e-planet **22** (1): 1-10 (June 2024)

Medicinal plants as green remediation agents: Nano-phytoremediation for heavy metal contaminated soil

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Date of receipt: 28.02.2024 Date of acceptance: 26.04.2024

ABSTRACT

The demand for traditional herbal medicines has experienced significant growth worldwide, primarily for their use in drug formulations, cosmetics and nutraceuticals. A number of research studies on medicinal plant improvement focuses on understanding the effects of environmental stress on plant growth and development. This has led to the identification of physiological mechanisms that not only protect plants from adverse environmental conditions but also render them suitable candidates for phytoremediation, an effective method for removing pollutants from contaminated soil and water. These mechanisms play a crucial role in extracting, immobilizing or eliminating salts, metals and organic compounds from the soil and water. In medicinal plants, phytoremediation properties have the potential of precluding the safe use of the plant for human consumption while removing contaminants from soil or water. Heavy metal pollution poses a significant threat to both human health and the environment, endangering food chains and environmental sustainability. There is an urgent need to address this issue, especially considering the vulnerability of children and adult females to heavy metal contamination and its carcinogenic effects. Phytoremediation while utilizing aromatic and medicinal plants, offers a sustainable and practical solution to soil contamination without altering its biological or physical characteristics. The unique morphological characteristics and biosynthesis of secondary metabolites in medicinal plants make them ideal candidates for effective phytoremediation of heavy metals. Nano-phytoremediation, an emerging bioremediation approach utilizing biosynthesized nano-particles and plant species, has shown promising result as an efficient, economical and environmentally friendly technique for removing toxic heavy metals from the environment. Simulated nano-materials have been found to significantly mitigate the adverse effects of metal exposure on various plant species. This review aims to provide an update on recent studies focusing on the utilization of medicinal and aromatic herbs for phytoremediation of polluted soils containing heavy metals, highlighting its efficiency and sustainability compared to other methods.

Key words: Environmental stress, medicinal and aromatic plants, phytoremediation, pollutants

INTRODUCTION

The extraction of heavy metals from ores and their subsequent utilization across various industries has resulted in the release of certain harmful elements into the environment (Bogatu et al., 2007). As heavy metals cannot be broken down naturally, they tend to accumulate posing significant risks to both the environment and human health leading to contamination within the food chain (Vangronsveld et al., 2009). Their resistance to biodegradation processes makes heavy metal contamination a serious environmental threat. Prior research has indicated that heavy metals negatively impact biological processes, with their accumulation in various organs and are associated with health issues such as cancer, diabetes, developmental abnormalities, neurologic and behavioural disorders, and cardiovascular diseases (Briffa et al., 2020). Some heavy metals possess mutagenic and carcinogenic properties, while others can cause neurological and behavioural changes. A wide range of pollutants, broadly categorized as inorganic ions, organic pollutants, organo-metallic compounds, radioactive isotopes and gaseous pollutants are known to cause environmental pollution. Organic pollutants comprise of organo-chlorine insecticides, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons. Inorganic pollutants on the other hand include heavy metals and metalloids that pose significant challenges due to their non-biodegradable nature, severe toxicity and their tendency to accumulate in living organisms through the food chain (Kumar et al., 2016). Therefore, addressing the pollution caused by heavy metals requires urgent attention and there is a need to find effective and sustainable measures in order to control the same.

Phytoremediation is a promising method that involves the extraction and removal of elemental contaminants from the environment by plants, either in their natural state or through genetic modifications. Phytoremediation maximizes plants ability to absorb toxic metals into their tissues, thereby reducing the availability of inorganic contaminants in the soil (Antonio et al., 2017). In the unfavourable contaminated environments, where plant growth is usually hindered, various plants demonstrate the capability to thrive in both terrestrial and aquatic settings and exhibit significant variances in the absorption of toxic pollutants. The selection of an appropriate plant for phytoremediation relies on its capacity to absorb pollutants, especially where conventional crop plants may not be suitable (Hamzah et al., 2016).

Nano-phytoremediation is an emerging bio-remediation approach which uses biosynthesized nanoparticles from different plant species for the removal of toxic heavy metals from the environment. It is an efficient, economical, and environmental friendly technique. As nano-materials have tiny dimensions and huge surface area, these are known to have an attraction towards metals and hence quickly enter the contaminated zone of ecosystems. The current review provides an overview of various aspects of phytoremediation for heavy metal remediation.

TOXIC EFFECTS OF METAL STRESS ON PLANTS

Certain heavy metals, including cobalt (Co), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), zinc (Zn), and copper (Cu) play crucial roles in various plant development processes and are essential micronutrients for proper growth at low concentrations (Arif et al., 2016). They actively participate in important metabolic processes and serve as cofactors for numerous cellular enzymes, engaging in oxidation-reduction reactions. However, when the concentrations of these heavy metals exceed their threshold levels, they become toxic to the plant development (Table 1). These effects include the generation of reactive oxygen species (ROS), leading to oxidative stress, inhibition of cytoplasmic enzymes and damage to essential cell structures such as DNA, proteins, and lipids. Moreover, excessive concentrations of heavy metals can impede vital physiological processes, including photosynthesis, respiration, transpiration, mineral nutrition and biomass production, ultimately posing a risk of plant death. Metal toxicity has detrimental effects on plant roots, compromising their ability to effectively absorb water and essential nutrients from the soil. This disturbance in the normal functioning of roots and leaves can significantly impact key processes in the plant's life cycle, including flowering, fruiting, and seed formation.

Table 1. Toxic effects associated with elevated concentrations of heavy metals

Heavy metals	Toxic effects of heavy metals on plants
Cd	Reduction in biomass and root length; inhibition of seed germination; growth reduction; wilting; chlorosis, and cell damage
Cu	Inhibition of root, shoot and leaf development; quantity reduction in leaves per plant; decreased antioxidant activities; shoot length reduction; decreased total chlorophyll content; reduction in chlorophyl biosynthesis; decreased enzyme activities; decreased plant growth and yield; leaf chlorosis; generation of oxidative stress and ROS(reactive oxygen species)
Zn	Decreased total chlorophyll content; reduction in transpiration rate, inhibition of transport of microelements; limitation of root and shoot growth; reduction in photosynthetic and respiratory rate; enhancement of generation of reactive oxygen species; chlorosis in the younger leaves; reduction in germination
As	Inhibition of growth and low crop production; reduction in leaf quantities; chlorosis; leaf senescence necrosis; defoliation; reduction in shoot and root growth; restricted stomatal conductance and nutrient uptake; chlorophyll degradation; limited biomass and yield production; overproduction of ROS leading to carbohydrate, protein, and DNA damage.
Ni	Reduction in chlorophyll content; decreased levels of sugar, starch, and protein nitrogen; decrease in shoot yield; chlorosis; inhibition of root growth; inhibition of growth, induction of chlorosis, necrosis, and wilting; generation of ROS
Pb	DNA damage; decrease in chlorophyll content; decrease in protein content; stunted foliage; reduction in photosynthesis; impaired nutrient uptake; decrease in seed germination, root elongation, decreased biomass; inhibition of chlorophyll biosynthesis; inhibition of mineral nutrition and enzymatic reactions, induction of ROS production

*Jach et al., 2022

In response to exposure to heavy metals, plants have evolved detoxification mechanisms, categorized into avoidance and tolerance strategies. The avoidance strategy focuses on limiting the uptake of heavy metals and involves the contribution of factors such as mycorrhizae, extracellular exudates (including organic acids and amino acids), and the cell wall. On the other hand, the tolerance strategy comes into play once the metal ions have entered the cytosol, employing intracellular defence mechanisms. Chelation, achieved through the complexation of metal ions with ligands, is a key aspect of this strategy, with phytochelatins and metallothioneins being prominent peptide ligands (Arif et al., 2016).

Phytoremediation

Phytoremediation involves the utilization of plants to mitigate contamination in soil or water. This method has emerged as a cost-effective and widely accepted approach for addressing environmental pollutants due to its non-invasive nature. Plants play a crucial role in accumulating both organic and inorganic contaminants, metabolizing organic pollutants and promoting the microbial breakdown of contaminants in the root zone. However, the widespread adoption of phytoremediation faces limitations, such as the restricted habitat range or size of plants with remediation potential and the insufficient capacity of native plants to tolerate, detoxify, and accumulate contaminants. Plants have demonstrated the ability to survive comparatively high levels of xenobiotic chemicals without experiencing toxic effects. They can quickly absorb chemicals and transform them into less toxic metabolites. Hyper-accumulator plants are those plants that efficiently take up heavy metals from the soil and remove them from the environment (Singh et al., 2003).

Earlier used conventional methods, involving physical and chemical approaches, suffer from various drawbacks such as high expenses, labour intensiveness and alteration of soil characteristics and disruption of native soil microorganisms. Phytoremediation on the other hand involves leveraging plants and their associated soil microbes to reduce contaminant concentrations or their toxic effects in the environment. This approach is perceived as a cost-effective, efficient, innovative, environment friendly technology that garners positive public acceptance. It remains an active area of research, focusing on discovering new highly efficient metal hyper-accumulators for use in phytoremediation.

Mechanisms of phytoremediation

The process of hyper-accumulation of heavy metals encompasses the transport of metals across the plasma membrane of root cells, their access in xylem, subsequent translocation and finally, the detoxification and sequestration of metals. Several techniques for heavy metal phytoremediation exist, including rhizo-filtration, phyto-extraction, phyto-stabilization and phyto-volatilization (Fig. 1). Among these, phyto-extraction and phyto-stabilization are considered the most prominent methods for arsenic phytoremediation.

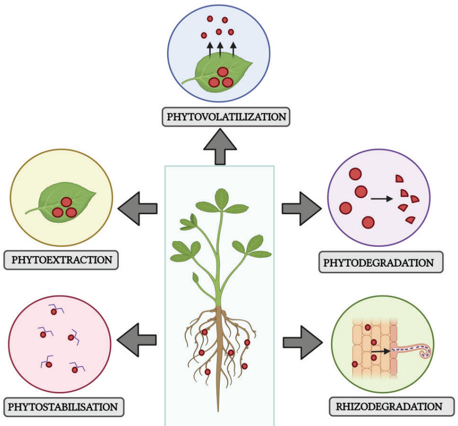

Fig. 1. Different mechanisms of phytoremediation

Phyto-extraction

Phyto-extraction refers to the process wherein plant roots uptake metal and metalloid contaminants from soil or water and subsequently transport and accumulate them in aerial parts of plants, which can then be safely disposed of in a designated area. The translocation of metals to the shoots is a vital biochemical process essential for effective phyto-extraction. This method is most suitable for stable and long-term heavy metal remediation (Vardhan et al., 2019). The effectiveness of phyto-extraction relies on the careful selection of plant species, with key factor being its metal-accumulating ability. The various stages of heavy metal phyto-extraction comprise of metal mobilization and uptake by plant roots, translocation from roots to aerial plant parts, and eventual compartmentalization and sequestration in plant tissues. *Trifolium alexandrinum* (Berseem), for example is known for efficient phyto-extraction of Cd, Zn, Cu and Pb due to its substantial biomass and rapid growth. There are plant species from Asteraceae, Brassicaceae, Fabaceae, Lamiaceae and Scrophulariaceae families that have been reported to hyper-accumulate heavy metals (Suman et al., 2018).

Phyto-filtration

Phyto-filtration involves the removal of pollutants from contaminated surface or wastewater either through rhizo-filtration (using plant roots) or blasto-filtration (employing seedlings) or caulo-filtration (utilizing excised plant shoots). Phyto-filtration helps to get the contaminants absorbed or adsorbed, thereby minimizing their movement into underground water sources. Rhizo-filtration is an environment friendly, effective and cost-efficient phyto-filtration that is used for the remediation of wastewater by absorbing and precipitating organic and inorganic contaminants on plant roots, effectively removing them from contaminated aquatic environments. Rhizo-filtration is particularly effective for remediating polluted areas contaminated with metals such as Cu, Cr, Cd, Ni and Pb. Different plant species, including Indian mustard, rye, spinach, sunflower and tobacco are found suitable for rhizo-filtration (Carolin et al., 2017).

Phyto-stabilization

This technique curtails the mobility and availability of pollutants, preventing their migration to groundwater and entry into the food chain. Plants achieve this by immobilizing heavy metals in soils through root absorption or precipitation, ultimately transforming the metals into less hazardous forms

(Mercedes et al., 2018). This method effectively inactivates and stabilizes heavy metals without removing them from the soil, thereby preventing groundwater pollution with heavy metals by impeding their percolation and mobilization. In a field study, *Populus nigra, Juglans regia* and *Salix alba* has shown phyto-stabilization capacity of Cu, Cr, As, Ni and Pb (Mataruga et al., 2020).

Phyto-volatilization

Phyto-volatilization involves plants absorbing pollutants from soil, transforming them into volatile forms, and subsequently releasing them into the atmosphere. This technique is suitable for organic pollutants and certain heavy metals like Hg, As and Se (Vangronsveld et al., 2009). It has limitation as the released compounds can contaminate the air, and there is a risk of recontaminating the soil through precipitation, making it an incomplete remediation method (Padmavathiamma et al., 2007).

Phyto-degradation

It refers to the breakdown of organic pollutants by plants with the help of enzymes like dehalogenase and oxygenase, without relying on rhizospheric microorganisms. Plants have the ability to accumulate organic xenobiotics from contaminated environments and detoxify them through their metabolic processes. Phyto-degradation specifically addresses the removal of organic pollutants as heavy metals are non-biodegradable. Recently, studies have also shown interest in exploring the phyto-degradation of various organic pollutants, including synthetic herbicides and insecticides (Doty et al., 2007).

Rhizo-degradation

Rhizo-degradation involves the decomposition of organic pollutants in soil by microorganisms in the rhizosphere. Increased microbial numbers leading to increased metabolic activities causes enhanced pollutant degradation in the rhizosphere. Plants stimulate microbial activity in the rhizosphere, boosting it by about 10 to 100 times through the secretion of exudates containing carbohydrates, amino acids and flavonoids. These exudates released by plant roots provide carbon and nitrogen sources for soil microbes, creating a nutrient-rich environment that fosters microbial activity. Additionally, plants release certain enzymes capable of breaking down organic contaminants in soils (Yadav et al., 2010).

Phyto-desalination

This process involves the use of halophytic plants or mangroves to extract salts from salt-affected soils, making them suitable for supporting normal plant growth and life cycle. Halophytic plants are naturally better adapted to cope with heavy metals compared to glycophytic plants that have been suggested for this purpose (Manousaki and Kalogerakis, 2011). Consequently, these plants can successfully accumulate NaCl from highly saline soils, enabling subsequent crop production after repeated cultivation and harvest.

PHYTOREMEDIATION POTENTIAL OF MEDICINAL PLANTS

The preference for medicinal plants over crop plants in phytoremediation can be attributed to several factors including the presence of a diverse array of secondary metabolites such as alkaloids, flavonoids and terpenoids which have properties of facilitating the absorption, sequestration or transformation of pollutants. These enhance the phytoremediation potential of medicinal plants compared to other crop plants (Angelova, 2013). Certain adaptive mechanisms are used by these plants to survive in environments with elevated levels of contaminants. These include enhanced tolerance to heavy metals or the ability to accumulate and store pollutants in specific plant tissues. Numerous plants have undergone investigation as potential phyto-remediators and many of them are categorized as hyper-accumulators which are plants capable of accumulating substantial amounts of metals in their root parts and subsequently transferring them to their aerial parts (Table 2).

The selection of an appropriate plant for contaminant removal is a crucial aspect of phytoremediation. Presently, researchers are actively seeking plants that not only possess efficient contaminant-accumulating capabilities but also have the potential to yield value-added products, either simultaneously or after the crop have been harvested. Various medicinal and aromatic plants have been identified as tolerant to both biotic and abiotic stresses. These plants demonstrate the ability to accumulate contaminants, making them suitable phyto-remediators (Jach et al., 2022).

Table 2. Heavy metal accumulator species of medicinal plants

Species	Family	Accumulated heavy metal toxic substance	Accumulator vegetative organ	Reference
Thalspi caerulescens	Brassicaceae	Zn, Cd	Shoots	Robinson et al., 1998
Catharanthus roseus	Apocynaceae	Cr	Roots, leaves	Subhashini et al., 2013
Brassica juncea	Brassicaceae	Se, Zn, Cu, Pb	Roots, shoots, leaves	Turan et al., 2007
		Atrazin	Roots	
		Cd	Roots, shoots	
Hypericum perforatum	Hypericaceae	Cu, Cd	Roots, shoots, leaves	Bonari et al., 2019
Bacopa monnieri	Plantaginaceae	Hg, Cd	Roots, shoots	Dineshkumar et al.,2019
Achillea milefolium	Asteraceae	Cu	Roots	Moklyachuk et al., 2012
Salvia officinalis	Lamiaceae	Cd	Shoots	Angelova et al., 2013
Centaurea cyanus	Asteraceae	Zn	Roots	Nouri et al., 2011
Echinophora platyloba	Apiaceae			
Ocimum basilicum	Lamiaceae	Cd	Roots, shoots, leaves	Bhatt and Gauba, 2021
Artemisia vulgaris	Asteraceae	Zn, Cu, Pb, Cd, Ni	Roots, shoots, leaves	Nikolić et al., 2015
Alyssum bertolonii	Brassicaceae	Ni	Roots	Robinson et al., 1997
Mentha spicata	Lamiaceae	Cr, Cu	Roots, shoots, leaves	Patel et al., 2016
Hippophae rhamnoides	Elaeagnaceae	Fe, Zn, Mn, Cu	Leaves, fruits	Bogatu et al., 2007
Rinorea niccolifera	Violaceae	Ni	Leaves	Fernando et al., 2014
Aloe vera	Asphodelaceae	Cd, Cr, Pb, Co, Ag, Se, Hg	Leaves	Elhag et al., 2018
Cannabis sativa	Cannabaceae	Pb, Cu, Zn, Cd, Ni	Shoots, roots, leaves	Ahmad et al., 2016
Urtica dioica	Urticaceae	Cr	Shoots, roots, leaves	Shams et al., 2010
Taraxacum officinale	Asteraceae	Cd, Cu, Zn	Leaves	Corneanu et al., 2016
Astragalus racemosus	Fabaceae	Se	Shoots, roots	Talukder et al., 2015

One notable example is *Vetiveria zizanioides*, commonly known as vetiver grass, which has been studied to be suitable for removing both organic contaminants (e.g., 2, 4, 6-trinitrotoluene, phenol and petroleum hydrocarbons) and inorganic contaminants, particularly toxic metals such as lead, cadmium, copper, zinc, and arsenic (Singhakant et al., 2009). Due to its substantial root biomass and the capacity to penetrate deep soil layers, it is considered suitable for remediating deeply contaminated soil. It is shown to be a potential phyto-remediator of arsenic (As) when cultivated in various soil types (Datta et al., 2011).

Hypericum perforatum L., a medicinal plant known for its antidepressant properties has also demonstrated an excellent ability to accumulate a substantial amount of cadmium (Cd) in aerial parts without significant negative effects on plant growth and dry biomass (Bonani et al., 2019). Another studies suggested that active compound hypericin present in essential oil, was not adversely affected by chromium (Cr) when cultivated in Cr-contaminated media (Schneider and Marquard, 1996).

Ricinus communis L., commonly known as castor, has been used as a medicinal plant, known to have properties such as anti-inflammatory, antitumor and anti-asthmatic. It is known to be a robust phyto-remediator for cleaning up various organic and inorganic type of pollutants (Adhikari and Kumar, 2012). This plant has also demonstrated the ability to accumulate higher amounts of heavy metals such as Cd, Ni, Pb, Cu, As, Cr, Zn, Ba etc.

Ocimum basilicum L. has demonstrated efficiency in accumulating chromium (Cr) in its tissues, employing a defence mechanism by sequestering the metal in its roots. A recent study has also highlighted the suitability of *Ocimum basilicum* for phytoremediation of Cd-contaminated soils (Bishehkolaei et al., 2011 and Bhatt and Gauba, 2021).

Cannabis sativa L. (hemp) grown in Ni, Pb, and Cd-contaminated soil has also showed the highest metal accumulation in leaves with no adverse effects on fibre quality and enhanced phytochelatin production, indicating a strong defence mechanism against metal toxicity (Citterio et al., 2003). *Allium sativum* (garlic) has also exhibited efficiency in accumulating cadmium in its roots, displaying tolerance toward Cd without toxic effects at lower concentrations (Jiang et al., 2001).

NANO-PHYTOREMEDIATION

Nano-technology is recognized as an advancing field with diverse applications in sectors such as agriculture, packaging, medical diagnostics, pharmaceuticals, nano-based encapsulation of pesticides, genetic material delivery in plants, human drug delivery and cancer treatment (Bhatt and Tripathi, 2011). The nano-particles produced through this process are referred as engineered nano-particles (ENPs), with at least one external dimension between 1 and 100nm. Nano-remediation encompasses the application of reactive nano-particles to contaminated soil or water, aiming for the transformation or detoxification of pollutants (Karn et al., 2009). The increasing adoption of nano-based materials for environmental cleanup arises from the urgent need for a technology that is cleaner, affordable, readily available, cost-effective and quicker in delivering results without imposing additional burden on the cleanup processes. A few nano-particles (NPs) which are proven to be efficient in environmental remediation include zinc oxide NPs (ZnO), TiO_2, multiwalled carbon nanotubes (MWCNTs), fullerenes NPs, nanoscale zerovalent iron (nZVI), salicylic acid NPs, silicon NPs and silver NPs etc. are widely employed in nano-phytoremediation efforts targeted at different heavy metals. For instance, the use of nanoscale hydroxyapatite has exhibited potential in mitigating Cd toxicity in mustard plants. The use of iron oxide nano-particles (Fe_3O_4 NPs) in cadmium-contaminated soil has shown results in reducing the adverse effects of cadmium, increasing plant growth rate, antioxidant enzymes and photosynthetic activity. Chromium-contaminated soil has been remediated using carboxymethyl cellulose (CMC)-stabilized nanoscale zero-valent iron (nZVI), leading to a significant improvement in chromium immobilization.

Due to their size and inherent properties, nano-materials possess larger surface areas, providing higher absorption sites, making them effective absorbents (Gong et al., 2018). Additional advantageous properties include lower temperature modification, adjustable pore size, and diverse surface chemistry. These characteristics render nano-materials exceptional catalysts capable of facilitating chemical reduction and catalysis for the mitigation of pollutants present in soil environments, such as heavy metals, organochlorine pesticides and polycyclic aromatic hydrocarbons (PAHs). As a result, nano-materials have gained significant attention and are actively being explored for soil remediation efforts.

ACTION OF NANO-PARTICLES TO ALLEVIATE THE HEAVY METAL STRESS

It is important to note that the use of nano-materials in phytoremediation can have varying effects on different plant species and contaminants. Some studies indicate that nano-materials can regulate gene expressions related to water homeostasis, metal stress, cell wall production, oxidative stress, cell division and photosynthetic processes, thereby promoting heavy metal accumulation in plants. On the other hand, the integrated effects of certain nano-materials may exacerbate toxicity and increase the production of reactive oxygen species (ROS) in specific organisms. Nano-particles enter plant cells either through plasma membrane channels or penetration, acting as signal molecules that induce stress signalling genes, thereby activating the plant defence system. Nano-particles transform or absorb heavy metals in the soil, minimizing their bioavailability and mobility. Within the plant cell wall, nano-particles form complexes by binding with heavy metals, rendering them biologically unavailable. These complexes are then adsorbed on the plant cell surface, hindering their migration throughout the plant and minimizing their biological activities (Wang et al., 2021). Additionally, damage caused by heavy metal stress in plants can be partially reduced by chelating organic acids accumulated in their cell walls.

To alleviate heavy metal stress, plant oxidation defences can be activated. Biochemical reactions in plants generate reactive oxygen species (ROS) as by-products, which, at lower concentrations, act as signalling molecules for growth, defence and development. However, under stressed conditions, ROS accumulates in higher concentrations, leading to damage to proteins, cell membranes and other cellular components. Antioxidant enzymes play a crucial role in maintaining ROS levels in plant cells, scavenging these reactive species when present in high levels. Enzymes such as peroxidase (POD), superoxide dismutase (SOD), ascorbate peroxidase (APX), catalase and glutathione reductase (GR) are responsible for ROS scavenging. In response to stress, plants activate ROS clearance pathways. Plants employing antioxidant enzyme-activated nano-particles such as CeO_2 NPs, Mn_3O_4 NPs, and Fe_3O_4 NPs can effectively reduce ROS, ultimately mitigating the negative effects on crop production. This highlights the potential of nano-materials in enhancing plant stress tolerance and mitigating the impact of environmental stressors on crop productivity. While nano-phytoremediation shows promise for enhancing the efficiency of phytoremediation, careful consideration and further research are needed to understand the diverse effects of nanomaterials on different plant species and their interactions with contaminants and optimize application of nanotechnology for sustainable environmental remediation.

CONCLUSION

Heavy metal contamination posses a significant threat to various living organisms due to its harmful effects. Several techniques have been employed to clean up contaminated soils and among them, phytoremediation has emerged as a promising environment friendly method. The effectiveness of phytoremediation is influenced by the plant's ability to absorb heavy metals, transport and accumulate them within the plant and their capacity for high biomass production in contaminated soil. However, phytoremediation has certain drawbacks, especially in areas with moderate to high levels of contamination. The process is time-consuming and may take time to clear up heavy metal-affected soil. One contributing factor to this delay is the slow growth rate and limited biomass production of hyper-accumulator plants. To enhance the efficiency of phytoremediation, optimizing the performance of plants becomes crucial. Genetic engineering presents itself as a powerful tool for modifying plants to exhibit desired properties such as rapid growth, increased biomass production, high tolerance to heavy metals and adaptability to diverse climatic and geological conditions. This approach holds the potential to address the limitations associated with the natural capabilities of hyper-accumulator plants. Despite the progress made in utilizing genetic engineering for phytoremediation, further research is needed to understand the factors and mechanisms that control the efficacy of this strategy. The on-going research will contribute to the development of highly effective phytoremediation techniques, providing sustainable solutions for mitigating the impact of heavy metal contamination in soils.

ACKNOWLEDGEMENT

Authors are thankful to the authorities of Delhi Technological University to extend support to undertake the study.

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