TOXICITY OF HEAVY METALS IN THE ENVIRONMENT AND THE REMEDIATION ROLE OF *BRASSICA JUNCEA*: A COMPREHENSIVE REVIEW

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ABSTRACT

Heavy metal contamination of the environment presents a significant challenge due to its persistent, bioaccumulative, and toxic nature. These pollutants adversely affect plants, animals, and human health; therefore need effective remediation strategies. Conventional physical and chemical remediation techniques often face challenges such as high costs, environmental disruption, and difficulties in scaling. Phytoremediation has emerged as a promising sustainable and environmentally friendly alternative for detoxifying heavy metals. Among hyperaccumulator plants, *Brassica juncea* stands out due to its high biomass production, robust growth, and ability to accumulate different heavy metals. This review comprehensively examines the toxicity mechanisms of heavy metals and highlights the physiological, biochemical, and molecular traits that enable *Brassica juncea* to remediate contaminated environments. Despite some limitations *Brassica juncea* remains a promising plant for large-scale remediation, contributing to environmental restoration and human health protection.

Keywords: Heavy metals, *Brassica juncea*, phytoremediation, toxicity, sustainable remediation

1. Introduction

Industrialization serves as a fundamental catalyst for economic advancement; however, it simultaneously constitutes a primary contributor to environmental degradation (Khan and Majeed, 2023). The unregulated discharge of industrial effluents into terrestrial and aquatic environments has generated considerable environmental concern due to the progressive accumulation of toxic compounds, with particular emphasis on heavy metal contamination. These pollutants degrade soil quality in addition to posing significant risks to agricultural productivity, ecosystem health, and human well-being (Hurni *et al*., 2015). Unlike organic pollutants, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr) are non-biodegradable, highly persistent, and capable of bioaccumulating in the food chain. (Khalef *et al*., 2022). In humans, chronic exposure is linked to a spectrum of devastating health consequences, including neurotoxicity, organ failure, and carcinogenesis, making the remediation of metal-contaminated sites a critical priority for global public health and environmental sustainability (Angon *et al*., 2024).

Heavy metal contaminants need efficient cleanup techniques because of their non-biodegradable nature. Conventional physical and chemical methods for soil remediation are often expensive, time-consuming, and environmentally disruptive. As a result, biological methods such as phytoremediation have gained increasing attention for being cost-effective, eco-friendly, and sustainable alternatives (Kuppan *et al*., 2024). However, the success of phytoremediation depends largely on the choice of plant species, as different types of plants have different levels of tolerance or accumulation capacity to handle elevated concentrations of toxic metals.

Among the diverse group of species, *Brassica juncea*, also called Indian mustard, has attracted significant scientific and practical interest. This fast-growing species of the Brassicaceae family is characterized by high biomass production, a well-developed root system, a short life cycle, and remarkable adaptability to varied climatic conditions. Recent advances in plant biotechnology and omics approaches have further highlighted its potential for genetic improvement, making it one of the most studied and promising candidates for large-scale phytoremediation.

By consolidating existing knowledge, this review seeks to provide a comprehensive understanding of the environmental threats posed by heavy metals and to evaluate the potential of *Brassica juncea* as a sustainable, scalable, and practical solution for mitigating heavy metal contamination. The understandings will guide future research directions, policy frameworks, and support the integration of phytoremediation into broader environmental management strategies.

2. Heavy Metals in the Environment

Heavy metals are naturally occurring components of the Earth's crust; however, their concentrations in the environment have risen drastically due to anthropogenic activities. Once released, these elements persist in environmental compartments, soil, water, and atmosphere, where they interact with biotic and abiotic systems. Unlike organic pollutants, heavy metals do not undergo microbial or chemical degradation and thus tend to accumulate, creating long-term ecological and health challenges. Understanding their sources, pathways and persistence is crucial to assessing their environmental risks.

2.1. Pathways of Heavy Metal Contamination

Heavy metals occur naturally in the Earth's crust and are released through weathering, erosion, and volcanic activity, resulting in low background concentrations in soils and waters (Cimboláková *et al*., 2019). Volcanic eruptions are major natural contributors, while forest fires, dust storms, and sea spray provide minor inputs (Bradl, 2005). However, anthropogenic activities overwhelmingly dominate heavy metal contamination (Table 1). Industrial processes such as smelting, coal combustion, and manufacturing release substantial amounts, while mining exposes sulfide ores, generating acid mine drainage with extremely high concentrations. Agricultural practices add further inputs through phosphate fertilizers, sewage sludge, and historically metal-based pesticides and fungicides (Masindi *et al*., 2021). Urbanization, transport emissions, and improper disposal of electronic waste and consumer products create additional hotspots, making human activity the principal driver of heavy metal pollution worldwide.

Table 1. Major heavy metals, sources, and environmental compartments.

Metal	Anthropogenic Sources	Natural Sources	Env. Compartment
Pb	Mining, smelting, paints, batteries	Weathering of galena ores	Soil, air, sediments
Cd	Fertilisers, electroplating, e-waste	Weathering of zinc ores	Soil, water
Hg	Coal combustion, mining, incineration	Volcanic activity	Air, water, sediments
As	Pesticides, smelting, wood preservatives	Sulfide mineral weathering	Soil, groundwater
Cr	Tanning, textile, electroplating	Ultramafic rocks	Soil, water
Ni	Metallurgy, batteries, industrial waste	Ultramafic rocks	Soil, water

2.2. Environmental Fate

Heavy metals disperse and persist across soil, aquatic, and atmospheric environments, creating interconnected pathways of contamination. Soils act as the primary sink, receiving inputs from industrial effluents, atmospheric fallout, and agricultural practices. Although metals bind strongly to soil particles, their mobility and bioavailability depend on pH, organic matter, redox status, and microbial activity, often resulting in reduced soil fertility and uptake by crops (Jayakumar *et al*., 2021). Aquatic systems serve as both transport media and secondary sinks, with inputs from industrial discharges, acid mine drainage, leaching, and runoff (Shah, 2021). Once in water, metals may undergo transformations that enhance their toxicity, while accumulation in aquatic organisms drives bio magnification through the food chain. The atmosphere contributes to global dispersal via emissions from fossil fuel combustion, smelting, and waste incineration. Fine particulates containing lead, cadmium, or arsenic can travel long distances before deposition, ultimately enriching soils and waters and prolonging contamination.

2.3. Persistence and Bioaccumulation

A hazardous characteristic of heavy metals is their persistence in the environment. Unlike organic pollutants that degrade into less harmful forms, heavy metals remain chemically stable, undergoing only oxidation-reduction or complexation reactions. Their long-term presence in soils and sediments ensures continued exposure for decades, even after the source has been removed. Heavy metals also exhibit strong tendencies for bioaccumulation and biomagnification (Angon *et al*., 2024). Bioaccumulation occurs when organisms absorb metals faster than they can metabolize or excrete them, leading to a gradual buildup in tissues. Biomagnification amplifies this effect across trophic levels, where predators accumulate higher concentrations than their prey. Thus, the persistence, mobility, and bioaccumulative potential of heavy metals make them among the most hazardous classes of environmental pollutants.

3. Toxicity of Heavy Metals

Heavy metal toxicity arises from complex interactions with cellular systems, often disrupting vital biochemical and physiological processes in plants, animals, and humans. The consequences range from oxidative stress and metabolic impairment to organ system damage and carcinogenesis (Jaishankar *et al*., 2014). Understanding the mechanisms of toxicity and organism-specific responses is essential to evaluating ecological risks and guiding remediation efforts**.**

3.1 Mechanisms of Toxicity in Living Organisms

Heavy metals exert toxicity through several interrelated mechanisms in humans, animals and plants. Table 2 summarizes the principal mechanisms by which heavy metals exert toxicity and their subsequent effects. At the cellular level, metals such as cadmium, lead, and mercury disrupt redox balance, inhibit enzymes, displace essential ions, and damage genetic material, leading to oxidative stress and mitochondrial dysfunction (Jomova *et al*., 2025; Raikwar *et al*., 2008). In plants, these mechanisms manifest as inhibited growth, impaired photosynthesis, nutrient imbalance, and visible stress symptoms such as chlorosis and necrosis. In animals and humans, chronic exposure contributes to neurotoxicity, carcinogenicity, organ dysfunction, respiratory disorders, and reproductive or developmental abnormalities.

Table 2. Toxicity mechanism and health/ecological effects of major heavy metals.

Category	Processes/Effects	Metals	Consequences
Mechanisms of Toxicity	Generation of Reactive Oxygen Species (ROS)	Cd, Pb, Hg	Oxidative stress; lipid, protein, DNA damage
	Protein/Enzyme Inactivation	Pb, Hg	Inhibition of δ-ALAD; impaired enzymatic activity
	Disruption of Ion Homeostasis	Cd, Pb, Zn, Ca^{2+} displaced	Dysfunction of ion channels and signaling
	DNA and Genetic Damage	Cr^{6+}, As	DNA adducts, strand breaks, mutagenesis, carcinogenesis
	Mitochondrial Dysfunction	Cd, Hg	Reduced ATP, apoptosis induction
Effects on Plants	Growth Inhibition	Pb, Cd	Reduced germination, root/shoot elongation
	Photosynthetic Impairment	Cd, Pb	Chlorophyll reduction, PSII inhibition, chlorosis
	Nutrient Imbalance	Cd, Zn, Fe displacement	Deficiency symptoms; impaired metabolism
	Oxidative Stress	Cd, Ni, Cr	ROS accumulation; activation of antioxidant enzymes
	DNA/Protein Damage	Cr, Ni	DNA fragmentation; misfolded proteins
	Visible Symptoms	Pb, Cd	Necrosis, stunted growth, reduced yield
Effects on Animals and Humans	Neurotoxicity	Pb, Hg, As	Cognitive deficits, behavioral changes, motor dysfunction
	Carcinogenicity/Mutagenicity	As, Cd, Cr^{6+}, Ni	DNA mutations, tumors; IARC Group 1 carcinogens
	Renal/Hepatic Dysfunction	Cd, Hg, As	Kidney tubular damage, liver toxicity
	Respiratory Effects	Cr^{6+}, Ni	Lung fibrosis, lung cancer
	Reproductive/Developmental Toxicity	Pb, Cd, Hg	Infertility, fetal defects, hormonal imbalance
	Cardiovascular and Endocrine Disruption	Pb, Cd, As	Hypertension, endocrine signaling disruption

4. Conventional Remediation Technologies

The remediation of heavy metal-contaminated environments has historically relied on conventional engineering approaches that focus on physical removal, chemical treatment, or immobilization of contaminants (Table 3). These technologies have proven effective in specific applications but often face significant limitations in terms of cost,

environmental impact, long-term sustainability, and applicability to large-scale contamination scenarios (Sharma *et al*., 2018). Understanding these limitations is essential for appreciating the need for alternative remediation strategies and the development of more sustainable approaches.

Table 3. Conventional remediation methods for heavy metal contaminated soils.

Method	Mechanism	Advantages	Limitations
Excavation and Landfilling	Physical removal	Immediate risk reduction	Expensive, land-use issues, transfers contamination
Soil Washing	Washing with water/agents	Reduces contamination in coarse soils	Secondary waste, ineffective in clay soils
Immobilization and Capping	Physical containment	Prevents leaching	Does not remove metals, long-term risk
Stabilization and Solidification	Chemical binding	Reduces mobility	Alters soil, unsuitable for agriculture
Chemical Precipitation	Converts metals to insoluble forms	Effective in water treatment	Residue disposal required
Chemical Leaching	Dissolves and extracts metals	High removal efficiency	Soil degradation, toxic leachates

4.1. Biological Limitations of Conventional Methods

A drawback of conventional techniques is their adverse impacts on biological systems. Methods such as excavation, thermal treatment, and intensive chemical washing severely disrupt the soil ecosystem by eliminating beneficial microorganisms, fungi, and soil fauna that are essential for nutrient cycling and long-term fertility (Liu *et al*., 2020). Solidification and stabilization approaches, while effective at immobilizing contaminants, often result in land sterilization by forming concrete-like masses that prevent plant growth and render soils unsuitable for agricultural or ecological restoration. Furthermore, the application of harsh chemicals may leave soils structurally intact but biologically inactive, stripping them of organic matter and suppressing microbial activity, thereby hindering the natural recovery of ecosystem functions.

5. Phytoremediation as a Sustainable Alternative

In contrast to conventional physical and chemical remediation technologies, phytoremediation utilizes green plants and their associated rhizospheric processes to mitigate, stabilize, or remove environmental contaminants. It has emerged as a promising, eco-friendly, and cost-effective strategy for the remediation of heavy metal–contaminated sites (Adeoye *et al*., 2022). The approach integrates natural plant processes with soil chemistry and microbial interactions, offering not only contaminant removal but also restoration of ecological functions.

5.1. Mechanisms of Phytoremediation

The term "phytoremediation" encompasses a suite of distinct mechanisms by which plants can interact with and manage heavy metals:

- ***Phytoextraction:*** The most relevant mechanism for heavy metal remediation. Plants absorb contaminants from the soil and translocate them via the xylem into the above-ground harvestable biomass (shoots and leaves). The plants are then harvested, effectively removing the metals from the site. Success depends on high biomass production and high metal bioaccumulation factors (BAF).
- ***Phytostabilisation:*** Plants immobilize contaminants in the soil through absorption and accumulation by roots, adsorption onto root surfaces, or precipitation within the rhizosphere. This process reduces the mobility and bioavailability of the metal, preventing its migration to groundwater or entry into the food chain. It does not remove the contaminant but secures it.
- ***Rhizofiltration:*** The use of plant roots to absorb, adsorb, or precipitate metal contaminants from aqueous sources (wastewater, groundwater, surface run-off). This is particularly useful for treating industrial effluents or wetland remediation.
- ***Phytovolatilization:*** Plants absorb contaminants, transform them into volatile species, and release them into the atmosphere through transpiration. This is less common and primarily applicable to metals like selenium (Se) and mercury (Hg), though the release of volatilized metals into the atmosphere raises its own environmental concerns.

- ***Rhizodegradation:*** While more relevant for organic pollutants, this involves the breakdown of contaminants in the soil through microbial activity enhanced in the plant's rhizosphere. The root exudates (sugars, acids, enzymes) stimulate microbial populations that can contribute to metal transformation and mobilisation.

5.2. Advantages and Limitations of Phytoremediation

Phytoremediation offers significant economic and environmental benefits compared to conventional methods (Fig. 1). It is often cost-effective 10–100 times cheaper, while preserving soil fertility, preventing erosion, and avoiding secondary waste generation. As an *in situ*, visually appealing, and non-intrusive approach, it enjoys strong public acceptance and is particularly suited for large or diffuse contaminated sites such as agricultural lands and mine tailings. In some cases, metal-rich biomass can also be processed for resource recovery (phytomining), providing an added economic incentive (Etim, 2012).

Phytoremediation faces challenges that limit large-scale application. The process is time-intensive, often requiring years to decades, and is constrained by shallow root systems that leave deeper contamination untreated (Moosavi and Seghatoleslami, 2013). Risks include food chain transfer if metal-accumulating plants are consumed, reduced plant growth under high contamination, and limited uptake of metals bound tightly to soils. Safe disposal of contaminated biomass also remains a critical issue, with incineration or landfilling posing additional costs and regulatory hurdles.

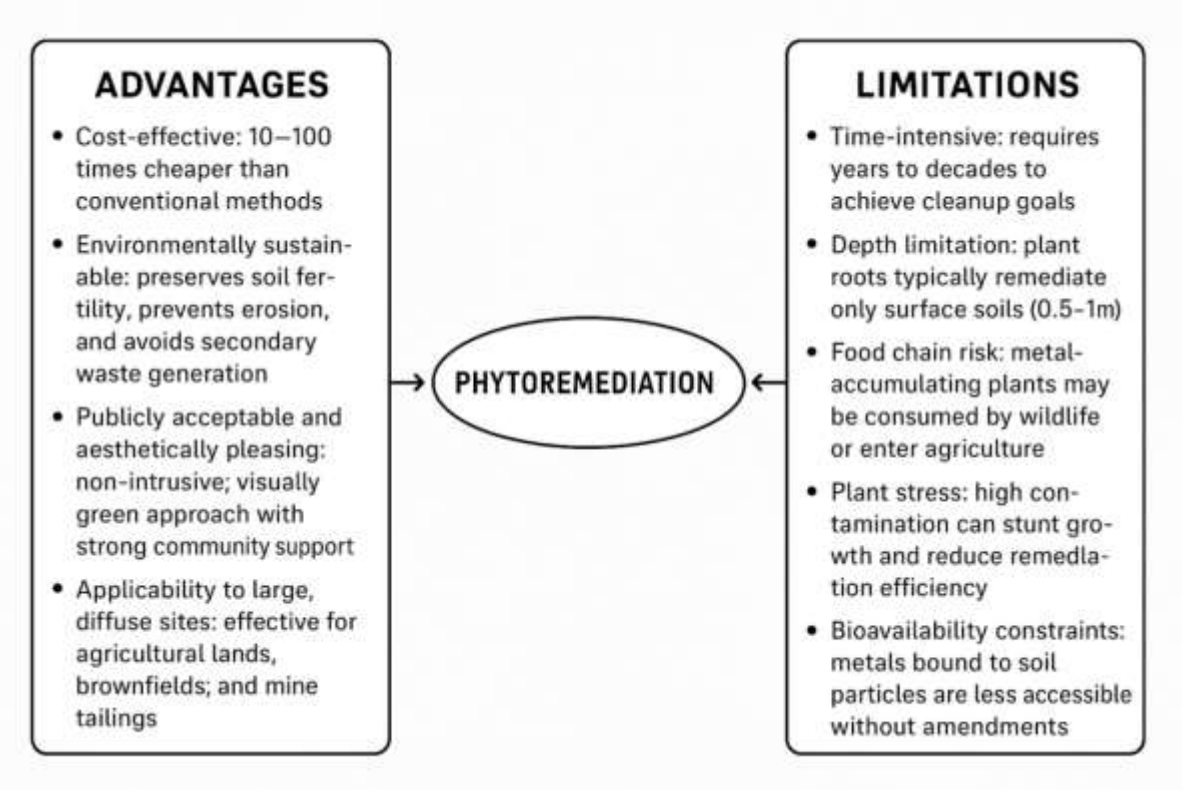

Fig. 1. Advantages and limitation of phytoremediation.

5.3. Phytoremediation vs. conventional methods

The comparison between conventional methods and phytoremediation shows a compromise between efficiency and sustainability (Fig. 2). Traditional methods are more efficient and capable of treating deeper contamination, but are faster, more expensive, eco-disruptive, and poorly accepted by the public. On the other hand, phytoremediation are more effective, low-cost, eco-friendly, and easier to implement at large scales, but their effectiveness is limited to the root zone and requires longer treatment times (Adki *et al*., 2014). This comparison emphasises phytoremediation's value as a sustainable alternative, particularly for moderately contaminated soils where ecological restoration and community acceptance are priorities.

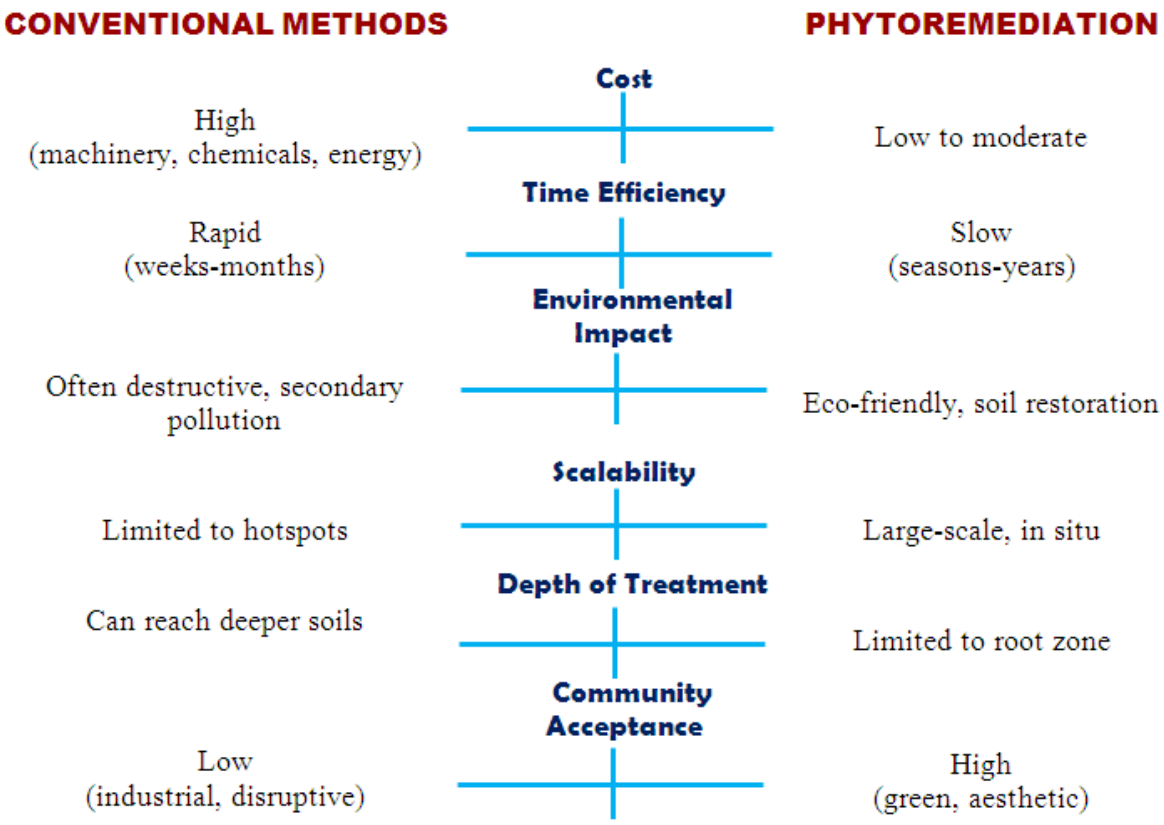

Fig. 2. Comparative advantages and limitations of phytoremediation and conventional methods.

6. *Brassica juncea* as a Model Phytoremediator

Brassica juncea, also known as Indian mustard, has appeared as one of the most effective plants for phytoremediation because of its rapid growth with high biomass production, environmental adaptability, and ability to uptake and accumulate heavy metals. Its physiological, biochemical, and genetic characteristics make it a widely studied species among hyperaccumulators (Goswami and Das, 2015).

6.1. Taxonomy, Morphology, and Growth Features

Brassica juncea belongs to the family Brassicaceae (Cruciferae), which also includes economically important crops like cabbage, broccoli, and rapeseed. It is an annual herbaceous plant that can reach 30–150 cm in height. It has broad, lobed leaves with a waxy cuticle, a taproot system, and inflorescences consisting of yellow flowers. *B. juncea* can complete its life cycle in 90-120 days, which is considered relatively short, and it can also grow in a wide spectrum of climates and soils. *B. juncea* is well known for its use in phytoremediation due to its short life cycle, propensity to grow in above-ground biomass, and adaptability to contaminated growth sites (Harun-Ur-Rashid *et al*., 2015).

6.2. Physiological and Biochemical Adaptations for Heavy Metal Uptake

B. juncea demonstrates a set of physiological and biochemical strategies that allow it to efficiently absorb, translocate, and tolerate heavy metals (Shehzad *et al*., 2023). It absorbs metals through specialized root transporters and efficiently translocates them to aerial tissues via xylem loading, enabling harvestable accumulation. To mitigate toxicity, the plant synthesises phytochelatins and metallothioneins that chelate metals, followed by vacuolar sequestration to prevent cellular damage (Shehzad *et al*., 2023). Heavy metal stress-induced reactive oxygen species (ROS) are countered by antioxidant enzymes such as superoxide dismutase, catalase, and glutathione reductase. Additionally, root exudates (citric, malic, and oxalic acids) mobilise metals in the rhizosphere, while symbiotic microbes further enhance solubilization and uptake (Małecka *et al*., 2021). These combined adaptations allow *B. juncea* to sustain growth while accumulating substantial metal loads in contaminated soils.

6.3. Mechanisms of Heavy Metal Remediation

The ability of *Brassica juncea* to remediate heavy metals relies on a coordinated set of physiological, biochemical, cellular, and molecular processes that enable metal uptake, translocation, detoxification, and tolerance (Fig. 3). Heavy metals are primarily absorbed through the roots, where transport proteins and ion channels facilitate entry into root cells (Rathore *et al*., 2019). Metals are subsequently translocated to aerial tissues via the xylem, often accumulating in shoots and leaves at concentrations higher than those in the surrounding soil. Root exudates such as organic acids, amino acids, and phenolics enhance metal mobilisation in the rhizosphere, improving solubility and bioavailability. Chelating agents such as citric acid, EDDS, and NTA further support uptake by forming stable complexes, simultaneously reducing toxicity and supporting plant growth under contaminated conditions (Quartacci *et al*., 2007).

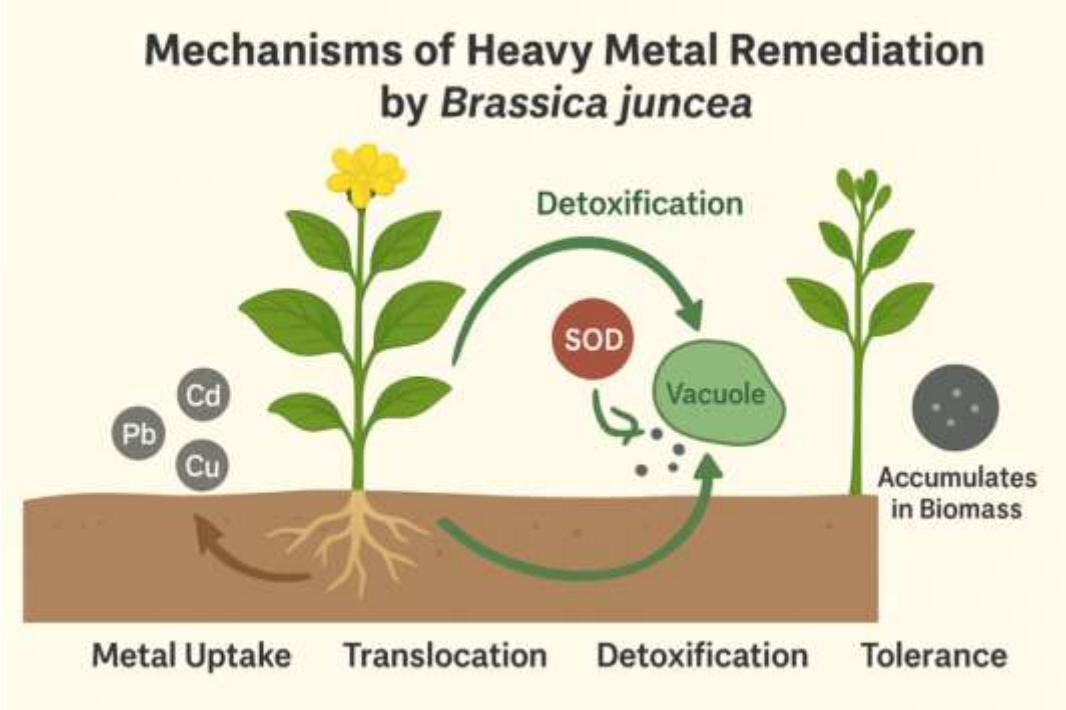

Fig. 3. Mechanism of heavy metal remediation by *Brassica juncea*.

6.4. Stress Tolerance Mechanisms

The remediation efficiency of *Brassica juncea* is largely determined by its ability to tolerate metal-induced stress. The plant employs several adaptive mechanisms. Antioxidant defenses, including superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and peroxidases, mitigate oxidative damage caused by reactive oxygen species (Thakur *et al*., 2019). Accumulation of osmolytes such as proline, glycine betaine, and soluble sugars stabilises proteins and membranes under stress conditions. Stress-responsive genes and heat shock proteins (HSPs), along with transcription factors (MYB, WRKY, bZIP), enhance stress signalling and cellular protection (Shehzad, Khan, *et al*., 2023). Metal sequestration in roots through cell wall binding and vacuolar storage restricts excessive metal transport to aerial tissues, thereby safeguarding photosynthesis. Notably, *B. juncea* maintains relatively stable chlorophyll content and photosynthetic activity even under high metal exposure. These integrated tolerance mechanisms enable the species to sustain growth and maintain phytoremediation efficiency in contaminated soils.

6.5 Efficiency of B Juncea across Different Heavy Metals

B. juncea demonstrates high remediation efficiency across a range of heavy metals (Table 4). It effectively accumulates cadmium, lead, copper, chromium, zinc, and arsenic in various environmental settings. Percentage accumulation in aerial parts compared to roots varies by metal, with Cd and Cu often showing high translocation to shoots, facilitating harvest-based removal. While Pb tends to accumulate more in roots, *B. juncea* still shows substantial uptake. Such versatility across metals and environmental conditions makes *B. juncea* a valuable species for phytoremediation of mixed contaminations (Kaur *et al*., 2010).

Table 4. Efficiency of *B. juncea* in accumulating different heavy metals.

Metal	Uptake/Detox Mechanism	Accumulation (mg/kg DW)	Effectiveness
Pb	Root exudate mobilization + vacuolar sequestration	3,000–5,000	Very High
Cd	ZIP/NRAMP uptake + phytochelatin binding	200–1,000	High
Cr (VI)	Reduction to Cr (III) + root cell wall binding	500–1,200	Moderate
As	Uptake via phosphate transporters + sequestration	100–600	Moderate
Zn	Zn transporters + chelation with organic acids	2,000–4,000	Very High
Ni	NRAMP/HMA transport + GSH-mediated detox	100–500	Moderate

6.6. Comparative Uptake Capacity with Other Hyperaccumulator Plants

Numerous studies have compared *Brassica juncea* with other hyperaccumulator species. While certain plants (e.g., *Thlaspi caerulescens* for Zn, Alyssum spp. for Ni) exhibit higher metal specificity, *Brassica juncea* offers a balanced combination of high biomass and moderate-to-high metal uptake, making it superior for field applications.

Table 5. Comparative uptake capacity of *Brassica juncea* and other hyper accumulator plants.

Plant Species	Target Metals	Uptake Efficiency	Biomass Yield	Field Suitability
Brassica juncea	Pb, Cd, Cr, As, Zn, Ni	High	High	Excellent
Thlaspi caerulescens	Zn, Cd	Very High	Low	Limited (slow growth)
Alyssum spp.	Ni	High	Low–moderate	Moderate
Pteris vittata (fern)	As	Very High	Moderate	Moderate (shade tolerant)
Helianthus annuus (sunflower)	Pb, Cd	Moderate	High	Good (fast growth, high biomass)

Table 6. Evidence synthesis of case studies on *Brassica juncea* in heavy-metal phytoremediation (PRISMA style).

Location	Experimental Setup	Key Findings	Limitations / Bias
USA (Blaylock *et al*., 1997)	Contaminated soil; chelating agents (EDTA) added; short-term growth	Shoot Pb ~1.5% (w/w); EDTA enhanced phytoextraction	High risk of leaching; pot-scale; EDTA not field-friendly
USA (Vassil *et al*., 1998)	Hydroponic with $Pb(NO_3)_2$ + EDTA	Pb-EDTA complexes transported to shoots; ~1.1% Pb DW	Hydroponic system; EDTA toxicity; unrealistic for field
USA (Bennett *et al*., 2003)	Transgenic *B. juncea* (γ-ECS, GS, APS) vs WT; contaminated mine tailings	1.5× Cd/Zn; 2–3× Cr/Cu/Pb uptake vs WT; 6–25% soil reduction	GMO field restrictions; greenhouse pot on field soil
USA (Bañuelos *et al*., 2005)	Se and B contaminated sediment; WT vs transgenic APS/γ-ECS lines	Enhanced Se uptake and sediment cleanup	Se-focused; GMO concerns
India (Gurajala *et al*., 2019)	80 cultivars screened in contaminated soil; multi-season	Genotypic variation in uptake; identified high-uptake lines	Site-specific; uncontrolled soil heterogeneity
India (Rathika *et al*., 2021)	Pb-contaminated soil; biochar + EDTA	BC+EDTA increased Pb uptake, improved growth	Small pots; EDTA risks; not scaled

6.7. Previous Studies of *Brassica juncea* in Phytoremediation

The application of *Brassica juncea* in contaminated soils has been widely studied in controlled laboratory conditions, greenhouse experiments, and field trials. These case studies provide valuable insights into the efficiency, adaptability, and challenges associated with deploying *Brassica juncea* in real-world remediation.

Conclusion

Heavy metal contamination in the environment poses a significant and persistent threat to ecosystems and human health. Traditional remediation methods, while effective to some extent, are often constrained by high costs, secondary pollution risks, and limited scalability. Phytoremediation, particularly using *Brassica juncea*, presents a sustainable, cost-effective, and eco-friendly alternative since "phytoremediation. *Brassica juncea* is distinguished by its high biomass production, rapid growth, and ability to accumulate a wide range of heavy metals, including lead, cadmium, chromium, copper, and arsenic. It is physiological and biochemical adaptations, such as efficient metal uptake, chelation, antioxidant defense, and metal sequestration, make it a robust model phytoremediator. Several past studies provide compelling evidence of the potential of *Brassica juncea* in real-world remediation scenarios. However, challenges such as limited remediation speed, bioavailability constraints, and post-harvest biomass management must be addressed to enable wider adoption. Integrating phytoremediation with soil amendments, plant-microbe interactions, and modern biotechnological approaches offers a promising path toward overcoming these limitations. *Brassica juncea* represents a powerful, sustainable tool for mitigating heavy metal pollution, bridging the gap between ecological restoration and environmental management. With continued research, technological innovation, and policy support, phytoremediation strategies centered on *Brassica juncea* can contribute significantly to building a cleaner, healthier, and more sustainable future.

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