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Remediation of heavy metals contamination in soil under global climate change situation: A review

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Abstract
In today's era there is a necessity to study the impact of climate change, particularly global warming, and its accompanying extreme events on soil pollution caused by heavy metal contamination, their mobility in soils, and potential remedies. Furthermore, with increasing concerns about soil health and the safety of agricultural products, heavy metal pollution in soil has become a significant global environmental challenge. Heavy metals, including cadmium, mercury, arsenic, lead, and chromium, possess biological toxicity and enter the soil ecosystem through both human activities and natural processes. This pollution poses a serious threat to all living organisms, including humans, due to the risk of accumulation in the food chain. In response to this challenge, resilient phytoremediation has emerged as a sustainable alternative to conventional methods, owing to its affordability, environmental friendliness, and visual appeal, it has been determined that more than 500 taxa are hyper accumulators of one or more metals due to their innate capacity to remove them from the soil. However, further study is required to improve plant tolerance and reduce the build-up of harmful heavy metals in soils. However, additional research combining biotechnological approaches with comprehensive multidisciplinary studies is required to enhance plant tolerance and decrease the accumulation of hazardous metals in soils. This review explores the sources of heavy metals, their behaviour in soil ecosystems under the influence of global climate change, and environmentally friendly remediation methods for removing heavy metals from soil.

Keywords: Heavy metal, climate change, resilient phytoremediation

Introduction

The influence of climate change, notably global warming and associated extreme weather events, on soil pollution and the dynamics of heavy metals within soil ecosystems is a vastly neglected subject. While there's widespread acknowledgment of climate change impacting various environmental facets, its direct consequences on soil contamination and metal mobility have been largely overlooked. Soil contamination is a global concern, exacerbated by the rapid expansion of agriculture and industry, along with disruptions to natural ecosystems due to population growth (Sarwar *et al.*, 2016) [86].

Rising soil and air temperatures are brought on by global warming, which also intensifies and increases the frequency of extreme weather events including hurricanes, wildfires, floods, and heavy rains. These occurrences have a role in soil erosion, which causes heavy metals or metalloids to be redistributed. By raising atmospheric chemical loads, which can result in acid rain and the remobilization of metals, wildfires worsen this problem. According to Balbus *et al.*, (2013) [20], floods also contribute to the dispersion of metal(Loid) s from mining and industrial sectors into residential and agricultural areas. Furthermore, metals like lead are more readily mobilised due to the Arctic's rapid melting, which causes metals to accumulate in both marine and land species (Balbus *et al.*, 2013) [20]. Rainfall increases the likelihood of pollutants spreading laterally over greater

According to the 2015 United Nations Climate Change Conference, COP 21 or CMP 11, Paris agreement, the estimated increases in global surface temperature by the end of this century range from 2 °C to 4 °C (assuming significant measures to reduce greenhouse gas emissions are not implemented) (Barros *et al.*, 2014; IPCC, 2014) [11, 49]. In addition to changing ice and snow patterns in high-latitude areas, this temperature rise will have an effect on the physical and geochemical characteristics of the soil contaminant-groundwater system (e.g., Augustsson *et al*., 2011) [6]. In addition, an increase in the mean annual precipitation is anticipated in the Arctic and many temperate regions.

Many polluted sites are located close to watercourses because of the concentration of past industrial operations and the current high population densities around rivers and coastal areas. The dangers of exposure and contamination are greatly increased by this proximity (Destouni *et al*., 2010; Persson *et al*., 2011; Andersson *et al*., 2014) [23, 73, 4]. In addition, hazardous, persistent materials such as heavy metals have had detrimental effects on river mouths and coastal zones (Newton *et al*., 2012) [69]. These materials can build up in sediments (Abrahim and Parker, 2008; Jaishankar *et al*., 2014; Naser, 2013; Pietron *et al*., 2018) [2, 50, 68, 74]. It is critical to reduce the amount of contaminants that enter groundwater from soil and the downstream dispersal of those contaminants in order to reduce exposure concerns. As such, the identification, evaluation, and development of comprehensive, all-encompassing, regional, and national remediation methods is necessary (Schiedek *et al*., 2007; Naser, 2013; Karthe *et al*., 2017; Thorslund *et al*., 2017) [87, 68, 56, 99].

Concept of Heavy metals/metalloid

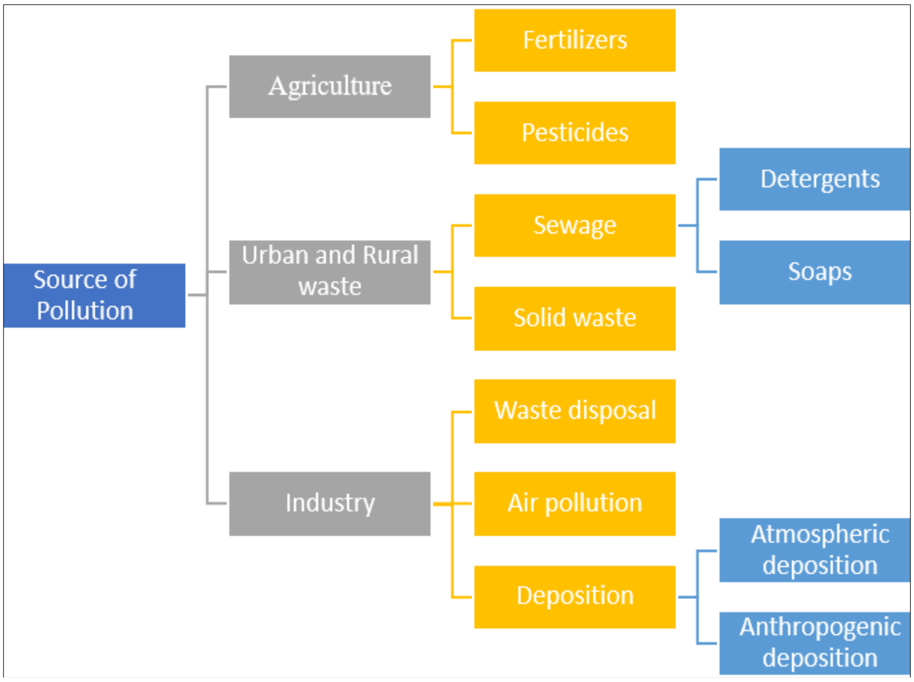
According to chemistry, heavy metals are periodic table elements with an atomic number more than 20 and a specific gravity higher than 5 gm/cc. Mercury (Hg), copper (Cu), arsenic (As), chromium (Cr), nickel (Ni), zinc (Zn), cadmium (Cd), and arsenic (As) are a few examples. In terms of biology, "heavy" refers to a class of metals, occasionally metalloids that can be hazardous to plants and animals even at low concentrations (Rascio & Navariizzo, 2011) [77].

Heavy metal pollution, on the other hand, is persistent, irrevocable, and deceptive. By building up in the food chain, it endangers not only the health and welfare of humans and other living things but also the quality of water bodies, the atmosphere, and food crops (Kankia and Abdulhamid, 2014) [54].

Different sources of soil contamination with heavy metals

In addition to being produced in the environment as results of human activity, heavy metals come from natural sources as parent rocks. 1. The movement of heavy metals from mines to various environmental site; 2. Increased production rates due to human activity over natural cycles; 3. The transformation of various forms of heavy metals into more bioavailable forms in the environmental system; 4 and high concentrations of metals and metalloids in waste products relative to the receiving environment are some of the pathways through which soil becomes contaminated with heavy metals (Duruibe *et al*., 2007; Lianwen *et al*., 2018) [27, 61].

The main industries causing heavy metal pollution in the air, groundwater, and soil are mining and manufacturing. The problem of heavy metal contamination is further exacerbated by urbanisation and industrialization. These factors include the discharge of different exhaust gases, sewage irrigation, industrial waste, and the application of sludge to farms (Chandrasekaran *et al*., 2015; Huang *et al*., 2016; Rezania *et al*., 2016; Wan *et al*., 2016; Karakagh *et al*., 2012) [18, 45, 79, 103, 55]. The process of industrialization leads to the degradation of soil by contaminating rivers, releasing effluents directly into sewage systems, or releasing them outside of urban areas. The atmospheric deposition of heavy metals from fuel combustion, waste from industries like textile and dyeing, electroplating waste, cycles and spare parts, smelting and mining processes, metal coating, sewage sludge, and the use of chemical fertilisers are some of the causes of heavy metal deposition in the environment (Zeng *et al*., 2017) [112]. In agricultural soil, the presence of heavy metals is influenced by factors such as the composition of parent rock material, aerosol particles from fossil fuel combustion, landfilling, application of organic materials, and contaminants in fertilizers and other sources (Bolan *et al*., 2014) [15]. Several common causes contribute to the deposition of heavy metals in the environment.



Pollution caused by anthropogenic sources
It is both natural processes and human activity that release heavy metals into the atmosphere. They naturally arise in soil as a result of paedogenic processes that weather parent rocks. But in the last few decades, human activities like mining, smelting, car exhaust, and lead-based paint use have increased the amount of heavy metals like lead that are released into the atmosphere, surpassing the natural release of these metals from parent rocks (Miralles *et al*., 2006) [66]. In a similar vein, waste products from the lead and zinc refining operations release metals like cadmium, while the degassing of the earth's crust releases mercury (Sumiahadi and Acar, 2018) [98]. Heavy metals can find their way into the environment through a number of different channels, such as leaded petrol consumption, fertilizer application, waste from livestock, coal combustion, landfills, and atmospheric deposition from metal mines.

Mining operations
The main causes of heavy metal emissions are human-induced, especially mining operations; even after mining operations stop, metals continue to exist in the environment (Nriagu, 1989) [70]. One major cause of water pollution is mining activity (INECAR, 2000) [48]. Emissions of heavy metals can come from elemental, inorganic, and organic molecules, among other sources. When mined ores are disposed of manually during dressing procedures, there is an increased chance of heavy metal contamination (Huan *et al*., 2017) [44].

Use of fertilizers
First and foremost, through agriculture, humans affect the soil. For growth and the completion of their life cycle, plants need both macronutrients and micronutrients. Plants are nourished with vital elements which can be in short supply in the soil by either foliar spraying or applying them directly to the soil (Dhaliwal *et al*., 2019; Dhaliwal *et al*., 2013) [24, 114]. In order to supply enough nitrogen, phosphorous, and potassium for crop growth, a substantial amount of fertilizers is applied to soils during extensive and intensive farming (Huan *et al*., 2017; Dhaliwal *et al*., 2019) [44, 24]. On the other hand, according to Duruibe *et al*., (2007) [27], using some phosphorus-containing fertilizers unintentionally adds lead, mercury, and fluorine to the soil.

Pesticides application
Historically, many pesticides used in agriculture were rich in heavy metals, and currently, about 10% of UK-approved fungicides and insecticides contain metals like lead, mercury, and copper, including products such as copper oxychloride and Bordeaux mixture (Ghnaya *et al*., 2009; Goswami and Das, 2015) [36, 38]. Previously, lead arsenate-controlled pests in orchards, while today, compounds with arsenic, chromium, and copper are used for timber preservation at many sites, potentially complicating future agricultural use of these lands (Huang *et al*., 2016; Jinadasa *et al*., 2016) [45, 52].

Biosolids and manures
Organic remains left behind resulting from wastewater treatment treatments are known as biosolids, and they are frequently recycled for mutual benefit. Reusing biosolids from urban populations is made possible by the common practice of applying biosolid materials to agricultural land in many nations. However, heavy metals are unintentionally introduced into the soil environment when different biosolids, like manures, compost, and municipal sewage sludge, are applied to the soil (Ghnaya *et al*., 2009) [36]. Although manure is acknowledged as a significant fertilizer, adding copper (Cu) and zinc (Zn) to diets in pig and poultry husbandry as growth boosters can have negative health effects (Lianwen *et al*., 2018) [61].

Pollution through atmospheric deposition
In terms of heavy metal contamination, industrial processes like burning coal and petroleum leave a lasting impression on soils. Over time, heavy metals like nickel, zinc, lead, and copper are released at rates higher than they would naturally occur (Boyd, 2004) [16]. It has been recognised that pollution brought on by atmospheric activity poses a risk to a great number of lives, especially in industrialised areas of the northern hemisphere (Shotyk *et al*., 2003) [92].

Table 1: Sources of various heavy metal contaminations in the environment. (Lone *et al*., 2008) [63]

Heavy metals	Sources
Cd	Geological origins, human activities, metal refining and smelting, burning fossil fuels, phosphate fertilizer application, and sewage sludge
As	Wood preservatives, semiconductors, mining and smelting, coal-fired power plants, herbicides, volcanoes, petroleum refining, and additives for animal feed
Pb	Metalliferous ore mining and smelting, burning of gasoline, sewage from towns, Pb-enriched industrial waste and paints
Cr	Tanneries, sludge, solid waste, and the electroplating industry
Hg	Volcanic eruptions, wildfires, emissions from the caustic soda-producing industry, burning of wood, and peat
Cu	Electroplating industry, mining, biosolids, smelting and refining
Ni	The weathering of soils and geological materials, industrial effluents, kitchen appliances, surgical tools, steel alloys, automotive batteries, land fill, forest fires, bubble bursts, gas exchange in the ocean, and so on.
Zn	Mining, biosolids, smelting and refining, and the electroplating industry

According to Mielke *et al*., (2005) [65], lead and boron are ubiquitous markers of anthropogenic pollutants in the environment and in healthcare. Power stations, smelting facilities, vehicle emissions, and natural sources like volcanoes and hydrothermal vents are the main sources of lead emissions (Weiqing *et al*., 2016) [107]. The atmospheric concentration of boron ranges from 0.2 to 300 parts per billion (ppb). The element is present in both gaseous and particulate forms, with the gaseous phase accounting for more than 90–95% of the total quantity (Rose *et al*., 2000) [83].

Metals such as arsenic, lead, and cadmium are released as volatile particles during high-temperature processing and thereafter become fine particulates in the form of oxides (Duruibe *et al*., 2007) [27]. When dry or wet precipitation processes remove stack emissions from the gaseous stream, they can be distributed over a large region by wind. However, because they are discharged close to ground level, fugitive emissions are usually distributed across smaller areas.

The kinds of sources and site-specific factors affect the concentration of metals released. It has been shown that lead (Pb), zinc (Zn), and cadmium (Cd) concentrations are often high in plants and soils close to smelting factories. Furthermore, burning petrol releases lead into the atmosphere, where it ends up in the soil of cities and the surrounding areas. According to Huang *et al*., (2016) [45] and Jinadasa *et al*., (2016) [52], the tyre and lubricating oil industries also contribute zinc (Zn) and cadmium (Cd) to the soil.

Pollution caused through contaminated water

Although wastewater irrigation has been shown to lower soil pH, raise organic carbon content, and improve soil conductivity, it also accumulates heavy metals in the farmland's ploughing layer. Studies have found that soils treated with wastewater sewage sludge on a regular basis have higher amounts of hazardous metals (Azad *et al*., 1986; Sharma and Dhaliwal, 2019) [8, 89]. When compared to well-irrigated soils with pipes, land irrigated with wastewater had significantly greater quantities of Pb, Cr, Cd, and Ni extractable with DTPA and total digestable, namely 1.8, 35.5, 3.6, and 14.3 (Dheri *et al*., 2007) [25].

Table 2: Indian Standards of heavy metals in soil, food and drinking water (Source: Awasthi, 2000)

Heavy metals	Soil (ug/L)	Food (mg/kg)	Water (mg/L)
Cd	3-6	1.5	0.01
Cr	-	20	0.05
Cu	135-270	30	0.05
Fe	-	-	0.03
Ni	75-150	1.5	-
Pb	250-500	2.5	0.1
Zn	300-600	50.0	5.0
As	-	1.1	0.05
Mn	-	-	0.1

Threshold limit of heavy metals

It is nothing but the maximum permissible limit of heavy metals in soil, food or groundwater that can be safe for consumption. But beyond this threshold level consumption becomes unsafe.

Remediation of heavy metal polluted soils

The primary goals of new environmental policies and initiatives are soil protection, prevention, and remediation. While soil is an important and non-renewable ecological system, human endeavours has always degraded it extensively. Point source and diffuse contaminants in soil pose the greatest risks. Heavy metal contamination in soil must be remedied in order to safeguard the environment, restore soil fertility, comply with regulations, and maximise land use choices. Various techniques and approaches have been used to address soil contamination; however, remediation technologies can generally be divided into two main categories: 1. In-situ remediation, 2. Ex-situ remediation (Gomes *et al*., 2013) [37].

1. **In-situ remediation:** It involves the treatment of the pollutant in the original place, without moving the contaminated soil itself.
2. **Ex-situ remediation:** It involves excavation and removal of the polluted soil elsewhere for treatment.

In-situ remediation presents a number of possible technical, financial, and environmental benefits when compared to ex-situ remediation (Song *et al*., 2017) [95]. However, the characteristics of the site, the types of pollutants to be removed, the concentration of the contaminants, and the intended use of the contaminated medium all play a role in choosing the best soil remediation technique (Mulligan *et al*., 2001) [61]. Remediation can be carried out by physical, chemical, and biological methods.

Why there is a need for sustainable remediation of heavy metal polluted soils under climate change scenario?

Contaminated soils are now treated or remedied using a variety of techniques. However, because the primary goal of many traditional technologies (Physical, chemical, and thermal) is to remove contamination without taking into account any potential side effects, they are currently viewed as outdated. Furthermore, it has been demonstrated that these methods are exceedingly costly in terms of energy and economy, as well as highly invasive, which exacerbates the already precarious environmental conditions (Song *et al*., 2019, Voccinate *et al*., 2021) [96, 102]. The main concern herein is how the behaviour of contaminants is affected by global change. Contaminated sites are not just affected by their location. Temperature, winds, precipitation, currents, and snow cover are examples of climate variables that can change. These variables can also affect how contaminants behave, including their bioavailability, toxicity, transport, transfer, deposition, and fate, as well as the potential inhabitants' migration and distribution (Maco *et al*., 2018) [64].

In recent times, industrialised nations' environmental policies have undergone modifications with an aim to evaluate remediation through precise risk calculations. In order to address the issue of soil contamination, the Environmental Protection Agency (EPA) developed the concept of "Green Remediation" (GR), which applies remediation methods to the sustainable recovery of polluted sites (EPA-2008, 2009; GSR-2009; Pedron and Petruzzelli, 2011) [72]. This new approach combines innovative ideas to create answers and methods that satisfy remedial as well as sustainable development requirements. However, more environmentally sound remediation techniques for contaminated soils are required in order to solve the emerging environmental issues such as food scarcity, global warming, and natural disasters and effective countermeasures must be implemented to lessen the impact of extreme events, which are happening more frequently and intensely. These occurrences include heatwaves, floods, droughts, water shortages, forest fires, typhoons, and tornadoes. This issue may be resolved using a remediation strategy that is resilient and sustainable.

Resilient Phytoremediation: Sustainable Approach of Heavy Metals Remediation

In Green Sustainable Remediation (GSR) projects, bioremediation and phytoremediation stand out as key strategies. Bioremediation primarily employs microorganisms to cleanse contaminated soil, providing an affordable and sustainable way to repair ecosystems impacted by heavy metals. Compared to traditional chemical and physical treatments, which can be costly, inefficient for low metal concentrations, and result in toxic sludge, this approach is very favourable. When treating Pb-contaminated soil, bioremediation proved to be 50–65% less expensive than traditional techniques like excavation and landfilling, according to Blaylock *et al*. (1997) [14].

Phytoremediation: It first appeared as a green method for cleaning up heavy metal-polluted soils in the late 1900s. Due to its ecological (Self-sustaining, solar-powered, non-invasive), economical (Low expenses), and social advantages, it was well accepted by policymakers, stakeholders, and remediation experts. This technique employs living plants to absorb or adsorb contaminants, thereby reducing their risk or eliminating them. Phytostabilization, phytovolatilization, phytoextraction, rhizofiltration, rhizodegradation, and phytodesalinization are the key types of phytoremediation (Shen and Chen, 2000) [90].

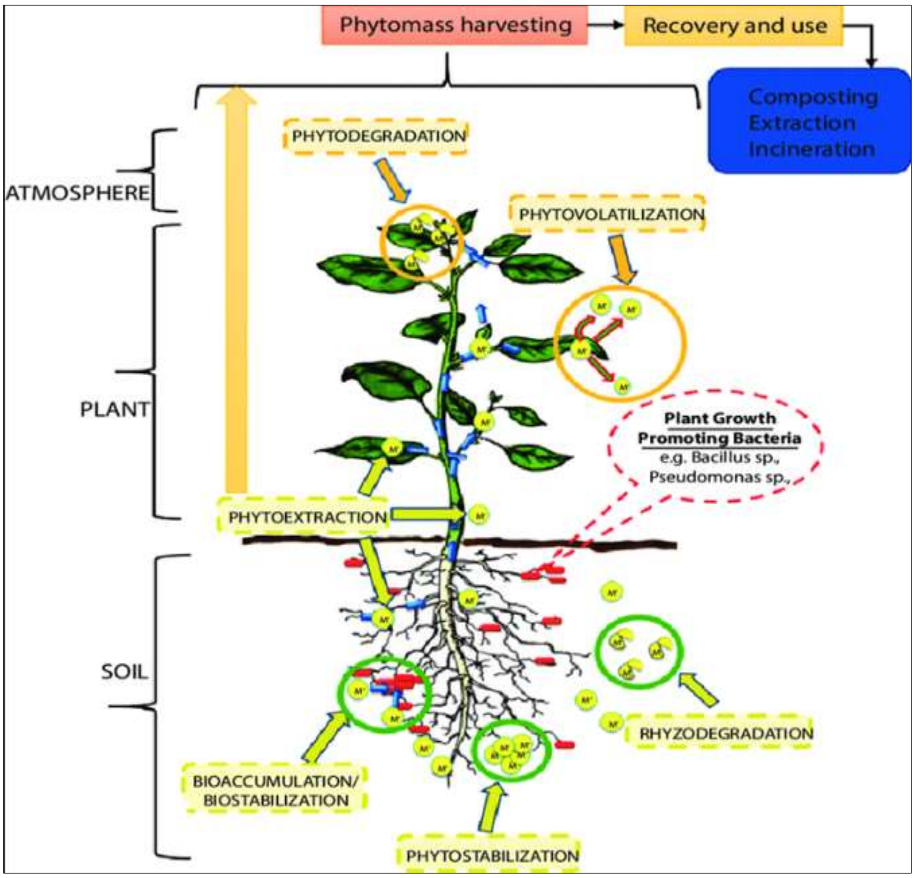


Fig 1: Phytoremediation technique for cleaning up heavy metal-contaminated soils and choices for managing the final product associated with the phyto extraction processes (Updated upon Rosca *et al*., 2017) [81].

Phytostabilization: In order to decrease the mobility and bioavailability of heavy metals and stop them from entering the groundwater and food chain, plants fix them via root adsorption, precipitation, and reduction. It does this by immobilising the heavy metals and prevents wind or runoff from dispersing them, therefore preserving the health of the soil at heavy metal contaminated areas. The removal of contaminated biomass is not necessary for phytostabilization, in contrast to phytoextraction (Arantza *et al*., 2022) [5]. The selection of appropriate plant species with deep root systems that can generate a sizable amount of biomass and tolerance to heavy metal environments is necessary for effective phytostabilization. Organic or inorganic materials added to the soil can modify metal speciation, decrease solubility and bioavailability, and enhance the physical, chemical, and biological characteristics of the soil. According to Burgess *et al.* (2018) [17], these additions improve the soil's organic matter content, necessary nutrient levels, plant colonisation, and water-holding capacity.

Phytovolatilization includes either the adsorption or conversion of heavy metals into gaseous matter by the use of specialised chemicals secreted by roots, or the transfer of heavy metals into a volatile form (Watanabe, 1997) [106]. Using a plant promoter, Bizily *et al*., (1999) [13] mutated the bacterial gene merBpe, which codes for organomercurial lyase (MerB), and expressed it in *Arabidopsis* thaliana to evaluate the plant's capacity for extracting and detoxifying mercury. In order to release Hg (II), a less mobile form of mercury, MerB catalysed the protonolysis of the carbon-mercury bond. Whereas plants devoid of the merBpe gene showed significant inhibition or died at comparable organomercurial concentrations, transgenic plants expressing merBpe grew vigorously over a broad range of monomethylmercuric chloride and phenylmercuric acetate concentrations. According to this study, native macrophytes (Trees, shrubs, and grasses) that have undergone genetic modification to express merBpe may be employed to degrade methylmercury in contaminated areas and store Hg (II) for eventual removal.

Phytoextraction involves the transport and storage of heavy metals in the aboveground portions of plants that are tolerant and accumulating. Evaluating the adsorption properties of various plants and determining which have high absorption capacity is essential to the success of this technique. The following qualities are suitable for high uptake plants, according to U.S. Department of Energy guidelines: 1) Significant ability to accumulate metals at low contaminant concentrations; 2) High concentrations of contaminants can be accumulated; 3) Different heavy metals can be accumulated; 4) Rapid growth with significant biomass production; 5) Resistance to pests and diseases (Wang and Wen, 2001) [105].

Rhizofiltration: It shows potential as a way to purify liquid waste and water, and different plant species have demonstrated efficacy in this regard. Contaminants such as methyl parathion, uranium, cesium, and copper are effectively removed by plants like Typha latifolia, Phaseolus vulgaris, Arundo donax, and aquatic species like Eichhornia crassipes, Salvinia molesta, and Pistia stratiotes (Guarino *et al*., 2020) [40]. Utilising plants with large surface surfaces and fibrous roots, rhizofiltration provides an economical and environmentally beneficial restoration method. However, compared to chemical treatments or excavation procedures, obtaining a significant reduction in pollutant levels might take longer (Yan *et al*., 2020) [108].

Rhizodegradation: Through the interaction of plant roots, bacteria, and contaminants, it provides an economical and natural method of remediating contaminated soils (Latif *et al*., 2023) [59]. It uses the bacteria found in the root zone of plants to break down toxins in the soil in the rhizosphere, an area of the soil with high microbial activity. Plant selection is critical as different species release varying exudates that shape microbial communities and their ability to degrade pollutants. Rhizodegradation has several advantages over traditional approaches, including low cost, a lower impact on the environment, and possible long-term effectiveness (Cristaldi *et al*., 2017) [22]. However, its effectiveness depends on factors such as soil contaminants, plant types, and environmental conditions. Optimal plant and microbe combinations are essential for successful remediation, considering their diverse pollutant degradation capabilities and adaptability to varying conditions (Ely and Smets, 2017) [29].

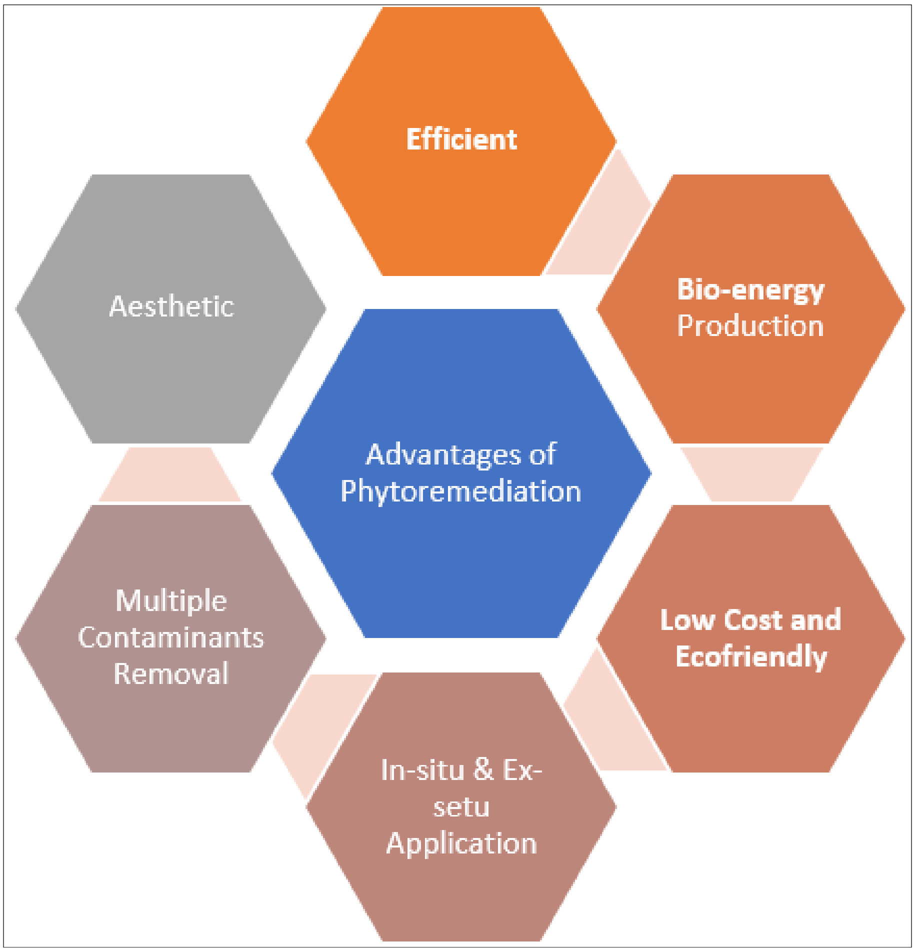


Fig 2: Advantages of phytoremediation

Microbial remediation

Although microorganisms are unable to directly break down or eradicate heavy metals, they can affect their movement and transformation through changes to their chemical and physical properties. The bioremediation process involves a variety of living creatures, such as worms, insects, bacteria, fungi, algae, and enzymes. The mechanisms involved in remediation include intracellular accumulation, oxidation-reduction reactions, precipitation, and extracellular complexation. A simple and efficient method for removing precious metals from low-grade ores and mineral concentrates is microbial leaching. In addition to being used in industry as a source of raw materials, microbial leaching has the ability to clean up mining sites, treat industrial waste products made of minerals, detoxify sewage sludge, and clean up heavy metal-contaminated soils and sediments.

Pseudomonas putida (Balamurugan *et al.*, 2014) [9], Bacillus subtilis (Imam *et al*., 2016) [47], and Sporosarcina ginsengisoli (Achal *et al*., 2012) [3] are a few examples of such microorganisms that have been researched and effectively used in bioremediation treatments for heavy metals. Instead of using a single strain culture, a consortium of bacterial strains is frequently used for successful bioremediation by microorganisms. The synergistic impact of bacterial mixes (Such as E. cloacae KJ-47, Sporosarcina soli B-22, Viridibacillus arenosi B-21, and Enterobacter cloacae KJ-46) on the bioremediation of an amalgam of Cd, Cu, and Pb from polluted soils was studied by Kang *et al*., (2016) [53]. When compared to single-strain cultures, they discovered that bacterial combinations had higher resistance and remediation efficacy against heavy metals.

Microorganisms employ a variety of mechanisms for eliminating heavy metals from polluted soils, such as precipitation, biosorption through metal-binding peptide sequestration within cells, and enzyme-mediated metal conversion to safe forms (Ojuederie & Babalola, 2017) [71]. Polluted soil can be cleansed up quicker and more efficiently by combining microbes and plants (Vangronsveld *et al*., 2009) [100]. Mycorrhizal fungi are being utilised extensively in the remediation of heavy metal-polluted soils. Research has shown that mycorrhizae can use a variety of strategies to influence the rhizosphere's trace metal transformation, including hyphal sequestration, chemical precipitation of metals, and the acidification, immobilisation, and modification of root exudates (Hristozkova *et al*., 2017) [43]. It is possible to extract native populations of metal-tolerant arbuscular mycorrhizal fungi from contaminated soils, and these populations are more resilient to metal toxicity than those isolated from uncontaminated soils (Cornejo *et al*., 2013) [20]. According to Bhalerao (2013) [12], extracting naturally occurring and presumably adapted arbuscular mycorrhizal fungi is a better option for phytostabilization than using lab strains, and it may even be a useful biotechnological tool for successfully repairing damaged ecosystems.

Plant growth-promoting rhizobacteria (PGPRs): In order to increase the effectiveness of remediation technologies, plant growth-promoting rhizobacteria, or PGPRs, are widely used in aided phytoremediation techniques (Franchi and Fusini, 2021; Franchi *et al*., 2019) [34, 33]. Furthermore, they provide a viable approach to increase plant resistance to climate change. By reducing abiotic stresses brought on by excessive salinity, drought, alkalinity, and high temperatures, PGPRs act at the rhizosphere level, improving plant health and environmental adaption. Their use as microbial inoculants in phytoremediation aims to increase plant absorption of metals and increase biomass output in a sustainable manner (Franchi *et al*., 2019; Prakash *et al*., 2021) [33-34]. PGPRs are essential because they improve plants' capacity to fend off the damaging impacts of abiotic stressors (Enebe and Babalola, 2018; Shah *et al*., 2021) [30, 88]. Because of their diverse metabolic activities, PGPRs can control how nutrients are absorbed by plants by modifying their structure and morphology at the root level in response to certain molecules (Such extracellular polymers, antioxidants, and phytohormones) generated during stressful situations. PGPRs can alleviate water stress inhibition in plant development under saline stress by enhancing nitrogen fixation, solubilizing inorganic phosphorus and other necessary elements, or forming hydrating biofilms (Franchi and Fusini, 2021; Dimpka *et al*., 2009) [34, 26]. Consequently, by limiting erosion, PGPRs greatly aid in soil stabilisation and promote the growth of a robust, well-branched root system.

Current efforts are directed at creating metal hyperaccumulator plants resistant to climate change through molecular methods. This entails using genome editing to introduce genes expressing stress-tolerance proteins into plants. Thus, under shifting stress conditions, transgenic plants with increased stress resilience can aid in phytoremediation. Furthermore, studies are being conducted to develop metal hyperaccumulators that can endure high-temperature stress through non-transgenic molecular manipulation of particular genes (by addition or deletion. (Sanz-Fernández *et al*., 2017) [84].

Recent advances in sustainable removal of heavy metals:

Biocatalyst: Strong biological agents capable of chemically changing both organic and inorganic substances are known as biocatalysts. Microbes' secreted enzymes and entire microbial cells act as environmentally friendly biocatalysts that remove heavy metals from contaminated areas. It has been observed that microbial enzymes catalyse the biocarbonation of heavy metals. In particular, urea is broken down by the urease enzyme that microbes create into carbonates and ammonium ions. After that, during the process of biocarbonation, these carbonates combine with heavy metals to form insoluble complexes, which effectively lower the concentration of heavy metals in contaminated soil (Abdel-Gawwad *et al*., 2020) [1]. The microbial cell experiences stress as a result of the heavy metal carbonate complexes that surround them. The efficacy of bacterial urease in heavy metal removal varies depending on the strain. Additionally, without imposing stress on the soil microbiota, plant-derived urease enzyme (PDUE) facilitates the precipitation of heavy metals and the hydrolysis of urea, therefore aiding in the biocarbonation process (Zhao *et al*., 2019) [113].

Plant exopolysaccharides: They are complex assemblages of high molecular weight microbial homopolysaccharides and heteropolysaccharides, as well as other carbohydrates, proteins, and metallic ions including Fe, K, Mg, and Mn, make up plant exopolysaccharides. It has been discovered that microbial EPS detoxifies heavy metal-contaminated soil by means of a biosorption mechanism. EPS draw positively charged heavy metal ions to form complexes because of their negative charge. EPS have shown to be effective heavy metal scavengers, providing a number of advantages such as affordability, sustainability, and environmental friendliness (Singh *et al*., 2019) [93].

Microalgae: The key characteristic of microalgae is their demonstrated ability to grow in environments high in heavy metals and their role in the biosorption process in removing heavy metal pollution. The cell wall of microalgae has a unique complex structure, metal-binding proteins, and functional groups (Such as carboxyl or amino groups) that provide binding sites for heavy metal ions. Compared with traditional treatment methods, biosorption is a cheap, simple and environmentally friendly method that does not produce toxic byproducts or gases (Spain *et al*., 2021; Khan *et al*., 2021) [97, 57].

Apart from biosorption, microalgae are also highly proficient in the processes of bioaccumulation and biodegradation, which help with detoxification. Because of their diverse extracellular and intracellular mechanisms, microalgae are able to withstand the toxicity of heavy metals, making them an excellent choice for bioremediation activities at contaminated locations. Furthermore, it is acknowledged that microalgae are ecologically harmless, multipurpose organisms that may perform multiple functions at once, such as carbon reduction, bioremediation, and biofuel production (Kumar *et al*., 2015) [58].

Biosensors: The development and application of sensor-based era, focusing on sensitivity, reproducibility, portability, limit of detection, and accuracy, are critical for powerful environmental surveillance (Yantasee *et al*., 2007) [109]. Making use of artificial biology techniques, various sensors with distinct benefits have been advanced up to now. Those sensor systems offer great possibilities by using permitting fast, sensitive, and correct detection of heavy metals in a way that allows smooth interpretation. The improvement of optical, electrochemical, fluorescent, and nanoparticle sensors with multiplexed detection skills for heavy metals has propelled studies from conceptualization to realistic implementation.

Bioengineered char: Within the realm of mitigating heavy metal contaminants in soil, Biochar (BC) emerges as a tangible answer of tremendous effect. Biochar, a porous material enriched with black carbon, is derived from the pyrolysis or incomplete combustion of organic waste materials including agricultural waste, slaughter waste, and activated sludge in a confined oxygen supply (Reddy *et al*., 2014 and Gaur *et al*., 2021) [78, 35]. It has confirmed robust efficacy in heavy metal elimination, boasting versatile traits like excessive aromaticity, cost-effectiveness in manufacturing, eco-friendliness, thermal and mechanical stability, and the abundance of raw materials in nature (Wang *et al*., 2021 and Gupta *et al*., 2020) [104, 41].

Conclusion

In response to environmental challenges like climate change, natural disasters, and food security concerns, implementing innovative green remediation techniques, particularly resilient phytoremediation, offers a sustainable solution for treating soils contaminated with heavy metals. This approach aims to preserve soil quality, enhance environmental health, and ultimately boost soil productivity. By adopting resilient phytoremediation, we can address these challenges while promoting environmental, social, economic, and food security goals.

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