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Phytoremediation Strategies for Heavy Metal Contamination: A Review on Sustainable Approach for Environmental Restoration

Mariam Salifu[1,2], Matthew Abu John[3], Murtala Abubakar[2,4*], Ibukunoluwa Abimbola Bankole[3], Nneka Damola Ajayi[5], Olawumi Amusan[3]

[1]Department of Chemistry and Biochemistry, University of Mississippi, Olemiss, MS, USA
[2]Department of Biochemistry, Ahmadu Bello University, Zaria, Nigeria
[3]Department of Plant Pathology, North Dakota State University, Fargo, ND, USA
[4]Directorate of Research and Development, Nigerian Institute of Leather and Science Technology (NILEST), Zaria, Nigeria
[5]Department of Chemistry, University of Akron, Akron, OH, USA
Email: *mayahya29@yahoo.com

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Abstract

Current globalization trends and important breakthroughs globally need a complete study of heavy metal contamination, its causes, its impacts on human and environmental health, and different remediation strategies. Heavy metal pollution is mostly produced by urbanization and industry, which threatens ecosystems and human health. Herein, we discuss a sustainable environmental restoration strategy employing phytoremediation for heavy metal pollution, the carcinogenic, mutagenic, and cytotoxic effects of heavy metals such as cadmium, copper, mercury, selenium, zinc, arsenic, chromium, lead, nickel, and silver, which may be fatal. Phytoremediation, which was prioritized, uses plants to remove, accumulate, and depollute pollutants. This eco-friendly method may safely collect, accumulate, and detoxify toxins using plants, making it popular. This study covers phytostabilization, phytodegradation, rhizodegradation, phytoextraction, phytovolatilization, and rhizofiltration. A phytoremediation process's efficiency in varied environmental circumstances depends on these components' complex interplay. This paper also introduces developing phytoremediation approaches including microbe-assisted, chemical-assisted, and organic or bio-char use. These advancements attempt to overcome conventional phytoremediation's limitations, such as limited suitable plant species, location problems, and sluggish remediation. Current research includes machine learning techniques and computer modeling, biostimulation, genetic engineering, bioaugmentation, and hybrid remediation. These front-line solutions show that phytoremediation research is developing towards transdisciplinary efficiency enhancement. We acknowledge phytoremediation's promise but also its drawbacks, such as site-specific variables, biomass buildup, and sluggish remediation, as well as ongoing research to address them. In conclusion, heavy metal pollution threatens the ecology and public health and must be reduced. Phytoremediation treats heavy metal pollution in different ways. Over time, phytoremediation systems have developed unique ways that improve efficiency. Despite difficulties like site-specificity, sluggish remediation, and biomass buildup potential, phytoremediation is still a vital tool for environmental sustainability.

Keywords

Phytoremediation, Heavy-Metal, Contamination, Sustainability, Restoration

1. Introduction

The expansion of industries and urbanization across many parts of the world has led to increased contamination of surface waters, ground waters and soil by heavy metals [1]. Metal distribution in the environment results from the influence of environmental factors and the properties of the metals [2]. Heavy metals exist in the environment and are constantly increasing due to the environment through various anthropogenic activities such as mining, effluent discharge, and farming practices. The increased utilization of synthetic pesticides may lead to water pollution and harm to non-target organisms, thereby affecting the environment [3]. Heavy metals represent a group of dangerous environmental pollutants that, due to their toxic effects on human health in concentrations above the permissible limits, cause widespread concerns [4]. The term "heavy metal" refers to any element possessing metallic properties, has an atomic number greater than 20, a relatively high density greater than 5 g/cm^3, and has a toxic or poisonous effect even at a deficient concentration [5] [6]. Also, metals that are five times as heavy as compared to water have been termed "heavy metals", inclusive of metalloids such as arsenic, which can cause a toxic effect even at a low level of concentration [7]. It is common knowledge that heavy metals are naturally occurring elements on the earth's crust. However, environmental contamination and subsequent exposure to humans result from several anthropogenic activities such as tanning, mining, electroplating, smelting, and domestic and agricultural uses of compounds containing these metals [8]. Many of these heavy metals are toxic at deficient concentrations; arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), selenium (Se), silver (Ag) and zinc (Zn) are cytotoxic, carcinogenic, and mutagenic [9].

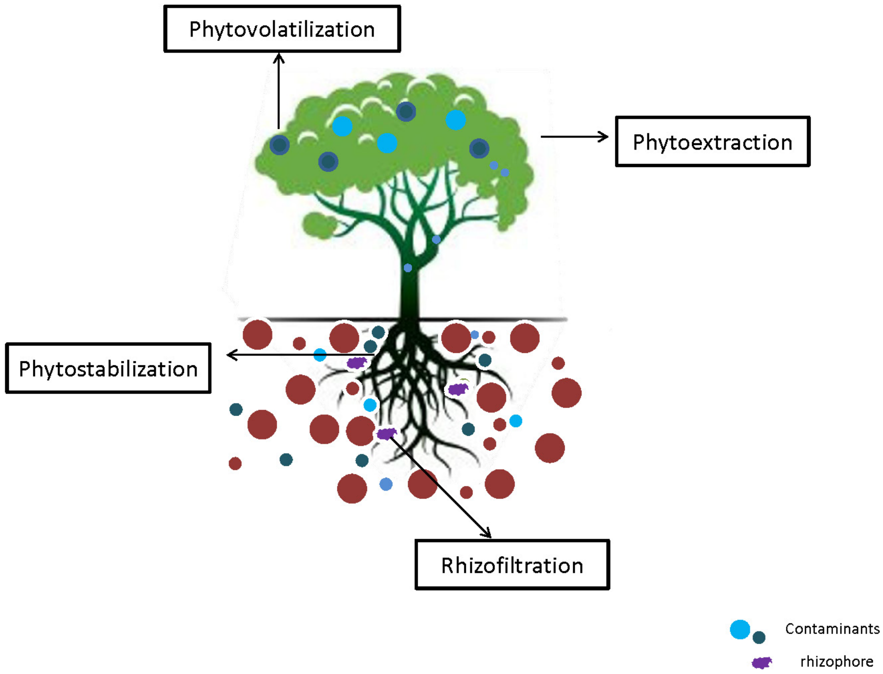
Heavy metals comprise an essential group of toxic substances encountered in everyday living, from mild to acute, impacting human health [10]. Heavy metals may enter the human body via different routes, including ingestion from contaminated food sources, drinking contaminated water, inhaling the atmosphere, and dermatological contact [11]. These metals may possess beneficial functions due to their oxidative and reductive properties when coordinated with biological macromolecules. They may act as competitive ions binding to active sites of proteins and inactivating them or leading to malfunctions [10]. The binding of heavy metals to cellular components such as proteins, enzymes and nucleic acids may result in oxidative deterioration, eventually interfering with biological functions [12]. Also, electrostatic interaction between Cr (III) and negatively charged phosphate groups of DNA can result in the formation of Cr (III)-DNA complexes, which are toxic and mutagenic. Inorganic forms of arsenic are testified to be toxic to the environment and lethal to living organisms [13].

Humans, now equipped with knowledge of the downside and long-term effects of these contaminants' health and the environment at large, have turned to various removal strategies to preserve the integrity of our ecosystem. Various *in-situ* and *ex-situ* techniques address soil and waterbody pollution, with some recorded successes and drawbacks. Some conventional methods include ion exchange, membrane filtration, precipitation, electrocoagulation, and adsorption. Specific issues have risen concerning their efficiency, some of which include the incomplete removal of the sludge, their high energy requirement and the possibility of secondary contamination due to the disposal of these materials, not to mention the high operational cost associated with these methods [4] [14] [15].

Over the past few years, in an attempt to turn towards safer options for removing contaminants from the environment, phytoremediation has become a viable option. As an environmentally safe method, phytoremediation utilizes plants to extract, accumulate and depollute contaminants through various mechanisms [16]. Phytoremediation is one of the most sought-after techniques for environmental clean-up due to its non-hazard approach to eliminating contaminants from the environment. Hyperaccumulator plants with enhanced metal binding abilities were genetically modified to improve their metal accumulation capacity. Sustainability methods ensure the removal of contaminants without creating any adverse effect that may affect agricultural processes [16]. This treatment may remove many contaminants beyond metals, such as antibiotics, petroleum hydrocarbons, pesticides, polychlorinated hydrocarbons, and many others. However, making this process toxicity-free requires a careful implementation process to dispose of contaminated biomass. One such way is to find usefulness for these materials post-harvest [17]. Agromining and phytomining describe processes that recover metals from plant biomass after cultivation on contaminated soil or water. Several studies successfully used this method to recover heavy metals such as nickel [18], precious metals such as gold [19] and rare earth metals such as cerium, samarium, and yttrium [20].

2. Processes of Phytoremediation

The phytoremediation method has been mainly composed of six strategies which are: Phytoextraction, Phytostabilization, Phytovolatilization, Phytodegradation, Rhizofiltration, and Rhizodegradation.



a) Phytoextraction: This process is also known as phytoaccumulation, phytoabsorption, or phytosequestration [21] and involves both the phyllosphere and rhizosphere of plants used [22]. The roots of the plants absorb the contaminants from the soil or water and accumulate the contaminants in the above-ground parts, that is the shoots and leaves. The type of plants used for phytoextraction are hyperaccumulator species because they can accumulate contaminants [23]. Also, they are plants with high biomass production, high pollutants' translocation factor into the surface biomass, high detoxification and contaminants' tolerance, and are easy to harvest [22] [24].

b) Phytostabilization: This method is called phytoimmobilization [25]. Here, the uptake of heavy metals is done in the rhizosphere, limiting the migration of the contaminants into the soil [26]. In this strategy, the plant that is being used alters the soil chemistry but facilitates the absorption and precipitation processes of heavy metals in soil by precipitating them into insoluble compounds [27] [28]. Moreover, this technology is an effective application when the preservation of groundwater and surface waters is needed [25].

c) Phytovolatilization: Phytovolatilization is also called phytopumping, and highly depends on the physical properties of the pollutants [29]. In this process, plants absorb contaminants from soil, transport the contaminants through the xylem, convert the contaminants into less toxic and volatile components, and release them into the atmosphere via the stomata [26] [30]. Thus, the mode of remediation is in the phyllosphere of the plants. Although phytovolatilization has the advantage of lowering the toxicity of the pollutants, however, it could lead to air pollution [31]. Phytovolatilization can be used for heavy metals such as As, Se, Hg, vinyl chloride, carbon tetrachloride, and 1,4-dioxane [32].

d) Phytodegradation: In this method, plant enzymes are required to first break down complex organic contaminants, then are incorporated into plant tissues in the phyllosphere [21]. Hence, this process is called phytotransformation because the plants transform the contaminants before releasing them into the atmosphere [25]; Enzymes usually involved are; laccases, dehalogenases, nitroreductases which break down anilines, pesticides, and chlorinated solvents, and nitroaromatic molecules respectively [21].

e) Rhizofiltration: This process is mostly used in a contaminated aqueous environment such as; contaminated wastewater, groundwater, and surface water. Here, plants adsorb and precipitate the organic and inorganic contaminants through the rhizosphere. Thus, rhizofiltration is primarily used to remediate an aquatic system with low levels of contaminants and is usually used for heavy metals including Cd, Cr, Cu, Ni, Pb, and Zn which are retained within roots and do not translocate to the shoots [29]. Research work done by [33] made use of *Phaseolus vulgaris* and *Helianthus annuus* for rhizofiltration to remove uranium from contaminated groundwater. The uranium removal result by the plants through rhizofiltration has an efficiency of more than 90%, and the uranium is accumulated at the root [26] [33]. The criteria for selecting a plant to use for this method include plants with a high surface area for adsorption, high root biomass, high accumulation capacity, and contaminants' tolerance [21].

f) Rhizodegradation: This process is also called phytostimulation because plant roots stimulate soil microbial communities in plant root zones to break down contaminants [29]. Thus, Rhizodegradation is performed by microorganisms such as fungi, bacteria, and yeasts found present in the rhizosphere of plants. Plant-microbial interaction plays a critical role in the efficiency of this treatment method and is normally applied in terrestrial contamination media [34]. These microorganisms in the plant rhizosphere can break down hazardous organic contaminants, such as herbicides, perchlorate, crude oil, Polyhydroxy aromatic compounds, and diesel [35] into harmless and/or nontoxic products. Sugar, amino acids, and alcohols are released by plant roots and microbial communities use these energy and food sources for consuming and digesting organic pollutants. This method is a highly rapid treatment system in comparison with phytodegradation because of microbial community association [34].

3. Microbial Mediated Phytoremediation

Phytoremediation of Polycyclic aromatic hydrocarbons (PAHs) in the soil can be done either by direct uptake by plants, leading to transformation under enzyme activities, sequestration inside the plant, or transpiration via leaf stomata [36] or through the release of rhizosphere exudates and enzymes by plant roots to stimulate rhizosphere microbial degradation of PAHs [37]. The rhizosphere of plants harbors a diverse range of microorganisms that are involved in plant interaction with contaminated soils [29]. According to [38], microbes support plants in enduring abiotic and biotic stresses, absorbing nutrients and water, producing plant hormones, and inhibitory allelochemicals [25]. They also boost the growth of plants and induce an increase of biomass in plants which elevates the remediation capacity of plants with the increased surface area for pollutant adsorption [25]. Moreover, the success of phytoremediation is a function of the plant's ability to resist and accumulate high concentrations of pollutants while producing a large amount of plant biomass [39]. Efficient phytoremediation processes therefore depend on the complex interactions among soil, contaminants, microbes, and plants [40]. Although several plant species are capable of hyperaccumulating pollutants in their tissues. However, phytoremediation in practice has numerous challenges as there are a variety of contaminants [41]. Thus, the combined phytoremediation with microorganisms has been encouraged widely [29] [42]. Among these microbes are Rhizobacteria, *Azotobacter*, *Bacillus*, *Pseudomonas*, *Arthrobacter*, *Achromobacter*, and *Enterobacter* [43], and Streptomyces spp., which have been reported to have an advantageous influence on various plants growing in contaminated soils [25] [44] [45]. The heavy metal-resistant bacteria strain, *Burkholderia* sp. significantly increases the biomass of maize and tomato plants and increases between 38% - 192% the Pb and Cd contents in tissue [46]. [47] have also reported that *Pseudomonas fluorescens* G9 and *Bacillus subtilis* Tp8 are biosurfactant-producing bacteria that have the potential to remediate Cd-contaminated soils. [48] also reported that *Rhodococcus* sp., *Variovorax paradoxus*, *Pseudomonas fluorescens* Pf 27, and *Flavobacterium* sp. enhance exchangeable and water-soluble Cd concentration in polluted soil. This in turn increased the Cd uptake and plant biomass of *Brassica juncea*. Interestingly, arbuscular mycorrhizal fungi (AMF) belonging to Glomeromycota, a monophyletic functional group that forms mutualistic associations with the roots of 80% of vascular plant species [49], can promote the absorption of nutrients and improve plant biomass, as well as act as a bridge between soil, plant roots, and rhizosphere microorganisms [50]. *Salix viminalis* is considered a potential woody plant for soil remediation of heavy metals by phytoextraction [51]. However, the inoculation of *Funneliformis mosseae* (PM), *Laroideoglomus etunicatum* (PE), and *Rhizophagus intraradices* (PI) for a combined remediation, showed an increased phytoremediation of up to 62.32% in PM after 90 days in comparison to remediation with *Salix viminalis* only [51]. Review papers by [25], [29] and [52] have also made mention of a diverse list of microorganisms reported to augment the phytoremediation of contaminated soils.

4. Chemical-Mediated Phytoremediation

Chelation refers to attaching a specific organic molecule with mineral or metal ions to form a metal complex [53]. In the phytoremediation of potentially toxic elements (PTEs), such as Cu, Pb, Cd and others, a chelating agent is a chemical reagent used to enhance the bioavailability of various PTEs in the soil for metal translocation into a plant [54] [55]. Due to the limitations in the standard phytoremediation procedure, such as low decontamination rate, low bioavailability of targeted metals, and reduction of plant growth due to metal toxicity, scientific studies have been made to enhance phytoremediation for PTEs clean-up in the soil using chelating agents [56] [57]. The chelating agents act as a chemical bond to form metal chelate complexes, which enhances the bioavailability and solubilization of PTEs in the soil, for easy translocation into the roots and above-ground part of the plants [34] [54] [58]. Several chelating agents such as ethylene-diamine-tetraacetic acid (EDTA), N, N-dicarboxymethyl glutamic acid tetrasodium salt (GLDA), and ethylene-diamine-N,N'-disuccinic acid (EDDS), diethylene-triamine pentaacetate (DTPA) have been explored to examine their potential to enhance phytoremediation of PTEs in soil [53] [59] [60]. EDTA is the most widely used chelator and extensively studied in field experiments [52]. This may be due to the reason that such chelates are very costly in widespread application, though a limited number of in situ studies have been exploited for other chelating agents. [61] suggested that the addition of GLDA could enhance Cd and As's bioavailability effectively. EDDS was found to improve the phytoextraction of Ni by *Coronopus didymus* L. from polluted soils [62]. In addition, [63] utilized citric acid for phytoextraction of metals from multi-metal contaminated soil by soybean plants aided by *Kocuria rhizophila* (*Glycine* max L.) [34]. The addition of EDTA enhanced the phytoextraction of Cd and Pb by *Pelargonium hortorum* [64]. The enhancement of metal accumulation and extraction by *Brassica juncea* plants in the presence of EDTA significantly enhanced Pb extraction by solubilizing soil-bound Pb [65]. Chelating agents in combination with plants can enhance the phytoremediation efficiency in various types of plants and contaminated sites [54] [58] [66]. However, it has conclusively been shown that plants may experience some phytotoxicity as a result of the high concentration of added chelating agents and the formed metal complex in the soil, which can consequently affect the performance of the plants to uptake toxic metals and contaminants in the soil [67]. Also, the application of chelating agents can reduce the chlorophyll content and plant biomass by suppressing the chlorophyll synthesizing enzyme (α-aminolevulinic acid dehydratase) activity [67]. The inhibition of this enzyme activity might limit the water absorption surface and photosynthetic activity thus reducing the overall plant growth [34] [56].

5. Factors Influencing Phytoremediation Efficiency

Phytoremediation, a promising, eco-friendly, and cost-effective strategy for the remediation of contaminated environments, has been widely investigated for its effectiveness and the variety of pollutants it can remediate [68]. This method capitalizes on the inherent ability of plants and their associated microbiota to degrade, absorb, or stabilize contaminants. The science of phytoremediation has been lauded for its potential to harness natural processes in the treatment of contaminated environments. However, the efficiency of phytoremediation depends on several interconnected factors that influence the overall remediation performance.

Selection of plant species:

Different plant species have varying abilities to uptake and translocate pollutants, and their tolerance to different types and levels of contaminants can greatly differ (Marchiol *et al.*, 2014). High biomass producing species with rapid growth, wide distribution roots, and tolerance to pollutants are often preferred. For instance, sunflowers and Indian Mustard have been identified as hyperaccumulators for heavy metals, including lead and cadmium [69]. Certain plant species are known for their higher metal uptake and tolerance, such as sunflower for lead, Indian mustard for chromium, and willows for cadmium and zinc [70]. The inherent physiological and biochemical characteristics of these plants, including high biomass production, rapid growth rates, and deep root systems, facilitate effective phytoremediation [71]. Phytoremediation efficiency is primarily governed by the type of plant species utilized [72]. Different plant species possess varying capabilities in terms of uptake, translocation, and detoxification of pollutants. For example, hyperaccumulator plants are more effective in extracting heavy metals from soil than non-hyperaccumulators [73]. The use of hyperaccumulators, plants that can take up and concentrate high levels of certain contaminants in their tissues, has been a focal point in phytoremediation research [74]. Moreover, the use of genetically modified plants, with enhanced tolerance and accumulation characteristics, has shown promising results but also raises ethical and environmental concerns [75]. Certain species exhibit higher capacities to uptake, accumulate, or degrade pollutants due to variations in their genetic makeup [75]. Selecting an appropriate plant species is therefore crucial to the success of a phytoremediation initiative.

The role of plant-microbe interactions:

Microorganisms can influence plant health and productivity, increase bioavailability of pollutants, and directly or indirectly contribute to pollutant degradation [76]. In rhizoremediation, a subcategory of phytoremediation, plant root exudates stimulate microbial activity, enhancing the degradation of pollutants [77]. Plant-microbe interactions also significantly influence phytoremediation efficiency. These interactions can enhance the availability of pollutants in the rhizosphere and increase the tolerance of plants to pollutants [78]. Certain bacteria can produce siderophores that mobilize heavy metals, facilitating their uptake by plants [79].

Impact of soil properties:

Soil properties, such as pH, texture, organic matter content, and pollutant concentration, are other crucial factors influencing the efficiency of phytoremediation. Soil pH affects the solubility of metals, with lower pH generally increasing metal solubility and thus availability for plant uptake [80]. Organic matter content can influence pollutant bioavailability and plant-microbe interactions [81]. Moreover, the physicochemical properties of the contaminated site, including pH, temperature, humidity, nutrient availability, and the presence of other pollutants, significantly influence the phytoremediation process [82]. For example, low pH levels can increase the availability of heavy metals, promoting their uptake by plants [83]. Soil properties, such as pH, organic matter content, and microbial population, can significantly influence phytoremediation efficiency [84]. A favorable pH can enhance the bioavailability of contaminants, while a high organic matter content can inhibit the plant uptake of heavy metals [85]. The role of soil microorganisms should not be understated, as they can aid in contaminant degradation and influence plant health [86]. Soil properties, including its physical, chemical, and biological characteristics, can substantially affect phytoremediation. Factors such as soil pH, texture, organic matter content, and microbial population play crucial roles in determining the bioavailability and mobility of contaminants, subsequently affecting plant uptake and degradation of pollutants [87]. Therefore, manipulating these factors, through soil amendments, for instance, can enhance phytoremediation efficiency.

Contaminants concentration:

The type of contaminant plays a pivotal role in the efficiency of phytoremediation. Some contaminants, such as heavy metals, are more readily absorbed and accumulated by plants, while organic pollutants, like petroleum hydrocarbons, may require specific plant-microbe interactions to enhance degradation [78]. Furthermore, the presence of multiple contaminants can influence the overall phytoremediation process, as certain compounds may antagonize or synergize the plant's ability to remediate others [88]. Contaminant characteristics also play a pivotal role in phytoremediation outcomes [71]. Variations in contaminant solubility, form, concentration, and depth of penetration in soil can significantly affect the bioavailability of pollutants for plant uptake [89]. Thus, a detailed characterization of the contaminant is necessary to accurately predict phytoremediation efficiency.

Environmental conditions*:*

The influence of environmental conditions, such as temperature, rainfall, and light intensity on phytoremediation is not fully understood. They can alter plant physiology and growth, potentially affecting their capacity to uptake and metabolize pollutants [90]. However, more research is needed to elucidate the precise impacts of these environmental factors on phytoremediation efficiency. These factors influence microbial activity in the rhizosphere, affecting the overall remediation process [71]. Environmental conditions such as temperature, precipitation, and sunlight influence plant growth and metabolism, thus impacting the phytoremediation process. The optimal temperature and sufficient sunlight are necessary for photosynthesis, which directly impacts plant growth and pollutant uptake [91].

In conclusion, while phytoremediation is a promising strategy for environmental remediation, its success relies on a complex interplay of several factors, and a comprehensive understanding of these factors, along with the development of techniques to optimize them, could greatly enhance phytoremediation efficiency, offering a viable and promising pathway towards a cleaner and healthier environment.

6. Recent Developments and Innovative Techniques in Phytoremediation

The application of traditional Phytoremediation techniques to reclaim contaminated sites has been publicly accepted [92]. But in recent times research has unveiled its limitations to the field and large-scale applications. This is because naturally occurring hyper accumulators are slow growing with low above-the-ground biomass production and also their poor ability to tolerate heavy metals toxicity effect [93]. The advent of new technological advancement in the field of phytoremediation strategies has resulted in significant improvements in the increased above the ground biomass production of the hyper accumulator plant species and their enhanced heavy metals tolerance ability [94]. The new technological advancements are discussed below:

6.1. Chemical Assisted Phytoremediation

The success of phytoremediation technique is rated by the fast growth and high amount of above the ground biomass production of the hyper accumulator plants, fast translocation ability, and bioavailability of the heavy metal contaminants around the plant rhizosphere for subsequent uptake. Hyper accumulator plants are classified as plants that accumulates high proportion of heavy metals in their aerial parts due to their efficient translocation ability, but with poor growth and low above the ground biomass production [95], however non hyper accumulator plants have poor translocation ability for heavy metals but grow fast and produce excess above the ground biomass. Therefore, non hyper accumulator plants are studied by researchers to enhance their heavy metals extraction ability using synthetic or organic chelating agents in a strategy called chemical-assisted phytoremediation or induced phytoremediation [96]. In this strategy, specific chemicals such as organic chemicals and chelating agents are employed to decrease the pH when applied to the soils and this enhances the bioavailability and bioaccumulation of heavy metals in the plants. In several studies, it was revealed that application of chelating chemical-ethylene diamine tetraacetic acid (EDTA) significantly enhanced the phytoextraction and bioaccumulation of Cd, Zn, and Pb in plants [95] [97]. Also, application of diethylene triamine penta-acetic acid (DTPA) and ethylene glycol tetra-acetic acid (EGTA) to the soils, has significantly enhanced the phytovolatility and phytoextraction of heavy metals in plants [98].

6.2. Microbial Assisted Phytoremediation

The understanding of symbiotic relationships that exist between plants rhizosphere and its microbial community is the key to improved phytoremediation technology. In this scenario, the plant root, in relation to microbiome, secretes certain class of enzymes capable of degrading pollutants and also certain low and high molecular weight organic compounds. The low molecular weight organic compounds are amino acids, organic acids, sugars and phenols that serves as an energy source to the microbial communities around the rhizosphere, while the high molecular weight organic compounds are mucilage, proteins that alter the physical and chemical properties of the soil to enhance the root-soil interaction respectively [99]. In trying to explore, researchers have identified several bacteria and fungi that aid plants ability to degrade harmful contaminants [100] [101] and their diversity examined through high throughput sequencing to have an insight on the effect generated in response to heavy metal stress [102].

Among these microorganisms, plant growth promoting rhizobacteria genera (Such as *Pseudomonas, Arthrobacter*, *Agrobacterium*, *Bacillus*, *Azoarcus*, *Azospirillum*, *Azotobacter*, *Burkholderia*, *Klebsiella*, *Alcaligenes*, *Serratia*, *Rhizobium*, *and Enterobacter species*) has been placed in fore front among other genera [103]. They are known for their ability to enhance plant growth and stress tolerance through symbiotic relation with the host plant by various mechanisms such as atmospheric N fixation, N, P and K solubilization, Organic acids, 1-aminocyclopropane-1-carboxylate deaminase (ACCD) and phytohormone production [104].

Another important class of microorganisms believed to aid heavy metals detoxification by plants, are the endophytic fungal community colonizing the plant's internal tissues, which are believed to have asymptomatic and mutualistic relations with their host plants [105]. They play vital roles in plant growth and development via nutrient acquisition enhancement [106] [107] and shielding the plant from bacterial attack by secretion of antibacterial siderophores [108] and biotic/abiotic stress [109]. In essence, to enhance the plants ability to tolerate heavy metal toxicity, we can inoculate them with endophytic fungi [101]. Several research work has reported a successful application of endophytic fungi in phytoremediation technology [110].

6.3. Organic-Char Assisted Phytoremediation

Organic-char is a carbon rich material, produced by pyrolysis of organic materials under limited oxygen supply. It has excellent physical characteristics such as large surface area, high porosity and different functional groups with different ionic charges. It is highly enriched with nutrients such as Ca, K, Mg, and P which originate from the raw material of the char [111]. The application of organic-char to remediate organic and inorganic contaminants in soil is an emerging and promising sustainability approach [112] [113]. It offers a range of benefits to the ecosystem, as it generally leads to reduce greenhouse gases emission, improves soil structure and replenish its nutrients and increases its microbial diversity. Also, integrating organic char, microbes and plants during phytoremediation influences the precipitation, mobilization, uptake and transport of pollutants in contaminated soil [99]. In recent times, there are various research works that demonstrate the success of this phytoremediation strategy [114] [115] [116], though with challenges such as over carbonization and generation of other toxic compounds (e.g. PAHs) when excessive heat is applied in the process of producing the char. Therefore, the processes involved in producing the organic-char has to be standardized and carefully monitored [117].

6.4. Transgenic Plants Applications

The application of transgenic plants to improve phytoremediation can be achieved by genetic reconstitution and generation of new phenotypic and genotypic characteristics of the potential plant candidate [118]. Interestingly, researchers have made progress in trying to enhance the phytoremediation ability of various candidates by overexpression of specific genes that results in the overall improvement in uptake, transportation, vacuolar sequestration and chelation of different pollutants [119]. In this regard, transgenic plants have been engineered to express specific genes that increase their ability to take up and accumulate pollutants from the environment [118] [120] [121] [122]. For instance, genes encoding transporters such as expression of Zn transporter gene (*ZRC1*) in *Arabidopsis thaliana* and *Populus alba* leads to overexpression of the zinc transporter (*ScZRC1*) in shoots and increased Zn tolerance is observed making the plant more tolerant to high concentration of heavy metals, hence effective during phytoremediation [119] [122]. However, despite the fact that successes have been recorded in the application of transgenic plants in phytoremediation, challenges and concerns cannot be ruled out. For instance, there may be the risk of interbreeding between the engineered plants and the wild species (*i.e.* gene flow) and potentially leading to the spread of engineered genes to the natural ecosystem and hence the natural populations are endangered. Therefore, the use of transgenic plants in phytoremediation needs to be strictly monitored and ensure that their application in phytoremediation does not lead to ecological shifts [93] [122].

7. Exploration of Genetic Engineering and Plant-Microbe Interactions in phytoremediation

Biotechnology paves a way for researchers to understand the intricate relationships that exist between plants and their microbiome, and this had led to enhanced phytoremediation strategies [123]. In this scenario, omics technologies such as proteomics, genomics, transcriptomics, and metabolomics have been used to gain a comprehensive understanding of the molecular mechanisms underlying plants-microbes interaction during phytoremediation. The key approaches used in achieving enhanced phytoremediation are as follows;

7.1. Genes Identification and Modification

Scientists are conducting research to identify and characterize genes that are responsible for pollutant uptake, translocation and tolerance in plants. These genes can be potentially manipulated by genetic engineering techniques and transferred to target plants species in order to enhance their phytoremediation potential [122].

7.2. Metabolic Engineering Approach

Metabolic engineering of pathways to favour expression of certain enzymes that break down organic pollutants such as pesticides, herbicides has been explored and huge success recorded since the last two decades [124].

7.3. Synthetic Biology and Signaling Molecules Approach

The application of synthetic biology tools to engineer plants and microbes to customize and design their genetic circuit is promising and has enabled targeted responses to specific pollutants by the engineered plants/microbes. Also, the plants are manipulated to enable their production of signaling molecules that can attract beneficial microbiome and improve their colonization around the rhizosphere [125].

7.4. Plant-Microbe Symbiosis Exploration

The beneficial relationships that exist between plants and microbes, for instance the mutual coexistence between the growth promoting rhizobacteria and the root zone of a particular plant species can be optimized by genomics, proteomics or transcriptomics to achieve improved pollutant degradation in the rhizosphere [126].

7.5. Biofilm and Microbial Consortia Engineering

Biofilms are hotspots for optimum microbial activity [127]. In this instance, their formation around the plant roots to provide a stable environment for pollutant-degrading microorganisms is encouraged by engineering the plant through omics technology, which can significantly enhance phytoremediation. Also, microbial consortia are engineered organisms that work in synergy with transgenic plants. They are designed through proteomics, genomics, or transcriptomics to perform complementary functions that lead to an efficient phytoremediation strategy [128].

8. Challenges and Limitations in the Application of Phytoremediation

While phytoremediation is promising and environmentally friendly technology to reclaim a contaminated environment, it faces several challenges and limitations which include:

8.1. Slow Remediation Rate

The relative growth rate of plants and the time required for pollutant uptake and transformation is generally a slow process, hence it prolongs the overall remediation process. It takes many years to remediate significant amounts of pollutants from a contaminated site, especially when dealing with large-scale remediation areas [129].

8.2. Limited Plant Species

The effectiveness of phytoremediation depends on finding a suitable hyperaccumulator plant species for particular contaminants that possess the required characteristics of a good phytoremediation candidate such as extensive dense mass root system, fast growth, and high above the ground biomass production with high toxicity tolerance capacity [130].

8.3. Climatic and Site-Specific Factors

The efficiency and success of phytoremediation are influenced and limited by climatic/seasonal and site-specific factors such as extreme temperatures of cold or heat, soil type, soil pH, soil nutrient availability, and the presence of competing contaminants [131]. Therefore, to overcome this, careful site assessment and tailored phytoremediation strategies are highly recommended.

8.4. Potential Biomass Accumulation

The phytoremediation process can lead to the accumulation of highly contaminated plant biomass if not properly disposed of or handled. Therefore, to avoid re-contamination and unintended consequences, proper disposal and management of the harvested plant biomass is recommended [132].

9. Ongoing Research

The field of phytoremediation is rapidly growing and drawing the attention of the scientific community to elucidate new strategies to deal with toxic environmental contaminants. Hence, investigations in various areas of research are ongoing that could improve the existing phytoremediation strategies. The major areas of ongoing research in phytoremediation include;

9.1. Computational Modelling and Machine Learning Algorithm

In recent times, the use of computational modeling and machine learning algorithms have been employed by researchers to predict plant-microbe interactions and, the behavior of pollutants in the environment and select the best model that can be applied for an optimized phytoremediation strategy [123].

9.2. Bioaugmentation and Biostimulation Approach

Bioaugmentation is the addition of suitable microbes to the plants rhizosphere that aid the plant to degrade pollutants around the rhizosphere. This is achieved by adding microbes that are naturally present in the environment, or by adding microbes that have been specifically engineered to degrade pollutants. Biostimulation is the addition of nutrients to support the growth of microbes around the rhizosphere. This is achieved by adding nutrients, such as nitrogen and phosphorus, or by adding substances that can help to break down pollutants, such as chelating agents. Both Bioaugmentation and Biostimulation are currently being explored by researchers for optimization of phytoremediation outcomes [114].

9.3. Hybrid Remediation Systems Approach

The integration of phytoremediation with conventional remediation processes is currently being explored for a successful outcome. For instance, phytoextraction has been integrated with electrokinetic remediation to create a hybrid system for an improved phytoremediation process [133].

9.4. Genetic Engineering Approach

Advancements in the applications of genetic engineering such as synthetic biology and gene editing using CRISPR-Cas9 have offered the potential to engineer plants with precise modifications, targeting highly specific sequences of DNA and transferring or modulating some desired genetic traits to the plant genome for optimized phytoremediation strategies [113]. Therefore CRISPR-Cas9 aims to identify and manipulate genes that improve pollutant uptake, translocation, and tolerance in the potential plant candidates [27] [113].

10. Conclusion and Potential Future Prospect

Phytoremediation, an eco-friendly method of using plants for removing pollutants should be prioritized for environmental safety. In essence, as scientists continue to explore, phytoremediation will be more efficient, cost-effective, and widely applicable. However, it might be difficult to balance these with the safety of our environment, regulatory concerns, and public acceptability to ensure sustainable implementation. Nevertheless, the potential prospects for the improvement of phytoremediation can be achieved by collaborative efforts between researchers, governments, and stakeholders to address the aforementioned challenges. Despite its challenges, phytoremediation remains crucial for environmental sustainability. Also, extensive research for improved phytoremediation strategies is crucial in areas such as the development of engineered plant species for efficient phytoremediation, the development of new methods such as bioaugmentation for enhanced phytoremediation, and the development of new technologies to monitor and optimize phytoremediation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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