower showed higher tolerance (Table 1). The application of biological wastes, such as coir pith and poultry manure to chromium contaminated soil was effective in reducing bio-available fractions of chromium by forming organic complexes demonstrating potential for bioremediation chromium contaminated soil. Extensive studies by Ramen *et al.* investigated the remediation of soils contaminated with heavy metals using plants like aster, calendula, tuberose, dahlia, nerium, rose, marigold and xerophytic species such as *Euphorbia milli, Agave angustifolia, Furcaea gigantea*. These studies identified marigold and tuberose as possessing characteristics of cadmium hyper-accmulation, suggesting these crops could be used for the phyto-extraction of cadmium from soils with low to medium contamination levels. Additionally, chrysanthemum was found to be useful for the phyto-stabilization of cadmium contaminated soils.

Table 1: Suitable plant species adopted for remediation of mine spoils sites in India

Mine spoils	Suitable plant species used for remediation
Bauxite mined area of Madhya Pradesh	*Grevillea pteridifolia, Eucalyptus camalduensis, Shorea robusta*
Lime Stone mine spoils of outer Himalayas	*Salix tetrasperma, Leucaena leucocephala, Bahunia retusa*
Lignite mine spoils of Tamil Nadu	*Eucalyptus species, Leucaena leucocephala, Acacia and Agave*
Iron ore waste of Orissa	*Leucaena leucocephala*
Hematite, magnetite, manganese spoil from Karnataka	*Albizia lebeck*

(Source: Prasad, 2007) [24]

Impact of heavy metals accumulation under vegetables cultivation

When vegetables are grown in areas contaminated with heavy metals and irrigated with wastewater these metals get accumulated near the root zone. Plants absorb these metals along with nutrients leading to their accumulation in various plant parts particularly root and leaves. Consequently, many researchers have found that leafy vegetables and root crops tend to accumulate high levels of heavy metals. Commonly affected vegetables include *Amaranthus sp*., spinach, lettuce, cabbage, coriander, cauliflower, potato, onion, garlic, carrot and radish. Singh and Singh (2014), analyzed different seasonal vegetables such as mustard (*Brassica campestris*), cauliflower (*Brassica oleracea var. botrytis*), cabbage (*Brassica oleracea var. capitata*) and spinach (*Spinach oleracea*) from the Kalching-Wabagai area using atomic absorption spectroscopy to measure Fe, Cu, Zn and Pb concentrations. Their results showed that Fe and Zn levels were above permissible limits, however, Cu levels were lower and Pb was not detected. Specifically, Fe and Cu concentration in spinach, cauliflower and cabbage exceeded permissible limits with no detectable Pb during the 2008-2010 period. Another study reported 5.5mg/kg of Pb in spinach and tomato surpassing the maximum permissible limit set by international organizations such as the Food and Agriculture Organization (FAO) and the World Health Organization (WHO). The Cd concentration in spinach was 0.3 ppm and 0.2 ppm in tomato, both above the permissible limit. Additionally, spinach contained 0.03 mg/kg of Cu and 2.0 mg/kg of Zn. The high Cd levels in spinach and tomato posed numerous health risks to consumers. Bui *et al.* (2016) [10] investigated heavy metals contamination in vegetables near mining sites in Northern Vietnam. They found that average Pb and as concentrations in fresh vegetables from four mining sites exceeds the maximum levels set by International Food standards for Pb (70.6% of samples) and as (44.1% of samples). However, average Cd concentrations in vegetables at all sites were below the maximum limit of 0.2 ppm. They suggested that irrigation water might be the source of heavy metals contamination. Vegetables irrigated with wastewater become highly contaminated with heavy metals and thus serving as a primary threat to humans. Smin *et al.* (2013) studied the accumulation of Cu, Ni, Fe, Zn, Cr, Mn, Co and Pb in red onion (*Allium cepa*), garlic (*Allium sativum*), tomato (*Solanum lycoperscium*), and eggplant (*Solanum melongena*) irrigated with wastewater. The presence of heavy metals in vegetables irrigated with wastewater was significantly higher than those irrigated with tube well water. Notably, onions showed heavy contamination, with Mn accumulation (28.05 mg/kg) in edible parts being 50 times greater than in onions irrigated with tube well water.

Certain heavy metals such as arsenic (As), cadmium (cd), mercury (Hg), lead (Pb) and selenium (Se) are not necessary for plant growth as they don't play any known physiological role in plants. Other metals, including cobalt (Co), Copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn), are essential for normal plant growth and metabolism. However, these beneficial metals can become toxic if their concentrations exceed optimal levels. The use of compost to enhance agricultural yields without considering potential negative impacts can be problematic, especially since composted waste is frequently applied to soils used for growing vegetables. Given that many vegetables are consumed directly, the risk of transferring heavy metals from soil to humans is a significant concern. The uptake of heavy metals by plants and their subsequent accumulation in the food chain pose potential threats to animal and human health. Plant roots absorb heavy metals which is a primary route for these contaminants to enter the food chain. The extent of heavy metal absorption and accumulation in plant tissues is influenced by several factors including temperature, moisture, organic matter, pH and nutrient availability. [Table 2.] During the summer, higher transpiration rates lead to increased absorption of heavy metals compared to winters. The degree of heavy metal accumulation varies among plant species and is assessed by measuring plant uptake or the soil-to-plant transfer factors of these metals. *Battacharyya et al.*

(2008) found that high concentrations of lead in soils can reduce soil productivity and even low concentrations of Pb can inhibit critical plant processes such as photosynthesis, mitosis and water absorption. Toxic symptoms include dark green leaves, wilting of older leaves, stunted foliage and short brown roots. Heavy metals are inherently toxic and can cause phototoxicity in plants, leading to choloris, poor plant growth, reduced yield, diminished nutrient uptake, metabolic disorders and a decreased ability to fix atmospheric nitrogen in leguminous plants (Guala *et al*., 2007) [14].

Table 2: Important heavy metals and their health implications

Heavy Metals	Permissible level (mg/L)	Major Sources	Toxic effects
Lead	0.1	Mining, Paint, Burning of coal & Pigments	Anemia, Brain damage, Anorexia, Malaise, Liver & Kidney
Copper	0.1	Printing operation, Paint & Copper polishing	Neurotoxicity or Acute toxicity & Diarrhea
Zinc	15	Mining, Refineries & Brass manufacturing	Causes short term metal-fumes fever
Mercury	0.01	Batteries, Paper Industry & Paint industries	Damage to nervous system, protoplasm poisoning corrosive to skin
Nickel	0.2	Porcelain enameling & non-ferrous metal	Chronic bronchitis, reduced lung infection & lung cancer
Arsenic	0.02	Smelting, mining, rock sedimentation & pesticides	Hepatomegaly, Hemolysis & Bone marrow depression
Cadmium	0.01	Welding, fertilizer, mining & refining	Kidney damage, Bronchitis, Gastrointestinal & Cancer.

(Source: Muhammad Umair Sattar *et al*., 2012; Ruqia Nazir *et al*., 2015)

Seed germination in most of the crops have been found to be affected by the presence of increased concentrations of lead. Higher lead levels are found to delay the germination, potentially due to prolonged incubation periods during which the toxic effects of lead might be mitigated through mechanisms such as leaching, chelation, metal binding or accumulation by microorganisms (Ashraf and Ali, 2007) [9]. The application of compost to agricultural soils can improve crop yields, but it also introduces toxic heavy metals into the soil, which can be absorbed by plants. The absorption is influenced by environmental factors like temperature, moisture, organic matter, soil, pH and nutrient levels. For instance, plants tend to absorb more heavy metals in summer due to increased transpiration. The efficiency of metals uptake varies among plant species, and this is evaluated by either plant uptake metrics or the soil-to-plant transfer factors. High levels of Pb in soil can decrease its productivity and even small amounts can disrupt essential plant functions like photosynthesis, mitosis and water absorption, manifesting as dark leaves, wilting older leaves, stunted growth and short brown roots. Heavy metals are toxic to plants, causing chlorosis, weak growth, lower yields, reduced nutrient uptake, metabolic disorders and impaired nitrogen fixation in leguminous plants (Guala *et al*., 2007) [14]. Lead (Pb) is also found to delay the seed germination possibly due to prolonged exposure leading to neutralization of its toxic effects through mechanisms like leaching, chelation, metal binding or microbial accumulation.

Conclusion

Continuous accumulation of heavy metals in agricultural soils becomes an urgent issue which requires immediate scientific attention to ensure the sustainable agricultural goal along with food safety and security. Adopting different phyto-remediation techniques, soil conditioners and amendments, careful crop inspection and selection and regular soil monitoring can be easy to mitigate the adverse effects of these heavy metals on soil health, crop productivity and human health. Furthermore, for achieving the sustainability goals in the agricultural sector, adoption of some holistic approach which integrates scientific knowledge, technological innovation and proactive policy measures to manage and remediate the heavy metal contamination. Selection of suited scientific methods will not only safeguard the environment and ecological balance but also will ensure the long-term viability and agricultural systems productivity. High concentrations of metals like Pb and Cd are found to inhibit the essential physiological processes in plants, such as photosynthesis, respiration, nutrient uptake and as a result leading to stunted growth**,** chlorosis and reduced crop productivity. Moreover, the presence of heavy metals in soils have potential to alter the soil microbial communities and enzyme activities. One of the major significant concerns with heavy metals in agricultural soils is that their potential transfer into the human food chain. Plants absorb these metals from the soil through their roots and the metals get accumulated in edible parts of the plants. Consumption of such contaminated plants can lead to various health issues in humans, including kidney damage, neurological disorders and increased risk of cancer. Therefore, our study concludes that management of these heavy metals is crucial and requires a load of scientific attention for ensuring the food quality, soil health and ecological equilibrium.

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Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review paper.

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