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Accumulation of heavy metals in soil: sources, toxicity, health impacts, and remediation by earthworms

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ABSTRACT: Heavy metals pose serious threats to both individuals and the environment, and there is growing global concern over potentially harmful elements. Heavy metal contamination can have a significant impact on the soil ecosystem's functioning. This requires convenient, efficient, and beneficial remediation approaches. The "ecosystem engineer", earthworms, can modify and enhance soil quality. The ability of earthworms to bioaccumulate metals in substantial amounts in their tissues makes them potentially beneficial as an ecological indicator of soil pollution. Vermiremediation is a new discipline of research in which earthworms are used to detoxify organically contaminated soils. Earthworms have an influential metabolic system, and their gut bacteria and chloragocyte cells play a significant role in their tendency to valorize and detoxify heavy metals. Remediation by earthworms can be considered sustainable, efficient, and ecologically beneficial. The present review provides a wide range of information on earthworms' appropriateness as prospective species for bioremediation and detoxification of toxic metal-contaminated soil to mitigate human health and environmental problems.

Keywords: Bioaccumulation; Detoxification; Earthworms; Heavy metals; Toxicity; Vermiremediation; Vermibiotechnology.

1. INTRODUCTION

As a consequence of significant economic development and rapid expansion in several areas, including agriculture and manufacturing, the environment has become substantially more contaminated [1]. Environmental contaminants are dangerous compounds that enter the ecosystem from both manmade and naturally occurring sources. The two potentially adverse environmental pollutants for ecosystems are toxic metals and insecticides [2]. Toxic metal pollution of the soil has been a major issue since heavy metals affect living organisms. Because of their persistence and lack of biodegradability, heavy metals more easily accumulate in the ecosystem [3]. There are 5 million areas globally where heavy metals or metalloids are contaminating the soil, with current quantities surpassing regulatory norms [4]. Heavy metal poisoning raises the prospect of land tenure concerns and poses several hazards to ecology and humanity. It also has an impact on agriculture safety, food standards, and the capabilities to use the land for farming productivity, all of which have an influence on agricultural production [5].

Toxic metals are a major source of soil contamination. Elements, particularly Cu, Co, Ni, Cd, Zn, Cr, and Pb, play vital roles in environmental heavy metal contamination [6]. Toxic metal poisoning in agricultural fields can disrupt soil functionality, limit plant development, and potentially endanger human health by damaging the food supply. The process by which heavy metals bioaccumulate in ecosystems and the consequent increase in concentration when they transit from one level of the hierarchy to another is referred to as biological concentration. An aggregation of components in the ecosystem can be characterized as excessive heavy metal accumulation. Heavy metals have detrimental effects on soil microorganisms, which alter their population size, variety, and physical performance [7]. Soil heavy metal contamination of varying types and quantities changes the density and functioning of both microorganisms and enzymes, which is a clear indicator of soil biology [8]. Toxic metals are not implemented and aren't biodegradable. As a result, excessive quantities of heavy metals constitute a significant health danger to humans when they are absorbed by plants and subsequently accumulated along the food chain [9]. Hazardous metals must be remediated from the environment due to the substantial health risks they cause to humans and the environmental damage they generate [10].

Vermiculture technology is receiving greater attention for a variety of applications in environmental preservation and sustainable development. Earthworms have been functioning as the ecosystems' "environmental managers" for more than 600 million years [11]. Many social, economic, and environmental issues affecting human society could be solved more affordably by earthworms. The pathogens (hazardous microorganisms) in the waste biomass are selectively consumed by the earthworms, which ingest and bioaccumulate environmental toxins. The final product is much less contaminated, "detoxified", "disinfected", and richer in "plant-available nutrients and humus". Vermibiotechnology is the most effective strategy for managing biological waste and heavy metal accumulation in the soil through the utilization of earthworms [12]. The earthworms are then isolated from the soil and examined for certain toxins [13]. Earthworms also promote crop growth and development [14]. Earthworms, for instance, are one of the few soil-dwelling invertebrates or soil bioindicators that can reduce contamination from heavy metals [15, 16]. Numerous investigations have shown that earthworms can influence toxic metal accessibility, assimilation, and accumulation by transmitting and accumulating toxic pollutants throughout their tissues and organs. The concentration of dangerous chemicals, soil pH, and organic carbon content all influence the degree of bioaccumulation [17]. Earthworms are particularly vulnerable to cadmium (Cd), chromium (Cr), lead (Pb), and zinc (Zn) poisoning and accumulation [11]. Heavy metal bioaccumulation is greatly influenced by environmental factors such as pH and organic compounds [18]. Heavy metals were detected in earthworms susceptible to industrial wastes and sludge [19, 20]. Heavy metals in sewage sludge can be detoxified by earthworm gut microbes and chloragocyte cells [20].

Vermiremediation is one of the remedial strategies that have been implemented for the remediation and restoration of damaged environments as a result of the search for an environmentally sustainable strategy for the impacted areas. It is effective for heavy metal-contaminated soils and uses earthworms to destroy and purify environmental contaminants [21, 22]. This article aims to provide an illustrative overview of earthworm exploitation in soil and environmental remediation by bioaccumulation of heavy metals in its body tissues.

2. EARTHWORMS: THE ECO-BIOLOGICAL ENGINEERS

An organism that enhances the soil's biological and ecological functioning is an eco-biological engineer. As a consequence, earthworms modify the characteristics of pesticide- or heavy metal-contaminated soil, reducing environmental damage caused by toxic pollutants introduced by humans [23, 24]. They function as soil health biomarkers and contribute to the restoration of degraded land. Earthworms are an effective bioindicator for monitoring soil contamination [25]. These are classified into 23 groups and include 700 genera and 7,000 distinct species. Earthworms, which act as the earth's natural intestine, are promising bioreactors that have the potential to improve soil texture, physicochemical characteristics, and microbial activity while also assisting in the effective elimination of organic waste generated by households, municipalities, or the agricultural sector [26, 27]. Earthworms are crucial detritus feeders that are necessary for the soil's metabolism and the decomposition of organic substances. According to various studies, earthworms are believed to be a significant component in the improvement of reclaimed soil [28, 29]. The unstable organic material is oxidized and stabilized through a composting or humification process as a result of the earthworm's feeding behavior, which also causes the waste substrate to be fragmented, enhances microbial activity, and results in faster rates of decomposition [30].

Earthworms are well known for detoxifying soil contamination and sustaining soil health [31]. Metals such as Cu, Cd, Ni, Cr, Pb, Co, and Zn have been observed to bioaccumulate in the internal biological cavities of earthworms [32-34]. Ions containing heavy metals enter the earthworms' symmetrical and longitudinal muscles via the epidermal or ingesting mechanism [35-37]. Earthworms might produce the metallothionein (MTs) molecule in response to the stress caused by heavy metal toxicity [38, 39].

3. HEAVY METALS

Heavy metals are mostly elements with a higher atomic weight and a density greater than 5 g/cm^3 [40]. Heavy metal contamination is a big issue and a considerable source of concern owing to the detrimental effects it is generating all over the world. These inorganic contaminants are being dumped into our rivers, soils, and surroundings as a result of rapidly expanding agricultural and metal industries, as well as inadequate waste management, chemicals, and insecticides [41]. There are 5 million locations where soil contamination from heavy metals or metalloids exceeds permitted values [4]. Heavy metals often found in soil pollution comprise arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pd), copper (Cu), zinc (Zn), and nickel (Ni). This sort of contaminant is harmful to the biosphere, is pervasive, and remains in the soil [42]. After growing on land affected by municipal, domestic, or commercial pollutants, plants can collect heavy metals in the form of mobile ions from soil solution via their roots or foliage absorption.

4. SOURCES OF HEAVY METAL CONTAMINATION IN THE ENVIRONMENT

Heavy metal distribution in soils has been attributed to both natural and anthropogenic processes. Natural sources include volcanic activity, the disintegration of primary igneous rock, and so on. Anthropogenic sources of excessive inorganic toxin concentrations in soils include extensive use of agrochemicals (both inorganic and organic), insecticides, wastewater irrigation, high atmospheric depositions by industry sectors, and fossil fuel burning [3]. Even though several soils in rural and urban areas may accumulate one or sometimes more heavy metals over the expected value, causing threats to human health, crops, animals, habitats, and other mediums. This is because humans have accelerated and disrupted nature's normal metal cycle on Earth [43]. Inorganic and organic fertilizers, pesticides, and fungicides usually contain varying levels of Zn, Ni, Pb, Cd, and Cr, as well as organic manure, field irrigation through industrial and municipal wastewater, and environmental contamination resulting from motor vehicles and the usage of fossil fuels, are all examples of human influences [44-48]. Heavy metals like Cr, Pb, Zn, Cd, Fe, and Cu are commonly mentioned in investigations about the potential impacts and prevalence of contaminated soils [49, 50]. Because of the growing problem of heavy metal contamination and its detrimental effects on crops, ecosystems, and other organisms, it is essential to minimize toxicity by providing acceptable, environmentally sustainable, and viable solutions [51].

5. HEAVY METALS TOXICITY

Heavy metals have been discovered in soils, water, air, as well as other natural habitats. Heavy metals are undoubtedly hazardous and carcinogenic. They have detrimental impacts. Care must be taken when dealing with heavy metals. While certain heavy metals are very reactive, most tend to be less so. These are regarded as poisonous or seriously damaging to the environment [52]. According to adequate assessments of untreated industrial effluent and residential wastewater irrigation, the soil-crop interaction in agriculture has been contaminated with heavy metals [53, 54]. Concentrations of heavy metals were determined to be highest in grassland, with higher variability in industrial and mining reserve land, household territory, and commercial ground. According to the survey findings, human activity has had a considerable impact on the amounts of heavy metals in the soil of various land use groups [55]. The frequency at which a particular component leached metals defined its concentration primarily. The proportion of heavy metals that leached to the soil's reduced genetic levels rose with soil pollution [56]. Toxic metal concentrations in urban soil are a significant indication of environmental degradation [57]. Each heavy metal has its method for inducing toxicity.

A significant amount of heavy metals, such as Cr, As, Pb, Cu, Fe, Cd, Zn, and Ni, can cause toxicity through a number of different processes, including the production of reactive oxygen species, decreased enzyme activity, and slowed antioxidant defense mechanisms [58]. Chromium, manganese, nickel, lead, cobalt, cadmium, copper, and zinc are some of the abundant heavy metals in the environment. Cr, Hg, As, Cd, Pb, Ni, and Cu are carcinogenic metals [1]. Cadmium mainly interferes with or induces renal dysfunction, although it can also affect the liver, bones, circulatory tissue, and neurological functions [59-62]. Chromium overdose raises the risk of developing lung, liver, gastrointestinal, and brain malignancies. It also results in female miscarriages [63, 64]. Nickel poisoning can lead to serious issues with the liver, kidneys, spleen, brain, and organs, as well as vesicular eczema, nose, and lung disease.

6. THE EFFECT OF HEAVY METAL TOXICITY ON PLANTS AND HUMAN HEALTH

Heavy metals in soil are indicative of toxic substances in plants. The plant releases reactive oxygen species when exposed to substantial levels of heavy metals. The root system of numerous plants, especially legumes, is the primary target area for soil toxicity [65]. Numerous heavy metals, including As, Cd, Hg, Pb, and Se, are not required for plant growth since they serve no physiological function in plants that have been observed. Other elements, such as Co, Cu, Fe, Zn, Mn, and Ni, are essential for normal plant development and metabolism, but their concentrations can surpass permissible levels, causing contamination [66, 67]. Excessive quantities of toxic metals can disrupt the growth of plants, cause oxidative stress, and interrupt cellular structure by supplementing inadequate components with toxic substances and inhibiting photosynthetic mechanisms in plant tissue [68]. By reaching the food chain, heavy metals, which are potentially harmful pollutants, threatened animals, plants, and other living beings [69].

The presence of heavy metals in the environment enhances the likelihood that living beings may consume these harmful substances and retain them in various body organs like the kidney, liver, and skeleton (Figure 1). Heavy metal deposition also has an impact on various physiological, neuromuscular, endocrine, immunological, and cardiovascular systems [70, 71].

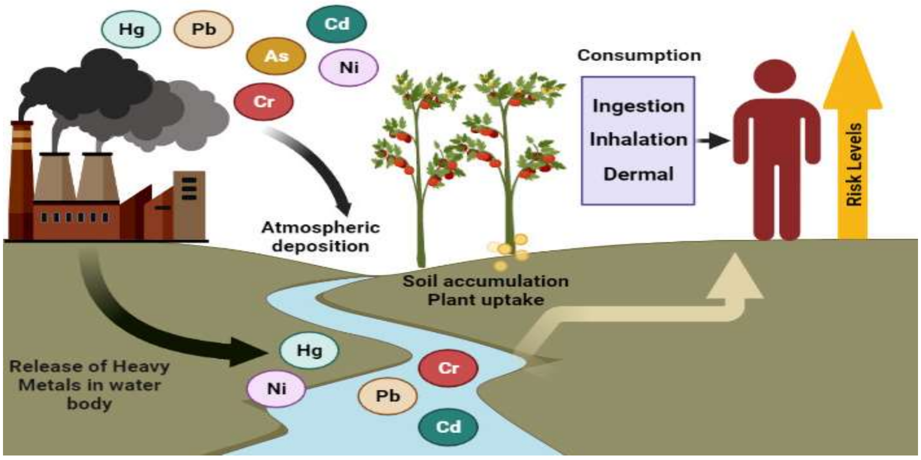

Figure 1. Heavy metal transmission routes from many sources to the environment.

For human biological function, cadmium is not considered necessary. The kidney is the major human organ affected by cadmium exposure in both the general population and those who are exposed at work [72]. Because there are so many different chemical and physical forms of nickel, the pathophysiology of nickel toxicity is rather complicated. Pb is a hazardous metal, and the majority of the population and animals get most of their daily dose via food. Adult lead poisoning leads to anemia, some forms of cancer, and impairments in male reproduction [73]. Mercury poisoning can impair a variety of physiological processes, including the neurological and digestive systems, as well as organs like the lungs and kidneys [74].

7. EXISTENCE OF EARTHWORMS IN CONTAMINATED SOIL

In terrestrial ecosystems, earthworms are well-known for their significant contribution to metal contamination assessment [75]. Their distribution in the soil is governed by parameters such as soil pH, moisture concentration, and levels of organic matter. They require dark, humid locations to live within. Organic matter such as humus, kitchen garbage, and animal manure is particularly appealing environments for some species [76]. Metals or metalloids such as arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb), and antimony (Sb) are examples of conceivably trace components in soils, as are micronutrients such as chromium (Cr), copper (Cu), nickel (Ni), selenium (Se) and zinc (Zn), whose concentrations can be detrimental when they reach critical peaks [77-79] (Figure 2).

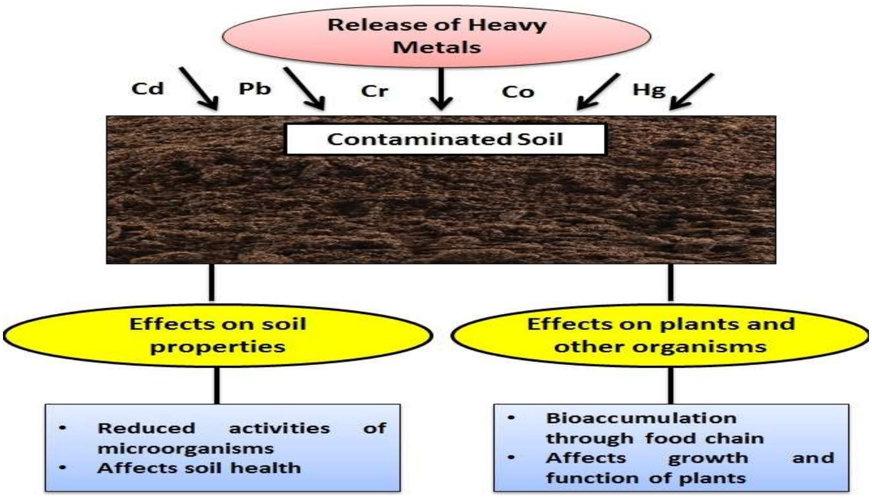

Figure 2. Release of heavy metals in surrounding soil and its impacts.

Possibly hazardous toxic metals are naturally dispersed throughout the Earth in proper concentrations [80]. The biodiversity of the soil and its interactions can also be influenced by earthworms [81]. Earthworms accumulate metals in their guts after ingesting metals from contaminated soil, fly ash, and sludge. In general, metallic deposition by earthworms proceeds via two routes: absorption upon cutaneous contact and adsorption through digestive tissues.

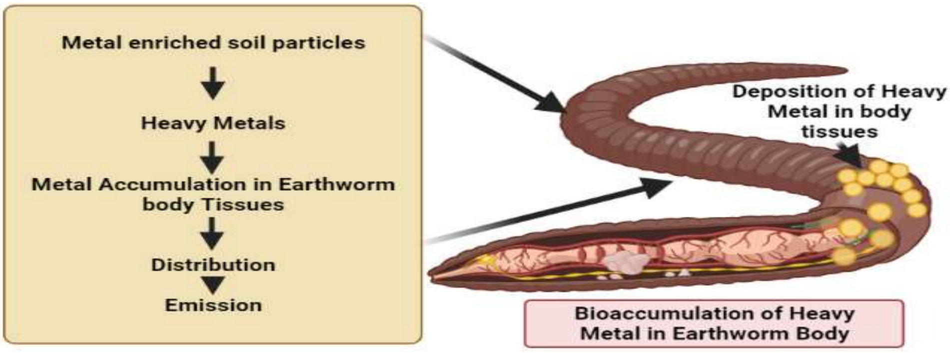

Figure 3. Bioremediation of heavy metal by earthworms.

They have been effectively used by vermicomposting technology to illustrate how they are prospective bio-accumulators and can reduce the toxicity of urban and industrial waste [82]. Because earthworms have bioaccumulation capabilities in their bodies, using them for soil bioremediation is a biological strategy for lowering contaminant concentrations in the soil [83-85] (Figure 3). Seribekkyzy *et al*. [86] reported that earthworms accumulate heavy metals from polluted soil, simulating the functions of key substances in the body, interfering with metabolic activities, and causing disorders. As a result, one of the primary factors for identifying the favorable physical and chemical states of the soil is the abundance and species composition of the earthworm population.

8. ROLE OF VERMICOMPOSTING TO REMOVE METAL CONTAMINANTS

Earthworms are excellent metal accumulators because these metals are absorbed into their soft tissues, particularly zinc, and cadmium. Earthworms can modify metals into a valent state, which increases their availability to plants. Vermicomposting and composting have both been shown to be effective strategies for the breakdown of organic contaminants [87]. In addition to making the end product less poisonous to earthworms, it also provides nutrients. The potentially toxic metal buildup has been observed in three earthworm species: *Eisenia andrei*, *E. fetida*, and *Dendrobaena veneta* [88]. Vermicomposting using *E. fetida* can significantly alter the quantity and variety of pathogens while reducing toxicity and overall heavy metal concentrations [89]. Vermicomposting is a biological method that requires the cooperation of bacteria and earthworms to degrade organic waste in an aerobic environment. It can convert the great majority of organic molecules into nitrogen, phosphorus, and potassium-rich byproducts [90, 91].

Earthworms could accumulate harmful metals in their tissues, thus functioning as an ecological indicator of soil pollution [92]. Earthworms such as *Eisenia fetida, Lampito mauritii*, and *E. andrei* are commonly utilized in vermicomposting procedures to digest organic material, as well as in possible ecological, toxicological, and genetic research. Vermitech is a vermicomposting method that employs native epigeic and anecic earthworm species including *Perionyx excavatus* and *Lampito mauritii* [93, 94]. All combinations of varied animal manure with municipal solid waste resulted in a significant decrease in the levels of heavy metals such as cobalt (Co), chromium (Cr), lead (Pb), nickel (Ni), and cadmium (Cd) after vermicomposting by the earthworm *Lampito mauritii* [95].

9. VERMIREMEDIATION OF HEAVY METALS

The primary focus is on the efficacy of vermiremediation in detoxifying toxic metals and polycyclic aromatic compounds. Vermiremediation's improved soil microbial vitality (i.e., higher soil enzyme capabilities, bacterial populations, and density) is connected with better soil remediation employing earthworms, crops, and microbes, in addition to improvements in metal supply and fractional dispersion. Vermiremediation is a bioremediation technique that can be used alone or in conjunction with other bioremediation technologies to remediate potentially harmful substances in contaminated soil, particularly in situations where the contamination is minor to moderate [96].

This remediation process is based on the activity of earthworms that accumulate and absorbs, transform, or eradicate toxins in the soil environment by utilizing its life cycle (feeding, burrowing, metabolism, excrement) or combination with other abiotic and biotic variables [97] (Figure 4). Vermiaccumulation and vermiextraction, vermitransformation, and drilodegradation are the fundamental features used in the vermiremediation of organically degraded soils. Worm casts may contain significant quantities of organic metal components derived from ingested soils, which may be associated with trace metals in the casts. Earthworms bioaccumulate a large variety of harmful metals, including Cu, Cd, Pd, and Zn, and they can consume an enormous amount of metal-contaminated soil [98, 33].

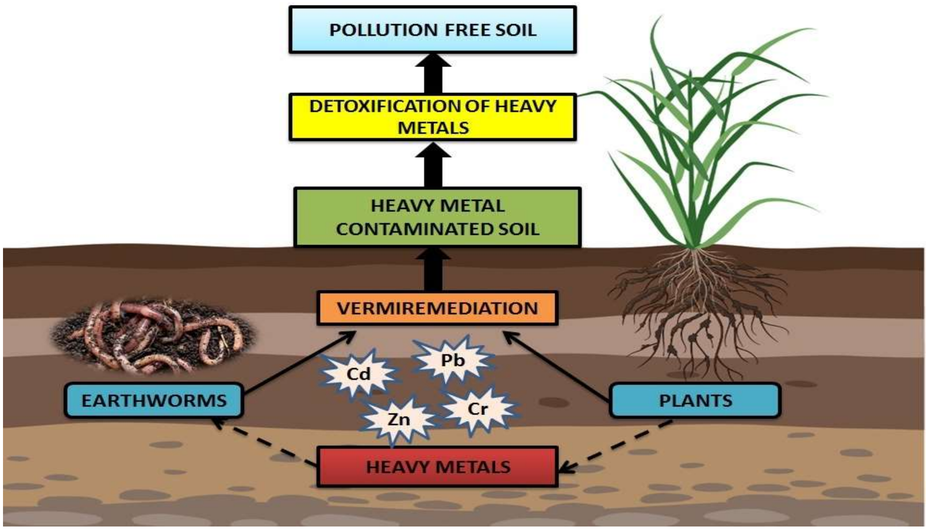

Figure 4. Vermiremediation of toxic metal contaminated soils.

10. HEAVY METAL DETOXIFICATION BY EARTHWORMS

In soil, earthworms can alter the concentrations of both accessible and total metals. While their excretions may include lower quantities of metals than their tissues, earthworm cells may contain significant amounts of heavy metals [99]. The type of mineral soil, the quantity of organic matter, and metal concentrations in their vicinity all influence earthworm heavy metal absorption. Earthworms can obtain exceedingly hazardous compounds from soils through epidermal assimilation in soil groundwaters or digestion of soil particles and organic soil constituents carrying significant concentrations of persistent organic contaminants [17, 23]. Through their metabolic processes, earthworms can collect organic xenobiotics from contaminated environments. Toxic and undesirable industrial wastes can be stabilized by combining them with cattle manure or other organic matter in a sufficient volume, and a vermicomposting technique can be standardized for such pollutants. Toxic metals are ingested by earthworms in a diverse range of ways, from non-essential element linear absorption rates to critical component stable uptake processes [100-102]. After being ingested by earthworms, metals undergo detoxification and are stored in subcellular compartments [103, 104]. It has been established that there are three main detoxifying mechanisms:

- Elimination from the earthworms
- Deposition of granules in the earthworm's inorganic exoskeleton
- Specific protein reactions (such as metallothioneins and other ligands) [105-107].

Different metals generate many detoxifying and subcellular compartmentalization routes in earthworms, resulting in varied forms of accumulation [108, 109]. According to several research studies, earthworms tend to bioaccumulate cadmium over extended periods. The interior tissues of *Lampito mauritii* and *Drawida sulcata* have higher concentrations of extractable hazardous metals such as Cd, Cu, Cr, Pb, and Zn. Pb accumulates in earthworms' interior chloragogenous cells, where it binds to a protein that is not metallothionein. Through this detailed analysis, a significant level of detoxification is accomplished [31].

Some earthworm species, including *Eisenia fetida*, *Lumbricus terrestris*, *L. rubellus*, *Dendrobaena rubida*, *D. veneta*, and *Allolobophora chlorotica*, have been reported to be capable of detoxifying heavy metals from the environment [110]. Exotic earthworms are commonly used in the preparation of vermicompost, and Shahmansouri *et al*. [111] observed from their research findings that vermicompost made from sewage sludge utilizing *Eisenia fetida* reduced concentrations of heavy metals confirming the bioaccumulation of metals Cr, Cd, Pb, Cu, and Zn in earthworm tissues. In addition to improving vermicompost, excessive metal accumulation in earthworms has a biomagnification effect that has an impact on the food chain [112]. The bioaccumulation of heavy metals by *Libyodrilus violaceus*, *Eudrilus eugeniae,* and *Alma millsoni* from the soils of abattoirs is inversely linked to the concentration of those heavy metals in the soil [113]. Table 1 shows different heavy metals remediated by various earthworm species.

Table 1. Vermiremediation of heavy metals.

S.No.	Metals remediated	Earthworm species	Effectiveness of vermiremediation	References
1.	Cr, Pb, Cd, Fe	*Eisenia fetida*	Cr decreased by 4.5-113.21 mg kg^{-1}, Pb decrease by 1550 mg kg^{-1}; No change in Cd, Fe levels concentrations	[110]
2.	Cr, Cd, Pb, Cu, Zn	*Eisenia fetida*	Metals concentration decreased with increasing vermicomposting time	[111]
3.	Cd, Pb, Zn, Cu, Mn	*Eisenia fetida*, *Eudrilus eugeniae*, *Perionyx excavatus*	*Eudrilus eugeniae* reduced Pb by about 32%, Zn by 37%; *Eisenia fetida* reduced Pb by 45%; Zn by about 44%; *Perionyx excavatus* minimized Pb level by 51% and Zn by 56%	[112]
4.	Co, Cr, Pb, Ni, Cd, As	*Eisenia fetida*	*Eisenia fetida* reduced Co by 2.47%, Cr by 0.40%, Pb by 64.12%, Ni by 8.02%, Cd by 0.34, and As by 2.10% in combination of buffalo dung with kitchen wastes	[114]
5.	Co, Cr, Pb	*Lampito mauritii*	*Lampito mauritii* reduced Co concentration by 43.75%, Cr by 9.40% and Pb by about 30.91%	[115]
6.	Cu and Zn	*Metaphire posthuma*	*Bacillus licheniformis* strain KX657843, which is linked with the alimentary tract of earthworm (*Metaphire posthuma*), developed extracellular polymeric material that can flocculate and remove Cu and Zn toxic substances	[116]

Kokhia *et al*. [117] reported that after being exposed to heavy metal solutions, earthworms of various species, including *Aporrectodea rosea*, *Eisenia veneta*, and *Allolobophora chlorotica*, bioaccumulate different concentrations of heavy metals such as Cu, Zn, and Pb. Fatima and Singh [115] reported that *Lampito mauritii* species are efficient in lowering detrimental metal concentrations from rice grains as well as metal toxicity (Co, Cr, and Pb) from various combinations of animal dung during the production of vermicompost.

11. CONCLUSION

It is clear from the above accounts that the focus is now shifting to biologically in situ alternatives due to the high costs and environmental deterioration associated with conventional physicochemical cleanup approaches. The utilization of earthworms is beneficial for remediating soils contaminated with heavy metals, particularly when the contamination is mild to moderate. Earthworms are excellent ecological bioindicators for heavy metal-contaminated soil restoration. Earthworms usually bioaccumulate heavy metals in their body cells, which accelerates metal absorption while also making them resistant to metal toxicity. So we can say that earthworm characteristics have substantial advantages for assessing contamination, monitoring soil quality, and vermiremediation process.

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