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Phytostabilization of contaminated soils

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Abstract

One of the major problems the world facing nowadays is soil contamination. The accumulation of the contaminants especially heavy metals is hazardous not only for soil but also contaminate water bodies and the agricultural crops that alters the healthy food chain. Therefore, an effective remediation strategy is crucial. Phytoremediation techniques are advantageous over conventional biological, physical & chemical remediation methods. Phytostabilization among them is an environmentally safe and sustainable way to reduce the effects of contaminated soils. The selection of appropriate plant considering different aspects such as growth, tolerance and site-specific adaptability is the key for successful phytostabilization. Understanding soil properties, weather conditions, the contaminants present, regular evaluations and ongoing monitoring is essential for the successful implementation of phytostabilization. The mechanisms involved are the absorption & accumulation of contaminants in roots, formation of a vegetative cover, changes in rhizosphere and hydraulic control which were affected by nature of contaminants, soil, plants employed and environmental conditions. Phytostabilization presents a practical approach to remediate contaminated soils, providing an economic and ecological substitute for conventional remediation techniques. This review highlights fundamental points and factors that must be considered for its successful implication, mechanisms involved and its potential as an ongoing solution for controlling polluted areas and advancing environmental health.

Keywords: Phytostabilization, remediation techniques, heavy metal contamination, hydraulic control

Full length review article *Corresponding Author, e-mail: sarayaqoob401@gmail.com

1. Introduction

Nowadays, soil contamination is a global concern that affects other naturally occurring ecosystems, human health, and the growing production of safe food. Soil pollution is found at almost 5 million places which are getting over 500 million hectares of land where soil is contaminated by heavy metals with concentration greater than the permitted level [1].Tanning, mining and smelting activities, fossil fuel burning, military & warfare training, industries, industrial effluents, waste disposal, agrochemical usage, irrigation, pesticides application and urban activities are the major causes of the soil contamination in the world [2]. Contaminants are classified into organic and inorganic types. Organic contaminants include methylene blue (a common dye compound) emitted by different paint, paper and textiles industries. Pesticides, polycyclic aromatic hydrocarbons, bisphenol A, phthalate esters, per-fluorinated compounds, organic flame retardants and some others are the major contaminants [3-5]. Inorganic contaminants include radionuclides and heavy metal ions in waste water [6]. Maximum level of contamination which can be allowed for different heavy metals are: 0.05 mg/l, 0.005 mg/l, 0.015 mg/l, 0.002 mg/l, 0.1 mg/1, 0.05 mg/l & 0.006 mg/l for Arsenic, Cadmium, Lead, Mercury, Chromium, Selenium and Antimony respectively [7]. Soil pollutants and the accumulation of these toxic metals in the soil have hazardous effects on environmental health, food quality and safe crop development which all indirectly leading to destroy the human life and other living beings [8-9]. In order to overcome the dreadful effects of contaminated soil, there is a great need to remediate the contaminated soil by applying best remediation techniques- requiring short time period, minimum cost and showing long term effectiveness. Therefore, it is important to make use of modern and site-specific remediation techniques which could practicably and expeditiously remediate the contaminated soils. Many remediation technologies have been developed over the last 20 years [10-11]. The primary goal of these technologies is to reduce the heavy metals /metalloid accumulation in the soil. Figure 1 shows different approaches for remediation of contaminated soils. Conventional technologies used for contaminated soil remediation were based on physical, chemical & biological means which can be applied together to reduce the contamination to allowable level and further their accumulation in food chain [12]. Although these techniques are very efficient but there are some drawbacks- these are costly, harmful to environment and more time consuming. Now phytoremediation- a cost friendly green technology in which plants are employed to remove, assimilate, metabolize or adsorb hazardous contaminants in soil, should be considered best because this technology is environmentally friendly, cost-effective and usually shows long term effectiveness [13].

Many applications and techniques come under the term "phytoremediation" which only differ in the way by which plants can reduce, degrade or immobilize the contaminants. For example, some plants are involved for the removal of organic or inorganic contaminants from soil or water and accumulate them in their harvestable tissues by a process called phytoextraction. In another technique called phytovolatilization, using plants, contaminants are removed by volatilization. While in a technique called phytostabilization plants are used to restrict the movement of heavy metals and their bioavailability in soil due to stabilization. This method doesn't remove the contaminants from the soil but restrict their off-site movement [14]. Phytostabilization restricts heavy metals to remain in the vadose region of plant by accumulating heavy metals by roots or precipitation within the rhizosphere. This helps to prevent offsite contamination which may be due to water erosion, wind, soil dispersion or leaching [15]. In the last few years, many studies proved that phytoremediation and nanotechnology combined are used as a working remediation technique for the treatment of heavy metals. This modern technology is helpful for treatment of toxic heavy metals in soil and much nanomaterial [16-17]. This review analyzes various techniques to remediate the contaminated soil and their comparison for best selection and application considering the cost, time, and their long-term effectiveness. It focuses on different phytoremediation approaches with major emphasis on processes involved in phytostabilization; its implementation; different factors affecting this technology; advantages and limitations and valuable prospects.

2. Assessment of heavy metal contamination in soil

Heavy metals (HMs) in soil are reported to present in three different forms. Some of them exist as organic complexes for example Hg^{+2}, Cu^{+2} and Pb^{+2} bonding with dissolved organic matter or as dissolved ions like Cu^{+2}, Cd^{+2}, $Cr_2O_7^{-2}$ and MnO_4^{-2}. Some as exchangeable ions adsorbed on solid particles of the soil e.g. Zn^{+2} and Ni^{+2} and in the form of co-precipitates part of the solid soil e.g. ZnS and $HgSO_4$ [18] . Different studies have exposed that it is the reactive proportion of heavy metals in soil that determines their toxicity towards humans, plants, and other organisms rather than their total concentration. The exchangeable and water-soluble forms of heavy metal ions are more reactive than the precipitated form of heavy metals [19]. The accumulation of these metals affects the quality of food as well as water and disturbs the functioning of the ecosystem. Several countries have measured the ambient background concentrations, or ABCs, of heavy metals in soil to evaluate the quality of the soil. ABCs are also referred to as geochemical baselines of HMs in soil. The geo-accumulation index was calculated by following formula to find the degree of contamination in soil by heavy metals [20]:

$$I_{geo} = \log_2\left(\frac{Ci}{1.5Bi}\right) \qquad (1)$$

Here Bi and Ci are the background concentration and the present concentration in mg/Kg of the element I in soil, respectively. On the basis of I_{geo} values contaminated soil is classified into 7 classes which are presented in table 1. [21]. Although the soil quality is checked by calculating ABCs values, but prevention is always best option for controlling soil pollution. Hence several remediation approaches are applied to get rid of these toxic heavy metals which are damaging urban and agricultural land [18].

2.1. Sources & Effect in environment

Naturally, heavy metals are found in the earth's crust, but due to various anthropogenic activities, they entered the soil and raised their concentration to toxic levels. These activities include smelting, mining, coal combustion, waste disposal, use of pesticides, and fertilizers [22-26]. Different researches revealed that anthropogenic activities are of much importance than natural sources of heavy metals in environment [27]. Cadmium, copper, lead, mercury, chromium, and zinc are very common heavy metal contaminants. Biological systems are very badly affected by heavy metal pollution because they are not biodegradable. But these heavy metals accumulate in the living beings and cause different diseases & even when they are in low concentration. Heavy metals which remain in the soil for thousands of years pose different health dangers to higher living beings. They affect plant growth, ground cover & soil microorganisms. As these metals do not degrade so thy must have to be removed or converted into some non-toxic form [28].

2.2. Food chain contamination and human health

Food and water are the key factors for the existence of life on earth. Therefore, we should pay attention to the issues that lead to contamination of our food and drinking water. Nowadays soil contamination due to heavy metals is a serious issue in the world [29-32]. Metal contamination in food is a very critical problem related to health risk especially in agriculture and aquatic ecosystem. Soil provides a direct path for heavy metals contamination in crops & vegetables through roots [33]. Vegetables and crops grown on such contaminated soil contaminate the plants. As animals eat such contaminated food continuously then heavy metals start accumulating in them at toxic levels. Which damages the whole food chain leading to dangers to the animals. Accumulation of these toxic metals causes various disorders in human beings. These metals also cause the deficiency of nutrients from human body i.e. intra-uterine growth retardation, unbalancing physico-social faculties, upper gastro-intestinal cancer, and disability due to deficiency of nutrients & also affect their defense system [34].

3. Remediation techniques for contaminated soil

Several techniques have been developed to remediate the contaminated soil. Based on the site of remediation technique, remediation methods are classified as in-situ methods and ex-situ methods [35]. In-situ method comprises the treatment of contaminants within the same place, without the transport of contaminated soil. In the ex-situ method, contaminated soil is transported from its original place to somewhere else for treatment. [36]. Based on the type of remediation process, remediation techniques are generally categorized as physical, chemical, and biological remediation. Here is a brief introduction of these remediation techniques.

3.1. Physical remediation

In physical remediation, soil contamination is prevented by various physical techniques. This may comprise of installing barriers or replacing or removing soil. Because of this, physical remediation techniques are thought to be the most efficient in terms of the time needed to fully clean up contaminated areas. These techniques include vitrification, electro-kinetic remediation, soil isolation and soil replacement. In soil replacement contaminated soil is completely or partially replaced by uncontaminated soil. This lowers the amount of contaminants present in the soil. [29]. It can be accomplished by:

1) Soil spading **2)** New soil importing

In soil spading, the polluted site is excavated deeply, and heavy metals are spread into these deep sites, hence metal dilution. In new soil importing, clean soil is added into the contaminated soil thus reducing the concentration of metal contaminants. This technique is useful for the small contaminated area because of heavy workload & high cost [11]. Soil isolation is the separation of contaminated soil from un-contaminated soil, but other supplementary techniques are also used for complete remediation. These techniques are developed to prevent the movement heavy metals & other contaminants from their original place, by retaining them in that specified portion [30].

In Vitrification/thermal treatment**,** the movement of heavy metals in the soil can be reduced by applying high temperature, as a result a vitreous material is formed [31]. At high temperatures, some metals may be volatilized and can be collected for further disposal or treatment. Electro-kinetic remediation works on the principle that electric field gradient of suitable intensity is established between two ends of an electrolytic tank in which saturated contaminated soil is present. Then heavy metals present in the contaminated soil are separated through electrophoresis & electro-migration, thus reduces the contamination [29-32].

3.2. Chemical remediation

In this approach chemical reagents, reactions and principles are used for the treatment of contaminated soil. It comprises immobilization, encapsulation and soil washing [33]. Immobilization is the decrease in metal mobility and bioavailability of heavy metals in soil due to the addition of immobilizing agents into the contaminated soil. These metals are immobilized in the contaminated soil by several processes which include precipitation, adsorption, and complexation reactions. Due to these processes heavy metals redistribute themselves into solid particles from soil solution. In this way they limit the transport of heavy metals and their bioavailability in the soil. Organic and inorganic amendments are used for the immobilization of heavy metals in soil [11-34-36].

Encapsulation is the mixing of contaminated soil with other materials such as concrete, asphalt or lime. Hence the contaminated soil does not contaminate nearby soil due to immobilization of soil. A number of products are used for the formation of solid blocks but the most preferable is the cement as it is easily available, versatile and cost effective [37]. Encapsulation is an effective method for the prevention of organic material's leaching [38]. Algin is an excellent encapsulating agent as well as effective sorbent for metal ions due to the presence of carboxylic groups [39]. These reactive groups interact metal cations through chelation and also help in gelling biopolymer. Algin encapsulated poly-ethylene imine (PEI) derivative micro-particles were tested for the recovery of copper (II), zinc (II) and cadmium (II) from synthetic solutions [40].

Soil washing is the removal of heavy metals from the contaminated soil by using extractants & reagents that can take away heavy metals from that soil [41-42]**.** This method has been used as an alternative for various conventional remediation technologies. In this technique the contaminated soil is dug out and a suitable extractant is added. Further, both the contaminated soil and extractant are mixed thoroughly for a specific time. Then the heavy metals in the soil are transferred from the soil to the liquid phase through an ion exchange, precipitation, adsorption, or chelation and get separated from the leachate [43].

3.3. Biological remediation

Remediating contaminated soil through biological means is one of the most practical approaches. Biological remediation uses microorganisms or plants to detoxify or remove heavy metals from polluted soil known as microbial assisted phytoremediation or phyto-remediation. Heavy metals may be removed from soils using a variety of microorganisms, including bacteria, yeast, and algae. These microbes include *Bacillus subtilis*, *Pseudomonas putida*, and *Sporosarcina ginsengisoli*. In the rhizosphere, mycorrhizal fungi are also capable of transforming trace metals [44-46]. These methods provide a long-term solution at a reasonable cost and with minimal environmental impact. These methods are phytoremediation and microbial assisted phytoremediation [47].

3.3.1. Phytoremediation

Phytoremediation makes use of plants to lower the levels of pollutants in environment or lessen their harmful effects [48]. The plants employed for phytoremediation may be hyper-accumulator. These plants absorb pollutants through their roots. The use of hyper accumulators increases the capacity of accumulation of contaminants from 50~100 times as compared to simple plants. On the other hand, amendments are also added in the soil to remediate the soil employing the normal plants. Phytoremediation comprises three types: phytovolatilization, phytoextraction & phytostabilization [18]. Phytovolatilization converts the contaminants from the soil to the less toxic volatile form and releasing them into the atmosphere. Because mercury and selenium have high volatility, phytovolatilization has been used extensively to remove these metals [49-50].

In phytoextraction plants are employed for collecting heavy metals, radionuclides & metalloids from the contaminated soil into the harvestable components of plants. In this way contaminants are concentrated in the biomass of plants which is easily re-cycled & oxidized than the soil [51]. In Phytostabilization plants are employed to immobilize the pollutants in the soil so that they cannot contaminate nearby soil and avoid their leaching into the ground water [52]**.**

Hence this method doesn't reduce the concentration of pollutants but lessen their mobility & bioavailability in soil. Phytostabilization restrict the movement of contaminants in the vadose part of plants by accumulating/precipitating them in roots/rhizosphere [15].

3.3.2. Microbial assisted Phytoremediation

This type of phytoremediation involves microorganism's usage e.g. bacteria along with plants to accelerate the remediation process. Several phytoremediation procedures, including phytoextraction and phytostabilization methods, may involve the use of microorganisms. They can alter the bioavailability of heavy metals in soil, lessen the harmful effects of heavy metals on plants, and increase the biomass and growth rate of plants. It was investigated that lead (Pb) is phyto-stabilized in the rhizosphere of *Suaeda salsa* through the use of the fungus *Trichoderma asperellum*. Many types of bacteria were also reported to degrade the heavy metals and also helps to reduce their transportation [53].

4. Nano phytoremediation- A novel strategy

Different studies in the last few years revealed that both phytoremediation & Nanotechnology can be used effectively for the remediation of heavy metal's contaminated soil. Nano phytoremediation has been proven to be more effective for the removal of toxic pollutants from the contaminated soil. Various nanomaterials such as nano titanium dioxide, nano nickel, nano silver, nano zinc, nano zero-valent iron, and nano-carbon black can be used for the treatment of toxic heavy metals including lead, cadmium, copper, chromium, and zinc. [16-17-54]. Nanomaterials are helpful for the remediation process as they rapidly enter into the contaminated areas and also have large surface area in comparison to their bulk form [55]. Many researchers are interested in combining plants and nanomaterials to manage the environment because some nanomaterials can significantly increase plant growth and heavy metal absorption by plants. Thus it improves the efficiency of phytoremediation [56].

5. Evaluation of techniques for selection and application

Different factors such as cost, required time & effectiveness of the method must consider choosing and apply a technology from the available technologies. Physical and chemical remediation methods are usually expensive and may be harmful to the environment. These methods may require small to moderate time. While biological remediation is more economical than both methods. Biological methods usually require large time span but are cost effective, environment friendly and may be applicable on large scales. Table 1 shows the comparison of the physical techniques. In table 2 chemical remediation approaches are compared. In the table 3 comparison of various biological techniques is given [65].

6. Phytostabilization-An emerging remediation technology

Plants which can tolerate contaminants, are employed in this technique to confine the movement of contaminants (especially heavy metals) underneath the ground. So that they couldn't transport into the eco-system, hence reducing their bioavailability in the soil and constraining their entry into the food chain [57-58]. This method does not involve the degradation or removal of the contaminants rather it restricts their movement, thus preventing the contamination of nearby soils. Therefore, this method is used where phytoextraction is impossible or where the application of an appropriate technique for remediation is postponed due to technical or monitoring issue. Figure 2 shows how plants stabilize the heavy metals which in result reduces the bioavailability of HMs (heavy metals) in soil. In Belgium, berignite was used for the remediation of zinc and lead contaminated places that was a fruitful example of phytostabilization [59]. Plants employed for this technique should have to consider for the different characteristics shown in figure 3.

For example, *Lolium perenne, Agrostis stolonifera & Festuca rubra* (excluder plants) satisfy the above characteristics so they have been employed for the stabilization of contaminated soils. Some of the plants employed for stabilization of various heavy metals are given in Table 2. Trees because of their deep & vast root systems and ability of adding litter to soil cover, forms an organic layer that improves the cycling of nutrients, aggregation of soil, and the holding capacity of water. Usually, many species of trees require large amount of water and have a high rate of transpiration e.g. Salix species, which in result decreases the downward stream of water in soil, so minimizes the chance of metal leaching. A wide range of plant cover inhibits the dispersal of contaminants (because of wind & water erosion) and reduces the availability & movement of heavy metal (due to accumulation in roots or precipitation in rhizosphere). Phytostabilization can also be combine with some other techniques e.g. usage of microorganisms and amendments to enhance the immobilization of contaminants in contaminated soil [60].

7. Phytostabilization benefits over other remediation techniques

This technique is useful for the site where phyto-extraction is impracticable. It is also used as a temporary strategy to stop the movement of contaminants into the nearby places until an appropriate remediation technique is employed. This method requires relatively less time and cost than other remediation techniques. Phytostabilization is considered a more promising technique as it ensures the immobilization of contaminants. This technique is more environment friendly as it doesn't produce secondary waste which **requires** another treatment. The fertility of soil is increased by using this technique which contributes to restore the ecosystem [11].

8. Implementation

Planting trees depending on the contaminants, soil type, and climate can help to phytostabilize an industrial area. For planting purposes, industrial areas need to have open fields. Planning and creation of fields would be necessary if there aren't enough vacant land. Plantations are laid out in a row at a set distance from one another to occupy the maximum area and stop migration of pollutants to another natural environment. The implementation of this techniques involves: preparation of soil, direct seeding or transplanting, maintenance of the system & regular monitoring. Prior to using phytostabilization strategy, we must consider the factors shown in figure 4.

8.1. Preparation of soil

Preparation of soil is the key components in starting a successful plantation. Fertilized soil that retains moisture and allows for adequate air circulation is the ideal soil for planting. The soil must be properly prepared for a productive plant to develop and emerge. The process of preparing soil also involves physical modification, which includes tilling, chelating agent application, pH control, and drainage maintenance. Tillage aims to produce suitable physical conditions for fast plant growth and successful germination of seeds. The area and nature of the soil determine which type of tilling equipment is best. Employing a small gardening tractor or a full-sized tractor, tilling with the aid of a rotary tiller and hand digging are some of the options. The best tools for tilling the ground are gardening tractors, large farm tractors, rotary tillers and hand shovels [61].

8.2. Direct seeding or transplanting

Usually more uneven vegetation cover is produced by using seeding approach as compared to transplanting, but the yield is better through transplanting. Because direct seeding is less reliable for establishment on some areas, it has less application in the remediation process. Furthermore, the chance of survival of useful seeds is low. Despite these disadvantages, it is still in use because seeds are cheaper than transplants and are simpler to store and transport. In a recent study conducted in a greenhouse, *Lygeum spartum* grown from rhizomes as well as seeds was studied for metal uptake. Compared to plants cultivated from rhizomes, those grown from seeds absorbed noticeably more metals. As noted by the authors, the study's findings were probably impacted by greenhouse conditions, such as homogeneity of the sediments and greater humidity content. Transplants give the season a major head start because they mature sooner and have many benefits, including the capacity of becoming more resistant towards insects and other unfavorable conditions because of their strength as well as maturity. But transplanting is more costly than direct seeding so this is the main point that needs to consider [62].

8.3. Maintenance of the system & regular monitoring

The system must continue to function properly for remediation to proceed and be successful. Maintenance could be scheduled or unscheduled. Variations in plants, climate, and contaminants might require, some extra measures, including re-planting, fencing/pest control, water for irrigation, pH control, chelating agents, and soil amendments. It's crucial to maintain each of these elements in good operating order, depending on the circumstances [63]. Regular monitoring of the phytoremediation system is essential for evaluating the progress and efficacy of the final product. The monitoring is based over the remediation goal and the selected phytoremediation technique. Figure 5 presents the criteria needed to meet by the monitoring strategy [64].

9. Mechanisms involved in phytostabilization

The basic idea behind this technique is that plants store pollutants in their root systems. Thereby reducing the mobility as well as bioavailability of metals by either accumulating them inside the roots or relieving them in the substrate. A reduced power to transport metals through sediment is the potential effect of excessive metal accumulation. [65-66]. The main mechanisms of phytostabilization are the chemical immobility of contaminants, restricted penetration by water, and decreased soil erosion [67-68]. The basic process involves chelation with molecules that bind metals and complexation with exudates from roots [69].

9.1. Removal of contaminants

Plant-based pollutant removal may still be important to this technology even though it may not be the primary mechanism in phytostabilization. In addition to producing biomass rich in zinc that might be utilized as nutrient-rich stock feed, agricultural crops could improve phytostabilization of metal contaminated soils. High concentrations of Boron (B) were extracted by poplars employed in the phytostabilization of a sawdust pile polluted with boron. In this case, the biomass might be applied to neighboring orchards (lacking in B) as a Boron rich mulch. But the plant's main role was the stabilization of soil in eithercase. Hence the removal of metal increases the worth of biomass [83].

There are many plants employed in phytostabilization for many years which remove heavy metals are *Festuca specie*, *Festuca ovina* L., *Festuca rubra* (Cd, Zn, Cu, Pb,) , *Secale cereale*, in a moderately acidic mine . And the other plants which are involved in decreasing soil erosion & causes the stabilization of soil are *Lolium perene* (perennial *ryegrass*: Cd, Pb, Ba, P, Al, Cu, PAH), *Festuca arundinacea Schreb.* (N, Pb, P, K, Cd, Zn, PAH, Cu, TPH), *Dactylis glomerata* (Zn , Cd, Pb,), *Triticum aestivum* L. (Cu, Ba, Pb, Cs, Zn,), *Agrostis capillaris* (common bent: Cu, Pb, Zn, Cd), *Sorghum halepense* L. (Johnsongrass: Ni, As, Al, Cs, Mn, Cu, U), and *Agrostis castellana* (highland bent: Cd, As, , Zn, Pb, Al hyper-accumulator) *Agrostis stolonifera (*creeping bent grass: Pb, Cd, Zn, Cu, As). These also comprises grasses that show the dual effect [60]. Metal excluder plants take up substantial amounts of heavy metals from the soil into their roots due to restricted transit to their aerial parts. These plants are very effective for phytostabilization but have limited potential for extracting metals [58]. The phyto-availability, mobility, and solubility of metal ions eliminated from roots are necessary for phytostabilization. During the development of natural plants, a large amount of the photo-synthates produced by leaves is transferred from the roots toward the rhizosphere.

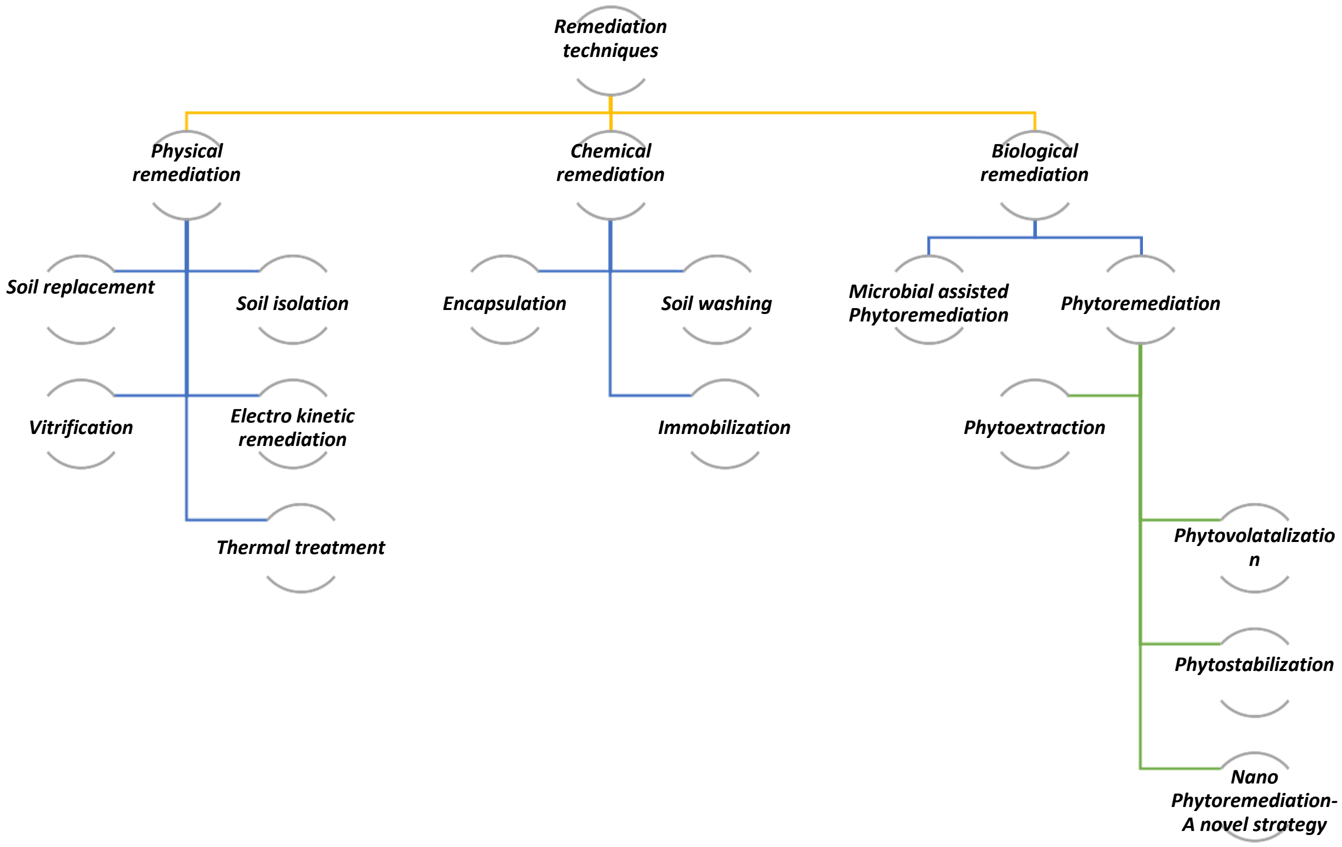

Figure 1: Different approaches of remediation

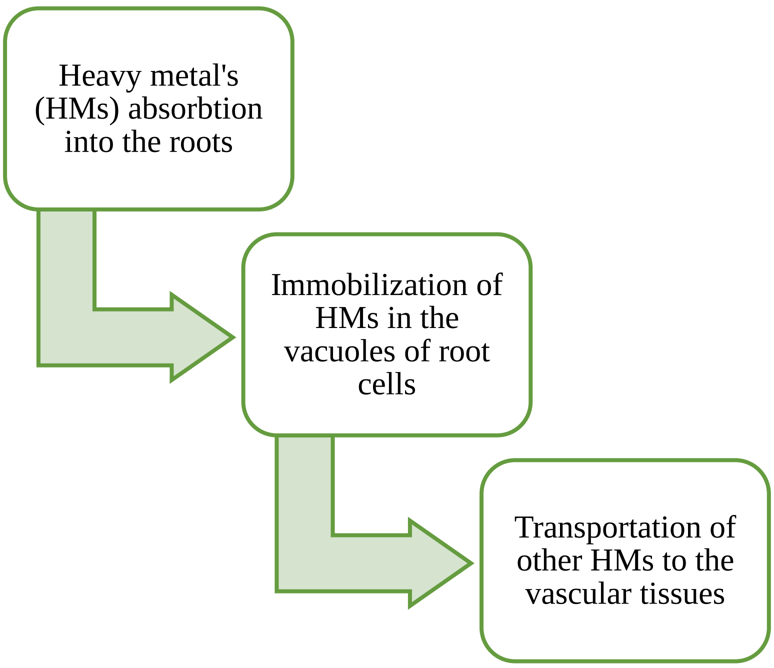

Figure 2. Metals uptake by the roots and their immobilization

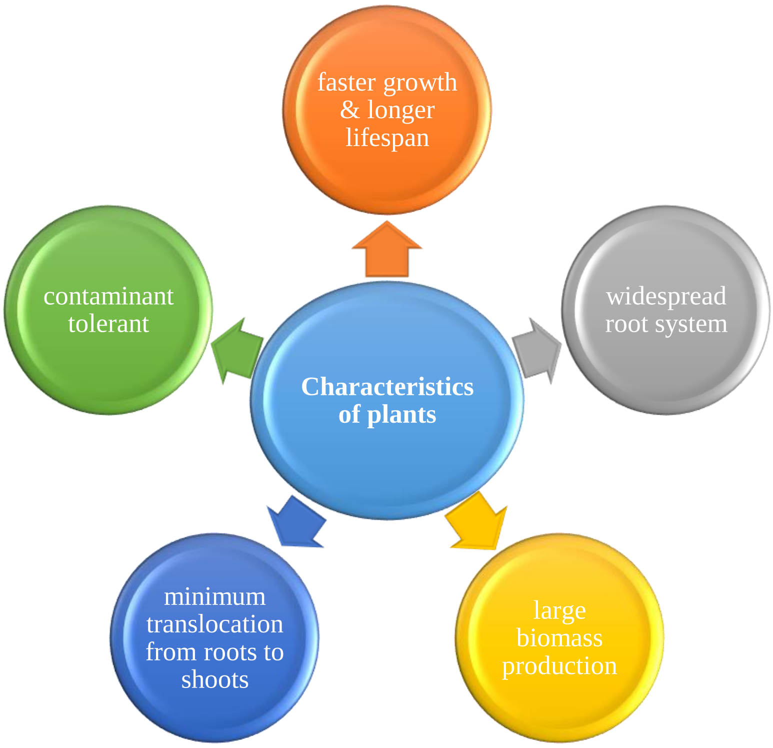

Figure 3. Characteristics of plants plants employed for phytostabilization

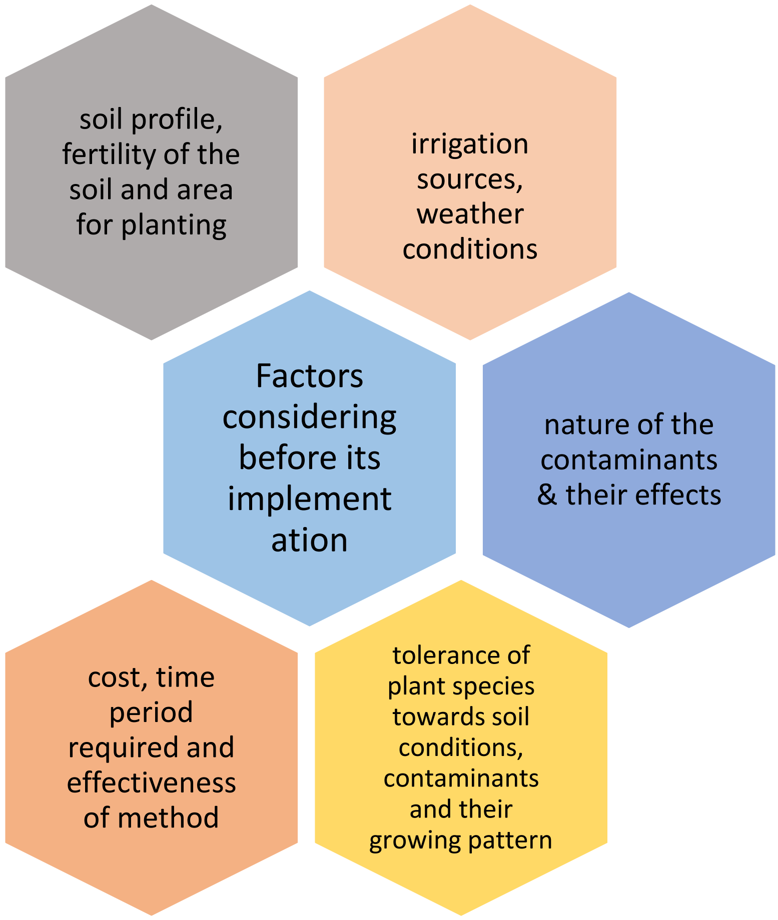

Figure 4. Factors considering before the implementation of phytostabilization

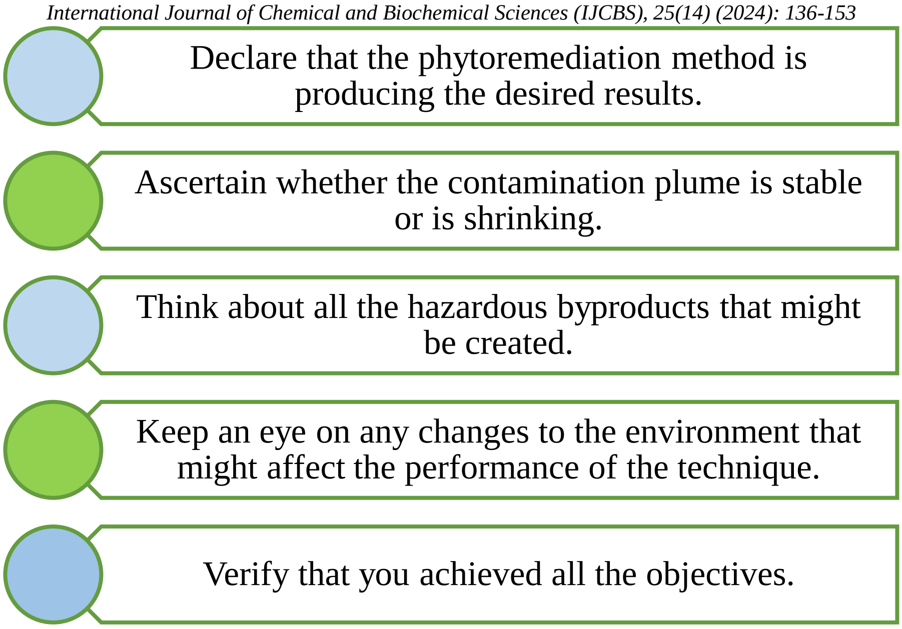

Figure 5. Monitoring criteria

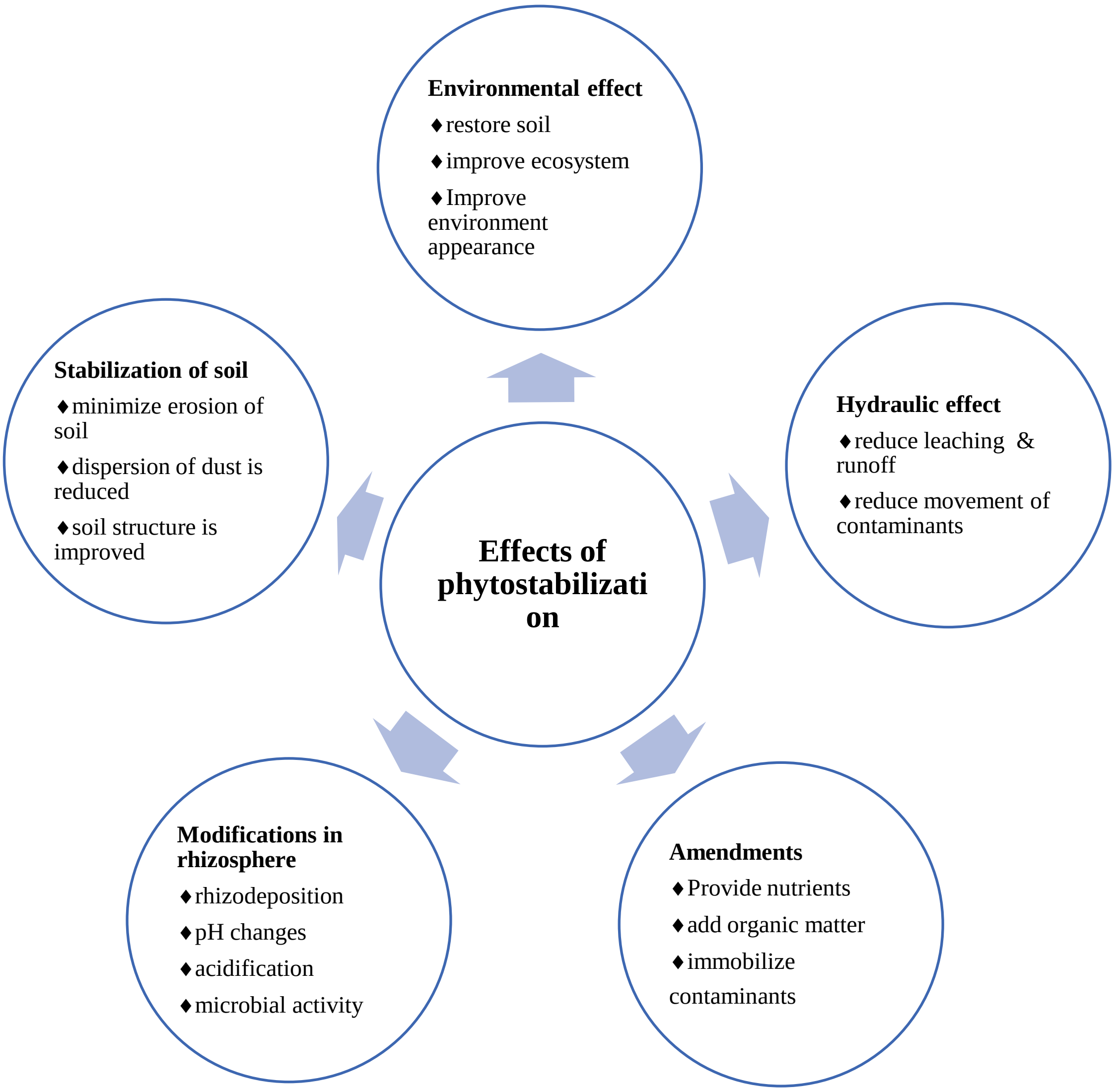

Figure 6. Effects of phytostabilization

Table 1. Classification of contaminated soil based on I_{geo} values

Classes	**I_{geo} value**
Class 0	≤ 0 (uncontaminated)
Class 1	≤ 1 (slightly to moderately contaminated)
Class 2	≤ 2 (moderately contaminated)
Class 3	≤ 3 (moderately to strongly contaminated)
Class 4	≤ 4 (strongly contaminated)
Class 5	≤ 5 (strongly to seriously contaminated)
Class 6	> 6 (seriously contaminated)

Table 2. Comparison of physical techniques

Techniques	Process used	Benefits	Drawbacks	Applicability	Time period
Soil replacement	Contaminated soil is replaced by un-contaminated soil	• Efficient for contaminants separation in highly polluted area • effective for long term	• High cost • deleterious impacts on soil • toxic waste production	small scale	Relatively less time
Vitrification	Sub-surface barriers are installed	• easy to apply • efficient for variety of contaminants • effective for long term	• Costly method	small scale	very less time
Electro kinetic remediation	Removal of contaminants through electrophoresis	• Easy method • soil nature remains unchanged • economical • long lasting	• Less permeable soil required • demands pH regulation	small scale	Relatively very less time

Table 3. Comparison of chemical remediation methods

Techniques	Process used	Benefits	Drawbacks	Applicability	Time period
Immobilization	Amendments are applied to immobilize metals	• Comparatively low-priced • Covers a wide range of inorganic contaminants	• Impermanent solution • not long lasting	For small to moderate scale	lesser to moderate
Soil washing	Extractants are used to remove contaminants from soil	• Totally eliminate the contaminants • cost-friendly • may be long term	• Environmental problems may arise • efficiency differs according to metal, soil & extractant's nature	On small scale	lesser to moderate

Table 4. Comparison of biological methods

Techniques	Process used	Benefits	Drawbacks	Applicability	Time period
Phytovolatilization	Accumulation of heavy metals & vapors released into atmosphere	• Cost-effective • less troublesome • long term	• only for volatile metals • may create environmental issues	Small to intermediate scale	Large time span
Phytostabilization	Immobilization of contaminants through plant	• Cost-effective • less disturbing	• temporary solution • efficiency may vary with nature of soil, plant & contaminant	Small to medium	Very large
Phytoextraction	• Contaminants are concentrated in the biomass of plants • which is easily re-cycled & oxidized	• cost-friendly • less disruptive • environment friendly • usually long term	• Hyper-accumulator plants are less in number • parameters like tolerance& metal's bioavailability may effect	large scale usually long term	Very large
Microbial assisted phytoremediation	Microorganisms are employed along with plants	• Cost-effective • time of remediation is reduced • speed up the plant growth & uptake of metals	Reliant on micro-organism, plant, soil & metal kind	On large scale	Very large but shorter than other remediation technique alone

Table 5. Plants employed for phytostabilization of various heavy metals

Heavy Metal	**Plants used for phytostabilization**
Iron	*Clerodandrum indicum* (L) [70], *Leucaena leucocephala* [71]
Nickel	*Ricinus communis [72], Conocarpus erectus* [73]
Zinc	*Jatropha curcas [74], Lemna gibba(L)*[75], *Solenum nigrum (L) and Spinacia oleracea (L)*[76]
Copper	*Amaranthus spinosus (L)* [77], *Oenothera glazioviana* [78] , *Solanum Nigrum (L) & Spinacia oleracea (L) [76]*
Chromium	*Solanum tuberosum (L), Solenum nigrum (L) and Spinacia oleracea (L)* [76]
Arsenic	*Solanum tuberosum (L), Acanthus ilicifolius L* [79]
Lead	*Amaranthus spinosus (L)* [77] *Solenum nigrum (L) & Spinacia oleracea (L) [76]*
Mercury	*Mentha aquatic, Brassica juncea* [80], *Miscanthus × giganteus* [81]
Cadmium	*Amaranthus spinosus (L)* [77], *Acanthus ilicifolius L* [82]

Exudates can contain different types of compounds, including organic acids, polysaccharides, sugars, peptides, amino acids, and proteins. Root exudates are essential to phytostabilization as they make it easier for pollutants from the soil to accumulate, stabilize, or volatilize. In addition to the benefits, root exudates have been shown to be a productive energy source for microorganisms in the soil. These materials also function as ligands to bind heavy metal (HM) ions, affecting the pH value of the rhizosphere [84]. The mobilization and re-absorption of metals by plant roots are impacted by pH changes in the soil. Therefore, through rhizodeposition, apoplastic, and complexation processes, roots regulate the pH range and electrochemical potentials of soil, changing the mobility of trace elements. Heavy metal ions become stabilized by root exudates, which prevent plants from absorbing them into their roots. The process of phytostabilizing is crucial. The amino acid phytosiderophore, which is synthesized by grain plants, can combine with, cadmium, zinc, iron, and copper to form stable complexes. Furthermore, siderophores secreted by roots can immobilize arsenic and increase the toxicity of detoxification. Similar to this, organic acids, e.g., citric, malic, and oxalic acids, restrain Cd^{2+} from penetrating the roots. Additionally, reports suggest that citrate and heavy metals from roots, like zinc and nickel, chelate histidine molecules to help limit their penetration into the cells [85].

It's interesting to note that microorganisms in rhizosphere region of plants assist them in stabilization of metals and re-vegetation. It has been reported that mycorrhiza and bacteria play a part in immobilization of metals through precipitation, adsorption of metals on their cell walls, or actively altering metal speciation. Soil micro-organisms are known to enhance root metal contents by growing more rapidly and immobilizing heavy metals in the soil [86]. Additionally, adding compost improves microbial diversity by letting plants to grow and gather more heavy metal ions in their roots through a long-term pH buffering effect [87]. *Brassica juncea* is known to be a hyper-accumulator and has a high tolerance level (from 500mg to 1000mg per kg soil) for mercury, it could be a useful tool in the phytostabilization mechanism for mercury removal. When the amount of mercury in the soil does not go above 1000mg per kg soil, it was found that *Brassica juncea* has high capacity for the phytostabilization of mercury without having a serious negative impact on the plant. The accumulation ability across various parts of the plant was *root* > *leaf* > *stem* in the second & third months of experiment and *root* > *stem* > *leaf* in the first [80].

9.2. Covering of soil

By absorbing or assimilating, vegetation cover functions as a sink for pollutants, lowering the quantity of contaminants that can be transported to groundwater. By lowering the amount of water that penetrates the soil profile, vegetation cover lessens the soil erosion and transport of related pollutant. If there is no or little plant or plant residue vegetative cover in the soil, the risk for soil erosion increases. For phytostabilization, it is essential to choose a range of grasses & shrubs along with trees (perennial in nature) for the re-vegetation of mine tailings. While shrubs & trees take root, but grasses offer a quick ground cover and momentarily restrict the dispersal of tailings. In order to stop erosion over time, shrubs and trees create a deeper root system and a wide canopy cover [88].

9.3. Rhizosphere modification

Changes in soil biochemistry brought about by the rhizosphere control the transformation, movement, and bioavailability of metals, which has influenced the phyto-stabilization of contaminated areas. The primary biochemical characteristics induced by the rhizosphere that influence metal dynamics are the enhanced microbial activity, release of organic acids and acidification. The primary cause of plant-based pH changes in the rhizosphere is associated with the different ways that plant roots absorb anions and cations. The plant’s primary source of nitrogen uptake was likely nitrate nitrogen and they simultaneously excreted hydroxyl ions to keep their roots electrically neutral. This led to rise in the pH of the rhizosphere soil [89].

Acidification has an impact on the speciation and solubility of metal ions. An increase in soil acidity almost always results in a decrease in metal adsorption. The bacteria and mycorrhizae that inhabit the rhizosphere of plants are able to actively contribute to the alteration of metal speciation and the regeneration of plants by surmounting the effects of phytotoxicity [90]. By introducing bacteria like, *Microbacterium arabinogalactanolyticum*, *Sphingomonas macroscopica* and *Alyssum murale* to soil, a pH decrease in some circumstances can greatly increase the phyto-availability of heavy metals as well as Ni, thereby promoting phytostabilization. "Rhizodeposition" is the process by which plant roots release carbon compounds and nutrients into the rhizosphere. The increased microbial growth is brought about by rhizodeposits, which are mainly comprised up of carbohydrates, amino acids & carboxylic acids. Citrate, malate and oxalate are predicted to have the most significant effects among the range of carboxylates released in the rhizosphere because of their role in the complexation of metal ions [91].

9.4. Rhizofiltration or Hydraulic control

The use of plants to prevent or regulate the accumulation and movement of contaminants is known as hydraulic control. Surface and subsurface waters are both treated with this technique. The amount of water that a single Salix tree is said to perspire in a day is 5,000 gallons. This technique can be applied to Salix, hybrid populous, and Eucalyptus trees. Generally speaking, the phyto-hydraulic control method dissolves both inorganic as well as organic (water-soluble) pollutants [92]. Metals like, Cr, Ni, Cd, and Pb as well as radionuclides like U and Cs can be removed through process. Trees with long roots function as pumps, extracting large volumes of water together with contaminants from the water table beneath the surface and in this way the movement of contaminants is controlled [93]. Figure 6 shows how the processes of phytostabilization affect the contaminants and in turn the environment.

10. Factors affecting the phytostabilization

The mechanism of phytostabilization is affected by various factors including soil, contaminant, plant, and environment.

10.1. Effect of Soil

The chemical, physical and biological characteristics of soils that regulate plant growth dictate whether this technology is successful. Additionally, the dynamics of heavy metals ions are regulated by the properties of soil, which influences their stability in soils. Because of the low microbial activity, deficiency in nutrients, and hazardous heavy metal content at contaminated sites, plant growth is not supported frequently. Therefore, soil amendments either organic or inorganic are applied to the soil. Both natural and artificial organic and inorganic amendments help plants to stop the movement of heavy metals in soil [94]. The immobilizing qualities of four different amendments: bone mill, furnace slag, bottom ash, and red mud combined with *Pteridium aquilinum* and *Miscanthus sinensis* helped to phytostabilize heavy metal-contaminated soil [95]. When *Pteridium aquilinum* and *Miscanthus sinensis* were growing in soil, the application of amendments dramatically decreased the extractable and soluble heavy metal ions fractions close to 99%. In order to maintain immobilizing conditions, sometimes soil amendments may be re-applied [15]. Sewage sludge was utilized at a location with low soil fertility and contamination with cadmium, lead, and zinc [96]. Better plant growth was achieved in the treatment plots because of the plants' complete utilization of the nutrients that were from the sludge. A comparison of the three organic amendments, i.e., paper mill sludge, cow slurry, and chicken manure, was studied. It was discovered that both cultivated and non-vegetated soil experienced a decrease in Zn and Pb availability following these amendment’s application, with soil treated with cow slurry producing the least number of extractable metals thus producing the largest biomass production in plant. According to these studies, organic amendments can effectively improve phytostabilization [97].

In recent years, biochar has become increasingly popular in environmental remediation. Black carbon produced by pyrolyzing biomass is called bio char. This porous substance with a wide surface area is useful for stabilizing metals in polluted soil. [98-99]. While biochar by itself is an effective means of immobilizing contaminants. A recent trend involves combination of traditional stabilization methods with phytostabilization achieved by adding bio-char. Increase in soil fertility can lead to increased plant growth in addition to the basic immobilization processes like raising the pH of the soil [100-101].

To improve the immobilization of heavy metal ions in soil, phytostabilization can be applied in conjunction with other remediation approaches like the usage of soil micro-organisms. It has been observed that soil microorganisms can raise the content of metals in roots by growing more rapidly and immobilizing heavy metals ions in the soil [102]. Additionally, the addition of compost greatly increased the diversity of microorganisms by acting as a long-lasting pH buffer, which permits plants to sprout and accumulate more heavy metals in their roots [103]. One of the most significant variables that directly affects phyto-availability is the pH of the soil. Low pH usually less than 5 for metal cations indicates increased mobility and phyto-availability. On the other hand, metal anions exhibit the opposite behavior at high pH levels, as metal cations are more likely to adsorb in soil, decreasing their mobility and availability [104-105]. The pH of soil also affects how organometallic ligands form. Higher pH levels promoted the synthesis of organometallic ligands and caused free metal ions to produce hydroxyl products. Hydrogen ions, on the other hand, become more reactive at lower pH values. These H^+ ions compete with certain metal ions for the easily accessible binding sites of organic materials (such as fulvic acid and humic acid). Thus, the formation of organometallic ligands is inhibited & the movement of the metal ion within the soil is increased [106].

10.2. Effect of Contaminants

Contaminants (like heavy metal ions) in soil experience a variety of reactions such as adsorption, precipitation, reduction, and complexation. These reactions regulate their bioavailability, leaching, and runoff rates of contaminants thus affecting the process of phytostabilization. Complexation and sorption with organic & inorganic ligands are two chemical processes that support soil ability to retain metal ions. Due to stronger covalent bonds as well as electrostatic interactions, the charged ions get attracted to charged surfaces of soil, which may be either non-specific or specific in character. Covalent bonding allows for the retention of certain metal cations in the inner sphere form of complexes. By complexation, precipitation, and ion exchange, metal ions can interact with organic matter present in soil. The sorption of metal ions onto soil particles is known to be impacted by the formation of organic complexes [88]. Precipitation has a negligible effect on normal soils, but in heavy metal-contaminated soils, especially in alkaline environments, it can have a significant remediation effect. Phosphate is being added more frequently to precipitate high metal concentrations, such as zinc and lead. However, phosphate can also mobilize arsenic if it serves as a co contaminant [107].

10.3. Effect of Plants

Plants that have undergone phytostabilization exhibit resistance to heavy metals, a high production of root biomass and a minimal translocation of absorbed heavy metals from the roots to the aerial tissues. For phytostabilizing soils contaminated by copper, chromium, zinc or lead, plants such as Red Fescue (*Festuca rubra*), hippo grass (*Vossia cuspidate*), Sibth (*Agrostis tenuis*), wiregrass (*Gentiana pennelliana*), Syrian bean-caper (*Zygophyllum fabago*), and thatching grass (*Hyparrhenia hirta*) are proved to be excellent choices [18-108]. Plant density has a significant impact on biomass production and plant growth, which in turn improves the remediation efficiency [109-110]. Reduced individual biomass from a high plant density could potentially reduce the remediation efficiency. Individual biomass & density of plants must therefore be balanced. The initial size of the plant can vary significantly, ranging from rods that are 1-2 meters in length to small cuttings that measure several centimeters long. A higher rate of re-sprouting and shoot growth is also linked to longer cuttings of willow and poplar [111].

Furthermore, different bacterial communities were found in poplar plants with variable initial sizes; for example, strains of the genus Flavobacterium were present in the root zone of bigger poplar trees. This finding may have an impact on the phytoremediation efficiency of poplars. The increased expression or suppression of membrane transporter proteins is one transgenic strategy that can be used to change the intake of inorganic pollutants. This method was effectively used to increase the accumulation of Zn in Arabidopsis thaliana. These transgenic plants clearly demonstrated improved metal accumulation and tolerance, along with a notable improvement in the breakdown of organic xenobiotics [112].

10.4. Effect of environment

Temperature, precipitation along with the effects of contaminants on plant growth & soil erosion, all have an impact on phytostabilization. Rainfall is crucial to the establishment of plants since most polluted areas may not have easy access to a steady supply of water for irrigation. Rainfall also regulates soil and sediment erosion as well as contaminant leaching. Temperature has an impact on soil surface properties like crust formation and cracking as well as plant growth. Although the process of cracking enhances the release of pollutants, exposed, dry, and loose soil can be eroded by wind through dispersion. It is unsafe to use exotic species because they could become weeds. However, native herbivores are more reluctant to harm exotic species, which promotes growth and lowers the quantity of contaminants that reach food chain. In phytostabilization, weed competition is frequently more challenging as compared to the soil contaminants. Every polluted site has a different environment. Thus, selecting the best species necessitates a brief planting trial that evaluates multiple cultivars on a limited portion of the site, especially for non-soil media like bio solids or mine spoil [88].

11. Advantages of Phytostabilization

One advantage of phytostabilization is that there is no need to remove the soil because the contaminants will remain in one location and also there is no chance of their spreading. So phytostabilization has found an effective and commercial use in industrial and urban areas to prevent the spreading of contamination. Additionally, there is a decreased likelihood of contaminants entering the food chain [113]. This technique causes less disruption than other remediation approaches. This is the most effective and targeted plant-based technique for removing toxins from industrially contaminated areas that has little effect on soil or water bodies. This method is both economical and environmentally beneficial. The vegetation used for phytostabilization has the potential to produce earnings. It is possible to manage phytostabilized sites so that the biomass produced by the vegetation yields useful products. These could be non-food items like wood, bio char, bioenergy or creation of phytochemicals and essential oils. By fixing soil through the roots of plants, phytostabilization also reduces leaching, runoff, and erosion by reducing the amount of metals that precipitate and transforming them into a minimum of bioavailable form [114].

12. Limitations of Phytostabilization

Phytostabilization is beneficial at places where contamination is relatively low and shallow. Plants that store heavy metals in their roots and zones of roots usually work at depths of as much as 23 inches. However, the technique is inappropriate for heavily contaminated environments where plant survival and development are unfeasible. This process takes a long time, and seasonal or climatic factors can hinder or interfere with plant growth. The inorganic and organic amendments used in this technique may be harmful to plants, which could have an impact on the plant's ability to survive. They may have unfavorable outcomes such as destabilizing the soil, introducing hazardous substances, or immobilizing vital nutrients [115]. The use of amendments must be done so carefully because they can have unfavorable effects. For example, improper usage of organic amendments can cause a decrease in soil biodiversity and underground contamination of water by antibiotics, nitrates and hormones, which can be unfavorable to the environment and public health [116-117].

A significant problem with phytostabilization is that, for the process to be successful, the contaminants must stay in place. As a result, the site will remain contaminated and inappropriate for other types of usage. On the other hand, the site can be used for the previous purpose using certain engineering technologies, like soil replacement. Long-lasting and self-sufficient, vegetative covers need little maintenance. In addition to being economical, phytostabilization is thought to be an environmentally beneficial method. However, because the remedied site requires continual monitoring, phytostabilization doesn't provide a long-term solution to soil contamination. However, applying soil amendments on a regular basis to improve immobilization raises the overall cost of maintenance [118].

13. Conclusions

Soil contamination from industrial development is a major environmental concern. Conventional remediation approaches are expensive and harmful, leading to the use of phytoremediation approaches. Phytostabilization among them is a cost-effective, environmentally friendly, and safe method that restricts contaminants' movement without polluting nearby resources. It also produces no secondary waste, saving time for further treatment. However, regular monitoring and amendments are necessary for optimal effectiveness. Plant species employed for this technique must be tolerant towards contaminants, soil conditions and showed a rapid growth. Transgenic plants and plants having microorganisms in their roots improves the immobilization of contaminants. Environmental conditions also play a major role in phytostabilization by affecting plant growth and promoting soil erosion due to excess rain fall and affecting the properties of soil due to temperature. Despite the various advantages of phytostabilization there are some limitations. Phytostabilization is not compatible for highly contaminated sites, use of amendments may harm the plants as well as soil & also their regular use may increase the cost. This provides a temporary solution as contaminants are remained in the same area. The phytostabilization technique can be made more effective in future by improving the characteristics of plants which is possible with the help of genetic engineering. Micro-organisms forming symbiotic relationship with plants can also contribute to phytostabilization by releasing growth hormones & nutrients. Thus, using genetic engineering to identify and create the right kind of symbiotic microbes can be very beneficial for phytostabilization. There should be field trials or pilot scale testing before applying the technique on large area. This will help to reduce the cost. Additionally, attention must be paid to designing such plants that can absorb multiple elements.

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