Advancements in Bioremediation and Phytoremediation: Combat Soil Pollution and Heavy Metal Contamination

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Abstract

The review article discusses the critical issue of soil pollution caused by open disposal of municipal solid waste, focusing on the contamination by heavy metals. It explores bioremediation and phytoremediation as effective techniques for mitigating heavy metal contamination in soils from dump sites. Bioremediation employs microorganisms to detoxify pollutants, utilizing in-situ and ex-situ methods such as bioventing, biosparging, and bioaugmentation. Phytoremediation leverages plants to remove, stabilize, or degrade contaminants through processes like phytoextraction, phytofiltration, phytostabilization, phytovolatilization, and phytodegradation. The article highlights the advantages of these methods, including cost-effectiveness and environmental friendliness, while addressing limitations such as time requirements and site-specific constraints. It emphasizes the role of microbial diversity, nutrient supplementation, temperature, and pH in enhancing remediation efficiency. The review concludes that integrating advanced biotechnological approaches can improve these eco-friendly, sustainable methods for long-term soil remediation.

Keywords: Bioremediation, phytoremediation.

Methodology of Review

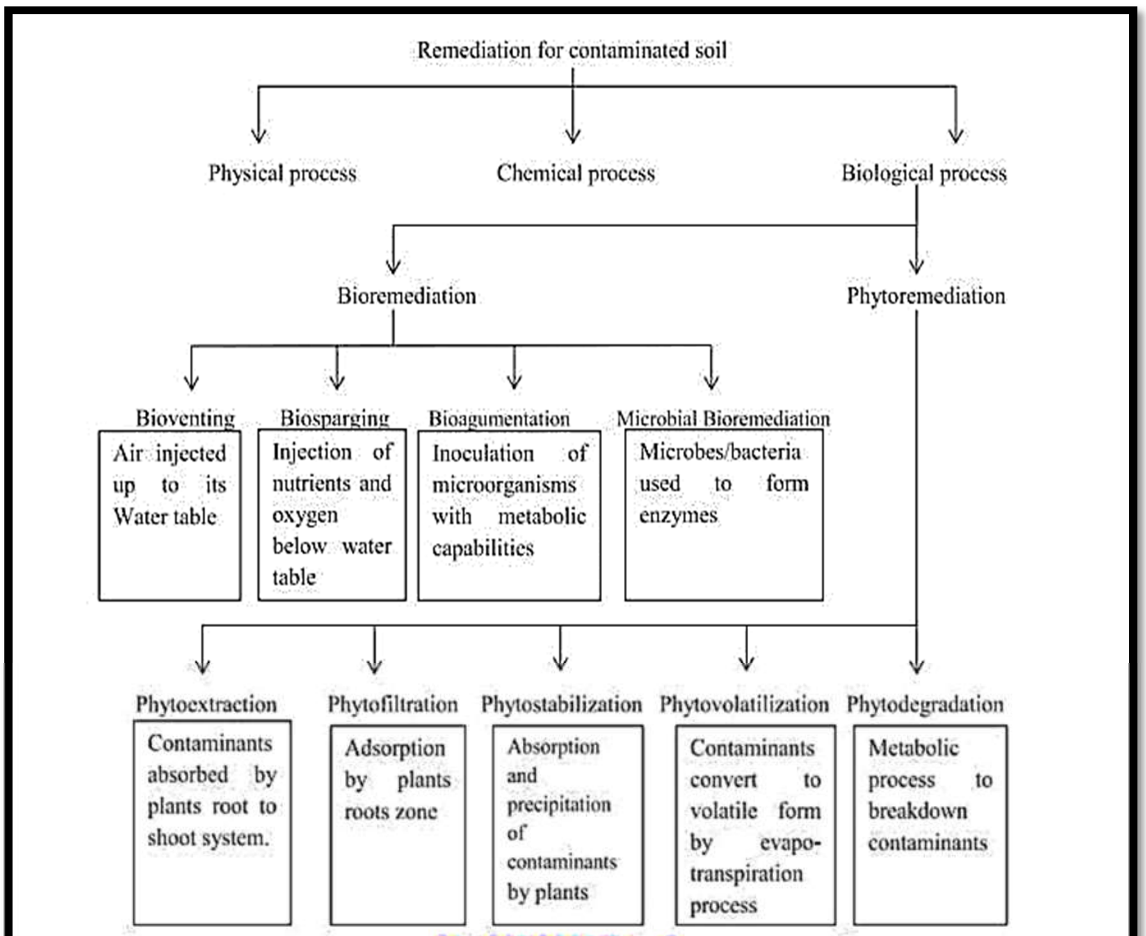


Fig. 1. Methodology of Flow Diagram.

Introduction

Soil pollution from heavy metals, largely due to open disposal of municipal solid waste, poses significant environmental and health risks. Bioremediation and phytoremediation are eco-friendly, cost-effective strategies to mitigate this issue. Bioremediation employs microorganisms to degrade or detoxify pollutants, utilizing techniques like bioventing, biosparging, and bioaugmentation for in-situ or ex-situ processes. Phytoremediation leverages plants to absorb, stabilize, or transform contaminants, with methods such as phytoextraction, phytofiltration. [1,3,4,6,7]

Bioremediation
Bioremediation is the process of using microorganisms to remove or detoxify pollutants, particularly heavy metals, from contaminated soil or water.

Types of Bioremediation:
1. In-situ Bioremediation
2. Ex-situ Bioremediation

- **In-situ Bioremediation**: Remediation occurs directly at the contaminated site without excavating the soil.

  Techniques:
  1.Bioventing: Involves injecting air (oxygen) and nutrients (e.g., nitrogen, phosphorus) into the soil above the water table to stimulate aerobic microbial degradation. Soil texture affects nutrient flow, and reduced airflow ensures sufficient oxygen for microbes.
  2.Biosparging: Similar to bioventing but injects air and nutrients below the water table to increase oxygen levels, enhancing microbial degradation. It's cost-effective and easy to install.
  3.Bioaugmentation: Introduces specialized microorganisms with metabolic capabilities to break down contaminants, particularly effective for chlorinated compounds, converting them into nontoxic forms.[14]

- **Ex-situ Bioremediation:** Contaminated soil is excavated and treated in a controlled environment away from the site.

  Techniques:
  1.Biopiling: Involves piling contaminated soil and adding nutrients to promote microbial activity for pollutant degradation.
  2.Composting: Mixes contaminated soil with organic materials to enhance microbial breakdown of pollutants.
  3.Landfarming: Spreads contaminated soil over a large area and treats it with microbes and nutrients to degrade contamination.

- **Limitations of Bioremediation:**

  1. High Concentrations of Toxic Chemicals

  a. Highly toxic pollutants, such as heavy metals or chemicals, can create concentration barriers that inhibit microbial growth or even kill microorganisms, reducing the effectiveness of bioremediation.

  2. Dependence on Optimal Environmental Conditions
  Successful bioremediation requires specific conditions:

a. pH: Microorganisms need an optimal pH range; deviations can hinder growth and metabolism.
b. Nutrient Availability: Insufficient mineral nutrients (e.g., nitrogen, phosphorus) can limit microbial activity.

c. Temperature: Microbes thrive best at 20-30°C; temperatures outside this range slow down or halt remediation processes.[2,9,10,5,19]

Phytoremediation

Phytoremediation involves using plants to absorb, stabilize, transform, or remove pollutants from the environment, reducing their hazardous effects. It is eco-friendly, cost-effective, and simpler than physical or chemical methods.[8]

Techniques:

1.Phytoextraction (Phytoaccumulation): Plants absorb heavy metals through their roots and translocate them to shoots or leaves. Hyperaccumulator plants, which absorb high metal concentrations, are used. After their lifecycle, plants are harvested and disposed of (e.g., incinerated or composted).
Application: Depends on pollutant type and soil conditions; multiple plant species may be used.

2.Phytofiltration (Rhizofiltration): Pollutants are adsorbed or deposited around the plant's root system. Primarily used for treating contaminated water, where polluted water is passed through plant roots for filtration.
Application: More suited for water than soil remediation.

3.Phytostabilization: Plants absorb and precipitate metals, reducing their bioavailability and preventing spread via erosion or leaching into groundwater. Metal-tolerant plants restore vegetation in contaminated areas.
Application: Rehabilitates ecosystems and prevents contaminant migration.

4.Phytovolatilization: Plants convert heavy metals into volatile forms, releasing them into the atmosphere through transpiration via leaves.
Application: Effective for organic pollutants and certain metals but may not fully remove contaminants.

5.Phytodegradation: Plants break down pollutants either internally (via metabolism) or externally (using enzymes). Degraded pollutants may be used as nutrients by the plant.
Application: Suitable for organic pollutants and some heavy metals.[8,11,12,15]

Application of Phytoremediation

Phytoremediation has diverse applications in managing soil and water contamination, with specific relevance to selenium and other heavy metals.

1. **Soil Decontamination:**
Phytoremediation is widely applied to remediate soils contaminated with metals like Cd, Zn, and Pb. For selenium, Brassica juncea reduces soil toxicity through volatilization, though careful monitoring is needed to mitigate atmospheric risks. Terrestrial plants like Tetraena qataranse stabilize multiple metals in arid soils, demonstrating versatility.

2. **Water Treatment:**
Aquatic plants, such as Eichhornia crassipes (water hyacinth), excel in rhizofiltration, removing metals from wastewater. While selenium-specific water remediation is less documented, the mechanism's success with Cd and Ni suggests potential applicability.

3. **Restoration of Mining Sites:**
Phytoremediation rehabilitates mining soils laden with metals. Athyrium wardii stabilizes Cd in mining ecotypes, and similar strategies could target selenium, reducing ecological damage.

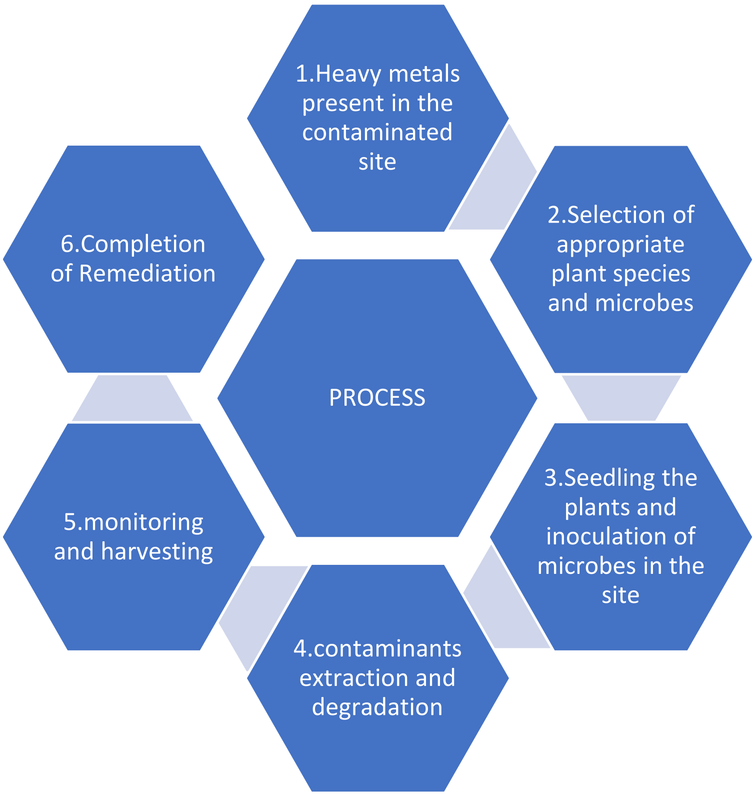
4. **Agricultural Safety:**
By stabilizing contaminants like Cd in the rhizosphere, phytoremediation ensures safer crop production. Intercropping Thalia dealbata with rice lowers Cd in grains, a model potentially adaptable for selenium management in seleniferous soils.

5. **Radionuclides:**
Certain plants can take up radionuclides from soil and water, reducing their concentration.

6. **Agriculture:**
Phytoremediation can help improve soil health and reduce the need for chemical fertilizers and pesticides.

7. **PCBs and Other Pollutants:**
It can help clean up sites contaminated with polychlorinated biphenyls (PCBs) and other industrial pollutants.[8]

Process of Phytoremediation



Limitations of Phytoremediations:

1. **Time-Intensive Process Phytoextraction:**

Remediation of highly contaminated sites with elevated metal concentrations takes a significant amount of time, making it less suitable for rapid cleanup needs.

2. **Limited Effectiveness for Heavily Contaminated Sites:**

This technique is less effective for heavily contaminated sites, as it is primarily suited for low-level contamination, particularly in water treatment.

3. **Incomplete Contaminant Removal:**

Does not fully remove heavy metals from the soil; it only reduces metal concentrations to some extent, potentially leaving residual pollutants.

4. **Unsuitability for Food Production:**

After remediation, treated sites are not suitable for food production due to residual contaminants or altered soil conditions, limiting agricultural use

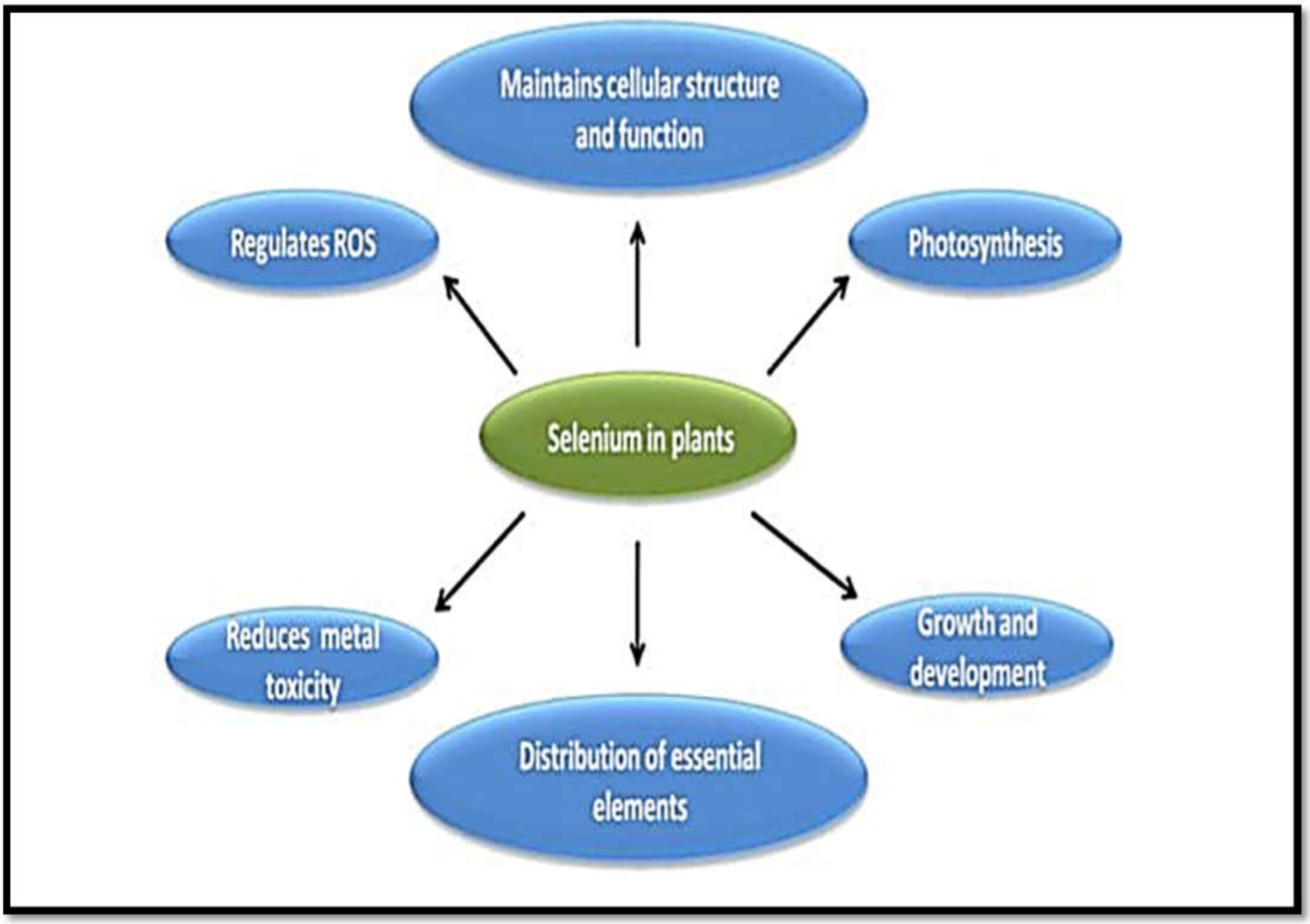
5. **Potential Ecological Risks:**

Accumulated heavy metals in plants can affect plant health (e.g., reduced biomass, chlorophyll, or yield) and, if not properly managed (e.g., through incineration), may reintroduce pollutants into the environment.[15]

SELENIUM (Se) as a Remediation Agent:

Introduction

Selenium (Se) is an essential micronutrient for humans and animals, crucial for antioxidant functions, immune responses, and thyroid hormone metabolism, but it can be toxic in excess. Discovered in 1817 by Jons Jacob Berzelius, Se is a metalloid chemically similar to sulphur, sharing similar physicochemical properties. Plants are the primary dietary source of Se,



absorbing it mainly through sulphate transporters in roots due to its chemical resemblance to sulphur. While Se's essentiality for plants remains debated, low doses can protect against abiotic stresses like drought and metal toxicity. However, high doses cause oxidative stress and protein disruption, leading to toxicity. Se exists in inorganic forms (selenate, selenite) and organic forms, with uptake and metabolism varying by plant species and soil conditions. Plants play a key role in addressing Se deficiency and toxicity globally, making understanding Se metabolism vital for phytoremediation and biofortification strategies.

Selenium (Se) in plants is primarily absorbed from soil as inorganic selenate or selenite via sulfate or phosphate transporters due to its chemical similarity to sulfur. Once inside, Se is metabolized through the sulfur assimilation pathway, mainly in plastids, converting selenate to selenite, then selenide, and finally to organic forms like selenocysteine (SeCys) and selenomethionine (SeMet). These can be further methylated and volatilized as non-toxic dimethylselenide (DMSe) or dimethyldiselenide (DMDSe).

Plants are classified based on Se accumulation:
1.Hyperaccumulators: (>1000 mg Se/kg DW, e.g., Astragalus, Stanleya) thrive in Se-rich soils, storing methylated Se forms.

2.Secondary accumulators: (100-1000 mg Se/kg DW, e.g., Brassica, Broccoli) tolerate moderate Se without toxicity.

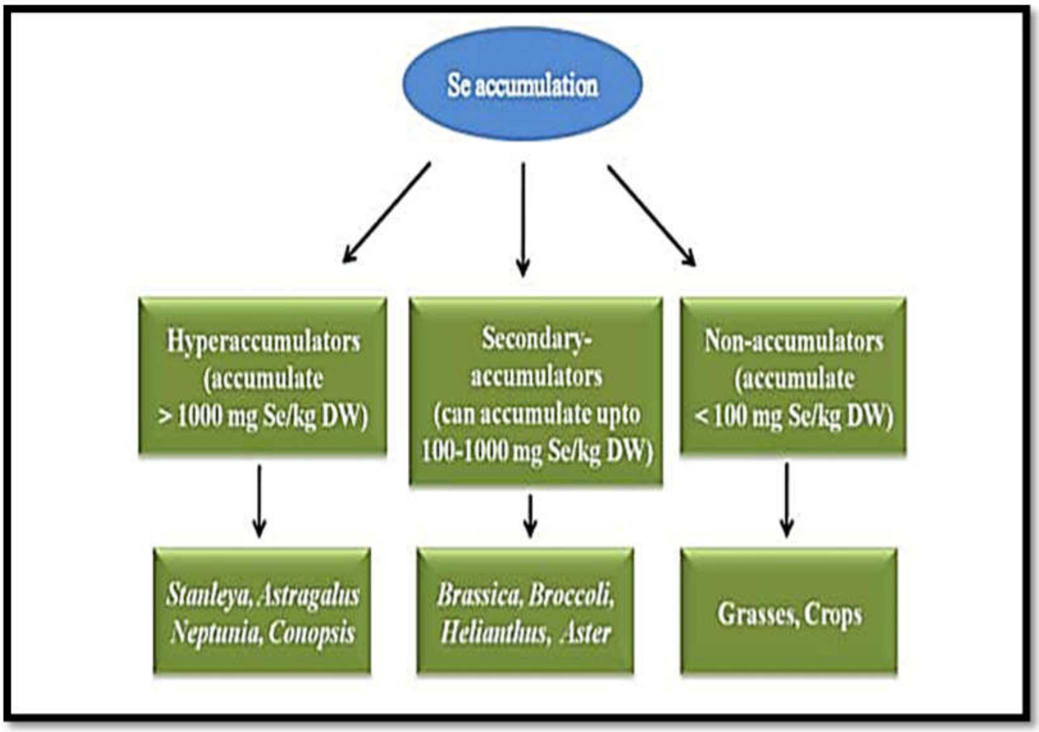
3.Non-accumulators: (<100 mg Se/kg DW, e.g., most crops) show toxicity in high-Se conditions.

Se uptake depends on soil pH, Se form, and nutrient status (e.g., sulfur or phosphorus levels). At low doses, Se enhances plant growth and stress resistance (e.g., drought, metal toxicity) by reducing reactive oxygen species. High doses, however, cause oxidative stress and protein misincorporation, leading to toxicity. Plants like wheat, rice, and garlic are key for dietary Se, with Se speciation (e.g., SeMet in grains, Se-MeSeCys in garlic) influencing their nutritional value.

Selenium Accumulation in Plant
Selenium (Se) accumulation in plants varies by species, soil conditions, and Se form (selenate, selenite, or organic). Plants take up Se primarily through root sulfate transporters (for selenate) or phosphate transporters (for selenite) due to its chemical similarity to sulfur. Accumulation depends on soil pH, Se bioavailability, plant physiology, and nutrient competition (e.g., high sulfate reduces selenate uptake).

Types of Plants Based on Se Accumulation:

1.Hyperaccumulators: Accumulate >1000 mg Se/kg dry weight (DW), thriving in seleniferous soils. Examples include Astragalus bisulcatus and Stanleya pinnata. They store Se as methylated forms like methyl-selenocysteine (Me-SeCys) or methyl-selenomethionine (Me-SeMet), which can be volatilized as dimethyldiselenide (DMDSe), conferring tolerance.
2.Secondary Accumulators: Accumulate 100-1000 mg Se/kg DW without toxicity. Examples include Brassica juncea, broccoli, and canola. They store Se as selenate, SeMet, or Se-MeSeCys, depending on the Se form supplied.
3.Non-accumulators: Accumulate <100 mg Se/kg DW and are sensitive to high Se, showing toxicity symptoms like stunted growth. Most crops (e.g., grasses, rice, wheat) fall here, storing Se in vacuoles or volatilizing.



Beneficial effect of Selenium in Plants

1.Stress Tolerance: Se helps plants withstand various abiotic stresses. It can protect against the effects of high and low temperatures, drought, salinity, and metal toxicity.

2.Antioxidant Properties: Se acts as an antioxidant, reducing the accumulation of reactive oxygen species (ROS) and thus oxidative stress.

3.Improved Growth and Yield: Se can enhance plant growth, development, and yield in certain crops.

4.Metal Detoxification: Se can help plants tolerate metal toxicity by regulating metal accumulation and subcellular distribution.

5.Nutrient Absorption: Se can improve the uptake and translocation of other nutrients, including phosphorus.

6.Photosynthesis: Se can regulate the photosynthetic process, protecting chlorophylls and enhancing photosynthetic pigments.

7.Enhanced Secondary Metabolites: Se can increase the production of secondary metabolites, which are important for plant defense and overall health.[12]

Selenium phytoremediation:

Selenium Phytoremediation refers to the use of plants to remove, stabilize, or detoxify selenium (Se) from contaminated soils or water, addressing Se toxicity in seleniferous regions. Due to its chemical similarity to sulfur, Se is readily taken up by plants, making phytoremediation a viable strategy for managing excess Se in the environment.

Selenium: (Specific Phytoremediation):
Selenium, a metalloid essential in trace amounts but toxic at higher concentrations, is a significant soil contaminant due to its long environmental persistence. Phytoremediation, particularly phytovolatilization, is a primary strategy for selenium management, though other mechanisms like phytoextraction also apply.[16]

1.Phytovolatilization of Selenium

Plants like Brassica juncea (Indian mustard) uptake selenium, predominantly as selenate (+6 oxidation state), via sulfate transporters. Within the plant, biochemical processes convert inorganic selenium into volatile forms, such as dimethyl selenide ($(CH_3)_2Se$), dimethyl diselenide ($(CH_3)_2Se_2$), and methaneselenol (CH_3Se), which are released through leaf stomata. This process reduces soil selenium levels but raises concerns about atmospheric toxicity, as volatile selenium compounds can be hazardous. The efficiency of phytovolatilization depends on plant species, soil conditions, and microbial activity, with Arundo donax volatilizing up to 75% of arsenic in similar systems, suggesting potential for selenium.[17]

2.Phytoextraction for Selenium

Hyperaccumulators, such as Stanleya pinnata, can accumulate selenium in their tissues, enabling its removal through biomass harvesting. This approach avoids atmospheric release, making it safer than phytovolatilization. However, the document notes limited data on selenium-specific phytoextraction, indicating a need for further research.

3.Role of Microbes in Selenium Remediation

Soil microorganisms enhance selenium bioavailability by altering soil pH or producing biosurfactants, facilitating plant uptake. Plant growth-promoting rhizobacteria (PGPR), such as Stenotrophomonas maltophilia, improve selenium transformation, though specific selenium-focused microbial studies are sparse compared to other metals like Cd and Pb.

Mechanism:
1. Uptake: Plants absorb Se primarily as selenate or selenite via sulfate or phosphate transporters in roots. Selenate is more bioavailable and mobile in alkaline soils, while selenite dominates in acidic soils.
2. Accumulation: Se is stored in plant tissues, mainly in vacuoles, as inorganic (selenate,

selenite) or organic forms (selenocysteine [SeCys], selenomethionine [SeMet], methyl-SeCys).

3. Volatilization: Plants, especially hyperaccumulators, convert Se into volatile, non-toxic forms like dimethylselenide (DMSe) or dimethyldiselenide (DMDSe), releasing it into the atmosphere, reducing soil Se levels.
4.Translocation: Se is transported from roots to shoots, with hyperaccumulators showing efficient xylem loading and high Se concentrations in leaves.

Limitation:
1. Slow Process: Phytoremediation requires multiple growth cycles for significant Se removal.
2. Plant Selection: Only specific species are effective, limiting application in diverse ecosystems.
3. Monitoring Needs: Continuous monitoring is required to ensure Se levels in plants and soils remain safe.

Benefits of Selenium Phytoremediation:
1. Eco-Friendly: A natural, low-cost method compared to chemical or physical remediation.
2. Dual Purpose: Can be combined with biofortification in Se-deficient areas by using edible parts of secondary accumulators.
3. Sustainability: Plants recycle Se into volatile forms, reducing environmental persistence.[16,17]

Future Directions:
To advance phytoremediation for selenium and other contaminants, research should focus on:

Safer Selenium Management: Developing plants that prioritize selenium phytoextraction over volatilization to minimize atmospheric risks.

Genomic Insights: Identifying and manipulating genes for selenium hyperaccumulation using CRISPR or similar technologies.

Microbial Engineering: Designing microbial consortia to enhance selenium bioavailability and plant tolerance.

Field-Scale Studies: Scaling up lab successes to real-world conditions, particularly for seleniferous soils.

Integrated Approaches: Combining phytoremediation with biochar, nanotechnology, or chemical amendments for synergistic effects.[18,20,21]

Conclusion:
Phytoremediation, as a cornerstone of bioremediation, offers a sustainable pathway to mitigate soil toxicity caused by heavy metals and metalloids like selenium. Its mechanisms—phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration—provide versatile tools to address diverse contaminants. Selenium remediation, primarily through

phytovolatilization by plants like Brassica juncea, is effective but requires careful management to avoid environmental trade-offs. Advancements in genetic engineering, microbial interactions, and soil amendments enhance its potential, though challenges like slow remediation rates and biomass disposal persist. By addressing these limitations through innovative research, phytoremediation can become a cornerstone of global efforts to restore contaminated environments, ensuring ecological and human health.[18,20,21]

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