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Hyperaccumulator Plants for Soil Remediation, Crop Protection, and Phytomining: An Integrated Sustainable Approach / Review Article

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Abstract: Heavy metal contamination of agricultural soil is one of the most serious environmental challenges. Traditional physical and chemical remediation methods are not only costly but also environmentally damaging and unsuitable for large-scale farming. Phytoremediation, particularly the use of superaccumulating plants, represents a novel and environmentally friendly approach to soil treatment. These plants possess a unique ability to accumulate metals at concentrations hundreds or thousands of times higher than ordinary plants, utilizing a range of advanced physiological and molecular techniques. The novel concept of using these plants as biological traps has paved the way for the preventative protection of food crops from contamination. By employing a combination of phytomining, nanotechnology, and plant-root-stimulating bacteria, the remediation capacity of these plants has been further enhanced, making this method economically viable. This paper explores the use of superaccumulating plants in soil remediation and food security protection, proposing a new and advanced framework for environmentally friendly remediation and protection. The Problem Statement: Heavy metals, such as lead, cadmium, mercury, nickel, and arsenic, accumulate in agricultural soils as a result of industrial, mining, and agricultural activities. The long-term degradation of heavy metals is attributed to their chemical stability, such as their translocation to edible plant parts. This leads to foodborne exposure risks, particularly chronic health risks to humans, such as neurotoxicity, kidney disease, and cancer. It also contributes to ecosystem degradation, including reduced microbial populations and loss of fertility. Traditional methods for treating heavy metals in agricultural soils are costly, polluting, and less sustainable, highlighting the need for new, environmentally friendly approaches. Objectives of the Article: This article aims to explore the physiological and molecular basis of how heavy metals accumulate in superaccumulators and detoxify. It also evaluates the use of superaccumulators as attractive crops to prevent the translocation of heavy metals to food crops. Furthermore, it explores the use of superaccumulators in conjunction with phytomining and biotechnology techniques to improve the sustainability of soil treatment and increase economic benefits. Finally, it highlights the research challenges and limitations in using superaccumulators for treating heavy metals in agricultural soils. Methodology: This article was conducted using peer-reviewed publications that included experimental, field, and modeling studies. It focused on super-accumulating plant species, their molecular and physiological adaptations, and their applications in soil remediation, food crop protection, and mineral extraction. Phytoremediation mechanisms include phytoremediation, phytoremediation, phytostabilization, root leaching, and phytodecomposition, as well as integrated approaches to biotrape bioculture, phytomining, microbial activation, the use of nanoparticles, and predictive modeling. Superaccumulating plant species are characterized by their ability to accumulate heavy metals at extremely high concentrations without causing phytotoxicity, making

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them effective biofilters. Biotrape bioculture systems strategically place superaccumulating plant species to intercept metals, reducing the amount of metals transferred to food crops. Phytomining has the potential to transform harvested plant biomass into a valuable commodity, providing a strong incentive in addition to environmental benefits. However, several challenges hinder the effective and efficient implementation of phytoremediation, including low treatment rates, variability in pollutant accumulation due to environmental factors, and the management of contaminated biomass.

Keywords: Phytoremediation, superaccumulating plants, heavy metal pollution, biotrape crops, phytomining

1. Introduction

Heavy metal pollution of agricultural soil has become one of the most complex and intractable environmental problems facing the world in the 21st century. Unlike many other pollutants, heavy metals are non-biodegradable, chemically stable, and resistant to environmental degradation processes. Once introduced into the terrestrial ecosystem, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), nickel (Ni), and arsenic (As) tend to persist for decades, undergoing physical and chemical transformations rather than degradation or decomposition [1]

1.1 Sources of Heavy Metal Pollution in Agricultural Soil: Heavy metal pollution of agricultural soil is primarily attributed to human activities. The main sources of heavy metal pollution in agricultural soil include • Mining and smelting activities, • Fossil fuel combustion, • Petrochemical and oil refining wastewater discharge, • Sludge use, • Excessive use of phosphate fertilizers and pesticides

The problem is particularly pronounced with phosphate fertilizers, which are a major source of long-term cadmium pollution due to the presence of naturally occurring cadmium impurities in phosphate rock [2]. Cadmium gradually accumulates in the topsoil over the long term, increasing the risk of its uptake by plants. According to the Food and Agriculture Organization (FAO), more than 20% of the world's agricultural soils suffer from varying degrees of heavy metal pollution, particularly in areas with high levels of industrialization, mining, or oil exploration. In developing countries, the problem is also exacerbated by poor waste management practices.

1.2 Mechanisms of Heavy Metal Translocation Between Soil and Plants: The risk posed by heavy metals is not determined by their total content in the soil, but rather by their bioavailable quantities. Various soil factors influence the translocation of heavy metals, including • Soil pH, • Organic matter content, • Cation exchange capacity, • Redox potential.

Types of metals acid soils increase the solubility of heavy metals, such as cadmium and lead, thereby increasing their uptake by plant roots. The presence of root exudates in the soil, including organic acids and amino acids, also affects the chemical composition of the metals.

Heavy metals tend to accumulate in plant roots via non-specialized transporters, which, under normal conditions, facilitate the uptake of essential micronutrients (such as zinc, iron, and calcium). After accumulating in plants, heavy metals tend to follow one of the following pathways:

- Remaining stored in root vacuoles
- Binding to phytochelatins or metallothioneins
- Moving to the aerial parts via the xylem tissue
- Accumulating in the edible parts of the plant

The third option is the primary pathway by which humans are exposed to heavy metals, particularly in plants.

1.3 Health and Environmental Effects: The adverse health effects of long-term heavy metal exposure through contaminated food include:

- Lead (Pb): Causes neurotoxicity and cognitive impairment, especially in children.
- Cadmium (Cd): Causes kidney and bone mineral deficiencies.
- Arsenic (As): Classified as a Group 1 carcinogen.
- Mercury (Hg): Causes disturbances in the development and function of the nervous system.

The World Health Organization (WHO) confirms that “long-term exposure to heavy metals, even at low concentrations, can lead to cumulative toxicity and chronic health effects [3]. In addition to the adverse health effects of heavy metals, the soil ecosystem is affected by reduced microbial diversity, inhibited enzyme activity, disruption of nutrient cycling, and decreased soil fertility.

1.4 Implications for Food Security: Food security is a concept that encompasses food safety, nutritional value, and availability. Therefore, when heavy metal concentrations rise in crops, it can pose a threat to food safety, even when the crop is available. Recent findings indicate that millions of tons of agricultural products are wasted annually due to exceeding the permissible limits for heavy metals according to international trade standards [4]. Thus, the problem of heavy metals in soil directly impacts global food security and sustainability.

1.5 Limitations of Conventional Treatment Techniques: Several physical and chemical treatment techniques have been developed to treat soil contaminated with heavy metals, including:

1. Soil leaching: This is the process of using chemicals to remove heavy metals from contaminated sites.
2. Chemical fixation: This is the process of using chemicals such as lime, phosphates, and biochar to treat heavy metals.
3. Excavation and soil replacement: This is the process of using chemicals to treat heavy metals, but it is expensive and environmentally unfriendly [5], asserted that these technologies, while effective in highly polluted industrial sites, may not be sustainable in agricultural environments due to their high economic, environmental and energy costs.

1.6 The Emergence of Phytoremediation as a Sustainable Alternative: Phytoremediation is considered an environmentally friendly, cost-effective, and sustainable approach to treating contaminated sites, given the limitations of conventional technologies. Phytoremediation techniques include: • Phytoremediation, Phytostabilization and Root leaching,

Among all the techniques, phytoremediation using superaccumulators has been identified as a promising technique for treating metal-contaminated sites, due to its ability to remove large quantities of metals from contaminated soil [6]. Superaccumulator species are characterized by their ability to accumulate extremely high concentrations of certain metals in their aboveground plant tissues, despite being able to tolerate these high concentrations without exhibiting symptoms of phytotoxicity.

Superaccumulator species are characterized by their ability to accumulate extremely high concentrations of certain metals in their aboveground plant tissues, despite being able to tolerate these high concentrations without exhibiting symptoms of phytotoxicity. These species form the basis of both phytoremediation and the recently proposed concept of phytomining [7].

1.7 Towards a Biotrap System for Soil and Crop Protection: In addition to their use in soil remediation, superaccumulating plants are considered biotrap systems. In this

approach, these plants are grown around or within agricultural fields to collect bioavailable heavy metals, thereby preventing crop exposure to heavy metals.

This dual according [8] approach aims to reduce the bioavailability of heavy metals, protect crops from heavy metal contamination, provide opportunities for extracting valuable minerals through phytomining and improve soil health

The shift from traditional phytoremediation to phytomining systems represents a paradigm shift in the sustainable management of land resources. This is because it changes the perception of soil from a burden to a vital mineral deposit that can be harnessed for resource recovery under responsible management, [9] the shift from traditional phytoremediation to phytomining systems represents a paradigm shift in the sustainable management of land resources. In this regard, this review aims to provide an in-depth discussion of the mechanisms, uses and prospects of super-accumulating plants as biological trap systems for soil remediation and crop protection from heavy metal pollution, integrating concepts of environmental biotechnology, sustainable crop production and green resource recovery [10].

Methodology

Methodology of this review study is founded by overview of large scale and systematic analysis of peer-reviewed literatures regarding the mechanism of hyperaccumulator plants in soil restoration, protection of crops and phytomining. Based on experimental, field, and modeling studies, the current perspective incorporates physiological, molecular, and ecological approaches to understand how some (hyper)accumulator species have developed, at least in part, the necessary mechanisms to tolerate and bioaccumulate heavy metals at extremely high concentrations without suffering phytotoxic effects. Only studies that were relevant to phytoremediation strategies (phytoextraction, phytostabilization, phytodegradation, and rhizofiltration) and superaccumulator species in particular were selected in the first instance. The mechanisms underlying the unique aspects of plant metal (Cu, Zn, Ni, Cr, As) absorption, transportation, chelation and detoxification processes by special transport proteins, chelation agents and antioxidants have been discussed in these references. The methodology then assesses the use of biological trap crop systems in which hyperaccumulator plants are grown inside or surrounding agricultural fields to capture the heavy metals and minimize their transfer to food crops. Also, the study integrates modern integrative strategy like phytomining, plant growth-promoting rhizobacteria, greener nanotechnology, and genetic enhancement approach to increase the efficiency of metal uptake and system sustainability. Using data across contrasting environmental conditions, soil properties, and plant species, comparative insights were synthesized that could be used to identify variability in performance and constraints. In addition, predictive modeling tools and worst-case scenario economic feasibility assessments were incorporated to assess potential for applicability on the scale needed for large-scale application. This integrative approach the methodology includes a holistic framework to enable understanding and optimisation of hyperaccumulator plants as sustainable, multifunctional systems for environmental remediation and agricultural protection.

2. Results and Discussion

2. Theoretical Framework of Phytoremediation

Phytoremediation is an environmentally friendly technique for cleaning contaminated soil and water, utilizing the ability of plants to purify the environment of pollutants. Recent research has demonstrated the effectiveness of this technique in cleaning various organic and inorganic pollutants, including heavy metals, hydrocarbons, pesticides, and industrial pollutants [11].

2.1 Basic Mechanisms of Phytoremediation: Phytoremediation relies on four mechanisms, depending on the type of plants and pollutants used in the cleaning process according [12] include :

2.1.1 Phytoremediation: The ability of plants to collect heavy metals from soil or water and store them in their aerial parts, such as leaves and stems. Superaccumulators constitute the primary mechanism of phytoremediation, as they accumulate heavy metals at concentrations up to 100 times higher than those of normal plants without exhibiting any symptoms of poisoning . Plant roots absorb heavy metals from the soil through the activity of HMA (heavy metal ATPase) enzymes and ZIP (zinc/iron regulated transport proteins after absorption, the metals are translocated to the aerial parts of the plant, where the plant can be harvested for safe disposal or for metal extraction.

Examples of super-accumulating plants such as *Thalasspi ceruleicens*, accumulation of zinc (Zn) and cadmium (Cd) and *Brassica johnsa* ,accumulation of lead (Pb) and nickel (Ni), this is permanent removal of metals from the soil and economic benefits through metal mining, more challenges include longer time required to achieve result and some metals do not accumulate in large quantities in certain plant species

2.1.2 Phytostabilization: A technique used to reduce the bioavailability of heavy metals in the soil, plants fix metals in their root zone or root area using root exudates containing organic acids and chelating agents root precipitation, thus preventing the metals from migrating to the topsoil or groundwater [13]. Plants with large, dense root systems are typically used to achieve the highest level of phytostabilization. And is used in highly contaminated soils where metal removal is expensive, examples of plant species used in this technique such as *Vetiver (Vetiveria zizanioides)*, this plant fixes arsenic (As) and lead (Pb) and oplar species (*Populus spp.*), this is fixes zinc (Zn) and cadmium (Cd)

2.1.3 Phytolysis : also known as plant metabolism, is the ability of a plant to break down organic pollutants into less toxic compounds within its tissues or root zone,organic pollutants include petroleum hydrocarbons, pesticides, and industrial chemicals. Plants produce enzymes such as oxidases and peroxidases that facilitate the breaking of complex chemical bonds organic pollutants include petroleum hydrocarbons, pesticides, and industrial chemicals [14].

Plants produce enzymes such as oxidases and peroxidases that facilitate the breaking of complex chemical bonds (Glick, 2010). Synergistic interaction between microbes in the root zone and the plant enhances the efficiency of the decomposition process, leading to the formation of a synergistic system , examples of plants include, poplar species (*Populus spp.*) and willow species (*Salix spp.*) for removing organic pollutants from soil and water, this is advantages removal of organic pollutants without transferring them to the edible parts of plants and no opportunity for pollutant transfer from one medium to another thanks to the natural synergy between the plant and microbes in the root zone.

2.1.4 Root Leaching: The absorption or adsorption of heavy metals and dissolved pollutants from aqueous solutions using plant roots, particularly aquatic or semi-aquatic plants. Plant roots act as filters, absorbing heavy metals such as lead (Pb), mercury (Hg), and nickel (Ni). The treated plants can then be safely disposed of or recycled to extract further metals [15]. Examples of plants used include common reed *Phragmites australis* and rhizome *Hydrilla verticillata*, advantages of this method include its effectiveness in treating surface water and industrial wastewater, as well as its compatibility with hydroponic systems and designed wetland systems.

2.2.5 Focus on Superaccumulating Plants: plants are key components of phytoremediation, particularly phytoremediation, as they are capable of absorbing and accumulating large quantities of heavy metals in their aerial parts. This is aided by molecular mechanisms involving chelating agents such as phytokelatins and phenolic compounds [16]. The selection of superaccumulating plants depends on the types of metals present, soil types, and local climate. This method can be supplemented with growth

stimulants such as nanoparticles and microbial stimulation of the root zone to achieve more effective results [17].

Integration with advanced strategies in recent studies have highlighted that integrating all four mechanisms improves the sustainability of phytoremediation. This includes using superaccumulators as biological trap crops to prevent metal accumulation in food plants, as well as phytoremediation and stimulating microbial activity in the root zone to improve hydrocarbon degradation. It also involves the accumulation and sequestration of metals in plant roots, preventing their transfer to edible parts, and using root leaching to clean groundwater and industrial wastewater. This approach will improve ecosystem restoration, food safety, and the economical extraction of valuable metals from food plants, a process known as phytomining [15]. Superaccumulators constitute a unique group of species with an exceptional capacity to accumulate heavy metals in their tissues, at rates 100 to 1000 times higher than those recorded in non-superaccumulators [18]. These plants play an important role in phytoremediation strategies, which rely on their ability to accumulate large quantities of heavy metals through their high absorption efficiency and tolerance to heavy metal stress, making them excellent candidates for phytoremediation strategies. Superaccumulator species are classified based on the minimum concentrations of metals they can accumulate in their dry aerobic tissues dry weight without becoming phytotoxic, the scientific criteria for classifying plants as hyperaccumulators define them as unique types of plants with an exceptional ability to absorb heavy metals from the soil and store them in their aerial parts (leaves and stems) at very high concentrations without becoming toxic. For a plant to be classified as a hyperaccumulator for a specific metal, the concentration of that metal in its dry weight (DW) tissues must exceed the following limits: Cadmium (Cd) > 100 mg/kg is highly toxic even at low concentrations. If a plant can store more than 100 mg per kilogram of its dry weight, it is considered a hyperaccumulator. Nickel (Ni) and lead (Pb) > 1000 mg/kg means the plant must absorb more than 1000 mg (1 gram) of nickel or lead per kilogram of its tissues. Lead is generally difficult for roots to absorb and utilize, so this figure represents a significant biological achievement for the plant. Zinc (Zn) > 10,000 mg/kg is an element that plants need in small amounts, but a super-accumulating plant can store more than 10,000 mg (i.e., 10 grams or 1% of its dry weight) of zinc without its growth being affected [19].

3. Molecular Mechanisms of Metal Accumulation

Over-accumulation is a highly complex process requiring the use of multiple physiological and molecular approaches to mineral accumulation, transport, and detoxification according to [20].

3.1 Enhanced Solubility in the Root Zone: The roots of plants with over-accumulation secrete compounds that increase mineral solubility in the soil. These compounds include:

- Organic Acids: Organic acids, including citric, malic, and oxalic acids, chelate minerals, facilitating their solubility.
- Siderophores: These are chelating agents for iron and also have the ability to chelate other metals, such as cadmium, nickel, and zinc.
- Other Chelating Agents: These include phenolic compounds that have the ability to chelate minerals, facilitating their solubility.

After metal dissolution, they are transported across the root cell membrane using the following metal transporters:

- ZIP transporters (zinc/iron regulatory proteins): ZIP transporters are known to transport zinc (Zn^{2+}) and iron (Fe^{2+}) ions in plant cells [17].

- NRAMP transporters phagocyte-associated natural resistance proteins : NRAMP transporters are known to transport cadmium (Cd^{2+}) and manganese (Mn^{2+}) ions in plant cells (Clemens, 2022).

- Heavy metal transporters (ATPases): Heavy metal transporters are ATP-dependent transporters that move lead (Pb^{2+}), zinc (Zn^{2+}), and cadmium (Cd^{2+}) ions within plant cells .

- Heavy metal transporters (ATPases): Heavy metal transporters are ATP-dependent transporters that move lead (Pb^{2+}), zinc (Zn^{2+}), and cadmium (Cd^{2+}) ions within plant cells.

- Heavy metal transporters: These transporters not only facilitate the absorption of minerals into plant cells but also regulate intracellular mineral balance, protecting the cell from metal toxicity also detoxify metals using the following steps:

- Phytokilittins (PCs): Phytokilittins are short peptides that chelate metal ions and protect the cell from metal toxicity.

- Methalothionines (MTs): Methalothionines are cysteine-rich metal chelating agents that play a role in Oxidative stress is an inevitable consequence of heavy metal accumulation, leading to the production of reactive oxygen species. Plants with excessive heavy metal accumulation have developed robust antioxidant systems to protect against oxidative stress:

- Superoxide dismutase (SOD): Converts superoxide radicals into hydrogen peroxide.

- Catalase (CAT): Decomposes hydrogen peroxide into water and oxygen.

- Peroxidase (POX): Detoxifies hydrogen peroxide.

These powerful antioxidant systems, which may also be activated in response to oxidative stress, are crucial for maintaining cellular homeostasis and successful plant extraction. The success of superoxide plants stems from a combination of physiological and molecular mechanisms working together to achieve the goal of plant extraction, these mechanisms according to [21] include:

1. Root zone modification: Enhancing mineral solubility to facilitate absorption.
2. Transporter regulation: Regulating mineral uptake in the roots and subsequent transport to the aerial parts.
3. Chelation: Detoxification of metals.
4. Antioxidant systems: Detoxification of oxidative stress.

This combination of all the above approaches enables superaccumulator plants to act as biological "sponges" for heavy metal processing, paving the way for the development of a remediation program known as phytomining.

4. Superaccumulating Plants as a Biological Trap System

Superaccumulating plants have traditionally been used to remediate previously contaminated soils. However, in modern approaches, these plants are used as a preventative measure to stop soil contamination in the first place. In this context, superaccumulating plants are used to trap pollutants in the soil. This new approach to using superaccumulating plants is known as the Biological Trap Crop System (BTCS). In this system, superaccumulating plants are used to trap pollutants, such as heavy metals, in the soil, thus protecting the food crops grown in it , this is a new concept in the use of these plants for soil remediation, and it differs significantly from their traditional use in remediating previously contaminated soils. The BTCS system can be implemented in agriculture through spatial distribution and crop management, and the transfer of pollutants to the edible parts of the crop is minimized in the BTCS system. In agriculture, the use of superaccumulatory plants in integrated plant treatment systems (BTCS) is essential to ensure the effective phytoremediation of soil pollutants without impacting crop productivity [13]. The transfer factor, expressed as the ratio of mineral concentration

in plants to their concentration in the soil, is a crucial factor to consider when assessing bioavailability. Studies have shown that using BTCS can reduce the soil-to-edible plant transfer factor by 40–70%, depending on the mineral and crop type [14]. This is attributed to competition among superaccumulatory plants, which accumulate minerals in their terrestrial and aerial parts, particularly those parts that are typically harvested and monitored separately. Consequently, by controlling the transfer factor, associated nutritional risks can be reduced heavy metals.

4.1 Advantages of Biological Trap Systems

1. Preventive Protection: This approach reduces the amount of metals entering the food chain, unlike post-contamination cleanup.
2. Integration with Conventional Agriculture: Trap plants can be grown without affecting crop yields.
3. Environmental Sustainability: This approach prevents the use of chemicals that could harm the soil ecosystem.
4. Economic Viability: Harvested superaccumulators are used in phytomining, which extracts valuable metals such as nickel, zinc, and cadmium .

This approach effectively transforms superaccumulators into dynamic biological filters, providing soil remediation, crop protection, and phytomining in a single system and an advanced form of superaccumulator utilization that extends beyond soil remediation. This practice involves cultivating these plants to extract valuable metals from contaminated soil. The steps of this practice according to [22] include:

1. Growing superaccumulators in mineral-rich soil.
2. Harvesting plants when minerals accumulate at their highest levels.
3. Burning the plants to obtain the resulting ash containing the minerals.
4. Extracting the minerals from the ash using chemical or electrochemical processes.

This method has proven successful with nickel (Ni), cobalt (Co), and gold (Au) in controlled natural environments , the extracted minerals can be sold, providing a profitable activity for participants, making phytomining a lucrative venture, particularly in areas with high mineral content in the soil. Therefore, phytomining is a technique that combines environmental cleanup with optimal resource utilization, integrating the environmental, agricultural, and economic aspects of sustainability. Economic models indicate that phytomining can cover up to 60–80% of soil treatment costs, depending on mineral concentration, crop yield, and market prices [14]. Factors affecting the feasibility of phytomining include, biomass yield per hectare, mineral concentration in plant tissues, mineral recovery potential using ash, market value of the minerals. Therefore, phytomining is an environmentally friendly and economical soil remediation method compared to other traditional techniques such as soil leaching and chemical extraction, which are costly and environmentally unfriendly.

To maximize the efficiency of the remediation process using super-accumulating plants, the integration of modern biotechnologies and nanotechnology into phytomining is being explored plant root growth-stimulating bacteria (PGPR), these microorganisms increase mineral uptake and plant growth under stress conditions, some strains also increase root exudates, which solubilize minerals and increase their bioavailability [7].

4.2. Green Nanoparticles for Soil Stabilization: Various nanoparticles, including zinc oxide and titanium dioxide, have the potential to increase the efficiency of mineral uptake, thereby reducing mineral leaching into the soil and facilitating their transport to plants [19], and genetic engineering by overexpressing genes responsible for mineral transport, the efficiency of mineral accumulation can be increased. Furthermore, levels of stress proteins, including phytoelinitates and methalothionines, can be increased to enhance plant resistance to large quantities of minerals accumulating in the soil [9].

Computational modeling and predictive tools include various models have been developed to predict the behavior of pollutants, this allows for maximizing the efficiency of the remediation process, along with maximizing accumulation using a combination of biological, chemical, and computational techniques, super-accumulation systems can evolve from simple soil cleaning agents into highly efficient, predictable, and cost-effective bioengineering tools.

5. Research Challenges in Superaccumulating Plant-Based Systems

Although the use of superaccumulating plants as biotrape crops and phytometallurgical agents represents a promising and sustainable cleaning technology, several research challenges must be overcome to fully realize its potential. One of the most significant drawbacks of phytometallurgical processing is the slow rate of mineralization compared to chemical or physical processing techniques. Superaccumulating plants need to grow to accumulate large quantities of minerals at economically and environmentally viable rates. The processing rate is influenced by factors such as mineral availability in the soil, the growth rate of the superaccumulating plants, and the physical and chemical properties of the soil, to overcome this limitation, strategies such as genetic improvement, inoculation with PGPR bacteria, and nanoparticle-assisted bioavailability have been proposed [4].

There is also a risk of minerals entering the food chain. Although superaccumulating plants are cultivated as non-food crops, there is always a risk of them accidentally entering the food chain. Therefore, continuous field monitoring is crucial to ensure that no superaccumulative plant biomass enters animal feed and that any contaminated biomass is collected and safely removed. This biomass can then be used in phytomining. Accumulation efficiency varies; for example, the mineral accumulation efficiency of superaccumulative plants is influenced by environmental conditions such as climatic factors like temperature, rainfall, and seasonal variations, which can affect plant metabolism and mineral uptake. Soil properties, including pH, cation exchange capacity, and the presence of competing ions, also affect mineral availability. Genetic variations are another factor, as differences in mineral accumulation capacity can exist even within the same species, managing contaminated biomass is essential because superaccumulative plant biomass is highly contaminated and cannot be left in the field after harvest. Challenges in phytomining according to [20] include:

- Safe disposal or treatment of contaminated biomass to prevent re-contamination of soil or water.
- Integrating phytomining to facilitate the extraction of valuable minerals.
- The potential for using bioenergy, provided that the minerals are safely removed from the biomass beforehand.
- Managing contaminated biomass in phytomining crucial to ensuring sustainability of the phytomining cycle while simultaneously safeguarding the environment [21].

6. Conclusion

The results and discussion indicate that the hyperaccumulator plants provide a viable and sustainable solution in rehabilitating heavy metal-polluted soils without compromising the food crops. Hyperaccumulator plants are capable of accumulating and storing toxic metals in their tissues at high concentrations, thus preventing the transfer of these metals to the food crops and minimizing the risk of metal-related hazards in the food chain. Physiological and molecular approaches of the hyperaccumulator plants allow them to accumulate metals in the rhizosphere, uptake metals through the action of specific metal-protein transporters, chelate metals in the vacuoles to reduce toxicity, and activate antioxidative systems to combat metal-related stress. Crop designs that include these hyperaccumulator plants as a biological trap system and provide a protective belt around the food crops are able to reduce the transfer factors of metals and preempt contamination. In addition, the integration of phytoextraction with phytomining is able to provide the biomass of the hyperaccumulator plants as a valuable resource,

and hence the overall feasibility of the system. The efficiency of the system can also be increased through the utilization of growth-promoting microorganisms, hyperaccumulator plants, and the utilization of green nanomaterials or genetic engineering techniques to upregulate the expression of metal transporters. However, the problems associated with the slow rate of cleanup, the handling of contaminated biomass, the differences in the rate of cleanup under various climatic conditions, and the potential risks of the transfer of metals from the plants need to be overcome. The overall analysis proves that the hyperaccumulator plants provide a multi-functional system that helps in the rehabilitation of the soil, food security, and the recovery of metals in a sustainable manner, providing an advanced model of ecology for the efficient management of agricultural lands contaminated with metals.

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