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Heavy Metal Toxicity Removal and Soil Reclamation: The Critical Role of the Family *Asteraceae*

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Abstract

Asteraceae plants, which include daisies, sunflowers, marigolds, dandelions, and their relatives, have attracted significant research attention for phytoremediation because of their rapid growth, broad environmental tolerance, and interactions with soil microbiota. As phytoextractors (removing metals into harvestable biomass) and phytostabilizers (reducing mobility and erosion), members of the family exhibit promise. Additionally, certain species stimulate rhizosphere microbes that break down organic pollutants. Physiological characteristics, mechanisms, applications in mine tailings and urban/industrial soils, case studies (most notably *Helianthus annuus*, *Taraxacum* spp., *Tagetes erecta*), management considerations (biomass handling, amendments, mixed planting), limitations, and research needs are all summarised in this review. Despite promising results, several limitations remain, including site-specific variability in performance and challenges in handling and disposing of contaminated plant biomass. Addressing these constraints is essential for improving the practical applicability of phytoremediation strategies. Asteraceae can be useful elements of inexpensive, nature-based reclamation techniques, according to data from controlled pot experiments and multi-site field trials, particularly when combined with soil amendments and microbial bioaugmentation.

Major Findings: This review demonstrates that Asteraceae plants possess remarkable potential for removing heavy metals and reclamation of contaminated soils due to their metal tolerance, high biomass, and efficient phytoremediation capabilities. These characteristics make them valuable resources for the sustainable restoration of contaminated ecosystems.

Keywords: Asteraceae, Heavy Metals, Phytoremediation, Soil Reclamation, Toxicity

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1. Introduction

Heavy metals such as arsenic, chromium, lead, mercury, and cadmium are highly toxic even at low concentrations, posing substantial threats to ecological integrity and human health[1]. Although natural processes-including weathering and volcanic activity- contribute to their environmental presence, mining operations, industrial discharges, and agricultural runoff remain the dominant anthropogenic sources[2-4]. Their persistence and non-biodegradable nature enable them to accumulate in soil and water systems, adversely affecting terrestrial and aquatic organisms[3,5,6]. Due to their density and long-term stability, these metals are often considered highly toxic environmental contaminants, capable of entering the human body via ingestion, inhalation, or dermal absorption and causing acute and chronic health disorders[7-9]. Bioaccumulation and biomagnification further intensify their ecological and health consequences[10,11].

Cost-effective and environmentally conscious restoration techniques are needed for degraded substrates such as mine tailings and contaminated soils (containing heavy metals, petroleum hydrocarbons, PAHs, salts, and acidic wastes). Plants and plant-microbe interactions are used in phytoremediation to extract, immobilise, or transform pollutants[12,13]. Asteraceae species are widely studied for phytoremediation due to their adaptability to contaminated environments and functional root systems.

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The mechanisms by which Asteraceae aid in reclamation, empirical evidence (important species and systems), operational considerations, and research gaps are the main topics of this review.

1.1 Rationale for Asteraceae in Phytoremediation

Relevant ecological and biological characteristics of Asteraceae species make them excellent candidates for remediation. Many Asteraceae members demonstrate rapid growth and high aboveground biomass production, which are critical traits for enhancing contaminant removal in phytoextraction-based systems. Their well-developed fibrous root systems and active rhizosphere interactions contribute to soil stabilisation, reduce erosion, and promote microbial communities that transform pollutants[14]. Furthermore, some Asteraceae species have shown BCF values greater than 1, indicating effective metal uptake. These species produce a variety of secondary metabolites and root exudates that can influence metal bioavailability through mechanisms such as pH modification, chelation of metal ions, and stimulation of microbial activity; for example, low-molecular-weight organic acids may enhance metal solubility and facilitate uptake[15]. However, the extent and direction of these effects can vary depending on plant species, soil characteristics, and environmental conditions. In addition to their remediation potential, several Asteraceae species, such as *T. erecta* and *H. annuus,* possess ornamental and agricultural value, providing ecosystem services including pollinator support, seed oil production, and aesthetic benefits. These combined traits make Asteraceae species promising and multifunctional candidates for sustainable phytoremediation applications.

2. Materials and Methods

Information on the roles of Asteraceae species in soil reclamation and phytoremediation was gathered through a thorough review of the literature. Peer-reviewed research articles, review papers, and book chapters were retrieved from online scientific resources, including Google Scholar, PubMed, ScienceDirect, Scopus, and Web of Science. FAO, WHO, ICAR, CPCB, MoEFCC, and other pertinent institutional websites provided more grey literature and recent updates. The search covered publications from 2005 to 2025, focusing on studies related to keywords including "Asteraceae," "phytoremediation," "soil reclamation," "heavy metal uptake," "rhizosphere interactions," "bioaccumulation," "ecological restoration," and "environmental stress tolerance" were used in the search. The search was refined using Boolean operators (AND, OR) (e.g., "Asteraceae AND soil remediation," "phytoremediation OR soil rehabilitation"). The inclusion criteria for this review comprised peer-reviewed research articles, studies published in English, experimental or field-based studies related to heavy metal stress or phytoremediation, and studies providing relevant physiological and growth-related data. Studies were excluded if they were published in languages other than English, lacked primary data (e.g., review articles, except when used for general background), were conference abstracts without full-text availability, or were not directly relevant to phytoremediation or heavy metal toxicity. All retrieved records were screened for duplicates, which were removed manually. The screening process involved an initial evaluation of titles and abstracts, followed by a full-text assessment of relevant articles. In total, approximately 32 studies were selected for the final analysis based on their relevance, data quality, and contribution to understanding phytoremediation mechanisms and performance (Figure 1). Using a narrative review methodology, this work synthesises qualitative data from several web sources without conducting statistical or quantitative meta-analysis. To ensure authenticity and reliability, cross-verification across multiple sources was conducted, particularly for grey literature found on publicly accessible websites[14].

3. Reclamation Mechanisms to Which *Asteraceae* Contribute

3.1 Phytoaccumulation

Uptake and accumulation of contaminants, particularly heavy metals, within plant tissues (roots and/or shoots), without necessarily implying their removal from the contaminated site[16].

3.2 Phytoextraction

Pollutants are absorbed by plants into their roots and then moved to their shoots for harvest. For the removal of Cd, Pb, and Zn, *H. annuus* has been thoroughly studied. phytoextraction is most effective in soils where metals are sufficiently bioavailable and when plant species exhibit

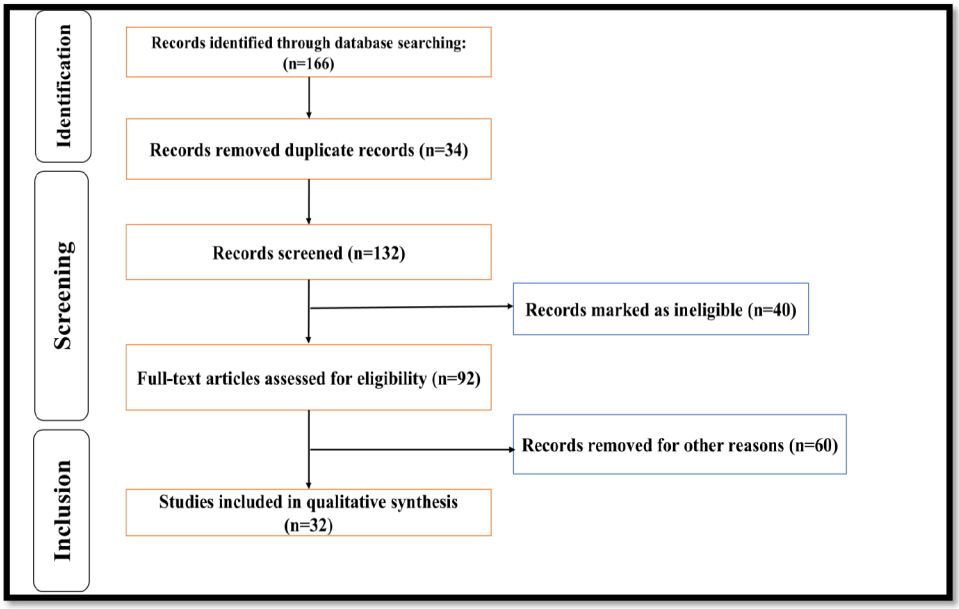


Figure 1. Prisma flow chart depicting inclusion and exclusion criteria.

high biomass production and efficient translocation (TF > 1)[14]. This mechanism is particularly suitable for moderately contaminated soils where repeated harvesting can gradually reduce pollutant levels. Under the right circumstances, Field and pot studies demonstrate that *H. annuus* exhibits higher metal uptake than several other Asteraceae species, largely due to its greater biomass production; however, its accumulation efficiency is generally lower than that of known hyperaccumulators such as *Brassica juncea* under similar conditions[16].

3.3 Phytostabilization

By immobilising pollutants in the root zone, plants lessen leaching and erosion. Numerous Asteraceae quickly take root in tailings and degraded soils, forming a vegetative cover that stabilises metals in situ and reduces wind and water erosion. This is especially helpful for phosphate wastes and mine tailings[17].

3.4 Organic Rhizodegradation and Rhizoremediation

These processes are most effective in biologically active soils where plant–microbe interactions are well established, and they play a significant role in the transformation of organic contaminants and, to a lesser extent, in influencing metal mobility. Microbial consortia capable of degrading organic pollutants (e.g., PAHs and petroleum hydrocarbons) are supported by root exudates. To speed up hydrocarbon degradation, several Asteraceae (such as *Tagetes* and some ornamentals) have been combined with microbial inocula or biochar. Research indicates that the removal of PAHs and hydrocarbons is frequently driven by rhizosphere stimulation rather than by direct plant metabolism[18].

3.5 Phytovolatilization

This mechanism is most applicable to specific elements such as mercury and selenium, and its effectiveness depends on the plant's metabolic capacity to transform contaminants into volatile forms; however, its applicability remains limited and species dependent. Asteraceae is less frequently reported; some organics may be volatilized in transformed forms or metabolised in roots or shoots, but this is typically more significant in other plant families and species, and remains case-specific[5]. A flowchart illustrating Asteraceae-based phytoremediation strategies for environmental contaminants is shown in Figure 2.

4. Cellular and Molecular Mechanisms of Phytoremediation in *Asteraceae*

Various phytoremediation methods (Figure 3) demonstrated by *Asteraceae* family plants for the uptake,

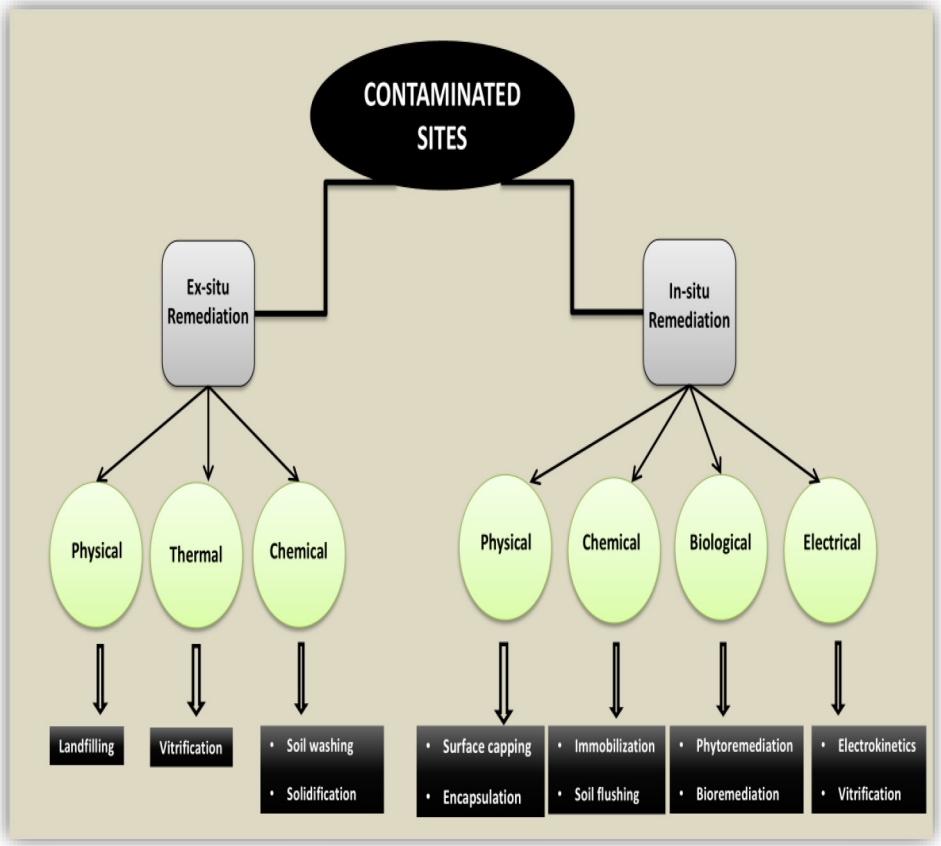


Figure 2. Flowchart on *Asteraceae*-based remediation strategy.

transport, sequestration, detoxification, and stability of heavy metals in contaminated environments are as follows:

4.1 Antioxidant Defence System

Oxidative damage results from the production of Reactive Oxygen Species (ROS) brought on by heavy metal stress. Enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD), which reduce oxidative stress and preserve cellular integrity, are part of plants' antioxidant defence systems[19].

4.2 Plant Growth-Promoting Rhizobacteria (PGPR)

By promoting plant growth, producing siderophores, and altering metal bioavailability in the rhizosphere, PGPR significantly contribute to phytoremediation. Depending on the surrounding circumstances, these microbes can aid in both metal uptake and stability[20].

4.3 Metal Uptake Pathways (Root Level)

ZIP (ZRT/IRT-like proteins), Natural Resistance-Associated Macrophage Proteins (NRAMP), and Heavy Metal ATPases (HMAs) are examples of root membrane transporters primarily responsible for metal uptake in plants. These transporters facilitate the entry of metal ions such as Cd^{2+}, Zn^{2+}, and Pb^{2+} into root cells, often through channels originally developed for the uptake of essential nutrients[21].

4.4 Gene-Level Responses

Metal stress induces the expression of genes encoding antioxidant enzymes, chelating proteins, and metal transporters at the molecular level. Plant tolerance and accumulation capacity are significantly influenced by the regulation of these genes[22].

4.5 Chelation

Toxic metals are detoxified after they enter the cell by being chelated by molecules like metallothioneins and

phytochelatins. These peptides help sequester metal ions within cellular compartments by binding them, thereby reducing their reactivity and toxicity[21].

4.6 Vacuolar Sequestration

Tonoplast-localised transporters then carry chelated metal complexes into vacuoles, where they are segregated and sequestered from sensitive cellular machinery, thereby reducing harmful effects[22].

4.7 Role of Rhizosphere

By expanding root surface area, enhancing nutrient uptake, and regulating metal availability, mycorrhizal relationships improve phytoremediation. Additionally, they help immobilise metals and enhance plants' ability to withstand stress[23].

5. Case Studies and Representative Species

5.1 The Model *H. annuus* Phytoremediator *Asteraceae*

The most researched Asteraceae species for metal remediation is sunflowers. According to numerous studies, sunflowers can withstand and accumulate Pb, Cd, Zn, and occasionally As or Hg, with varying translocation factors depending on cultivar, soil chemistry, amendments (such as chelants), and growth stage (Table 1). When grown in rotation or with repeated plantings, sunflowers have been successfully tested on mine tailings and industrial soils, occasionally resulting in significant reductions in available metal pools. The safe disposal of contaminated biomass and the extraction of metals from seeds and biomass remain operational challenges[23].

5.2 Bioindicator and Stabiliser *Taraxacum* spp. (Dandelion)

Because they accumulate multiple metals in their leaves, dandelions have been used as biomonitors and are frequently the first to settle in disturbed soils[24]. Although their lower biomass compared with sunflowers limits their use in large-scale phytoextraction, they are useful for monitoring contamination and for early stabilisation and ecological succession (Table 1).

5.3 Other Ornamentals and *Tagetes erecta* (Marigold)

When paired with biochar or microbial consortia, *Tagetes* has shown promise in rhizoremediation and

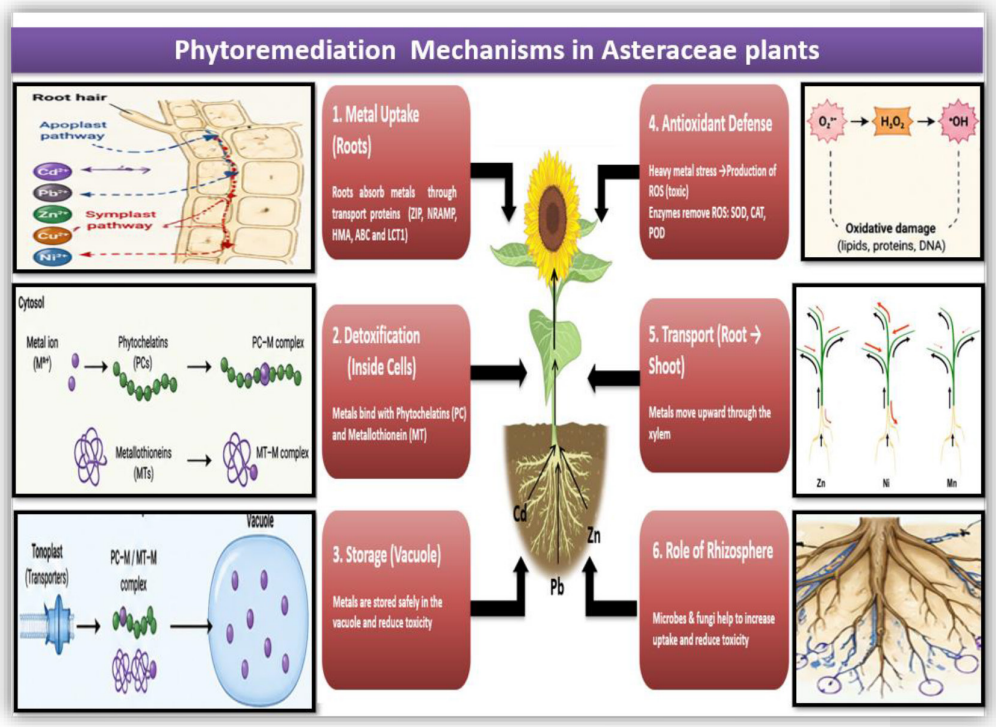


Figure 3. Different phytoremediation mechanisms in the plants of the *Asteraceae* family.

has been tested for the remediation of petroleum hydrocarbons. For combined aesthetic and remediation purposes, ornamental Asteraceae can be utilised in urban phytoremediation projects[25].

5.4 Native Species and Other Taxa

According to regional studies, native Asteraceae species can stabilise tailings or absorb metals; employing native species in reclamation projects frequently enhances establishment and biodiversity outcomes. For long-term success, studies emphasise the importance of selecting species adapted to the local environment[26].

5.5 Comparative analysis of selected Asteraceae species

Several *Asteraceae* species have been investigated individually for their phytoremediation potential; however, direct comparison across species is often lacking. To address this, a comparative synthesis of representative species is presented in Table 2, highlighting differences in contaminant uptake, dominant remediation mechanisms, and experimental conditions.

6. Useful Considerations for Reclamation with *Asteraceae*

6.1 Species Selection and Site Evaluation

The evaluation assessed the type of contamination (metal versus organic), concentrations, salinity, pH, and nutrient status. The species selection was based on local adaptability, root architecture, tolerance, and biomass potential. Sunflower for phytoextraction; native *Asteraceae* for revegetation of mine tailings; marigold and ornamentals for rhizoremediation and urban environments[5].

6.2 Agronomic Techniques and Soil Amendments

Microbial activity and establishment can be enhanced by amendments such as biochar, compost, and organic matter. Chelants can improve phytoextraction but increase the risk of leaching; use cautiously. Amendments affect metal bioavailability. When phytoextraction rates per crop are low, rotational techniques and repeated cropping can boost cumulative removal[11].

Table 1. Comparative phytoremediation potential of selected *Asteraceae* species

Plant species	Contaminants	BCF / TF (Typical Range)	Remediation Mechanism	Experimental Conditions	References
Parthenium hysterophorus L.	Cd, Cr, Ni	Moderate–high accumulation	Phytoextraction	Waste soils	[24]
Tagetes erecta L.	Pb, Cd	Moderate root accumulation	Phytostabilization	Soil remediation	[25]
Helianthus annuus L.	Pb, Cd, Zn	Variable BCF and TF depending on the metal	Phytoextraction	Field and pot	[26]
Verbesina encelioides (Cav.) Benth. and Hook.f. ex A.Gray.	Pb, Cd, Zn	Moderate–high uptake reported	Phytoextraction	Pot/greenhouse	[27]
Taraxacum spp.	Cd, Pb, Zn	BCF often <1–2; TF often >1 for Zn, Mn	Extraction + bioindicator	Field studies	[28]

Table 2. Comparative phytoremediation performance across plant groups

Plant Species	Family	Metal	BCF/TF	Key Advantage	Limitation
Helianthus annuus L.	Asteraceae	Pb, Cd	Moderate–High	High biomass	Lower concentration vs hyperaccumulators
Taraxacum officinale F.H.Wigg.	Asteraceae	Cd, Zn	Moderate	Wide adaptability	Moderate removal
Brassica juncea (L.) Czern. and Coss	Brassicaceae	Pb, Cd	High	High accumulation	Lower biomass
Pteris vittata L.	Pteridaceae	As	Very high	Hyperaccumulator	Species-specific

6.3 Microbial Collaborations and Bioaugmentation

Bacteria and fungi found in the rhizosphere play a key role in the breakdown of organic matter and in modifying metal availability. Results are frequently improved by combining *Asteraceae* with mycorrhizal inocula or known degraders[2].

6.4 Risk Reduction and Biomass Management

Harvested biomass that has accumulated metals needs to be handled carefully; options include secure landfilling, compost limitations, or incineration with metal recovery. Plant tissues may contain metabolites of organic contaminants and must be evaluated before reuse. Recent reviews emphasise planning for biomass fate as a central part of project design[29].

6.5 Phased and Combined Methods

Soil function and biodiversity recovery can be accelerated by integrating hydraulic control, physical stabilisation (cover soils), and revegetation with mixed communities (legumes, grasses, and woody species). *Asteraceae* often act as early colonisers, preparing soils for later successional plantings[30].

6.6 Decision Criteria for Selecting Remediation Strategies

Effective selection of phytoremediation strategies depends on site-specific conditions, contaminant characteristics, and plant traits. Factors such as soil properties, contamination level, plant biomass, and management feasibility determine whether phytoextraction or phytostabilisation is more suitable. Overall, a balanced, site-specific approach is essential for successful implementation[28].

7. Discussion

Quantitative indicators such as the Bioconcentration Factor (BCF), Translocation Factor (TF), and percentage removal efficiency are essential for evaluating phytoremediation performance[1]. In general, BCF values greater than 1 indicate effective metal uptake from soil, while TF values greater than 1 suggest efficient translocation to aboveground tissues suitable for phytoextraction[1]. Reported studies show variable performance, with BCF values typically ranging from 1.0 to 5.0 and TF values from 0.5 to 1.5, depending on species and environmental conditions[32]. In some cases, removal efficiencies of 40–70 % have been observed under controlled experimental conditions. These variations highlight the importance of considering both plant traits and site-specific factors when assessing phytoremediation potential. For instance, studies have shown that a decrease in soil pH from neutral to acidic conditions can significantly increase metal uptake efficiency, whereas the addition of organic amendments may reduce translocation by stabilising metals in the rhizosphere[17].

8. Limitations and Future Directions

Phytoremediation using Asteraceae species, although promising, is constrained by several practical and biological limitations that must be addressed to enhance its field applicability. One of the major challenges is variable metal uptake and translocation, which are strongly influenced by soil chemistry, plant cultivar, and management practices. Phytoremediation efficiency is influenced by seasonal variability, as plant growth, transpiration rates, and microbial activity fluctuate with climatic conditions. As a result, metal uptake and accumulation may vary significantly across seasons. This variability often results in inconsistent remediation performance across sites. To overcome this limitation, future research should focus on extended multi-site field experiments across diverse soil types and climatic conditions to better understand cumulative removal rates and ecological outcomes. In addition, genotype screening and breeding of Asteraceae varieties with enhanced uptake, translocation, and tolerance traits can help reduce variability and improve efficiency[29].

Another important concern is the risk of food-chain transfer, as several *Asteraceae* species, including dandelion and sunflower, are edible. The potential for contaminated biomass to enter the food chain poses ecological and human health risks. This limitation highlights the need for careful selection of non-edible cultivars, the development of management protocols to prevent consumption, and further research into safe deployment strategies in contaminated environments.

The costs and logistical challenges associated with biomass disposal also represent a significant barrier, as contaminated plant material requires safe handling and processing. To address this issue, future efforts should prioritise the development of safe biomass valorisation techniques, such as metal recovery from plant tissues or the conversion of biomass into bioenergy, thereby transforming waste into a resource.

Furthermore, phytoremediation is not a universal solution, particularly in sites with very high contamination levels or where rapid remediation is required. In such cases, phytotechnologies are most effective when applied to low-to-moderate contamination levels or as part of integrated remediation strategies that combine biological and engineering approaches[18]. The long-term sustainability of phytoremediation remains a concern, as the process is often time-intensive and may require repeated planting and harvesting cycles. Additionally, the gradual nature of contaminant removal may limit its applicability in sites requiring rapid remediation. To enhance effectiveness under complex conditions, future research should explore microbiome engineering approaches, including the development of rhizosphere microbial consortia that can improve metal stabilisation and support the degradation of persistent organic pollutants.

Finally, while phytoremediation provides environmental benefits, its broader ecosystem-level impacts remain underexplored. Future studies should therefore focus on quantifying co-benefits such as soil carbon sequestration, pollinator support, and biodiversity enhancement, particularly in reclamation landscapes. Multidisciplinary research integrating agronomy, microbial ecology, and socioeconomic assessment will be essential to fully realise the potential of *Asteraceae*-based phytoremediation systems[31].

9. Conclusion

Asteraceae species demonstrate considerable potential for phytoremediation due to their adaptability, biomass production, and functional rhizosphere interactions. However, their effectiveness varies significantly across species, contaminants, and environmental conditions, highlighting the need for careful selection and site-specific optimisation. Quantitative indicators such as bioconcentration and translocation factors further reveal that while some species are suitable for phytoextraction, others are more effective in stabilisation processes. Future research should focus on long-term field validation, genetic improvement for enhanced metal uptake and tolerance, and the integration of plant–microbe systems to improve remediation efficiency. In addition, sustainable strategies for biomass management and metal recovery require further development to ensure environmental safety. From a practical perspective, phytoremediation using Asteraceae species offers a cost-effective and environmentally sustainable approach to managing contaminated soils, particularly at low- to moderately polluted sites. However, its successful implementation depends on appropriate policy support, site-specific planning, and integration with conventional remediation methods. Overall, Asteraceae-based phytotechnologies hold promise, but their application must be guided by scientific evidence, environmental conditions, and long-term sustainability considerations. Future studies should focus on elucidating the molecular mechanisms of toxic uptake and tolerance, conducting field trials, and developing soil amendment strategies to optimise phytoremediation efficiency.

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Authors Contributions

AA: Conceived the study, provided supervision and guidance; **AT:** Contributed to manuscript writing; **KC and PB:** Collected the all-important information and prepared the initial draft.

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