E-ISSN: 2618-0618
P-ISSN: 2618-060X

www.agronomyjournals.com
2024; 7(7): 745-753
Received: 28-04-2024
Accepted: 30-05-2024

Kamble Vivek
M.Sc. Research Scholar,
Department of Soil Science and Agricultural Chemistry, Lovely Professional University, Phagwara, Jalandhar, Punjab, India

Robert Wayembam
M.Sc. Research Scholar,
Department of Soil Science and Agricultural Chemistry, Lovely Professional University, Phagwara, Jalandhar, Punjab, India

Princy Thakur
Assistant Professor,
Department of Soil Science and Agricultural Chemistry, Lovely Professional University, Phagwara, Jalandhar, Punjab, India

Meraj Ahmed
Assistant Professor,
Department of Soil Science and Agricultural Chemistry, Lovely Professional University, Phagwara, Jalandhar, Punjab, India

Corresponding Author:
Meraj Ahmed
Assistant Professor,
Department of Soil Science and Agricultural Chemistry, Lovely Professional University, Phagwara, Jalandhar, Punjab, India

Advanced phytoremediation strategies: Tackling heavy metal contamination in agricultural soils

Kamble Vivek, Robert Wayembam, Princy Thakur and Meraj Ahmed

DOI: https://doi.org/10.33545/2618060X.2024.v7.i7i.1130

Abstract
The extensive contamination of heavy metals caused by human activities has resulted in a significant global concern regarding soil pollution. The application of agrochemicals and the use of irrigation water that is contaminated have resulted in increased concentrations of chromium (Cr), copper (Cu), cobalt (Co), cadmium (Cd), and lead (Pb) in arable soils. This has had a negative influence on the overall health of the soil and the ecosystems it supports. These metals, which are resistant to decomposition and cannot be broken down by natural processes, infiltrate the food chain, so presenting substantial hazards to the health of both humans and animals. Volcanic eruptions and forest fires are natural sources of heavy metals, but human activities, particularly industrial processes, greatly worsen contamination. The remediation of soils polluted with heavy metals is a difficult and expensive process that requires the use of physical, chemical, and biological techniques. Conventional treatments frequently disturb soil characteristics and the indigenous microorganisms. Phytoremediation, on the other hand, provides a sustainable and cost-effective approach by using hyperaccumulators and microbes to trap and remove dangerous metals. Phytoextraction, Phyto stabilization, phytovolatilization, and Rhizo-filtration are methods that utilize plants' ability to absorb, stabilize, or volatilize pollutants, therefore converting polluted areas into safer surroundings. Nevertheless, the effectiveness of phytoremediation is restricted by the amount of plant biomass and the capacity of plants to absorb metals, which requires improvement using chemical agents, agronomic techniques, and genetic engineering. Novel techniques, such as rhizo-degradation and phytodegradation, utilize the interactions between plants and microbes to break down organic contaminants. Similarly, modern technologies like Phyto desalination and wetland restoration employ halophytic vegetation and artificial wetlands to control levels of salt and toxins. Although there have been notable breakthroughs, there are still obstacles to overcome in enhancing the absorption of metals, increasing biomass output, and ensuring the proper disposal of contaminated plant waste. Genetically modified plants and energy crops have the potential to produce greater amounts of biomass and recover metals, however, they encounter obstacles related to regulations and safety. By integrating these many tactics, the total effectiveness of phytoremediation can be improved. This holistic strategy helps to reduce heavy metal contamination in soils, safeguard ecosystems, and ensure the safety of food.

Keywords: Phytoremediation, phytoextraction, phyto-stabilization, bioremediation, phytovolatilization, phytodegradation, phytodesalination

Introduction
Soil pollution caused by human activities has led to significant levels of heavy metal contamination, which is now a global concern. The application of agrochemicals and contaminated irrigation water has resulted in elevated levels of heavy metals, such as chromium (Cr), copper (Cu), cobalt (Co), cadmium (Cd), and lead (Pb), in arable soils. This has led to a decline in soil health, as reported by Kaur *et al*. in 2023. The imprudent utilization of these compounds leads to contamination (Ruba *et al*., 2023) [78]. Heavy metals present in fertilizers have a non-biodegradable characteristic, which means they can persist in soil for extended periods of time. Eventually, these metals reach the food chain through the soil (Thakur *et al*., 2022) [97]. Heavy metals are derived from both natural and manmade sources. Heavy metals are commonly linked to volcanic eruptions, wind erosion, forest fires, and the overall use of fossil fuels. Metals derived from natural sources generally have a lesser impact on the environment, while metals originating from human activities such as smelters, thermal power plants, mines,

and foundries offer a significant risk to humanity (Angon *et al*., 2024) [7]. Eliminating heavy metals from the environment is exceptionally challenging due to their resistance to degradation, which renders them impervious to both biological and chemical processes. Different technologies are used for the removal of heavy metals from contaminated soil, both on-site and off-site. Several prevalent technologies include chemical elimination, electrophoresis, excavating, mechanical breaking down, soil cleaning, soil flushing, solidifying, and Nitrification (Wu *et al*., 2024) [101].

Over time, the gradual accumulation and interactions of heavy metals (HMs) in the soil can have detrimental effects on the ecosystem, presenting significant risks to living organisms. Vegetables could absorb heavy metals (HMs) and store them in sections that are safe for consumption (Madhav *et al*., 2024) [57]. Heavy metals are a significant source of pollution that has a widespread impact on plants and animals worldwide (Angon *et al*., 2024) [7]. Crops cultivated in soils contaminated with metals have a propensity to accumulate high levels of heavy metals, which poses a significant threat to the health of humans and animals (Ene *et al*., 2024; Hamoud *et al*., 2024) [25, 37]. Cropping practices and soil parameters have an impact on the heavy metal concentrations in agricultural soil (Xu *et al*., 2022; Srinivasarao *et al*., 2014) [102, 93]. Excessive amounts of heavy metals such as Cobalt (Co), Chromium (Cr), and Copper (Cu) might interfere with the regular functioning of organisms, despite their importance in plant and animal metabolism (Noor *et al*., 2024: Javed and Usmani 2013) [64, 43]. It is well-established that Cd and Pb exhibit considerable toxicity and carcinogenicity in both animals and humans (Cirovic and Satarug 2024) [19]. Prolonged exposure to heavy metals by inhalation, ingestion, or contact with air, water, soil, and food can lead to a range of health conditions including cancer, neurological disorders, heart attacks, hypertension, skin abnormalities, damage to internal organs, and dysfunction of the urinary, reproductive, and respiratory systems (Nucera *et al*., 2024) [65]. Lead (Pb) can endure in soil for a duration of 150–5,000 years and maintains elevated levels for as long as 150 years after sludge is applied to the soil (Beiyuan *et al*., 2020) [11]. On the other hand, the biologically active half-life of cadmium (Cd) is around 10–30 years (Azhar *et al*., 2022) [9].

Remediation of polluted soil

The remediation of soils contaminated with heavy metals is of paramount importance to mitigate their adverse effects on ecosystems (Saxena *et al*., 2020) [81]. This job is difficult in terms of both expense and technological complexity (Selvi *et al*., 2019) [83]. Thus far, various physical, chemical, and biological methods have been utilized for this objective. The usual procedures for remediating contaminated soil include in situ vitrification, soil incineration, excavation and landfill, soil washing, soil flushing, solidification, and stabilization using electro-kinetic devices (Razzak *et al*., 2022; Vardhan *et al*., 2019) [77, 99]. In general, physical and chemical treatments have drawbacks such as being expensive, labor-intensive, causing permanent changes in soil parameters, and disrupting the natural soil microbiota (Osman 2018) [68]. Chemical processes might potentially give rise to other pollution issues. Hence, it is imperative to conduct research in order to devise economical, highly efficient, and environmentally sustainable techniques for purifying heavy metal-contaminated soils (Azhar *et al*., 2022) [9]. Phytoremediation is a revolutionary method that is seen as an environmentally friendly answer to the issue of heavy metal contamination (Padbhushan and Kumar 2024) [69].

Phytoremediation Techniques

Phytoremediation is a specialized approach that effectively reduces environmental contamination. Hyperaccumulators, which are plants capable of absorbing heavy metals from both above and below ground, play a crucial role in this process. Microorganisms possess a high level of proficiency in the process of sequestering hazardous metals (Padbhushan and Kumar 2024) [69].

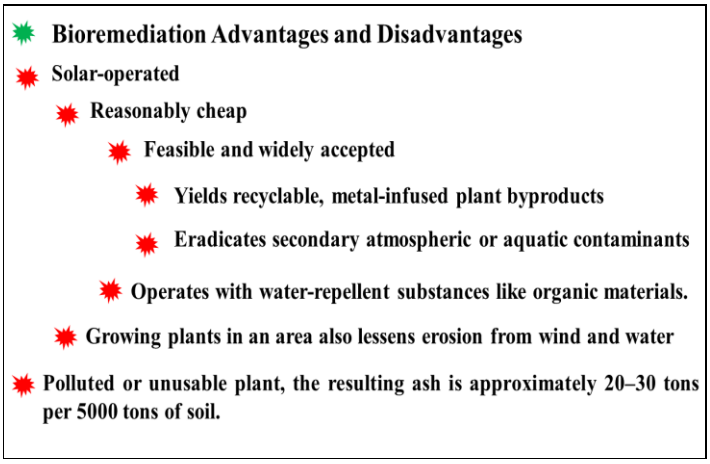
Bioremediation

Micro-organism-based cleanup approaches, including bioremediation procedures have the capacity to breakdown and detoxify certain pollutants. While these biological systems may be less adaptable to adverse environmental conditions compared to other conventional approaches, they are less expensive. Bioremediation encompasses a range of methods that utilize plants, microbes, and animals to address and mitigate the presence of pollutants. The technology described is a novel and effective method for remediation of heavy metal-contaminated environments. Importantly, it does not have any negative impacts on the surrounding environment (Gomes *et al*., 2016) [51].

Advantages and disadvantages of bioremediation

The advantages of bioremediation are numerous when compared to other technologies, which are:

- Feasible and widely accepted (Muhammad *et al*., 2024) [60].
- Reasonably cheap (Padma *et al*., 2024) [70].
- Eradicate secondary atmospheric or aquatic contaminants (Bustamante-Torres *et al*., 2024) [13, 14].
- Even if polluted and unusable plant, the resulting ash is approximately 20–30 tons per 5000 tons soil (Adepoju *et al*., 2024) [1].
- Growing plants in an area also lessens erosion from wind and water.
- Operate with water- replant substances like organic material (Patel and Kulwant 2024) [73].
- Solar-operated.
- Generates recyclable metal-rich plant residue (Hu *et al*., 2024) [38, 39]



Phyto-remediation

The process is rooted in plants and encompasses the activities of translocation, accumulation, transport, transformation, and volatilization (Lavanya *et al*., 2024) [52]. In addition, the ability of certain plant species (more than 400) to remediate has been verified (Wang *et al*., 2024) [100]. The technology is highly promising and efficient, with no adverse effects. Nevertheless, the limited ability of heavy metals to be absorbed by plants in soil and the low amount of plant biomass have hindered the effectiveness of this technique. Nonetheless, several diverse approaches have been employed to improve its efficiency. The methods encompass microbiological, physical and chemical, agronomic, and genetic engineering techniques (Hu *et al*., 2024) [38, 39]. Phytoremediation of soil contaminated with heavy metals involves the use of one or more mechanisms of phytoremediation. The primary methods of phytoremediation are phytoextraction, it Phyto-stabilization, phytovolatilization, and rhizo-filtration, as described by Madhav *et al*. (2024) [57].

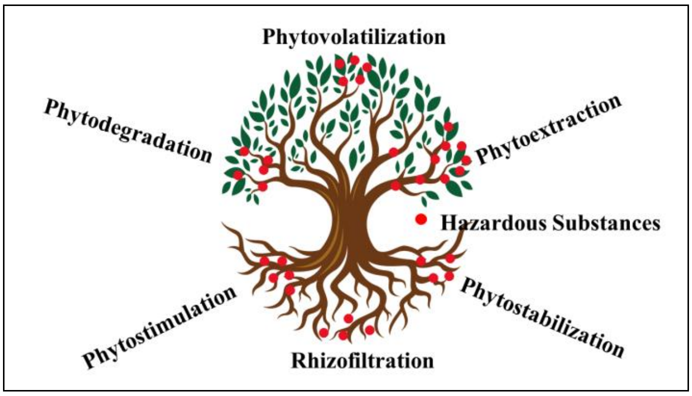


Fig 1: Different Phyto-remediation techniques

Phytoextraction

Plants absorb contaminants from the soil, water, or sediments through their roots and transport them to the aboveground biomass, where they collect in shoots or other sections of the plant that can be harvested. The technique is referred to as phytoextraction, as documented by Singh *et al*. (2024) [89] and Madhav *et al*. (2024) [57]. The transfer of metals to the shoot is an important biochemical process that is necessary for efficient phytoextraction, as it is usually not possible to harvest the root biomass (Yin *et al*., 2024; Deng *et al*., 2024) [106, 23]. Phytoextraction is regarded as a low impact technology, which means it has environmental advantages. In addition, the Phyto-extraction technique involves the use of plants to provide soil cover, which effectively reduces erosion and leaching. By using a process of repeated cultivation and gathering, it is possible to diminish the concentration of pollutants in the soil (Lavanya *et al*., 2024) [52]. The effectiveness of phytoextraction as an environmental remediation method depends on several factors, such as the accessibility of heavy metals, soil properties, the chemical form of heavy metals, and the plant's ability to absorb metals and accumulate them in aboveground parts. Around 450-500 distinct plant species have been identified as hyperaccumulators (Das *et al*., 2024) [21]. To be acceptable for phytoextraction, plant species must possess the following characteristics: (I) the ability to tolerate hazardous metals, (II) the capacity to produce a large amount of biomass, and (III) the capability to actively accumulate heavy metals in sections that may be easily harvested (Pajevic *et al*., 2016) [71]. The fundamental concept underlying phytoextraction in contaminated environments involves cultivating appropriate plant species on-site, harvesting the biomass containing heavy metals, and subjecting it to various treatments such as composting, compressing, dehydrating, and thermal breakdown to reduce its mass and size. The resulting biomass, which is enriched with heavy metals, contains significant amounts of metal pollutants. If it is economically viable, this biomass can be used to recover trace elements again or disposed of as hazardous waste with great care (Patra *et al*., 2020) [75]. (Evangelou *et al*., 2007) found that maize (Z. mays L.) has a notable ability to collect and accumulate phytochemicals from the soil. The potential was further enhanced by the inclusion of the metal chelating agent EDTA, resulting in a greater than thirteen times increase in the amount extracted of Lead and a greater than three times rise in the recovery of Cd. (Shiyab 2018) [88] conducted a study to explore the ability of three types of lettuce (Romaine lettuce, Redina lettuce, and iceberg lettuce) to accumulate copper (Cu) contamination. The study found that Redina lettuce has a high capacity for accumulating Cu. The root tissue exhibited an accumulation of 1.89 mg kg^{-1}, whereas the shoot tissue showed an accumulation of 0.71 mg kg^{-1}, which is comparatively high in relation to these three types of lettuces (Shiyab 2018) [88].

Phyto stabilization

Phyto stabilization, also known as Phyto immobilization, refers to the utilization of specific plants to stabilize pollutants present in polluted soils (Alkorta, 2010) [5]. The purpose of this strategy is to decrease the movement and accessibility of contaminants in the environment, hence preventing their movement into groundwater or their introduction into the food chain (Yaqoob *et al*., 2024) [105]. Plants can trap heavy metals in soils by absorbing them through their roots, causing them to precipitate, forming complexes, or reducing the metal's valence in the rhizosphere (Shackira *et al*., 2019) [84]. Utilizing metal-tolerant rhizobacteria that produce organic acids, either independently or in conjunction with biogas residues, effectively mitigates soil contamination by Cd through the stabilization of maize roots and the restriction of translocation to shoots (Tahir *et al*., 2021) [95, 96]. Additionally, it aids in enhancing the yield, quality, and physiological characteristics of maize biomass. In addition, the use of chicken manure alone or in conjunction with biogas wastes increases the movement of Cd to the shoot. The production of organic acids in the exudates of maize roots has a crucial role in stabilizing cadmium (Cd) in both the roots and shoots of the plant (Sohail *et al*., 2019) [91]. The generated amount of organic acid was increased as a consequence of to metal-tolerant rhizobacteria that benefit plants and biogas residues. However, the production was not as effective when poultry waste was used, resulting in a decrease in the Cd level in the root (Tahir *et al*., 2021) [95, 96]. Phyto stabilization halts the movement of pollutants in the root zones of plants, preventing them from entering the vegetative sections (Ogundola *et al*., 2022) [67]. This strategy can facilitate the restoration of flora in polluted areas with elevated metal levels, where the growth of natural vegetation is not feasible. Metal-tolerant plant species can be used as phyto stabilizers to restrict the movement of different pollutants through wind, rain, and leaching into groundwater sources (Adki *et al*., 2014) [2].

Phyto volatilization

Phytovolatilization is the process in which plants absorb heavy metal pollution and convert them into less harmful chemical species that may easily evaporate by transpiration. Certain heavy metals, such as Hg and Se, can be present in the environment in the form of gaseous species (Nwogwu *et al*., 2024) [66]. Several plants, including musk grass (Chara canescens), Indian mustard (Brassica juncea), and Arabidopsis thaliana, whether naturally occurring or genetically modified, have the ability to take in toxic substances and convert them to gaseous state before distributing these individuals into the surrounding atmosphere (Jabeen *et al*., 2009) [41]. Phytovolatilization can be regarded as a long-term solution for site remediation, as the gaseous products that are released are highly improbable to re-deposit at or near the site. While the understanding that microbes contribute significantly to the release of selenium from soils has been established for a considerable period, a subsequent study by Ogundola *et al*., (2022) [67] demonstrated that plants are also capable of performing this function. Alternatively, the items that have undergone remediation might be utilized for a multitude of applications in different remediation methods. Phytovolatilization should be avoided in densely populated cities and areas with atypical weather patterns since these locations can accelerate the release of volatile chemicals (Nissim *et al*., 2021) [63]. This method is applicable for the removal of organic contaminants as well as some heavy metals such as mercury (Hg) and selenium (Se). Nevertheless, its effectiveness is constrained by the fact that it does not eliminate the pollutant; rather, it only transfers it from one medium (soil) to a different medium (atmosphere), where it can potentially be redeposited. Phytovolatilization is the most contentious among the several phytoremediation processes, (Aithani and Kushwaha 2024) [3].

Phytodegradation

Phytodegradation refers to the process of breaking down organic pollutants using enzymes like dehalogenase and oxygenase, which are found in plants. This process does not rely on microorganisms in the rhizosphere (Maurya *et al*., 2023) [58]. Plants have the ability to gather organic contaminants from contaminated surroundings and eliminate them via the process of metabolism (Khan *et al*., 2023) [49]. From this perspective, green plants might be seen as the "Green Liver" of the biosphere. Phytodegradation exclusively targets the elimination of organic contaminants, while heavy metals are nonbiodegradable (Corami 2023) [20]. In recent times, researchers have displayed their fascination with investigating the process of phytodegradation of diverse organic pollutants, which encompasses synthetic herbicides and insecticides (Dehghani *et al*., 2024) [22]. Phytodegradation involves the uptake of pollutants by plants, which subsequently break them down into less hazardous and simpler forms. Breakdown in plants can occur in two ways: firstly, through metabolic processes that take place within the plant itself, and secondly, through the action of enzymes that are generated by the plant. The plant utilizes the pollutants that are decomposed into simpler substances to promote accelerated development (Pathak *et al*., 2024) [74]. Phytodegradation is a process that can break down solvents with chlorination, pesticides, and various other organic molecules, as well as other inorganic compounds (Gupta *et al*., 2024) [36]. Nitro reductase, laccase, dehalogenase, peroxidase, and nitrilase are catalysts that facilitate the mechanism of photo-degradation (Rani and Kumar 2024) [76].

Rhizo-degradation

Rhizo-degradation is the process by which microbes in the rhizosphere decompose up organic contaminants in the soil. The rhizosphere, which is approximately 1 mm in size, encompasses the area around the root and is subject to the plant's effect (Bansal *et al*., 2024) [10]. The primary factor contributing to the accelerated breakdown of contaminants in the rhizosphere is most likely the augmentation of microbial populations and their metabolic functions. Plants can enhance microbial activity in the rhizosphere by secreting exudates that contain sugars, amino acids, and flavonoids. This stimulation can increase microbiological activity by a factor of 10 to 100 (Eze and Amuji 2024) [28, 29]. Plant roots emit exudates that contain nutrients, which serve as carbon and nitrogen sources for soil microorganisms. This process creates a nutrient-rich environment that promotes microbial activity. Plants not only secrete organic substances to support the growth and functions of microorganisms in the rhizosphere, but they also produce specific enzymes that can break down organic pollutants in soils (Boujelben *et al*., 2024) [12]. Rhizo-degradation, also known as Phyto stimulation or improved rhizosphere biodegradation, is the process of soil pollutants being broken down by microorganisms in the soil, which is facilitated by the unique properties of the rhizosphere. Soil microorganisms play a crucial function in enhancing the accessibility of nutrients and the production of plant growth regulators (Gatla *et al*., 2024) [32]. Simultaneously, they engage in several processes that alter organic materials in the soil and contribute to the breakdown of foreign substances. Another role is to engage in the adsorption and desorption of different substances and the detoxification of both organic and inorganic contaminants (Ethiraj *et al*., 2024) [26]. Plants secrete chemicals that facilitate the establishment of microbes in the root area through advancement, adsorption, and the presence of polymers. This mutualistic relationship aids the plant in overcoming both living and non-living challenges (Shashirekha *et al*., 2024) [86].

Phyto desalination: This approach has been recently published and is currently emerging. Plant-based desalination is the process of using halophytic vegetation to extract ions from salt-affected soils, making them suitable for normal plant growth (John *et al*., 2024) [46]. According to Chen and Wang (2024) [100], halophytic crops are believed to possess inherent advantages in dealing with pollutants as opposed to glycophytic vegetation.

Rhizo-filtration

Rhizo-filtration, also known as hydraulic control, is a technique that relies on the ability of plant roots to collect and isolate metal contaminants from water. The process of phytoremediation can effectively remove metals including Cd, Cr, Cu, Ni, Pb, and V, as well as radionuclides like U, Cs, and Sr (Gatla *et al*., 2024; Jan *et al*., 2024) [32, 42]. Trees with extensive root systems can take in a significant amount of water, which was used as a main ingredient in this process. Long-rooted trees function as hydraulic pumps, extracting substantial quantities of water from the underground water table (Umid *et al*., 2024) [98]. Hence, impurities present in the water column are assimilated together with the water during this process. Root exudates, such as citric acid and malic acid, could either remove or increase the uptake, attachment, or settling of contaminants (Zou *et al*., 2024) [108].

Table 1: Different plant species used for metal accumulation using rhizo-filtration technique

Sr. No.	Plant species	Metal	Referances
1	Water hyacinth	Cd, Pb, and Zn	Yadav *et al*., (2015) [104]
2	Duckweed	Pb, Cd, Cu, Zn, Ni, and Cr	Kaur and Kanwar (2021) [48]
3	Tobacco	Cd and Zn	Kozak and Antosiewicz (2022) [50]
4	Sunflower	Cu, Cd Cr, Ni, Pb, Zn, and Fe	Nikolic and Stevovic (2015) [62]
5	Spinach	Pb, Cd, Cu, Ni, Zn, and Cr,	Sharma *et al*., (2020) [85]
6	Rye	Cd, Pb, Cu, Mo, Ni, and Zn	Nepal *et al*., (2024) [61]
7	Indian Mustard		

Metallophytes: Metallophytes are vegetation that possess specialized adaptations enabling them to flourish in soils that contain high concentrations of heavy metals (Smriti *et al*., 2024) [90]. Plants that are resistant to heavy metals are typically found in soils where ores are exposed, known as metalliferous or orogenic lands (Amils *et al*., 2024) [6]. The prolonged exposure of metallophytes to an excess of different metals for thousands of years has led to the development of metal resistance in these plants, adapting to the specific environmental circumstances of their local habitat. Mining operations have caused considerable damage to metal-rich habitats, resulting in a reduction in suitable environments for metallophytes, as documented by Saad *et al*. (2024) [79]. The plants are found within the plant family Brassicaceae. The utilization of these substances, either alone or in conjunction with microorganisms, for the process of phytoremediation in soils that are polluted with heavy metals, is a highly appealing concept. Metallophytes can be classified into three distinct.

Categories: Metal excluders, metallic indications, and metals hyperaccumulators of nutrients (Zhakypbek *et al*., 2024) [107].

Enhancement of plant-based remediation strategies

Plant-based remediation might be improved through the utilization of chemical or biological techniques (Madhav *et al*., 2024) [57]. There are multiple methods to improve phytoremediation procedures.

Augmented contaminants phytoextraction using chemical agents.

Compounds or surfactants as well including CDTA (Xu *et al*., 2024) [103], EDTA (Alam *et al*., 2024) [4], DTPA (Lindsay and Norvell 1969) [55], EGTA & CA (Su *et al*., 2024) [94], can enhance the movement of metals in soil. By utilizing these compounds, the rate at which metals are absorbed into the plants is further improved (Shen *et al*., 2024) [87]. Nevertheless, there exist specific risk factors, such as the process of metals leaching into the groundwater. In addition, these soil amendments can potentially endure in the environment, leading to the emergence of unforeseen complications (Selvam *et al*., 2024) [82].

Methods of agricultural work: The incorporation of chemical fertilizers, sources of carbon, and various other methods of agriculture can enhance the development of plants and microbial reproduction (Samantaray *et al*., 2024) [80]. One example is a multi-process structure that includes land farming (aeration and light exposure), microbial inoculation (introduction of contaminant degrading bacteria), and the phytoremediation (plant development) to increase the rate of uptake for organic pollutants from soil, thereby promoting the overall health and vitality of the ecosystem. The outcome obtained from this procedure indicated that the remedial impact was augmented by 50% (Aransiola *et al*., 2024) [8].

Techniques involving the interaction of plants and microbes

Microbes can be introduced into the root zone of soil to improve the phytoremediation mechanism. This approach is highly efficient in removing the pollutant from the soil. An instance of this phenomenon is the documented enhancement of absorbance and assimilation in plants when mycorrhizae are introduced to their roots (Liu *et al*., 2024) [56].

Wetland environment

There are two broad types of wetland plants that exhibit significant diversity and can be utilized for the purpose of restoration. Emergent plants, as described, are characterized by having the majority of their components situated above the surface of the water, with their stems anchored in shallow water. Submerged plants, as noted by Cahoon (2024) [15], yield a greater amount of biomass compared to other plants. This biomass is crucial for the absorption of decontaminants, as highlighted by Gaballah *et al*. (2024) [31]. A built wetland is employed to decelerate the flow of water in polluted areas and effectively capture toxins such as heavy metals. Additionally, it serves as a means of enhancing the aesthetic appeal of the wetland through landscaping efforts (Lim 2024) [54].

genetically developed plants

Plants that have undergone genetically modified can help during the phytoremediation operation. By changing the genes of hyper-accumulator plants, it is possible to get more biomass and metals out of the ground. But because of safety and legal issues, these plants can't be used for business. The MT-I trait from Mus Musculus was added to tobacco plants, which made them more resistant to cd from 10 to 200 µM (Jia *et al*., 2024) [44, 45]. Also, the MT-II trait from S. cerevisiae was added to Brassica oleracea, which made it more resistant to cadmium from 25 to 400 µM in aquatic solution (Chunduri *et al*., 2024) [18].

Energy crops

Annual crops that include Ricinus, the Miscanthus, Jatropha, or, and Populous have been found to be highly beneficial for both bioenergy generation and phytoremediation at the same time (Devi *et al*., 2024) [24]. Short-rotation woody plants were grown in polluted areas to aid in the cleanup process and also to meet fuel requirements.

Conclusion

The widespread problem of contamination by heavy metals in soils, primarily caused by human activities such as the excessive use of agrochemicals and the use of dirty irrigation water, presents a substantial risk to both the environment and human well-being. Conventional methods of cleanup, although successful, can incur substantial expenses and might result in long-term harm to soil ecosystems. Consequently, there is an increasing focus on implementing more sustainable and economically efficient approaches, such as phytoremediation. This novel strategy harnesses the inherent capabilities of plants and their accompanying microorganisms to assimilate, stabilize, release as gas, or break down pollutants. Phytoextraction, Phyto stabilization, phytovolatilization, phytodegradation, and rhizo-degradation are diverse techniques that employ various processes to decrease pollutant levels in the soil. Phytoextraction is the process by which plants absorb metals and are later collected, while Phyto stabilization restricts the movement of pollutants. Phyto-desalination and the utilization of metallophytes are additional techniques that boost the potential of phytoremediation. The incorporation of chemical agents, sophisticated agricultural practices, and microbial interactions can greatly enhance the effectiveness of these plant-based techniques. Wetland habitats and genetically modified plants offer additional options for remediation, although the use of genetically modified plants is currently limited due to regulatory and safety issues. The simultaneous utilization of specific crops for both bioenergy production and phytoremediation presents a synergistic strategy for effectively handling polluted areas. Although there have been promising breakthroughs, additional study is required to optimize these procedures, overcome the limits associated with biomass production and metal uptake, and guarantee the safe disposal or reuse of contaminated plant material. Future study should prioritize the improvement of genetic features in hyperaccumulator plants, investigate the combined effects of plant-microbe interactions, and create scalable models for implementing these strategies on a broad scale. The implementation of this interdisciplinary approach has the capacity to revolutionize soil remediation methods, enhancing their efficiency and sustainability, while also fulfilling the urgent requirements for environmental preservation and safeguarding public health.

References

1. Adepoju AO, Femi-Adepoju A, Jalloh A, Faeflen S. Soil pollution and management practices. In: Environmental pollution and public health. Elsevier; 2024, 187-236.
2. Adki VS, Jadhav JP, Bapat VA. At the cross roads of environmental pollutants and phytoremediation: A promising bio remedial approach. Journal of Plant Biochemistry and Biotechnology. 2014;23:125-40.
3. Aithani D, Kushawaha J. Heavy metals contamination in environment. Remediation of heavy metals: sustainable technologies and recent advances. 2024, 15-30.
4. Alam O, Zheng X, Du D, Qiao X, Dai L, Li J, *et al*. A critical review on advances in remediation of toxic heavy metals contaminated solids by chemical processes. Journal of Environmental Chemical Engineering. 2024;113149.
5. Alkorta I, Becerril JM, Garbisu C. Phytostabilization of metal contaminated soils. Reviews on Environmental Health. 2010;25(2):135-46.
6. Amils R, Escudero C, Huang T, Fernádez-Remolar D. Geomicrobiology of Río Tinto (Iberian Pyrite Belt): A geological and mineralogical Mars analogue. In: Geomicrobiology: natural and anthropogenic settings. Cham: Springer Nature Switzerland; 2024, 123-50.
7. Angon PB, Islam MS, Kc S, Das A, Anjum N, Poudel A, *et al*. Sources, effects and present perspectives of heavy metals contamination: soil, plants and human food chain. Heliyon. 2024.
8. Aransiola SA, Maddela NR. editors. Phytoremediation in food safety: risks and prospects. 2024.
9. Azhar U, Ahmad H, Shafqat H, Babar M, Munir HMS, Sagir M, *et al*. Remediation techniques for elimination of heavy metal pollutants from soil: a review. Environmental Research. 2022;214:113918.
10. Bansal K, Raturi A, Katiyar U, Mishra A, Tewari S. Microbial rhizoremediation as a strategy for decontaminating polluted sites and augmenting plant growth. In: Microbiome drivers of ecosystem function. Academic Press; 2024, 181-227.
11. Beiyuan J, Awad YM, Beckers F, Wang J, Tsang DC, Ok YS, *et al*. (Im)mobilization and speciation of lead under dynamic redox conditions in a contaminated soil amended with pine sawdust biochar. Environment International. 2020;135:105376.
12. Boujelben N, Bakari Z, Turki N, Del Bubba M, Elleuch B. Effects of short-term irrigation of olive (Olea europaea L. cv.'Koroneiki') trees using treated wastewater contaminated with heavy metals. Irrigation Science. 2024, 1-13.
13. Bustamante-Torres M, Torres O, Abad-Sojos S, Pardo S, Bucio E. Application of genetically modified microorganisms for bioremediation of polluted environments. In: Genetically engineered organisms in bioremediation. CRC Press; 2024, 18-51.
14. Bustamante-Torres M, Torres O, Abad-Sojos S, Pardo S, Bucio E. Application of genetically modified microorganisms for bioremediation of polluted environments. In: Genetically engineered organisms in bioremediation. CRC Press; 2024, 18-51.
15. Cahoon DR. Measuring and interpreting the surface and shallow subsurface process influences on coastal wetland elevation: a review. Estuaries and Coasts. 2024, 1-27.
16. Chávez-Hernández JA, Velarde-Salcedo AJ, Navarro-Tovar G, Gonzalez C. Safe nanomaterials: from their use, application and disposal to regulations. Nanoscale Advances, 2024.
17. Chen J, Wang Y. Understanding the salinity resilience and productivity of halophytes in saline environments. Plant Science. 2024, 112171.
18. Chunduri V, Kapoor P, Kumari A, Kumar A, Sharma S, Sharma N, *et al*. Biotechnological advancements in phytoremediation. Aquatic contamination: tolerance and bioremediation. 2024, 165-88.
19. Cirovic A, Satarug S. Toxicity tolerance in the carcinogenesis of environmental cadmium. International Journal of Molecular Sciences. 2024;25(3):1851.
20. Corami A. Phytoremediation and contaminants. In: Phytoremediation: management of environmental contaminants, Cham: Springer International Publishing; 2023;(7):15-48.
21. Das PK, Das BP, Das BK, Dash P. Rhizospheric soil chromium toxicity and its remediation using plant hyperaccumulators. International Journal of Phytoremediation. 2024;26(2):193-207.
22. Dehghani MH, Ahmadi S, Ghosh S, Khan MS, Othmani A, Khanday WA, *et al*. Sustainable remediation technologies for removal of pesticides as organic micro-pollutants from water environments: a review. Applied Surface Science Advances. 2024;19:100558.
23. Deng S, Zhang X, Zhu Y, Zhuo R. Recent advances in phyto-combined remediation of heavy metal pollution in soil. Biotechnology Advances. 2024;108337.
24. Devi P, Kaur A, Kumar P. Phytoremediation of metal contaminated soil using energy crops: soil health maintenance along with biofuel production. In: Bioremediation of emerging contaminants from soils. Elsevier; 2024, 307-33.
25. Ene A, Moraru SS, Moraru DI, Pantelica A, Gosav S, Ceoromila AM. Major and trace element accumulation in soils and crops (wheat, corn, sunflower) around steel industry in the Lower Danube Basin and associated ecological and health risks. Applied Sciences. 2024;14(13):5616.
26. Ethiraj S, Samuel MS, Indumathi SM. A comprehensive review of the challenges and opportunities in microalgae-based wastewater treatment for eliminating organic, inorganic, and emerging pollutants. Biocatalysis and Agricultural Biotechnology. 2024;103316.
27. Evangelou MW, Ebel M, Schaeffer A. Chelate assisted phytoextraction of heavy metals from soil. Effect, mechanism, toxicity, and fate of chelating agents. Chemosphere. 2007;68(6):989-1003.
28. Eze MO, Amuji CF. Elucidating the significant roles of root exudates in organic pollutant biotransformation within the rhizosphere. Scientific Reports. 2024;14(1):2359.
29. Eze MO, Amuji CF. Elucidating the significant roles of root exudates in organic pollutant biotransformation within the rhizosphere. Scientific Reports. 2024;14(1):2359.

30. Fletcher J, Willby N, Oliver D, Quilliam RS. Engineering aquatic plant community composition on floating treatment wetlands can increase ecosystem multifunctionality. Environmental Research. 2024;243:117818.
31. Gaballah MS, Yousefyani H, Karami M, Lammers RW. Free water surface constructed wetlands: review of pollutant removal performance and modeling approaches. Environmental Science and Pollution Research. 2024:1-20.
32. Gatla S, Kaur A, Sandhu K, Girisha R, Kamboj R. Impact of green manures in mitigating heavy metal toxicity: a review. International Journal of Environment and Climate Change. 2024;14(6):304-21.
33. Gautam A, Rai SC. Groundwater zoning and sustainable management strategies for groundwater resources in the Bist-Doab region of Punjab, India. Environment, Development and Sustainability. 2024;26(4):8421-42.
34. Gill S, Johal RK. Agrarian distress in Indian Punjab: a public policy paralysis. Case Studies in the Environment. 2024;8(1).
35. Gogoi R, Sharma MR, Chetia S. From pollution to prosperity: microbial solutions for soil remediation. A comprehensive exploration of soil, water, and air pollution in agriculture. 2024;342.
36. Gupta H, Dhiman S, Kumar A, Paliwal SK, Khan G, Singh H, *et al*. Photo-and bio-degradation of selected persistent organic pollutants. Separation & Purification Reviews. 2024:1-14.
37. Hamoud YA, Shaghaleh H, Zia-Ur-Rehman M, Rizwan M, Umair M, Usman M, *et al*. Cadmium and lead accumulation in important food crops due to wastewater irrigation: pollution index and health risks assessment. Heliyon. 2024;10(3).
38. Hu Y, Wang J, Yang Y, Li S, Wu Q, Nepovimova E, *et al*. Revolutionizing soil heavy metal remediation: cutting-edge innovations in plant disposal technology. Science of the Total Environment. 2024;170577.
39. Hu Y, Wang J, Yang Y, Li S, Wu Q, Nepovimova E, *et al*. Revolutionizing soil heavy metal remediation: cutting-edge innovations in plant disposal technology. Science of the Total Environment. 2024;170577.
40. Ionata E, Caputo E, Mandrich L, Marcolongo L. Moving towards biofuels and high-value products through phytoremediation and biocatalytic processes. Catalysts. 2024;14(2):118
41. Jabeen R, Ahmad A, Iqbal M. Phytoremediation of heavy metals: physiological and molecular mechanisms. The Botanical Review. 2009;75:339-364.
42. Jan M, Mir TA, Khare RK. Phytoremediation: the way forward. Aquatic Contamination: Tolerance and Bioremediation. 2024;145-164.
43. Javed M, Usmani N. Assessment of heavy metal (Cu, Ni, Fe, Co, Mn, Cr, Zn) pollution in effluent dominated rivulet water and their effect on glycogen metabolism and histology of Mastacembelus armatus. Springer Plus. 2013;2:1-13.
44. Jia H, Zhu Z, Zhan J, Luo Y, Yin Z, Wang Z, *et al*. NtARF11 positively regulates cadmium tolerance in tobacco by inhibiting expression of the nitrate transporter NtNRT1. 1. Journal of Hazardous Materials. 2024;473:134719.
45. Jia H, Zhu Z, Zhan J, Luo Y, Yin Z, Wang Z, *et al*. NtARF11 positively regulates cadmium tolerance in tobacco by inhibiting expression of the nitrate transporter NtNRT1. 1. Journal of Hazardous Materials. 2024;473:134719.
46. John JE, Thangavel P, Maheswari M, Balasubramanian G, Kalaiselvi T, Kokiladevi E, *et al*. Sesuvium portulacastrum mitigates salinity induced by irrigation with paper and pulp mill effluent. International Journal of Environmental Studies. 2024;81(3):1420-1432.
47. Kaur I, Dhillon HK, Sharma S. Human health risks in Ferozepur District, Punjab, India due to potentially toxic elements in agricultural soils. Toxin Reviews. 2023;42(3):640-654. Available from: https://doi.org/10.1080/15569543.2023.2213318
48. Kaur L, Kanwar N. Duckweed: a model for phytoremediation technology. The Holistic Approach to Environment. 2021;12(1):39-58. Available from: https://doi.org/10.33765/thate.12.1.4
49. Khan S, Galstyan H, Abbas M, Wenjing X. Advanced biotechnology strategies for detoxification of persistent organic pollutants and toxic elements in soil. Chemosphere. 2023;345:140519.
50. Kozak K, Antosiewicz DM. Tobacco as an efficient metal accumulator. Biometals. 2022;36(2):351-370. Available from: https://doi.org/10.1007/s10534-022-00431-3
51. Kumar R, Vaid U, Mittal S. Water crisis: issues and challenges in Punjab. Water Resources Management: Select Proceedings of ICWEES-2016. 2018, 93-103.
52. Lavanya MB, Viswanath DS, Sivapullaiah PV. Phytoremediation: an eco-friendly approach for remediation of heavy metal-contaminated soils-a comprehensive review. Environmental Nanotechnology, Monitoring & Management. 2024;100975.
53. Liang Z, Neményi A, Kovács GP, Gyuricza C. Incorporating functional traits into heavy metals phytoremediation: the future of field-based phytoremediation. Ecological Indicators. 2024;166:112262.
54. Lim CY. Constructed wetland for wastewater treatment [Doctoral Dissertation]. UTAR, 2024.
55. Lindsay WL, Norvell WA. Equilibrium relationships of Zn2+, Fe3+, Ca2+, and H+ with EDTA and DTPA in soils. Soil Science Society of America Journal. 1969;33:62-68. Available from: https://doi.org/10.2136/sssaj1969.03615995003300010020x
56. Liu YQ, Chen Y, Li YY, Ding CY, Li BL, Han H, *et al*. Plant growth-promoting bacteria improve the Cd phytoremediation efficiency of soils contaminated with PE–Cd complex pollution by influencing the rhizosphere microbiome of sorghum. Journal of Hazardous Materials. 2024;469:134085.
57. Madhav S, Mishra R, Kumari A, Srivastav AL, Ahamad A, Singh P, *et al*. A review on sources identification of heavy metals in soil and remediation measures by phytoremediation-induced methods. International Journal of Environmental Science and Technology. 2024;21(1):1099-1120.
58. Maurya A, Sharma D, Partap M, Kumar R, Bhargava B. Microbially-assisted phytoremediation toward air pollutants: current trends and future directions. Environmental Technology & Innovation. 2023;31:103140.
59. Mehra R. Health risk assessment from radioactive elements in the environs of Mansa District of Punjab. Journal of Radioanalytical and Nuclear Chemistry. 2024, 1-10.
60. Muhammad M, Batool S, Hivare V, Li WJ, Waheed A, Sinha D. Bioremediation techniques—classification, principles, advantages, limitations, and prospects. In: Microbiome-Assisted Bioremediation. Academic Press;

2024, 1-23.

61. Nepal A, Antonious GF, Bebe FN, Webster TC, Gyawali BR, Neupane B. Heavy metal accumulation in three varieties of mustard grown under five soil management practices. Environments. 2024;11(4):77. Available from: https://doi.org/10.3390/environments11040077
62. Nikolić M, Stevović S. Family Asteraceae as a sustainable planning tool in phytoremediation and its relevance in urban areas. Urban Forestry & Urban Greening. 2015;14(4):782-789. Available from: https://doi.org/10.1016/j.ufug.2015.08.002
63. Nissim WG, Labrecque M. Reclamation of urban brownfields through phytoremediation: implications for building sustainable and resilient towns. Urban Forestry & Urban Greening. 2021;65:127364.
64. Noor AE, Fatima R, Aslam S, Hussain A, Un Nisa Z, Khan M, *et al*. Health risks assessment and source admeasurement of potentially dangerous heavy metals (Cu, Fe, and Ni) in rapidly growing urban settlement. Environmental Research. 2024;242:117736.
65. Nucera S, Serra M, Caminiti R, Ruga S, Passacatini LC, Macrì R, *et al*. Non-essential heavy metal effects in cardiovascular diseases: an overview of systematic reviews. Frontiers in Cardiovascular Medicine. 2024;11:1332339.
66. Nwogwu NA, Ajala OA, Ajibade FO, Ajibade TF, Adelodun B, Lasisi KH, *et al*. Phytoremediation mechanisms of heavy metal removal: a step towards a green and sustainable environment. In: Innovative Bio-Based Technologies for Environmental Remediation. CRC Press; 2022, 207-236.
67. Ogundola AF, Adebayo EA, Ajao SO. Phytoremediation: the ultimate technique for reinstating soil contaminated with heavy metals and other pollutants. In: Phytoremediation Technology for the Removal of Heavy Metals and Other Contaminants from Soil and Water. Elsevier; 2022, 19-49.
68. Osman KT. Management of soil problems. Springer, 2018.
69. Padbhushan R, Kumar U. Phytoremediation: a novel strategy to decontaminate environmental pollution. Environmental Contaminants: Impact, Assessment, and Remediation. 2024, 255.
70. Padma S, Ghosh S, Srinivas B, Ghanta KC, Dutta S. Bioremediation of heavy metals—its pros and cons. In: Heavy Metal Remediation: Sustainable Nexus Approach. Cham: Springer Nature Switzerland; 2024, 213-235.
71. Pajević S, Borišev M, Nikolić N, Arsenov DD, Orlović S, Župunski M. Phytoextraction of heavy metals by fast-growing trees: a review. Phytoremediation: Management of Environmental Contaminants, 2016;(3):29-64.
72. Parui R, Nongthombam GS, Hossain M, Adil LR, Gogoi R, Bhowmik S, *et al*. Impact of heavy metals on human health. Remediation of Heavy Metals: Sustainable Technologies and Recent Advances. 2024, 47-81.
73. Patel D, Kulwant M. Bioremediation of xenobiotic contamination in soil. In: Bioremediation of Emerging Contaminants from Soils. Elsevier; 2024, 203-225.
74. Pathak A, Gupta MK, Rabani MS, Tripathi S, Pandey S, Gupta C, *et al*. Enzymatic approach for phytoremediation. Aquatic Contamination: Tolerance and Bioremediation. 2024;123-130.
75. Patra DK, Pradhan C, Patra HK. Toxic metal decontamination by phytoremediation approach: concept, challenges, opportunities and future perspectives. Environmental Technology & Innovation. 2020;18:100672.
76. Rani V, Kumar SB. Role of enzymes in the optimization of traditional phytoremediation processes of soil. In: Bioremediation of Emerging Contaminants from Soils. Elsevier; 2024, 421-442.
77. Razzak SA, Faruque MO, Alsheikh Z, Alsheikhmohamad L, Alkuroud D, Alfayez A, *et al*. A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater. Environmental Advances. 2022;7:100168.
78. Ruba UB, Chakma K, Ali MP, Khan AU, Samiul M, Talucder A. Environmental pollution from injudicious application of pesticides: Bangladesh context. Journal of Agroforestry and Environment. 2023;16(1):40-49.
79. Saad NA, Jabit NA, Ismail S, Ishak KEHK, Aminuddin MIKA, Halim MSM, *et al*. Management and treatment methods of acid mine drainage. In: Industrial Waste Engineering. Cham: Springer International Publishing; 2024, 441-507.
80. Samantaray A, Chattaraj S, Mitra D, Ganguly A, Kumar R, Gaur A, *et al*. Current research in microbial sciences. Current Research in Microbial Sciences. 2024;7:100251
81. Saxena G, Purchase D, Mulla SI, Saratale GD, Bharagava RN. Phytoremediation of heavy metal-contaminated sites: eco-environmental concerns, field studies, sustainability issues, and future prospects. Reviews of Environmental Contamination and Toxicology. 2020;249:71-131.
82. Selvam R, Kalaiyarasi G, Saritha B. Heavy metal contamination in soils: risks and remediation. Soil Fertility and Plant Nutrition. 2024;141.
83. Selvi A, Rajasekar A, Theerthagiri J, Ananthaselvam A, Sathishkumar K, Madhavan J, *et al*. Integrated remediation processes toward heavy metal removal/recovery from various environments—a review. Frontiers in Environmental Science. 2019;7:66.
84. Shackira AM, Puthur JT. Phytostabilization of heavy metals: understanding of principles and practices. Plant-Metal Interactions. 2019;263-282.
85. Sharma P, Singh SP, Pandey S, Thanki A, Singh NK. Role of potential native weeds and grasses for phytoremediation of endocrine-disrupting pollutants discharged from pulp paper industry waste. Bioremediation of Pollutants. 2020;17-37. Available from: https://doi.org/10.1016/B978-0-12-819025-8.00002-8
86. Shashirekha V, Sowmiya V, Malleswari RB, Seshadri S. Conserving soil microbial population and sustainable agricultural practices—polymers in aid of safe delivery, protection, population enhancement, and maintenance. Beneficial Microbes for Sustainable Agriculture Under Stress Conditions. Academic Press; 2024, 313-358.
87. Shen X, Sun T, Dai M, Aslam MMA, Peng C. Performance and mechanistic study of biochar and magnesium-enhanced phytoremediation in cadmium-contaminated soil by alfalfa. Chemosphere. 2024, 142737.
88. Shiyab S. Phytoaccumulation of copper from irrigation water and its effect on the internal structure of lettuce. Agriculture. 2018;8:29. Available from: https://doi.org/10.3390/agriculture8020029
89. Singh V, Punia A, Thakur A, Gupta S, Kataria RC, Kumar R, *et al*. Phytoremediation of chemical pollutants and heavy metals by higher plants. In: Phytoremediation: Biological Treatment of Environmental Pollution. Cham: Springer Nature Switzerland; 2024, 123-147.
90. Smriti S, Rai A, Shubham S, Kaushal S. Potential of plant-based metallophytes for phytoremediation in agriculture. Journal of Experimental Agriculture International.

2024;46(6):154-161.

91. Sohail MI, Arif M, Rauf A, Rizwan M, Ali S, Saqib M, *et al*. Organic manures for cadmium tolerance and remediation. Cadmium Tolerance in Plants. Academic Press; 2019, 19-67.
92. Sonkar V, Jaswal V, Chenlak S, Nandabalan YK. Pollution status and health risk assessment of heavy metals in the soil of Sahibzada Ajit Singh (SAS) Nagar district of Punjab, India and its source apportionment. Journal of Geochemical Exploration. 2024;261:107453.
93. Srinivasarao C, Rama Gayatri S, Venkateswarlu B, Jakkula VS, Wani SP, Kundu S, *et al*. Heavy metals concentration in soils under rainfed agro-ecosystems and their relationship with soil properties and management practices. International Journal of Environmental Science and Technology. 2014;11:1959-1972.
94. Su J, Zeng Q, Li S, Wang R, Hu Y. Comparison of organic and synthetic amendments for poplar phytomanagement in copper and lead-contaminated calcareous soil. Journal of Environmental Management. 2024;355:120553.
95. Tahir M, Khan MB, Shahid M, Ahmad I, Khalid U, Akram M, *et al*. Metal-tolerant Pantoea sp. WP-5 and organic manures enhanced root exudation and phytostabilization of cadmium in the rhizosphere of maize. Environmental Science and Pollution Research. 2021, 1-14.
96. Tahir M, Khan MB, Shahid M, Ahmad I, Khalid U, Akram M, *et al*. Organic acids induced by metal-tolerant Pantoea sp. WP-5 and biogas residues enhanced phytostabilization of cadmium in soil. Environmental Science and Pollution Research. 2021;28:14117-14128.
97. Thakur R, Sarvade S, Dwivedi BS. Heavy metals: soil contamination and its remediation. AATCC Review. 2022;10(2):59-76.
98. Umid M, Ramizitdin S, Khasanjon A, Rukhsora Z. Study of the physicochemical properties of cellulose obtained from Paulownia wood. Universum: Технические Науки. 2024;4(1):53-58.
99. Vardhan KH, Kumar PS, Panda RC. A review on heavy metal pollution, toxicity and remedial measures: current trends and future perspectives. Journal of Molecular Liquids. 2019;290:111197.
100. Wang J, Chen C. Phytoremediation of radium contaminated soils: recent advances and prospects. Radiochimica Acta. 2024;0.
101. Wu X, Xing C, Ju Q, Su S, Zhang X, Zhu T. Research progress in mining ecological restoration technology. Journal of Industrial Safety. 2024;100004.
102. Xu D, Shen Z, Dou C, Dou Z, Li Y, Gao Y, *et al*. Effects of soil properties on heavy metal bioavailability and accumulation in crop grains under different farmland use patterns. Scientific Reports. 2022;12(1):9211.
103. Xu L, Dai H, Wei S, Skuza L, Shi J. High-efficiency combination washing agents with eco-friendliness simultaneously removing Cd, Cu and Ni from soil of e-waste recycling site: a lab-scale experiment. Chemosphere. 2024;357:142047.
104. Yadav AK, Pathak B, Fulekar MH. Rhizofiltration of heavy metals (cadmium, lead and zinc) from fly ash leachates using water hyacinth (Eichhornia crassipes). International Journal of Environment. 2015;4(1):179–196. Available from: https://doi.org/10.3126/ije.v4i1.12187
105. Yaqoob S, Zahoor I, Kazerooni EA. Phytostabilization of contaminated soils. In: Environmental Science and Engineering. 2024;123-145.
106. Yin F, Li J, Wang Y, Yang Z. Biodegradable chelating agents for enhancing phytoremediation: mechanisms, market feasibility, and future studies. Ecotoxicology and Environmental Safety. 2024;272:116113.
107. Zhakypbek Y, Kossalbayev BD, Belkozhayev AM, Murat T, Tursbekov S, Abdalimov E, *et al*. Reducing heavy metal contamination in soil and water using phytoremediation. Plants. 2024;13(11):1534.
108. Zou L, Jiang O, Zhang S, Duan G, Gustave W, An X, *et al*. Effects of citric acid on arsenic transformation and microbial communities in different paddy soils. Environmental Research. 2024;249:118421.