

RESEARCH PAPER

# The Sustainable Phytoremediation of Lead and Cadmium using *Cannabis* Species: A comparative review of the detoxification ability

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## ABSTRACT

The contamination of the environment and human health by heavy metals is a major threat because of the persistence, toxicity and bioaccumulative properties of the lead (Pb) and cadmium (Cd). Cost effective and sustainable remediation strategies are thus necessary. Phytoremediation has become one of the promising green technologies whereby plants are used to eliminate, stabilize or even to detoxify contaminants in soil and water systems. *Cannabis sativa* and *Cannabis indica* are also among the possible phytoremediators, as they have become more and more popular because of their ability to grow fast, generate high biomass, and tolerate stress-induced by metals.

The present review compares the phytoremediation potentials of the two types of *Cannabis* to remove Pb and Cd. It compiles existing information on their physiological, morphological and biochemical processes in metal uptake, translocation and accumulation. Specific biomass distribution, root architecture and secondary metabolite production differences are critically analyzed to comprehend species-specific remediation efficiencies. In the case of *Cannabis*-based systems, the review also highlights the important phytoremediation processes, namely, phytoextraction, phytostabilization, and rhizofiltration.

Moreover, research gaps are also outlined, especially in terms of validation at the field level, soil-flora interactions, and the performance in specific regions when exposed to different environmental conditions. The possible two-fold positive effects of the *Cannabis* production such as cleaning up the environment and economic worth are also addressed. On the whole, this review helps to recognize the potential of *Cannabis* species as effective and sustainable candidates in the heavy metal remediation and offers the guidelines to the future research and application.

**Keywords:** Phytoremediation; *Cannabis sativa*; *Cannabis indica*; Heavy metals; Lead (Pb); Cadmium (Cd); Phytoextraction; Phytostabilization; Sustainable remediation; Metal uptake; Environmental pollution; Soil contamination.

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## 1. INTRODUCTION

The heavy metal contamination of the environment has been a significant issue of concern in the world regarding the high rates of industrialization, urbanization and increased agricultural activities. The toxicity of the heavy metals, especially lead (Pb) and cadmium (Cd) are of particular concern due to the presence of heavy metals, their persistent nature, non-biodegradable character, and significant toxicity even in low concentrations (Alloway, 2013; Tangahu et al., 2011). These metals get deposited in soil and water bodies and may integrate via plants in the food web and cause biomagnification which can cause severe effects on both human and ecological health (Sarwar et al., 2010). Both Pb and Cd have been linked with oxidative stress, damage to and breakage of DNA, as well as distortion of enzymatic and metabolic activities in living organisms (Stanley et al., 2018).

The common traditional techniques of excavation, chemical treatment and solidification are usually expensive, energy consuming and disruptive to the environment (Ghosh & Singh, 2005). Conversely, phytoremediation has become an economical and environmentally friendly option which makes use of plants to eliminate, stabilize or detoxify

pollutants in polluted environments (Ali et al., 2013; Pilon-Smits, 2005). This green technology involves various processes, such as phytoextraction, phytostabilization, rhizofiltration and phytovolatilization all of which help in the remediation of polluted soils and water systems (Blaylock and Huang, 2000).

Selection of suitable plant species that has high biomass, quick growth and ability to generate heavy metals have been found to strongly influence the efficiency of phytoremediation (Chaney et al., 2007). The growing interest in species of the genus *Cannabis* in this context is due to their outstanding adaptability, extensive roots, and massive biomass. (Linger et al., 2002; Andre et al., 2016). The possibility to accumulate heavy metal (Pb and Cd) by *Cannabis sativa* has been extensively investigated, and it is promoted through physiological and biochemical mechanisms and adaptations, such as improved antioxidant activity and formation of metal-binding compounds (Ahmad et al., 2015; Angelova et al., 2021). Likewise, *Cannabis indica* has been shown to withstand heavy metal stress and have the ability to root biostagnation, thus it can be used in phytostabilization initiatives (Rizwan et al., 2013).

Although they are different species of the same genus, *Cannabis sativa* and *Cannabis indica* have very different morphological and physiological properties that can affect their phytoremediation. Metal uptake, translocation, and accumulation by plants can be significantly influenced by differences in plant height, root architecture, biomass allocation, and secondary metabolite production (Hillig and Mahlberg, 2004; Clarke and Merlin, 2013). Nonetheless, there are still limited comparative studies that assess the efficacy of these two species to treat Pb- and Cd-contaminated soils and even more so under region-specific environment circumstances.

## 2. HEAVY METAL CONTAMINATION: SOURCES AND EFFECT

Heavy metal pollution poses a massive global environmental challenge, stemming from natural sources and intensified by human activities. Among the most hazardous are persistent, non-biodegradable metals like lead (Pb) and cadmium (Cd), which build up in ecosystems. These contaminants frequently appear in soil, water, and air, lingering for extended periods with lasting impacts on ecosystems and human health. Industrial expansion, urbanization, and farming methods have sharply elevated their concentrations far beyond natural baselines.

### 2.1 Source of Lead (Pb) and Cadmium (Cd)

Human activities primarily drive Cd and Pb pollution. Key industrial processes—such as mining, smelting, electroplating, and battery manufacturing—discharge substantial quantities of these metals into the environment. Vehicle exhausts, fossil fuel combustion, and improper industrial waste disposal further spread them widely. In agriculture, phosphate fertilizers, pesticides, and sewage sludge serve as major routes for Cd buildup in soils, while Pb pollution often stems from atmospheric fallout and historical leaded gasoline use.

Studies highlight that agricultural soils and irrigation practices act as critical vectors for heavy metals, facilitating their transfer into crops and ultimately the human food chain. Natural phenomena, including volcanic eruptions, rock weathering, and erosion, contribute baseline levels of these metals, though typically far less than human-induced inputs.

### 2.2 Environmental Distribution and Persistence

Once released into the environment, heavy metals prove highly persistent, accumulating in soils and sediments. Unlike organic compounds, they remain insoluble, enduring for decades as they cycle among soil, water, and living organisms without breaking down. Soil serves as the main repository, where metal mobility and bioavailability depend on factors like speciation, pH, and organic content. Cadmium, in particular, dominates agricultural soils as one of the most mobile and bioavailable metals, leading to its frequent uptake in crops.

Pb and Cd entering soils get absorbed by plants, then pass to grazing animals and humans, causing biomagnification up the food chain. This process amplifies their ecological

harm, making even trace environmental levels a long-term concern.

### 2.3 Environmental and Human Health Toxicology

Exposure to Pb and Cd exerts potent toxic effects by interfering with cellular and physiological processes. Both metals trigger oxidative stress through reactive oxygen species (ROS) production, resulting in lipid peroxidation, protein damage, and DNA harm. Lead stands out for its neurotoxicity, which disrupts cognitive growth and neurological function—especially evident in children. Cadmium, meanwhile, primarily accumulates in the kidneys and liver, causing renal failure, bone demineralization, and cancer risks.

### 2.4 Consequences to Sustainable Environmental Management

The enduring presence and toxicity of Pb and Cd highlight the urgency for sustainable cleanup strategies. Traditional physicochemical methods often fall short in effectiveness and affordability at large scales, particularly for agricultural soils. Ongoing metal buildup in ecosystems threatens biodiversity, food safety, and public health. This has sparked strong interest in eco-friendly, economical approaches like phytoremediation, which employs plants to extract and stabilize heavy metals while maintaining ecological harmony.

## 3. PHYTOREMEDIATION: THEORIES AND APPLICATIONS

Phytoremediation has become an environmentally friendly and sustainable technology of ridding heavy metals polluted soils and water systems. It entails the utilization of plants and the associated microorganisms to eliminate, stabilize or detoxify environmental contaminants. Phytoremediation in comparison to traditional physicochemical processes is affordable, is physically appealing, and causes minimal disturbance to ecosystems (Kumar et al., 2024; Zhang et al., 2024). The growing demand of eco-friendly remediation methods has made phytoremediation one of the most important methods of rehabilitating contaminated waters without disturbing the ecological balance.

### 3.1 Principles of Phytoremediation

Phytoremediation relies on the natural process of plants to uptake, store, and be able to convert contaminants in physiological and biochemical forms. The root systems absorb the heavy metals in soil/water by the plants and translocate them to aerial tissues where they are stored or detoxified (Islam et al., 2024). Various factors control this process, such as species of plants, root structures, rate of growth and ability to withstand metal- stress related stress. Plants at the cellular level have defense mechanisms which help them to deal with heavy metal toxicity. They involve phytochelating and metallothionein chelation, metals vacuolation and activation of antioxidant systems to counteract oxidative stress (Al-Obaidi et al., 2024). Phytoremediation is thus determined by how the plant will absorb the metals and detoxify, as well as absorb and

tolerate them.

### 3.2 Types of Phytoremediation Mechanisms

Phytoremediation has been characterized by a number of different mechanisms each of which is unique in terms of the type of contaminant and environmental conditions it aims to address.

#### 3.2.1 Phytoextraction

Phytoextraction is the adsorption of the heavy metals by the roots of the plants and then they are stored in the biomass that is above ground. In this process, hyperaccumulator plants are especially effective, in that they have the ability to accumulate metals to much higher levels than those found on the soil (Yadav et al., 2025). Once it builds up, we can then harvest and remove the plants also reducing contamination of the soil.

#### 3.2.2 Phytostabilization

Phytostabilization is the process of trapping the contaminants in the soil by use of the plant roots. Plants slow down the mobility and bioavailability of the heavy metals through adsorption of the metals onto root surfaces or precipitation with the rhizosphere, to eliminate the heavy metals being washed away into ground water (Mohamed et al., 2025). This technique comes in handy especially in the prevention of contamination.

#### 3.2.3 Rhizofiltration

Rhizofiltration involves the use of plant roots to either absorb or adsorb heavy metals in water. This method is widely used in treating polluted water bodies where plant roots can be used as biological filters (Acharya et al., 2025).

#### 3.2.4 Phytovolatilization

Under phytovolatilization, plants take up contaminants and transform their presence to volatile forms which are released to the atmosphere. In spite of the fact that this mechanism is not usually linked to the effect of heavy metals, it is also involved in the conversion of some metalloids including mercury and selenium (Acharya et al., 2025).

### 3.3 Role of Plant–Microbe Interactions

Recent developments in phytoremediation studies have focused on the importance of plant-related microorganisms, such as rhizobacteria and endophytes in maximizing the effectiveness of remediation processes. By synthesizing of phytohormones, organic acids, and siderophores, these microorganisms enhance plant growth, make metals more bioavailable, and enhance metabolism to face heavy metal stress.

Plant-microbe interactions are also a way of transforming and immobilizing the contaminants in the rhizosphere which is also referred to as rhizoremediation. Microbial consortia integration with phytoremediation systems have demonstrated a large possibility of enhanced performance of the whole remediation.

### 3.4 Factors affecting the ability of phytoremediation.

Phytoremediation has several factors that have to work together to be successful:

**Plant Characteristics:** High biomass species that have deep root systems and able to tolerate metals work best.

**Soil Property:** The parameters used, including pH, the level of organic matter and texture, affect the movement of metals and their bioavailability.

**Metal Speciation and Concentration:** There is the uptake and toxicity of metals and this depends on the chemical form of the metals.

**Environmental Conditions:** Climate, temperature, and moisture have a significant impact that influences the growth of plants as well as their efficiency in remediation processes (Salifu et al., 2025).

Moreover, the yield of genetic engineering, bioaugmentation, and soil amendments has been discussed in recent studies to improve the level of phytoremediation (Rehman et al., 2024).

### 3.5 Advantages and Limitations

Phytoremediation has a number of advantages which are low cost, environmental compatibility, and it is capable of treating a large area with minimum disturbance. It also helps to restore soil and sequester carbon, which helps in controlling the environment sustainably (Ahmed et al., 2025).

The method is however limited in that it is slow in remediation, applied only in limited areas where deep soil contamination is involved and chances of second contamination by using infested plant biomass. Efforts to overcome these issues should consider coordinated methods that involve the use of phytoremediation together with cutting edge biotechnological solutions.

## 4. CANNABIS SPECIES IN THE CAPACITY OF PHYTOREMEDIATION

*Cannabis*, especially *Cannabis sativa* and *Cannabis indica*, as a genus, has received a great deal of interest as a possible phytoremediator of heavy metal-contaminated soils. Recent research has shown that *Cannabis sativa* (industrial hemp) is remarkably tolerant to toxic metals like lead (Pb) and cadmium (Cd) and has the capacity to accumulate such contaminants but on the roots and aerial tissues of the plant. This capacity, along with its vigorous proliferation, large biomass manufacturing and extensive root zone, renders *Cannabis* an effective phytoremediator in comparison to a lot of traditional vegetative types.

### 4.1 Botanical and Physiological Characteristics

*Cannabis* species are quick growing, perennial plants that have a large rooting system and very adaptive to diverse environmental conditions. Their long and multiple roots make penetration to the soil deeper and more absorptive in terms of surface area where it can absorb metals. Furthermore, they have large biomass production capacity resulting in higher contaminant accumulation and removal per hectare.

Antioxidant defense mechanisms help *Cannabis* species to

withstand oxidative stress caused by heavy metals, particularly by promoting the physiological resilience of the species. It involves generation of oxygen radicals-scavenging enzymes and secondary products like flavonoids and terpenoids.

#### 4.2 *Cannabis sativa*

The most widely researched phytoremediation species is *Cannabis sativa*. It has established great capacity of extracting heavy metals through the process of phytoextraction because of the high biomass and good translocation processes. Research shows that hemp is capable of storing metals including Cd and Pb in large amounts and that they are mainly accumulated in roots and stems but can not be translocated to the seeds in large amounts hence less risk in some uses.

Recent studies also demonstrate that it can be used in sustainable remediation systems where harvested biomass can be used in industries like producing biofuels, therefore combining environmental cleanup with economic gains.

#### 4.3 *Cannabis indica*

Though *Cannabis indica*, unlike *C. sativa*, has not been investigated much, it has unique merits regarding phytoremediation. Its relatively small size and fully rooted system makes it especially adapted to phyto-stabilization where contaminants are fixed within the soil instead of being removed.

In addition, *C. indica* has been reported to produce more secondary metabolites, thereby related to an increased resistance to heavy metal-induced oxidative stress. Such

biochemical adaptations are what enable it to live and work under some of the most contaminated environments.

#### 4.4 Mechanisms of Heavy Metal Uptake and Detoxification

The heavy metal remediation in *Cannabis* species involves a number of physiological and molecular processes:

- Root Uptake: The process of uptake of metals occurs through root transporters and channels.
- Chelation: toxicity is reduced by binding with phytochelatins and metallothioneins.
- Moving the metal out of the roots into the shoots through the xylem.
- Sequestration: Vacuoles or cell wall storage to avoid cellular damage.
- Antioxidant Protection: ROS neutralization by enzymes and non-enzymes.
- All these processes make *Cannabis* species highly effective in the phytoremediation process.

#### Advantages of *Cannabis* in Phytoremediation

- High biomass production
- Rapid growth cycle
- deep and extensive root system.
- Multiple-metal-tolerance.
- Economic value (fiber, oil, bioenergy)
- Scalability to large scale.

These qualities make *Cannabis* a multi-use crop with the ability to both clean up the environment and provide economic value.

Parameter	<i>Cannabis sativa</i>	<i>Cannabis indica</i>
Growth habit	Tall, slender (up to 5–6 m)	Short, bushy (2–3 m)
Root system	Deep and extensive	Dense and compact
Biomass production	High	Moderate
Metal uptake	High phytoextraction capacity	Moderate uptake
Translocation ability	Efficient root-to-shoot transfer	Limited translocation
Primary mechanism	Phytoextraction	Phytostabilization
Stress tolerance	Moderate–high	High
Secondary metabolites	Moderate	High
Suitability	Large-scale remediation	Localized contamination control
Economic utility	Fiber, biofuel, industrial use	Medicinal and phytochemical use

### 5. COMPARISON OF *CANNABIS SATIVA* AND *CANNABIS INDICA* IN THE PHYTOREMEDIATION PROCESS

Owing to their specific physiological and biochemical abilities, the phytotransformation ability of *Cannabis sativa* and *Cannabis indica* has been subject to further research. Even though the two species are the same genus, they differ in terms of their differential growth behavior, root structure and the metabolic behavior which has a tangible impact on their effectiveness in the heavy metal remediation, especially of lead (Pb) and cadmium (Cd).

#### 5.1 Metal Uptake and Accumulation Capacity

The *Cannabis sativa* has proven to have better metal uptake especial on the Pb- and Cd-contaminated environments. It

has a large root system, thus increasing its metal uptake, as well as increasing its accumulation per area of a unit area due to the large biomass. Latest reports show that industrial hemp has the ability to accumulate high levels of Pb and Cd in root and shoots, and that the uptake is more efficient when amendments are made to the soil and chelating reagents are introduced.

However, *Cannabis indica* has relatively lower metal levels of uptake but has a higher level of retention in root tissues. The property lowers the risk of translocation of metal to aerial components so it is more apt to be employed in strategies of phytotranslocation as opposed to phytoextraction.

#### 5.2 Translocation and Sequestration Processes

One of the major differences between the two species is in

the aspect of translocation behavior. *C. sativa* exhibits a high level of root to shoot translocation of heavy metals thus is crucial in phytoextracting heavy metals. It is favourable with its vascular transport system and increased rates of transpiration.

On the other hand, *C. indica* is more likely to limit the movement of metals in the plant by the compartmentalization of metals in the root tissues or vacuoles. These sequestration systems increase survival in high levels of contamination, and lower toxicity. These variations raise the importance of species-differentiated approach to heavy metal stress management.

It is known that heavy metal can lead to metal toxicity, which in turn may alter growth.

### 5.3 Growth Response during Metal Stress

Mechanical stress growth in the presence of metal is a major aspect that defines phyto-remediation efficiency. Generally *Cannabis sativa* will still grow to significantly high biomass at conditions of contamination, though higher levels of metals can limit the growth and the photosynthetic rate. It has been demonstrated through experimental research that nutrient amendments can be very beneficial to stimulate biomass production and stress withering in hemp cultivated in Pb-contaminated soils.

In contrast, *Cannabis indica* has a higher level of physiological resistance, in part because its secondary metabolites of flavonoids and terpenoids are produced in large amounts and serve as antioxidants. These compounds alleviate oxidative stress and enhance the survival of the plants in the highly polluted environment.

### 5.4 Strategy and Efficiency of Phytoremediation

The relative efficiency of the two species varies mostly on the phytoremediation strategy applied:

- Phytoextracting: *C. sativa* performs better, owing to its greater uptake and translocation ability.
- Phytostabilization: *C. indica* is a more suitable option because it can immobilize metals in the rhizosphere, and root tissues.

Research holds that a range of *Cannabis* species has the potential to strip heavy metals (like Pb and Cd) in contaminated soils, and actually keep biomass productivity across large-scale cleanup efforts, which may be established as viable options to undertake remediation activities at that scale.

### 5.5 Environment and Soil Effect

Environmental factors greatly affect the performance of both species that include; soil pH, organic matter content and metal speciation. As an example, the uptake of cadmium is reported to rise with an increase in the soil metal availability and to fall with rise in the pH, which illustrates the significance in the soil chemistry of phytoremediation effectiveness.

Also, agronomic activities like growth of intercrops and use of fertilisers and even plant-microbe interactions can play a considerable role in increasing metal uptake and biomasses. The above factors should be maximized to maximize the

potential of phytoremediation of *Cannabis* species.

### 5.6 Comparative Analysis and Implications in Practice

Altogether, *Cannabis sativa* is more adapted to serve as an active remediation system (phytoextraction), and *Cannabis indica* serves as a passive remediation system (phytostabilization).

Choosing species is then to be based on location-specific conditions, levels of contamination, and remediation goals. Additionally, handling of contaminated biomass has also been an issue of great concern because when it is not properly managed, it may cause secondary pollution. As an environmentally friendly remedy to biomass that have been clean up, biomass ashing and metal recovery have been suggested as solutions to long term biomass management.

## 6. HEAVY METAL DETOXIFICATION OF CANNABIS SPECIES

The complex physiological, biochemical, and molecular detoxification systems are seen to be the main reason behind *Cannabis sativa* and *Cannabis indica* ability to tolerate and remediate the heavy metal-polluted environment. These mechanisms act at various levels, such as cellular uptake, intracellular sequestration, antioxidant defense, and genetic regulation, allowing the plants to survive in toxic conditions and contributing to phytoremediation.

### 6.1 Metal uptake and transport systems

The initial step in heavy metal detoxification is the uptake of metal ions (like Pb and Cd) via transporter proteins of the root membrane (ion channels, carrier proteins, etc.). These transporters control entry of metals into the root cells and their translocation between cell compartments. More recent research suggests that metal uptake is a strongly regulated process that depends on signaling pathways with calcium ions, phytohormones, and transcription factors .

After uptake, the metals are moved through the xylem to the aerial tissues. Vascular transport is an efficient means of promoting phytoextraction in *Cannabis sativa*, but *C. indica* is more likely to limit translocation, promoting localized detoxification.

### 6.2 Phytochelatins and Metallothioneins Chelation

Synthesis of metal-binding peptides like phytochelatins (PCs) and metallothioneins (MTs) is one of the major detoxification mechanisms in plants. Phytochelatins are peptides derived by a modification of glutathione, which binds heavy metal and helps to sequester it in the vacuoles, decreasing the toxicity of the cytosol.

Likewise, metallothioneins are proteins with multiple cysteine residues, which can bind numerous metal ions, such as Pb and Cd, and are essential in ensuring metal homeostasis and protecting cells against oxidative stresses.

### 6.3 Cellular Sequestration and Compartmentalization

Upon chelation, metal–ligand complexes are delivered to intracellular structures like vacuoles and cell walls. It is a process called sequestration and is an essential

detoxification process that combines toxic metals isolated by the sensitive parts of the cell.

Vacuolar sequestration is especially significant in *Cannabis* species, where it does not allow the interaction of metals with enzymes and nucleic acids. Moreover, cell wall binding further fixes metals making them move less in the plant system.

Research has shown that compartmentalization does not only reduce toxicity but also leads to long term storage of metal thus increases the overall phytoremediation capacity of the plants.

#### 6.4 Antioxidant Defense System

Exposure to heavy metals causes the production of reactive oxygen species (ROS), which may cause damage to lipids, proteins, and DNA. In response to this oxidative stress, both enzymatic and non-enzymatic antioxidant systems are activated by *Cannabis* species.

Most important antioxidant enzymes are:

- Superoxide dismutase (SOD)
- Catalase (CAT)
- Peroxidases (POD)

These enzymes counteract ROS and regulate redox in the cells. Moreover, non-enzymatic antioxidants like flavonoids, phenolics, and terpenoids are important in the scavenging of free radicals.

The recent results indicate that medicinal plants, such as *Cannabis*, have an increased antioxidant activity during heavy metal stress, which is essential in ensuring physiological stability and metabolic activity.

#### 6.5 Molecular and Genetic Control

Heavy metal detoxication at the molecular level carries out by the regulation of signaling pathways and gene expression. Metal stress is met by up regulation of genes that encode metal transporters, chelating proteins and antioxidant enzymes.

The calcium ions, mitogen-activated protein kinases (MAPKs) and phytohormones (abscisic acid and salicylic acid) signaling pathways are central in the integration of stress responses. Omics technologies, such as transcriptomics and metabolomics, have given new insights into these regulatory networks, allowing the identification of genes that cause improved metal tolerance .

These adaptations in molecules do not only enhance the survival of plants, but also the effectiveness of phytoremediation.

#### 6.6 The Detoxification by Secondary Metabolites

Secondary metabolites like flavonoids, alkaloids, and terpenoids play a significant role in the detoxification of heavy metals. These substances are antioxidants and chelators of metals, which limit oxidative damage and stabilize cell structures.

Nevertheless, the biosynthesis of these compounds can be influenced by heavy metal stress, which can change their concentration and composition. It has been shown that plants can reallocate metabolic resources to defense against stress, resulting in a change in secondary metabolite profile

of the plant .

These metabolites not only improve the stress tolerance in *Cannabis* species but also affect the economic and medicinal value of the plant.

#### 6.7 Combined Detoxification in *Cannabis*

The elimination of heavy metals in *Cannabis* species is a complex process that is multi-mechanism and multi-interacting:

- Managed metal uptake and transport.
- PCs and MTs chelation.
- Sequestration in vacuoles and cell walls
- Activation of antioxidant defense systems
- Gene expression and signaling pathways regulation.

This combination approach helps *Cannabis* plants to withstand the presence of high concentrations of Pb and Cd yet retain their growth and biomass formation, thus being viable phytoremediators.

### 6. 7. PRACTICES AND SUSTAINABILITY ISSUES OF CANNABIS-BASED PHYTOREMEDIATION

Potential to sustain environmental management: The use of *Cannabis sativa* and *Cannabis indica* in phytoremediation does not just end at laboratory-scale studies, but has great potential in providing hope to sustainable management of the environment. The adoption of *Cannabis*-based phytoremediation is in accordance with the global sustainability objectives such as alleviating soil contamination, enhancing the concepts of a circular economy, and creating economic value.

#### 7.1 Environmental Remediation Applications

*Cannabis* species have shown significant effectiveness in the treatment of heavy metal soils especially that of lead (Pb) and cadmium (Cd). The large root system and high biomass production make them effective and beneficial in uptaking, accumulating and stabilizing contaminants. Recent research notes that industrial hemp has the potential not only to be used in soil remediation efforts, but also in water purification systems and built wetlands, where it can promote the rhizofiltration and biosorption processes.

Moreover, *Cannabis* plants have been effectively used in the rehabilitation of industrially degraded lands such as mining activities and agricultural soils, which have been caused by fertilizers and pesticides. They can adapt to the varying environmental conditions thus increasing their applicability to different ecological habitats.

#### 7.2 Application in Sustainable Agriculture and Restoration of Soils

To achieve sustainable agriculture, phytoremediation with *Cannabis* helps to recover the health of the soil and increase the land utilization. The elimination or stabilization of the heavy metals decreases the toxicity, making it possible to cultivate crops in the formerly contaminated regions in a safer manner.

Besides, cultivating *Cannabis* has been linked to soil enhancement, and carbon sequestration since plant residues add to the organic matter content and improve soil structure.

According to life cycle assessments, the cultivation of hemp will be able to compensate carbon emissions and potentially achieve the results of carbon-neutral or even carbon-negative in favorable conditions.

These features are what render *Cannabis* a significant resource in terms of combining remediation and sustainable land management methods.

### 7.3 Economic and Industrial Uses of Biomass

Biomass dual-use is also one of the major benefits of phytoremediation based on *Cannabis*. In contrast to most hyperaccumulator plants, *Cannabis* will generate economically useful biomass, which can be used in other industries, including:

- Fiber (textile, biocomposites) production.
- Biofuel and bioenergy production.
- Paper and building materials.

Such dual capability increases the cost-effectiveness of phytoremediation by subsidizing the cost of remediation by using biomass. Recent research highlights the idea that hemp-based materials may as well be employed to carry out biosorption of contaminants, further purveying their use in the environment .

Nonetheless the entry of the heavy metals into the consumer products should be carefully managed to avoid entry into the consumer products especially in food or medicinal usage.

### 7.4 Contribution to Circular Economy and Sustainable Development Goals (SDGs)

The use of *Cannabis* as phytoremediation is in line with the principles of the circular economy, as it facilitates the recovery of resources, minimization of waste, and sustainability of production systems. The use of all plant parts-fibers, seeds and residues- ensures that there is minimal wastage and high economic returns.

Moreover, this practice contributes to several Sustainable Development Goals (SDGs) of the United Nations such as:

SDG 6: Clean water and sanitation.

SDG 12: responsible production and consumption.

SDG 13: Climate action

SDG 15: Life on land

Phytoremediation and biomass valorization is a holistic approach to attaining environmental sustainability.

### 7.5 Problems and Sustainability Issues.

Although *Cannabis*-based phytoremediation has its benefits, it has numerous challenges that need to be overcome to be used in large-scale applications:

- Regulatory implications: In most places, the use of *Cannabis* is hampered by legal restrictions on its cultivation.
- Biomass disposal risks: Biomass that is contaminated can be a threat to the environment and human health unless it is well handled.
- Variable efficiency: The amount of metal uptake depends on plant variety, soil conditions and environmental conditions.
- Extensive remediation period: Phytoremediation is normally slower than traditional methods.

## 8. RESEARCH DEFICITS AND DIFFICULTIES IN CANNABIS-BASED PHYTOREMEDIATION

A few research gaps have been identified during review of phytoremediation potential of *Cannabis sativa* & *Cannabis indica* like availability of limited comparative studies on the differential uptake and tolerance capacities both species; influence of soil properties such as pH, organic matter content and heavy metal speciation on the phytoremediation efficiency of these species is also poorly addressed.

There is insufficient data on how varying levels of Lead (Pb) and Cadmium (Cd) contamination impact the growth, biomass, and Cannabinoids content of *Cannabis sativa* and *Cannabis indica*. Understanding these impacts is crucial for balancing phytoremediation efficiency with potential industrial or medicinal uses of the plants.

## 9. FUTURE PERSPECTIVES

The research will provide insights into the efficacy of *Cannabis sativa* and *Cannabis indica* in removing heavy metals like Pb and Cd from contaminated soils, contributing to the detoxification and restoration of polluted lands. By identifying which species is more efficient in phytoremediation, the study will promote sustainable soil management practices and reduce the environmental and health risks associated with heavy metal contamination. The results will serve as a foundation for localized solutions enhancing the use of *Cannabis* species in managing soil contamination in industrially and agriculturally impacted areas. A successful study could lead to the development of cost-effective, eco-friendly strategies for soil remediation, providing an alternative to expensive and less sustainable traditional methods. The use of *Cannabis* in phytoremediation may open new agricultural opportunities and generate revenue for local farmers while simultaneously cleaning contaminated land. The research will also contribute to the growing body of knowledge on phytoremediation, specifically focusing on the comparative effectiveness of different *Cannabis* species in heavy metal removal.

## 10. CONCLUSION

Heavy metal pollution, especially from lead (Pb) and cadmium (Cd), is still a major environmental problem that has detrimental effects on both human health and ecosystem health. Even if they work well in some situations, conventional cleanup techniques are frequently not environmentally or financially viable for widespread use. In this sense, phytoremediation has become a promising green technique, providing an affordable and environmentally responsible substitute for cleaning up contaminated areas. The substantial potential of *Cannabis sativa* and *Cannabis indica* as effective phytoremediators is highlighted in this review. They are good candidates for the remediation of Pb and Cd-contaminated soils because of their quick development, high biomass output, large root systems, and exceptional resistance to metal-induced stress. A comparative analysis exhibits that *C. sativa* is extra effective in phytoextraction because of its superior metallic uptake and translocation capacity, while *C. indica* demonstrates

more performance in phytostabilization thanks to its stronger strain tolerance and steel immobilization skills.

## REFERENCES

- Acharya, A., et al. (2025). Current assessment and future perspectives on phytoremediation of heavy metals. *Plants*, 14(18), 2847.
- Ahmed, M. N., et al. (2025). Phytoremediation as a sustainable solution for heavy metal pollution and bioenergy production. *Environmental Science and Pollution Research*.
- Ahmad, R., Asad, S. A., Tehsin, Z., Malik, S. T., Khan, S. A., et al. (2015). Phytoremediation potential of hemp (*Cannabis sativa* L.): Identification and characterization of heavy metals responsive genes. *Clean – Soil, Air, Water*, 43(9), 1150–1156. <https://doi.org/10.1002/clen.201500117>
- Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—Concepts and applications. *Chemosphere*, 91(7), 869–881. <https://doi.org/10.1016/j.chemosphere.2013.01.075>
- Alloway, B. J. (2013). *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability* (3rd ed.). Springer.
- Al-Obaidi, J. R., et al. (2024). Plant responses to heavy metal stress: Mechanisms and adaptations. *Plant Physiology and Biochemistry*.
- Andre, C. M., Hausman, J. F., & Guerriero, G. (2016). *Cannabis sativa*: The plant of the thousand and one molecules. *Frontiers in Plant Science*, 7, 19. <https://doi.org/10.3389/fpls.2016.00019>
- Angelova, V., Ivanova, R., & Pevcharova, G. (2021). Accumulation of heavy metals in hemp (*Cannabis sativa* L.) grown on contaminated soils. *Environmental Science and Pollution Research*, 28(2), 1547–1557. <https://doi.org/10.1007/s11356-020-10524-7>
- Blaylock, M. J., & Huang, J. W. (2000). Phytoremediation of toxic metals: Using plants to clean up the environment. In I. Raskin & B. D. Ensley (Eds.), *Phytoremediation of toxic metals* (pp. 53–71). John Wiley & Sons.
- Chaney, R. L., et al. (2007). Phytoremediation of soil metals. *Journal of Environmental Quality*, 36(5), 1429–1443. <https://doi.org/10.2134/jeq2006.0514>
- Clarke, R. C., & Merlin, M. D. (2013). *Cannabis: Evolution and ethnobotany*. University of California Press.
- Deng, G., et al. (2024). Phytoremediation of lead-contaminated soil using industrial hemp (*Cannabis sativa* L.). *Journal of Environmental Management*.
- Ejaz, U., et al. (2023). Detoxifying heavy metals: Molecular and cellular mechanisms in plants. *Frontiers in Plant Science*. <https://doi.org/10.3389/fpls.2023.1154571>
- Faizan, M., et al. (2024). Phytochelatins: Key regulators against heavy metal toxicity in plants. *Environmental Research*.
- Flajšman, M., et al. (2023). Industrial hemp (*Cannabis sativa* L.) in contaminated soils: Environmental implications. *Environmental Science and Pollution Research*.
- Ghosh, M., & Singh, S. P. (2005). A review on phytoremediation of heavy metals and utilization of its by-products. *Applied Ecology and Environmental Research*, 3(1), 1–18.
- Guo, Y., et al. (2024). Industrial hemp for phytoremediation of heavy metals. *Chemosphere*.
- Hillig, K. W., & Mahlberg, P. G. (2004). A chemotaxonomic analysis of cannabinoid variation in *Cannabis*. *American Journal of Botany*, 91(6), 966–975. <https://doi.org/10.3732/ajb.91.6.966>
- Islam, M. M., et al. (2024). Phytoremediation as a green and sustainable approach for heavy metal removal. *RSC Sustainability*.
- Khan, T., et al. (2025). Multi-omics approaches to understanding heavy metal stress tolerance in plants. *Plant Stress Biology*.
- Kumar, A., et al. (2024). Phytoremediation: A sustainable approach for heavy metal remediation. *Environmental Advances*.
- Meffo Kemda, M. M., et al. (2024). Environmental impact assessment of hemp cultivation and its sustainability. *Frontiers in Environmental Science*.
- Mohamed, H. I., et al. (2025). Heavy metal toxicity in plants and phytoremediation mechanisms. *Environmental Science and Pollution Research*.
- Mukherjee, S., et al. (2025). Sustainable management of post-phytoremediation biomass. *International Journal of Environmental Science and Technology*.
- Patel, N., & Srivastava, R. K. (2025). Evaluation of plant species for phytoremediation in contaminated soils. *Current World Environment*.
- Pilon-Smits, E. (2005). Phytoremediation. *Annual Review of Plant Biology*, 56, 15–39. <https://doi.org/10.1146/annurev.arplant.56.032604.144214>
- Placido, D. F., & Lee, C. C. (2022). Potential of industrial hemp for phytoremediation. *Plants*, 11, 1234.
- Rehman, G., et al. (2024). Advances in phytoremediation techniques for heavy metal removal. *Environmental Science Materials*.
- Salifu, M., et al. (2024). Phytoremediation strategies for heavy metal contamination: A sustainable

- approach. *Journal of Environmental Protection*, 15, 450–474.
30. Sarwar, N., et al. (2010). Role of mineral nutrition in minimizing cadmium accumulation by plants. *Journal of the Science of Food and Agriculture*, 90(6), 925–937. <https://doi.org/10.1002/jsfa.3916>
  31. Stanley, J. A., et al. (2018). Lead and cadmium-induced oxidative stress and DNA damage. *Biocatalysis and Agricultural Biotechnology*, 16, 253–259. <https://doi.org/10.1016/j.bcab.2018.08.021>
  32. Tangahu, B. V., et al. (2011). A review on heavy metals uptake by plants through phytoremediation. *International Journal of Chemical Engineering*, 2011, 1–31. <https://doi.org/10.1155/2011/939161>
  33. Yadav, K., et al. (2025). Heavy metal phytoremediation mechanisms and applications. *Environmental Chemistry Letters*.
  34. Zhang, K., et al. (2024). Trends in phytoremediation of heavy metal-contaminated soils. *Chemosphere*.