Impact of Green Manures in Mitigating Heavy Metal Toxicity: A Review

ABSTRACT

The contamination of soil with heavy metals poses a serious threat to both ecology and public health. Human activity, such as mining, excessive fertilizer application, and industrial processes, are among the various sources of heavy metal pollution. There are various green manure plant species used as potential for mitigating heavy metal toxicity, certain legume plants like Albizia leibbeck L., Bauhinia purpurea L., Dalbergia sissoo, Millettia peguensis Ali, and Pongamia pinnata are being looked for applications in phytoremediation. Various techniques such as bioremediation, phytoextraction, phytofiltration, phytovolatilization, rhizofiltration, phytodegradation, and phyto desalinization are employed to address environmental pollution. Phytoremediation, in particular, aims to collect pollutants from the environment and convert them into forms that can be easily extracted from plant tissues. Contamination by heavy metals is a severe environmental matter. However, there are various contemporary methods that offer potential solutions to address this issue. One such approach involves the use of biochar to decrease the bioavailability of heavy metals in soil. By binding to them reducing their availability for plant absorption and entry into the food chain. Genetic engineering permits researchers to insert genes into plants that improve their acceptance of heavy metals or increase their ability to accumulate them (phytoextraction). Consequently, the utilization of these conventional methods in phytoremediation has demonstrated the most favourable and sustainable outcomes, ensuring an eco-friendly approach for the ecosystem.

Keywords: bioremediation, phytoremediation, phytoextraction, biochar, heavy metals

INTRODUCTION:

The earth's crust contains naturally contains heavy metals, which play a crucial role in various biological activities. High amounts of them are prevalent, endangering human health, the environment, and plant ecosystem where the metals get deposited in soil, and water which are highly toxic. There are approximately 40 elements that fall under this. Heavy metals are commonly found in aquatic and soil ecosystems, and to a lesser degree as vapours or particles in the atmosphere. The species of the plant, the particular metal, the amount of it, its chemical form, the pH and composition of the soil, and other variables can all affect how harmful heavy metals are to plants. It is important to note that while many heavy metals are essential for plant growth, they can also be harmful in excessive amounts [1,65,66,67,68]. The high density of heavy metals and metalloids, their natural occurrence in rock formations, and the increase in their presence in the biosphere due to human activities. These elements possess an atomic density higher than 4 g/cm3, which is significantly higher than the density of water. Heavy metals are naturally found scattered across rock formations. These metals can be released into water and soil through geological processes including weathering and erosion. Human activities such as industrialization and urbanization have been highlighted as important reasons that have led to higher amounts of heavy metals in the biosphere. This can occur through various ways, including mining, smelting, waste incineration, and the application of some fertilizers and insecticides. Heavy metals or metalloids include copper, manganese, lead, cadmium, nickel, cobalt, iron, zinc, chromium, arsenic, silver, and platinum. These elements have a high density, which can affect their transit and accumulation in the environment. Their presence can pose risks to human health and ecological systems when exposure levels exceed safe limits. It's important to implement effective environmental regulations and pollution control measures to minimize anthropogenic contributions of heavy metals to living things [2]

The heavy metals, which are elements in the periodic table with atomic numbers higher than 20, are referred to as such, except for alkali metals and alkali earth. Trace amounts of these metals are necessary for metabolism, growth, and development, but excessive amounts can lead to harm to the cells [3]. Heavy metals have several ways to enter the human body, including through food chains, both intake and inhalation. Humans have used heavy metals for a very long time to make metal alloys and pigments that are used in paint, cement, rubber, paper, and other items. Even so, several nations continue to employ heavy metals despite their well-known harmful impacts. Heavy metals can trigger the immune system once they've entered the body, which can lead to rashes, nausea, vomiting, anorexia, and gastrointestinal problems. In addition to altering blood composition and harming the kidneys, livers, lungs, and other vital organs, additionally, heavy metals might impede or harm the brain's central nervous system. High levels of heavy metals can also harm the body, muscles, and nervous system. It can lead to lung cancer and the respiratory system can harm humans. Constant exposure to these dangerous toxic metals can have a major negative impact on aquatic biota, soil, air quality, and human health. Remediation of heavy metals can be done by using certain plants and microbes to convert toxic form into non-toxic forms. Following certain techniques like bioremediation agents like (yeast, fungi, and bacteria), phyto extraction, rhizofiltration, rhizome degradation, and immobilization. Additionally, heavy metals can be eroded from soil and water bodies due to factors like acid rain, runoff, and erosion [4].

SOURCES OF HEAVY METAL CONTAMINATION:

The contamination of the soil environment occurs when heavy metals are transported from mines to different environmental sites, when man-made cycles produce them more quickly than natural ones, when the various forms of heavy metals in the environmental system become more bioavailable, and when waste products contain higher concentrations of metals and metalloids than the surrounding environment [5,6]. However, metallic materials have become more prevalent in both terrestrial and aquatic habitats due to the increased usage of heavy metals. Heavy metal pollution has resulted from this, and the main human causes include mining, smelting, foundries, and companies that deal with metals. Leaching of metals from landfills, garbage dumps, excretion, animal and chicken manure, runoffs, automobiles, and road building are additional origins. Furthermore, fertilizers, insecticides, and pesticides that contain heavy metals have been identified as secondary sources of agricultural pollution with heavy metals. Additionally, natural occurrences including volcanic eruptions, metal corrosion, metal evaporation from soil and water, sediment re-suspension, soil erosion, and geological weathering can lead to heavy metal pollution. Numerous sources are discussed in the table by [7,8,9,10,11].

Table 1. Heavy types of sources metals

Name of Heavy metals	Types of Sources
Arsenic (As)	Wood preservatives and various pesticides
Cadmium(Cd)	Mining, the atmospheric breakdown of combustion pollutants, and the application of fertilizers containing cadmium.
Chromium (Cr)	Industrial activities, stainless steel, anti-corrosion coatings
Copper (Cu)	Fungicides, sewage sludge
Mercury (Hg)	Ubiquitous weathering in earth’s crust, geothermal activity
Nickel (Ni)	Nickel alloy production, coinage manufacturing, electroplating
Lead (Pb)	Battery manufacture, insecticides, and herbicides
Zinc (Zn)	Mining activities
Manganese (Mn)	Industrialization and urbanization
Iron (Fe)	Ores /minerals dissolution

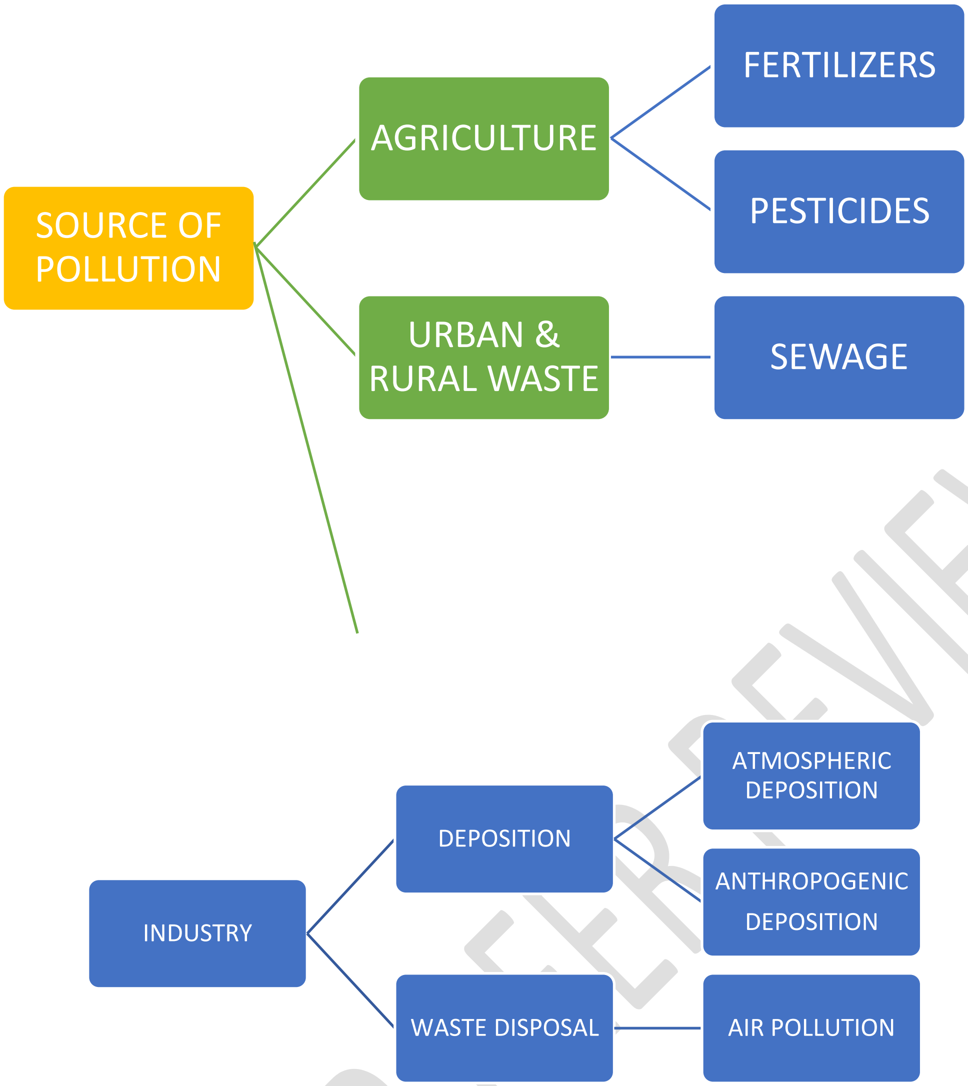

Chart 1. SOURCES OF HEAVY METAL POLLUTION

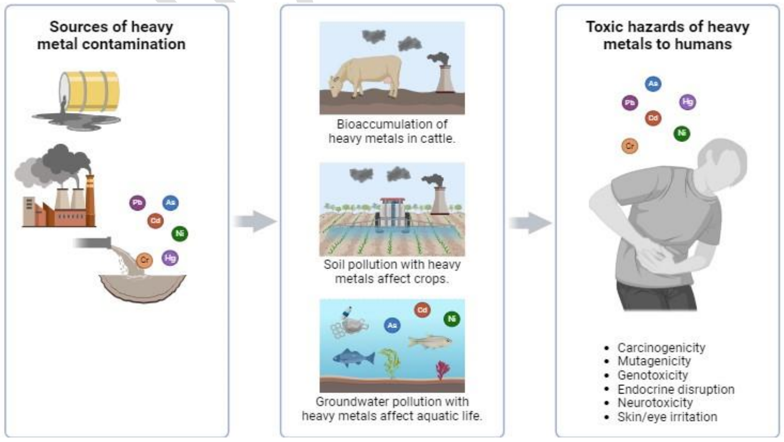

Fig 1. Sources of heavy metal contamination & hazardous effects on human health

GREEN MANURES:

Green manures involve incorporating fresh plant material into the soil which enriches soil productivity and fertility by adding plant nutrients and organic matter. Additionally, green manures increase the biomass as well as soil microbial activity, and we also notice noticeable alterations in the populations of soil microbes that help suppress diseases. Leguminous plants are mostly used as they fix nitrogen by rhizobia. The advantage of using green manure is that it improves soil water-holding capacity, promotes soil health, improves soil hydraulic properties, reduces soil erosion, and prevents surface runoff. By increasing the amount of soil aggregates, lowering soil exposure, and enhancing soil water-holding capacity, planting green manure helps to prevent soil erosion caused by wind. Moreover, it plays a crucial role in lowering surface runoff and flow rates, preventing surface soil erosion. Overall, incorporating green manure into agricultural practices proves to be a valuable method for reducing soil erosion and maintaining soil quality. It helps in lowering the daytime soil temperature, reduces evaporation, and increases soil permeability, thus maintaining the soil water content. Green manure, particularly leguminous green manure, provides a lot of nitrogen to plants, making it an excellent source of nourishment. Planting crops that decompose in the soil is a method used to replenish nutrients and enhance organic matter. Green manure crops are typically cultivated in between the main crops to prevent soil erosion, serve as winter cover crops, or increase the productivity of depleted land [12].

Green manuring is a centuries-old practice that involves incorporating both leguminous and non-leguminous green plants to increase soil fertility. However, its popularity has waned in recent years due to factors such as the need to increase food production, the availability of more profitable crops, and the accessibility of inexpensive artificial fertilizers. Nevertheless, green manuring has recently regained importance among organic growers and low-input farms that follow conventional agronomic methods, due to loss of soil fertility and the rise of soil-related concerns. Moreover, public concerns about abuse and energy conservation have also contributed to the renewed interest in green manuring. There are various methods to implement green manuring, including in-situ adoption or the introduction of plants that were specifically produced overseas for this purpose. Farmers can increase soil fertility and health by introducing green plants into the soil which can lead to higher crop yields [13].

There exists a wide range of plants that can be used as green manures. Some examples of green manuring crops include grain legumes like groundnuts, soybeans, green grasses, and pigeon peas. Furthermore, woody perennial legume trees with multiple uses, such as Cassia siamea Lam, Gliricidia sepium kunth, and Leucaena leucocephala (Lam) can also be utilized. Other legumes like sun hemp, Dhaincha, cowpea, etc. also appropriate for green manure purposes [14]. Out of the numerous plant species, only a small proportion have been thoroughly investigated because they might be grown as green manure crops. Legume crops are widely used in agriculture to increase the amount of nitrogen in the soil [15]. Legumes have the ability to fix atmospheric nitrogen through two different mechanisms: symbiotically with Rhizobium bacteria and non-symbiotically with free-living diazotrophic bacteria. Cyanobacteria also form associations with plants. Legumes' symbiotic nitrogen Fixation is a primary source of nitrogen for agriculture in organic farming systems [16, 17,18,19].

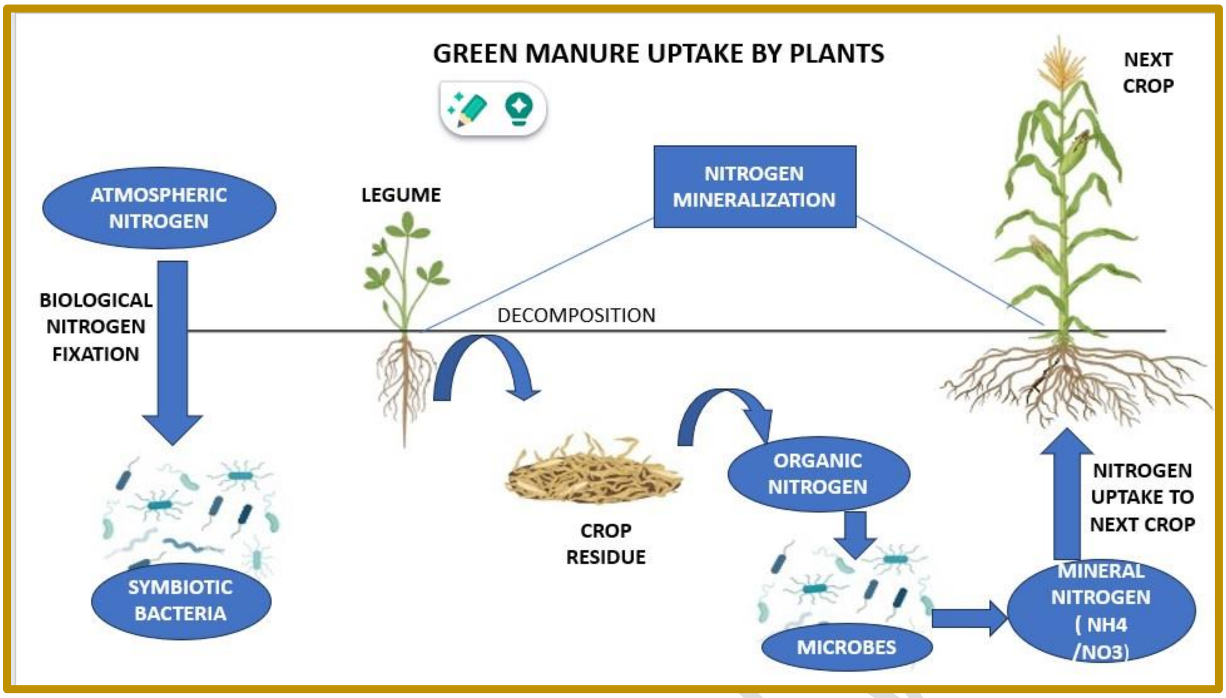

Fig 2. Role of Green manure crop in the management of soil nitrogen

ROLE OF GREEN MANURES TO REDUCE HEAVY METAL TOXICITY:

Planting green manure an advantageous technique that has the potential to decrease herbicide remnants, control weed growth in paddy fields, and enhance soil quality by introducing specific heavy metals, including Zn, Pb, and Cd. However, the benefits of green manure could change based on the kind of crop and the growth stage. Therefore, it is crucial to choose a suitable green manure crop and return method to optimize the farming process. Despite the diversity of green manure varieties available, their effects on different soil textures are not yet clear, so more research is needed to strengthen existing resources and develop new varieties employing cross-breeding and molecular methods. Green manure's contribution to nutrient enhancement and greenhouse gas emission reduction is still variable, and more investigation is needed to understand its effects. In addition, green manure helps to greatly reduce greenhouse gas emissions [20].

The process of bioremediation uses biological agents like microorganisms, green plants, and organic amendments to treat metalloid-contaminated soils. The effectiveness of this natural process depends the metabolic processes of higher plants, fungi, and microbes to break down pollutants and change the state of the environment. By incorporating organic soil additives into the so-called biostimulation/ bioaugmentation), the effectiveness of this process can be enhanced. The metabolic activities of these organisms can utilize chemical contaminants as an energy source, reduce bioavailability or produce less hazardous byproducts, making them harmless [21].

EFFECT OF IN SITU COMPOST RELATIVE TO HEAVY METAL MOBILITY:

Soil variations, such as pH, CEC, microecological structure, and active mineral morphology, can directly impact the movement of metals in the soil. Because of this, organic amendments (OAs) can enhance heavy metal in-situ remediation through a range of procedures, such as rhizosphere modification, co-precipitation, adsorption, complexation, and reduction [22]. Applying green waste compost reduced in calcareous contaminated soils, Greek cress absorbed 21%, 54%, and 16% of Zinc, Pb, and Cu respectively. It has been discovered that applying compost can successfully cut the toxicity of cadmium (Cd) to wheat by fifty percent. This is accomplished by increasing wheat growth and reducing the absorption of Cd by wheat tissue. The primary causes include high soil pH, co-precipitation with phosphorus (P) concentration, and Cd complexation with organic matter (OM) of compost application.

An increase in surface charges and metal adsorption onto molecules that bind metals, like carbonates and phosphates, are the primary reasons why metal(loids) occur retained in organic additions. However, the effectiveness of composted organic amendments is influenced by various variables, including soil type, the specific metal(loids) that require remediation, and the make-up of the amendment to reduce the mobility and bioavailability of metal(loids) in soils.

Organic soil additives can improve soil's physical properties by forming water-stable aggregates the distribution of particle sizes, the pattern of cracks, and porosity, hence preventing the dispersal of particles tainted with metals [23]. Soil organic matter can be increased by adding manures and organic additives that have been composted. This raises the quantity and variety of bacteria and other microorganisms, as well as soluble organic carbon and microbial biomass. Furthermore, these amendments also enhance different soil enzyme activity and soil respiration. Overall, the use of natural supplements in soil can significantly improve its quality. According to [24] soil immobilization is a method that involves specific soil amendments to induce chemical changes in soil. These changes result in a decrease in mobility and availability of trace elements to biota. This technique has been extensively studied It has drawn interest from academics and businesses as a possible substitute for the methods of landfilling and excavation. Numerous studies have shown that immobilization significantly improves soil properties while concurrently decreasing the toxicity, mobility, and bioavailability of trace elements.

To comprehend the influence of green manure impacts the accessibility of zinc and cadmium in soil to understand its effects on wheat's levels of these metals [25]. This is accomplished by looking at how it affects the soil's pH values and the metals' accessibility through organic matter that has decomposed [26] found that the application of a foliar ZnONP dressing combined with berseem and maize residues as green manure enhanced the characteristics and biomass of wheat yield. Along with lowering the EL, these alterations also increased the levels of leaf chlorophyll and the antioxidant enzymes' activity. Moreover, the application of these treatments resulted in a drop in soil-accessible Cd. Furthermore, Cd levels in wheat tissues, particularly in grains, dramatically dropped after ZnONPs were applied, with Cd concentration even going below the average.

THE EFFECT OF IN-SITU COMPOST ON HEAVY METAL BIO AVAILABILITY

Bioavailability is an important criterion when assessing environmental geochemistry and heavy metal's ecological consequences. Different searchers may interpret bioavailability differently depending on their place of birth. Bioavailability refers to the method by which substances from food (ingested orally) or the abiotic environment (externally) pass through an organism's cell membrane [27]. These characteristics, as defined by [28], include soil pH, soil type, soil texture (clay content), soil organic matter, and soil cation or anion exchange capability. Based on the data at hand, metals found in soil have been categorized into five main geochemical forms the initial four states are exchangeable, bound to organic materials, bound to the carbonate phase, bound to Fe and Mn oxides, and bound to residue metal. These metals in the soil can react to form low-molecular organic acids, polysaccharides, and bacterially secreted enzymes, among other organic compounds. Therefore, they can behave very differently in the soil regarding mobility, biological availability, and chemical behavior [29]. Research indicates that composting typically lowers bioavailability—the amount of dangerous heavy metals that plants can absorb—and phytotoxicity—the toxicity that heavy metals have to plants. Compost, however, does not affect arsenic (As). Two separate investigations revealed that compost decreased plant uptake of lead (Pb) but not arsenic [30]. There is disagreement over whether compost is a surefire way to get rid of heavy metals. According to some research, long-term compost use may migrate or release these metals in the soil when organic matter decomposes and the pH shifts [31]. This gives rise to worries about future dangers to human health, the environment. To completely understand how compost affects heavy metals in soil, more extensive field studies are required, and researchers must come up with strategies to deal with this possible problem.

TYPES OF GREEN MANURES USED FOR HEAVY METAL REMEDIATION

Legumes are a frequent crop to employ for green manure cultivation because they increase the soil's pH and availability of nitrogen (N), which promotes the growth and production of subsequent crops [32,33]. Legumes have the capacity to extort significant amounts of atmospheric nitrogen through the symbiosis of biological nitrogen-fixing bacteria [34]. Legume crops require fewer N fertilizers due to the availability of nitrogen from BNF [35] Legumes can be incorporated in crop rotations as a sustainable strategy to reduce the demand for nitrogen fertilizers while increasing the yields of crops that come after them. By increasing the structural features of the soil, lowering the concentration of organic carbon in the soil, and physically sheltering the soil surface, legume cover crops lessen the possibility of erosion [34]. The presence of organic carbon facilitates the binding of soil particles, leading to the formation of durable macroaggregates, thereby improving soil stability [36].

Heavy metal-contaminated soil is a severe global environmental problem, especially in industrialized countries. According to [37], heavy metals are non-biodegradable and can remain in the soil for a lengthy period. Heavy metal poisoning in soil is a major concern for both the agroecosystem and human health through the food chain. The utilization of plants to clean up contaminated regions it's referred to as phytoremediation has become a viable approach to solving this worldwide issue [38,39]. Several legumes have been recommended as relevant species for phytoremediation, including Anthylis, Cytisus, Lotus, Lupinus, Genista, Glycine, Ononis, Ornithopus, Pisum, Trifolium app., and Vicia [40]. For usage in phytoremediation, legume plants such as Pongamia pinnata, Dalbergia sissoo, Albizia lebbeck L., and Millettia peguensis Ali are being sought after. Certain tree species have shown the potential to remove heavy metals from urban woods watered using raw industrial wastewater. Chelating agents or organic correction are not required for the absorption and store heavy metals in different plant sections. This environmentally beneficial strategy may be able to lessen problems including the toxicity of untreated industrial wastewater, air pollution in cities, and the preservation of freshwater for irrigation purposes [41].

THE RIGOURS OF HEAVY METAL REMEDIATION:

Remediation and mitigation of heavy metals is an important process aimed at reducing the harmful consequences of human health and environmental contamination with heavy metals. There are certain mechanisms followed like

- Bioremediation
- Phytoremediation
- Phytoextraction
- Rhizo-filtration
- Rhizo-degradation
- Immobilization

BIO REMEDIATION:

Bioremediation is a process that uses microbes, plants, or enzymes derived from them to detoxify pollutants present in soil and other environments. This process utilizes the natural ability of microorganisms and plants to eliminate harmful pollutants and restore the environment to its original state [42,43]. This process can occur naturally or can be stimulated by adding fertilizers to increase the bioavailability in the medium. Ultimately, bioremediation employs the natural biological activity to destroy or neutralize various contaminants removed from the original site (ex-situ). In the case of contaminated soil, sediments, and sludges, bioremediation can involve land tilling to make nutrients and oxygen more available to microorganisms. Several bioremediation technologies are available, including phytoremediation, bioventing, bioleaching, landfarming, bioreactor, composting, bioaugmentation, rhizofiltration, and biostimulation. These techniques are generally low-cost and low-tech, making them highly accepted by the public [44,45].

PRINCIPLES OF BIOREMEDIATION:

The main principles of bioremediation aim to reduce the solubility of pollutants in the environment through modifications in pH, redox reactions, and pollutant adsorption from polluted areas [46]. Redox reactions involve the chemical transformation of hazardous pollutants into less dangerous, more stable, less mobile, or inactive substances [42]. Bioremediation is a process in which microorganisms attack pollutants and convert them into harmless products enzymatically. However, it requires favorable conditions for microbial growth and activity. Compared to conventional methods, bioremediation techniques are typically more economically efficient [45].

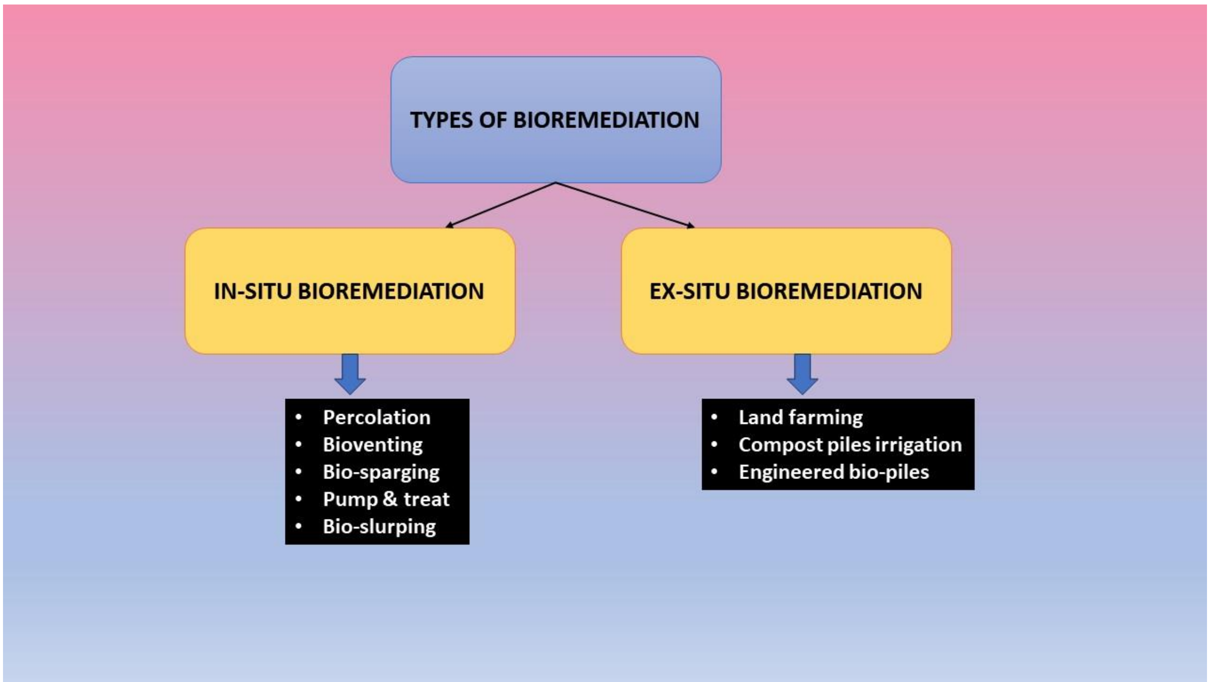

Fig 3. Types of bioremediation

MECHANISM OF BIOREMEDIATION

Fig 4. Mechanism of bioremediation

PHYTOREMEDIATION:

Phytoremediation is involves utilizing plants and soil microbes to reduce the amount of environmental toxins or their detrimental effects. This approach can remove radionuclides, heavy metals, and organic pollutants from soil. It is an innovative, economical, efficient, and environmentally benign remediation technique that uses solar power and is suitable for in situ use [38]. To remove environmental pollutants, this method combines phytotechnologies with both naturally occurring and genetically modified plant species [47]. This methodology's main goal was to gather pollutants originating from the surrounding as well as convert them into shapes. that could be easily removed from plant tissues. Essentially, conventional techniques such as phyto extraction, phyto stabilization, rhizofiltration, and phyto volatilization are used in pollution phytoremediation. Investigating using plants that hyperaccumulate metals as a potential treatment for agricultural soils containing trace amounts of heavy metals contamination could be beneficial. Over 582 species of metal hyperaccumulators belonging to the Braccicaceae family have been identified globally, and they are found in more than 50 families of vascular plants. Metal hyperaccumulating organisms are helpful in decontaminating soil of metals. Some of these plants include, for example, Haumaniastrum Robert (Lamiaceae), Noccaea caerulescens and N. rotundifolia (Brassicaceae), Virotia, Neurophylla (Proteaceae), Psychotria douarrei (Rubiaceae), and Ipomoea alpina (Convolvulaceae). Brassica juncea, or Indian mustard, is available in North America and Europe, a member of the Brassicaceae family, was frequently employed in phytoremediation.

Table 2. Traditional approach of phytoremediation

Phytoremediation techniques	Definition
1. Phytoextraction	accumulation of harmful contaminants in plant portions that can be harvested, such as shoots.
2. Phyto filtration	Plants' ability to sequester harmful contaminants from contaminated waterways.
3. Phyto stabilization	Instead of breaking down pollutants, the chemical compounds that the plants create immobilize them.
4. Phyto volatilization	Through their leaves, plants expel organic pollutants that they have absorbed from the water into the atmosphere.
5. Phyto desalination	Halophytes remove excess salts from saline soils.
6. Rhizosphere biodegradation	Through its roots, the plant releases natural chemicals that give soil microbes nourishment. The microbes speed up biological deterioration
7. Phyto degradation	Pollutants are broken down and eliminated by plants in their tissues.
8. Rhizo filtration	Utilize the roots of plants to gather, concentrate, and separate harmful elements found in tainted groundwater. To begin with, contaminated water is given to appropriate plants with sturdy root systems to acclimatize them. After being moved to the polluted area to gather the pollutants, these plants are collected after their roots are saturated. Rhizo-filtration minimizes environmental disruption by enabling in-situ treatment.

(Table source from Thakur et al., 2021 (48))

PHYTOEXTRACTION

Phyto extraction is a buildup of harmful contaminants in plant portions that can be harvested, such as shoots. It is also known as phyto accumulation, phyto adsorption, or phyto sequestration. There are two procedures involved in phyto extraction: natural and chelate-induced. Hyperaccumulator plants are vital to the natural process because of their slow growth rates and limited capacity to produce biomass. Additionally, they only collect specific heavy metal components. Conversely, the chelate-induced method depends on soil additives like compost, EDTA, and nitrilotriacetic acid to increase plant uptake concerning heavy metals [28, 49]. Since it is impossible to collect root biomass, the biochemical process of metal transfer to shoots is essential for phyto extraction [38]. Many factors influence phytoextraction efficiency, including soil conditions, metals accessible to plants, and so on. The sunflower (*Helianthus annus*) has emerged as a feasible hyperaccumulator plant to recover soil contaminated with cesium, strontium, and uranium [50]. Phytoextraction plants must exhibit the following traits: rapid growth, significant biomass production, capacity to hyper-accumulate heavy metals, wide distribution, capacity to translocate metals from the base to the tip, resistance to pathogens and pests, climatically well-adapted, ease of cultivation and harvesting,) unappealing to herbivores to prevent entry into the food chain, and vi) tolerance to heavy metals' harmful effects [47].

PHYTO FILTRATION:

Phyto filtration is the action of taking out dangerous pollutants that factories discharge into contaminated seas. In photo filtration the contaminants are absorbed or adsorbed, minimizing their migration into subsurface waterways [38].

PHYTO STABILIZATION:

The utilization of particular plants to stabilize chemicals in disturbed areas can prevent contaminants from moving into groundwater or entering the food chain [38]. The objective of Phyto stabilization has been summed up as follows: plants immobilize or lessen the number of soil pollutants that can be reached by plant roots and the the residing bacteria [51].

1) Modify the soil's trace element speciation to reduce the amount of exchangeable fraction and solubility.
2) Maintain a stable canopy of plants and reduce crop uptake of trace elements.
3) Reduction in the direct exposure of contaminants to soil-dwelling organisms.
4) Reduce the mobility of metals to boost biodiversity.

In order to phytostabilize an industrial site, specific trees can be planted based on pollutants, soil type, and temperature. Sufficient open space is necessary for planting in regions with an industrial component. If there isn't enough room for movement, it will need must be organized and produced. To effectively prevent pollutants from moving from the industrial site into the nearby natural environment, the trees are positioned in rows at predetermined distances from one another [52].

PHYTO VOLATILIZATION:

The procedure for phytovolatilization incorporates the absorption of pollutants by plants, which release them into the atmosphere after transforming them into less hazardous form. According to [53],volatile forms of toxic metals such as mercuric oxide and dimethyl selenide can be generated from them and subsequently volatilize or evaporate into the atmosphere. Mercury, arsenic, and selenium are some of these types. [55] suggests that transgenic Nicotiana tabacum with the merA gene might be used to remove mercury from soils. Additionally, Arundo Donax was beneficial when plants were cultivated in sterile garden soil treated with 2, 10, and 20 mg/L of NaAsO2, plant growth-promoting rhizobacteria tended to volatilize arsenic [56].

PHYTO DESALINISATION:

The process by which halophytes eliminate excess salts from saline soils is referred to as phyto desalinization. Halophytic plants, unlike glycophytic plants, are naturally resistant to heavy metals. Two halophytic plants, Suaeda maritima and Sesuvium portulacastrum, are capable of extracting 504 and 474 kg of sodium chloride from salty soil [38].

RHIZODEGRADATION:

The term "biodegradation" refers to the process by which microorganisms in soil break down organic pollutants. The rise in both the quantity and metabolic activity of microorganisms in the rhizosphere primarily contribute to the increased breakdown of contaminants in the environment. Plants emit compounds high in flavonoids, sugars, and amino acids, All of these promote microbial activity in the rhizosphere. The concentration of these exudates can be 10-100 times higher than that of the adjacent soil. Exudates contain nutrients derived from plant roots, which deliver carbon and nitrogen to soil microorganisms. This results in a nutrient-rich environment that promotes microbial activity [57,38].

RHIZOFILTRATION:

Rhizo-filtration refers to the process by which microorganisms that reside in soil breakdown organic contaminants. The enhanced degradation of contaminants in the environment is mostly caused by the increased number and metabolic activity of microorganisms in the rhizosphere. Plants emit compounds abundant in carbohydrates, amino acids, and flavonoids, all of which stimulate microbial activity in the rhizosphere. These exudates can have a concentration 10–100 times higher than that of the surrounding soil. The exudates, containing nutrients generated by plant roots provide carbon and nitrogen to soil microbes, creating a nutrient-rich environment that stimulates microbial activity [57,38]. Based on the research conducted by [58], it has been determined that Zea mays have a greater potential to absorb and accumulate mercury. The efficacy of two rhizofiltration species—Phragmites australis and Kyllinga nemoralis—in eliminating heavy metals from municipal wastewater was assessed after they were planted in a sewage treatment plant in KwaZulu-Natal, South Africa.

Table 3. MODERN APPROACHES OF HEAVY METAL REMEDIATION

Technique	Characteristics	References
1. Genetically engineered	**Transgenic plants** for remediation: Engineering plants with new genes allows them to tolerate better and accumulate pollutants, making them more effective in phytoremediation. **Engineered PGPR**: Research suggests genetically modified plant growth-promoting rhizobacteria can also play a significant role in breaking down organic pollutants. **Limitations of hyperaccumulators**: While naturally good at accumulating pollutants, hyperaccumulator plants often have limitations in phytoremediation, such as slow growth or low biomass. **Genetic engineering for improvement**: Introducing specific genes from other plants has shown promise in improving hyperaccumulators. For example: The SbMT-2 gene from Salicornia brachiata boosts tobacco plants' resistance to heavy metals such as copper, zinc, and cadmium. **OsMTP1 gene**: This gene from rice increased tobacco plant tolerance to cadmium, suggesting a role in cadmium resistance. It emphasizes the	[51,55,59].

	potential of genetic engineering to create more powerful tools for cleaning up contaminated environments through phytoremediation.	
2. Biochar	Biochar is a cost-effective way to utilize carbon sources, potentially even turning waste materials into a valuable product. Biochar's porous nature allows for a huge surface area which is key to its functionality in many applications. This porosity allows it to interact with various substances and hold them within its structure. Biochar can lower the amount of heavy metals in contaminated soil. By storing carbon within its structure, biochar can help mitigate climate change. Biochar can improve soil fertility and water retention. The porous structure of biochar makes it potentially useful for water filtration applications. Incorporating biochar into soil can significantly reduce the amount of available heavy metals like cadmium, lead, copper, and zinc. The study by [59] found reductions of up to 52% for Cd. Tea waste-derived biochar is a promising addition to phytoremediation strategies, particularly for cadmium (Cd) contamination. This suggests using biochar specifically created from used tea leaves, offering a sustainable way to utilize waste material. Biochar helps plants tolerate the harmful effects of cadmium, potentially allowing them to take up more of the contaminant without suffering as much damage. By alleviating Cd toxicity, biochar can promote healthier plant growth in contaminated areas. Biochar appears to stimulate the growth of microorganisms that produce enzymes, which may further aid in breaking down or transforming the cadmium in the soil.	[60,61]
3. Microbial	**Microbes and heavy metals:** Microorganisms in the soil, both those living directly on plant roots	[47]

	and those free-living, can affect how much and what kind of heavy metals plants take up. **Mycorrhizal fungi:** These fungi are the leading group of organisms in the root zone, forming symbiotic interactions with the majority of land plants. There are several varieties of mycorrhizal fungus, but the most prevalent are arbuscular mycorrhizal (AM) fungi. **Benefits of AM fungi for plants:** These fungi create a mutually beneficial partnership with plants. Their extensive network of hyphae (filaments) helps plants access essential nutrients like nitrogen, phosphorus, potassium, calcium, sulfur, zinc, cobalt, nickel, and copper. Mycorrhizal fungi can play a crucial role in phytoremediation by improving plant access to essential nutrients, AM fungi can potentially influence how much and what type of heavy metals plants take. A healthy plant with good access to nutrients is often better equipped to handle environmental stresses, including those caused by heavy metals.	
4. Soil washing	Soil washing is a well-established method for remediating soil contaminated with heavy metals. Soil washing involves removing the contaminated soil and then using a liquid solution (extractant) with specific properties to leach (dissolve and remove) the heavy metals. The choice of extractant is crucial and depends on the specific type of metal and soil characteristics. Soil washing offers an alternative to traditional cleanup methods and can be a more targeted approach for removing specific contaminants. The use of various reagents and extractants requires careful handling and proper disposal of the resulting wastewater. Soil washing may not be appropriate for all pollutants or soil compositions. The soil may require pre-treatment to achieve optimal results during the washing process. Reagents for mobilizing and removing heavy metals from soil include synthetic chelating compounds, organic acids, humic substances, surfactants, and cyclodextrins. These reagents	[62,63]

	work in various ways to detach metals from soil particles and make them more soluble, allowing for their removal or easier uptake by plants. Type of reagent functions: **Synthetic chelating agents (EDTA, EDDS):** These are lab-created molecules that can tightly bind to metal ions and expand more They essentially grab onto the metals and hold them in a soluble complex, facilitating their removal from the soil. **Organic acids (e.g., citric acid, malic acid):** These naturally occurring acids can lower the soil's pH and disrupt the bonds between metals and soil particles. This can make the metals more available for extraction. **Humic substances:** These complex organic molecules found in soil can bind to metals Depending on the specific type of humic substance and the metal involved, this binding can either immobilize the metal (reducing its availability) or make it more mobile. **Surfactants:** These molecules can act like detergents in the soil. They can reduce the surface tension of water, allowing it to better penetrate soil pores and come into contact with the metals. Additionally, some surfactants can bind to metals and enhance their mobility. **Cyclodextrins:** These cyclic sugar molecules have a unique structure with a hydrophobic center and a hydrophilic exterior expand more They can trap metal ions within their cavity, making them more soluble and easier to remove from the soil.	

5. Combined remediation	Combining multiple remediation techniques is a powerful strategy for tackling complex heavy metal pollution in sediments. **Challenges of single methods:** Due to the complexity of sediment contamination, relying on a single remediation approach is often ineffective. • **Combined remediation:** Using two or more techniques together can leverage their strengths and address the limitations of individual methods, leading to a more comprehensive and efficient cleanup process. **Physical-chemical remediation:** This group includes techniques that combine physical methods (e.g., electrokinetics) with chemical methods (e.g., acidification, adsorption). These methods are known for their high efficiency but can also be expensive. Here are some examples provided: • Remediation methods include electrokinetic acidification, flocculation, adsorption, ion exchange membranes, and permeable reactive barriers, as well as chemical leaching.Ultrasonic/microwave-chemical combination. Chemical-biological cleanup, phyto-microbial remediation, and other collective remediation are mentioned as other categories of combined remediation approaches. By combining different remediation techniques, we can potentially: • Address a broader variety of pollutants and complexities within the sediment. • Improve remediation efficiency and cost-effectiveness.	[63,64]

	• Reduce the environmental footprint of the remediation effort. Overall, integrated remediation is a promising technique to addressing heavy metal pollution in sediments.	

CONCLUSION AND FUTURE ASPECTS:

Green manures have proven to be effective in phytoremediation have demonstrated the capacity for uptake of pollutants in soil that contain heavy metals. Plants like sunflowers, Indian mustard, and alfalfa have shown particular effectiveness in accumulating metals like lead, cadmium, and arsenic. Beyond metal uptake, green manures also enhance soil health by boosting organic matter levels and enhancing soil structure to improve soil health and foster microbial activity. This leads to overall soil remediation and revitalization. This review focuses on heavy metal remediation through the use of green manures and hyperaccumulator plants to treat the soil. Various traditional approaches of phytoremediation, such as phytoremediation and soil replacement, green manures offer a sustainable, cost-effective, and environmentally friendly alternative. These methods need minimal external inputs and can be on a large scale with relatively low maintenance. However, several factors can influence the efficacy of green manures, including soil pH, metal speciation, plant species, and environmental circumstances.

Future research is necessary to determine and make the optimal use of specific plant species for varied soil conditions and heavy metal contamination kinds. Investigating genetically altering plants to improve their ability to absorb and tolerate metals is one aspect of this. Additionally, investigating the integration of green manures into agroecosystems or landscape designs can provide holistic solutions for both remediation and sustainable agriculture. This involves understanding plant-soil interactions, biodiversity, implications, and long-term ecosystem dynamics. Studying the bioavailability and fate of metals post-phytoremediation is crucial to assess the potential risks of metal re-release into the environment. Scaling up green manure-based remediation strategies from laboratory or small-scale trials to field applications requires addressing logistical challenges, economic viability, and stakeholder engagement. Developing supportive policies and regulations that incentivize the adoption of green manure-based remediation approaches is essential and public awareness of the benefits of sustainable remediation practices.

Disclaimer (Artificial intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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