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Review

Indian mustard: Phytoremediation tool for soil health management

M.L. DOTANIYA[1*], C.K. DOTANIYA[2], KULDEEP KUMAR[3], JAKIR HUSSAIN[4], R.K. DOUTANIYA[5], H.M. MEENA[6] and MANJU LATA[7]

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ABSTRACT*:* Metal and metallic dynamics in soil affect the ecosystem services and mediated the food chain contamination over a period. Industrialization of a country boost the economic growth, whereas waste generation during the different process poorly manage will be the source of pollution. Dumping of industrial effluents in natural resources reach the human body *via* food chain contamination is a major challenges in-front of researcher and policy makers. Different type of remediation methods are practicing, among them, phytoremediation is an eco-friendly and cheaper. Selection of Indian mustard (*Brassica juncea* L.) for phytoremediation is well established and popular practice in many countries. It is having the higher biomass and poor translocation of heavy metals from shoot to edible part. Research and development activities have been improved the greater biomass and crop yield in metal contaminated soils also. Long- term cultivation of mustard crop on contaminated soil improved the soil health parameters and reduces the metal concentration in soil solution. Use of mustard crop as a phytoremediation is a good practice without compromising the agricultural crop production in metal toxicity areas.

Keywords: Food chain contamination, Heavy metal, Indian mustard, Remediation methods, Soil health

Metal and metallic dynamics in soil greatly influenced by the origin of metals and their dispersion in ecosystem (Donald, 2003). Advancement of scientific tool and techniques explored the extraction and purification of metals from ore and further utilization of metal for human welfare. However, human development also generating the waste, mighty recovers the metal and discharge in natural resources (Gupta *et al*., 2012). Soil contamination poses a significant threat to global agriculture, ecosystems, and human health (Dehkordi *et al*., 2024). Heavy metals such as zinc (Zn), cadmium (Cd), arsenic (As), lead (Pb), mercury (Hg), chromium (Cr) and copper (Cu) accumulate in soils due to industrial activities, mining, wastewater irrigation, and excessive fertilizer use (Singh *et al*., 2011; Dotaniya *et al*., 2016a). These contaminants reduce soil fertility, inhibit plant growth, and enter the food chain, leading to bioaccumulation and toxicity (Dotaniya *et al*., 2022b). Traditional remediation methods, like soil excavation or chemical treatments, are often expensive, disruptive, and environmentally harmful. Phytoremediation emerges as a sustainable, cost-effective alternative, utilizing plants to extract, stabilize, or degrade pollutants in soil (Rajendiran *et al*., 2018).

Phytoremediation involves several mechanisms: phytoextraction (uptake and accumulation of contaminants in harvestable plant parts), phytostabilization (immobilization in roots to prevent leaching), rhizofiltration (filtration by roots in aqueous environments), and phytovolatilization (conversion to volatile forms) (Sharma and Dubey, 2005). Among hyperaccumulator plants—species capable of accumulating metals at levels 100 times higher than average—Indian mustard (*Brassica juncea*) stands out for its rapid growth, high biomass production, and tolerance to heavy metals (Ojuederie *et al*., 2022). Native to India and widely cultivated for oilseed, this plant has been extensively studied for its ability to remediate metal-contaminated soils, thereby improving soil health by reducing toxicity and restoring nutrient balance. Indian mustard's role in phytoremediation is particularly relevant in regions like India and China, where agricultural lands are increasingly polluted. Studies highlight its efficiency in accumulating metals like Zn and Cd, making it a promising tool for eco-friendly soil restoration (Shiyab *et al*., 2009). This draft explores the metal toxicity & it's mechanism in soil-plant continuum, phytoremediation potential of Indian mustard, phytoremediation mechanisms, enhancement techniques, benefits to soil health and challenges.

Role of metal in plant nutrition

As per the criteria of essentiality described by the Arnon and Stout (1939) indicated that many metal are playing role in the plant nutrition in required quantity however, exceed the concentration in soil or plant showed as toxicity system. Metallic micronutrients are essential for higher plants, functioning primarily as cofactors in enzymes, structural components in proteins, and participants in redox reactions (Kaur and Garg, 2021). They enable biochemical processes that macronutrients alone cannot support, particularly those involving electron transfer, oxygen handling, and specialized catalysis. Unlike zinc (Zn^{2+}), which does not change oxidation state and acts mainly as a Lewis acid (electrophile activator), the others (Fe, Mn, Cu, Mo, Ni) are redox-active transition metals. This allows them to shuttle electrons, cycle between oxidation states ($Fe^{2+} \leftarrow Fe^{3+}$), and catalyze reactions with high specificity due to unique coordination geometries, ligand preferences, and redox potentials. Table 1 listed the role of essential metal in plant nutrition.

Heavy metal toxicity

Metal toxicity in the soil ecosystem refers to the harmful effects caused by elevated concentrations of metals (especially heavy metals and metalloids) that exceed natural background levels or plant/ organism tolerance thresholds (Minhas *et al*., 2021). While, some metals (Fe, Mn, Zn, Cu, Mo, Ni) are essential micronutrients at low levels, they become toxic at high concentrations. Non-essential metals (Cd, Pb, As, Hg, Cr) are toxic even at trace amounts (Table 2). These metals persist in soils due to their non-biodegradable nature, accumulate over time, and affect the entire soil food web: plants, soil microbes, invertebrates, and higher trophic levels, ultimately threatening agriculture, biodiversity, food safety, and human health *via* the food chain.

Effect of metal toxicity in the soil ecosystem

Toxic substances in soil ecosystems affect organisms and ecological processes through several biological and chemical mechanisms. Contaminants such as heavy metals, pesticides, industrial chemicals, and persistent organic pollutants can cause direct toxicity to soil microorganisms by damaging cell membranes, proteins, and DNA, thereby reducing microbial growth and activity (Sparks, 2003). Many pollutants also cause enzyme inhibition, where toxic metals like cadmium, mercury, and lead bind to enzyme active sites or sulfhydryl groups, disrupting essential biochemical reactions involved in nutrient cycling. Another important mechanism is oxidative stress, in which toxic compounds stimulate the formation of reactive oxygen species (ROS) that damage

Table 1: Essential plant nutrients and their functions

Metal	Uptake form	Function
Iron (Fe)	Fe^{2+} (ferrous), though Fe^{3+}	Chlorophyll biosynthesis, Photosynthesis, Nitrogen metabolism, electron flow and preventing oxidative damage
Manganese (Mn)	Mn^{2+}	Photosynthesis and enzyme activation, Photosystem II water-splitting complex
Zinc (Zn)	Zn^{2+}	Structural and catalytic in >200–300 enzymes/proteins
Copper (Cu)	Cu^{2+}	Redox catalysis in oxidative enzymes
Molybdenum (Mo)	MoO_4^{2-}	Nitrogen assimilation/fixation
Nickel (Ni)	Ni^{2+}	Urea metabolism

cellular components such as lipids, proteins, and nucleic acids in soil organisms (Pepper *et al*., 2014). Toxic chemicals can also undergo bioaccumulation, where substances accumulate in organisms such as earthworms, nematodes, and insects faster than they can be eliminated, allowing toxins to move through the soil food web. In addition, contaminants may alter the structure and diversity of soil microbial communities, eliminate sensitive species and allowing resistant ones to dominate, which ultimately disrupts ecological balance and nutrient cycling processes (Innocent *et al*., 2024). Most of the trace metals are also cause phytotoxic effects, inhibiting root development, nutrient uptake, and plant growth. Furthermore, toxic substances can modify soil chemical properties such as pH and nutrient availability, indirectly affecting soil fertility and biological activity (Kabata-Pendias, 2011). Together, these mechanisms reduce soil productivity, biodiversity, and ecosystem stability, highlighting the importance of monitoring and managing soil contamination (FAO, 2018).

Effects of metal toxicity on plant health

Heavy metal toxicity severely impairs plant health by disrupting essential physiological and biochemical processes, primarily through the overproduction of reactive oxygen species (ROS) such as superoxide, hydrogen peroxide, and hydroxyl radicals, which cause oxidative stress leading to lipid peroxidation, protein oxidation, DNA damage, and cellular redox imbalance (Gill and Tuteja, 2010; Bhat *et al*., 2025). Non-essential metals like Cd, Pb, As, and Hg, as well as excess levels of essential ones such as Cu and Zn, interfere with nutrient uptake and translocation by competing with ions like Fe, Zn, Ca, and Mg at transport sites, resulting in deficiencies that further compromise metabolism. Photosynthesis is particularly vulnerable, with metals inducing chlorophyll degradation (*via* enhanced chlorophyllase activity or Mg^{2+} replacement in the porphyrin ring), inhibiting electron transport in photosystems (especially PS II), reducing CO, fixation, causing chloroplast disorganization, and triggering photo-oxidative damage, all of which manifest as chlorosis, reduced photosynthetic efficiency, and lowered biomass (Clemens, 2006). Enzyme activities are inhibited through direct binding to sulfhydryl groups or oxidative inactivation, affecting key processes like respiration, nitrogen assimilation, and antioxidant defences, while membrane permeability is altered, leading to electrolyte leakage, osmotic stress, and impaired water relations. Visible symptoms include stunted growth, shortened internodes, root browning or necrosis (often starting at tips), leaf rolling or wilting, interveinal chlorosis (especially in young leaves), necrotic spots, premature senescence, delayed flowering, reduced pollen viability, poor seed set, and overall yield losses ranging from 20–

Table 2*:* Key effect of heavy metals on plant health (Nagajyoti *et al*., 2010)

Metal/Metalloid	Essential	Common Sources in Soil	Typical Toxic Threshold (approx., mg/kg soil)	Key Affected Components
Cadmium (Cd)	No	Fertilizers, sewage sludge, smelting	>1–3 (very low tolerance)	Plants, microbes, humans (highly bioaccumulative)
Lead (Pb)	No	Historical gasoline/paint, mining, batteries	>100–400	Plants (roots), soil fauna, neurological effects
Arsenic (As)	No (some plants)	Pesticides (historical), mining, irrigation water	>10–50	Plants (root damage), carcinogen
Mercury (Hg)	No	Industrial, coal burning, artisanal mining	>1–5	Microbes, bioaccumulation in food chain
Chromium (Cr)	No	Tanneries, electroplating	>50–100	Oxidative damage
Copper (Cu)	Yes	Fungicides, fertilizers, mining	>100–300 (essential→toxic)	Roots, algae, invertebrates
Zinc (Zn)	Yes	Fertilizers, galvanizing, sewage	>200–400	Plants (chlorosis at excess), microbes
Nickel (Ni)	Yes	Mining, batteries, fertilizers	>50–150	Allergic/toxic effects
Manganese (Mn)	Yes	Natural, some fertilizers	>1000–5000 (acid soils mobilize)	Rare toxicity, but excess in acidic soils
Iron (Fe)	Yes	Natural, but excess rare	Very high (toxicity uncommon)	Rare, mostly in flooded/acidic conditions

60% or more in contaminated soils (Saha *et al*., 2017). These effects highlight a narrow tolerance window for metals, contrasting their essential micronutrient roles at low concentrations, and underscore the need for remediation in affected agricultural areas like those in Rajasthan where fertilizer and irrigation sources contribute to contamination (Dotaniya *et al*., 2016b).

Metal contamination in the food chain

Heavy metals and metalloids enter and contaminate the food chain primarily through polluted soils, where toxic elements like Cd, Pb, As, Hg, Cr, and excess Cu or Zn accumulate from anthropogenic sources such as industrial effluents, mining, phosphate fertilizers, sewage irrigation, and atmospheric deposition (Sharma *et al*., 2007). Plants absorb these metals *via* roots from contaminated soil or through foliar uptake from polluted water/air, leading to bioaccumulation in edible parts like leaves, grains, roots, and fruits—often exceeding safe limits in crops such as rice, wheat, vegetables (e.g., spinach, leafy greens), and fodder (Singh *et al*., 2010). This process transfers metals to herbivores (mostly livestock consuming contaminated plants or fodder), where they further accumulate in tissues, milk, and meat, and eventually reach humans as top consumers through the diet. Key mechanisms include bioaccumulation (buildup within an organism over time) and, for persistent non-essential metals like Cd, Pb, and Hg, biomagnification (increasing concentrations at higher trophic levels), amplifying exposure risks despite lower initial soil levels. In terrestrial systems, unlike aquatic food webs where biomagnification is pronounced (e.g., Hg in fish), terrestrial chains show more variable transfer, but significant risks persist *via* direct plant-to-human or plant-to-animal-to-human pathways (Chary *et al*., 2008). Globally, 14–17% of cropland exceeds toxic metal thresholds, potentially affecting 0.9–1.4 billion people through contaminated food. In regions like Rajasthan elevated Cd, Pb, and other metals in vegetables irrigated with wastewater or grown near industrial sites often linked to industrial pollution and groundwater use (Meena *et al*., 2020). Human health consequences arise from chronic ingestion, causing organ damage (kidneys, liver, brain), neurological disorders, reproductive issues, and increased cancer risk, particularly in vulnerable populations reliant on local produce. Mitigation requires soil testing, clean irrigation, phytoremediation, and regulatory limits on fertilizers/sludge to break contamination pathways and safeguard food safety.

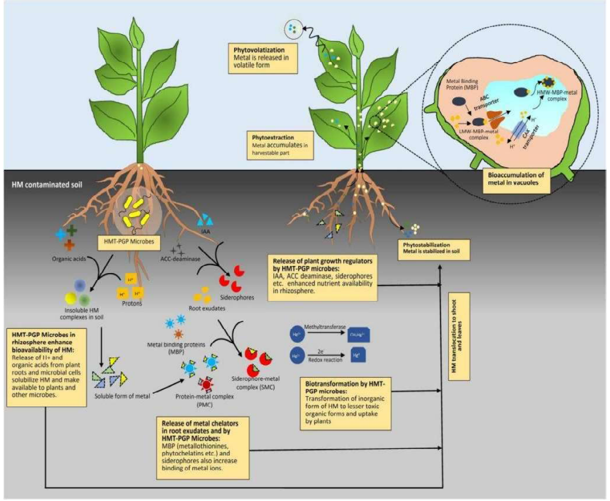

Fig. 1: Type of phytoremediation process and mechanism in plants (Mishra *et al*., 2017)

Phytoremediation mechanisms for heavy metal remediation

Phytoremediation is an eco-friendly, cost-effective, and sustainable technique that harnesses plants and their associated rhizosphere microorganisms to remediate heavy metal-contaminated soils and water by removing, degrading, stabilizing, or transforming pollutants through several key mechanisms depicted in Figure 2 (Mishra *et al*., 2017; Oubohssaine and Dahmani, 2024). The primary mechanisms include phytoextraction (or phytoaccumulation), where plants absorb metals from soil *via* roots, translocate them to above ground shoots/leaves (often storing them in vacuoles as metal-phytochelatin or metal-ligand complexes to avoid toxicity), and allow harvest of metal-laden biomass for removal—ideal for metals like Cd, Pb, As, Zn, and Cu, with hyperaccumulators (*Pteris vittata* for As, *Sedum alfredii* or *Brassica* species for Cd) accumulating concentrations far exceeding soil levels (Jakovljevi *et al*., 2024). Phytostabilization immobilizes metals in the rhizosphere by root adsorption, precipitation, or complexation (*via* root exudates or mycorrhizal fungi), reducing bioavailability, leaching into groundwater, and entry into the food chain—suitable for Pb, Cr, and As in mining-impacted sites. Rhizofiltration (or phytofiltration) uses plant roots (especially aquatic/hydroponic species) to adsorb, absorb, or precipitate metals from contaminated water or saturated zones, effectively treating wastewater or groundwater (Surriya *et al*., 2015). Phytovolatilization involves uptake, transformation (e.g., methylation or reduction), and release of volatile metal forms (like Hg or As) into the atmosphere *via* transpiration, though this transfers rather than fully removes the contaminant and is limited to volatile elements (Rani *et al*., 2023). Additional supportive processes include rhizodegradation (microbial breakdown in the root zone) and phytodegradation (internal enzymatic transformation). These mechanisms rely on plant tolerance strategies such as chelation by phytochelatins/metallothioneins, vacuolar sequestration, antioxidant defense against oxidative stress, and enhanced metal transporters (Zunaidi *et al*., 2024). In regions like Rajasthan, where heavy metal contamination from industrial effluents, fertilizers, and irrigation water affects soils, local tolerant species (e.g., maize, *Physalis angulata*, *Acalypha indica*, or wetland plants) show promise for phytostabilization or phytoextraction, often enhanced by chelators like EDTA or microbial inoculants to boost efficiency. Overall, phytoremediation offers a green alternative to conventional methods, though success depends on plant selection, soil conditions, metal type/speciation, and time required for significant clean up (Kumar *et al*., 2024).

Role of mustard in phytoremediatuion

Mustard plants, particularly Indian mustard (*Brassica juncea*), play a prominent role in phytoremediation as a fast-growing, high-biomass crop from the Brassicaceae family, widely recognized for its ability to tolerate and accumulate various heavy metals from contaminated soils (Singh *et al*., 2024). It functions primarily through phytoextraction (or phytoaccumulation), where roots absorb metals from the soil, translocate them efficiently to shoots and leaves (often with high translocation factors), and store them in aboveground tissues—facilitated by metal-binding compounds like phytochelatins, metallothioneins, glutathione, and organic acids that chelate and sequester metals in vacuoles to minimize toxicity (Yang *et al*., 2017). This species excels at extracting non-essential metals such as Cd (often 3 times more than many other plants), Pb (up to significant reductions like 13–36% in one season), As, Hg, Cr, and Se, as well as excess essential metals like Zn, Cu, and Ni. It also supports phytostabilization by binding metals in the rhizosphere *via* root exudates and associated microbes, reducing their bioavailability and preventing leaching or food-chain entry (Yadav *et al*., 2016). Singh *et al*. (2024) conducted an experiment to identify the role of cultivar in heavy metal uptake dynamics; suggested that *B. juncea* cv. Varuna and NRCHB 101 could be used for the phytoextraction of heavy metals and reducing their contamination in food chain, respectively in wastewater irrigated areas of peri-urban India.

It's advantages include rapid growth, large biomass production, short life cycle, tolerance to moderate contamination (high tolerance index >90% in many studies), and activation of robust antioxidant defenses (e.g., SOD, CAT, APX) to combat oxidative stress from ROS induced by metals (Kesawat *et al*., 2023). Efficiency is often enhanced by agronomic interventions such as applying chelators like EDTA (which increases metal solubility and shoot accumulation dramatically), sulfur amendments (to acidify soil and boost Cd uptake), peat or organic matter (improving growth and translocation), co-cropping with other plants (e.g., maize for combined remediation and production), or even induced mutations (e.g., EMS-treated genotypes for super-hyperaccumulation) (Zia-ur-Rehman *et al*., 2023). In contaminated regions like parts of Rajasthan (including Kota's industrial/agricultural areas with wastewater irrigation), *B. juncea* varieties show promise for remediating Cd, Pb, and other metals in soils, though harvested biomass must be disposed of safely to avoid re-contamination. Overall, Indian mustard stands out as one of the most studied and effective "green" tools for cost-effective, *in-situ* remediation of multi-metal polluted sites, balancing ecological restoration with agricultural feasibility.

The Brassicaceae family is renowned for containing a large number of metal hyperaccumulators. More than 100 species within this family are known to hyperaccumulate metals, particularly Ni and Zn, with fewer for Cd, As, Pb, and others (Rathore *et al*., 2019). Indian mustard (*Brassica juncea*), heavy metal uptake from contaminated soil follows a multi-step process involving root absorption, symplastic/apoplastic pathways, translocation *via* the xylem, and partitioning into various plant parts, often enhanced for phytoremediation purposes. Metals primarily exist as cations (e.g., Cd^{2+} , Pb^{2+} , Zn^{2+} , Cu^{2+} , Ni^{2+}) or anions (e.g., As as arsenate) in the soil solution, with bioavailability influenced by soil pH (higher uptake at lower pH), organic matter, and chelators (Zia-ur-Rehman *et al*., 2023). The process begins at the root level through active uptake *via* specialized plasma membrane transporters. *B. juncea* utilizes transporters from families such as ZIP (Zrt/Irt-like proteins, e.g., for Zn, Fe, Cd), IRT (iron-regulated transporters, which also handle Cd and other divalent metals), NRAMP (natural resistance-associated macrophage proteins, involved in Cd, Mn, Fe transport), and others like YSL (yellow stripe-like) for metal chelates. These transporters facilitate entry into root epidermal and cortical cells, often mimicking essential micronutrient pathways (Cd competes with Zn/Fe uptake). Some metals (e.g., Pb) primarily enter *via* the apoplast (cell wall space) before crossing the Casparian strip in the endodermis into the symplast for selective transport (Pasricha *et al*., 2021).

Once inside root cells, metals bind to chelators like phytochelatins (PCs), glutathione (GSH), or organic acids to prevent toxicity and enable safe movement. From roots, metals are loaded into the xylem for upward translocation to shoots, driven by transpiration pull. Translocation factors (TF = shoot concentration/root concentration) vary by metal: higher for mobile metals like Zn, Cd (often >1 in B. *juncea*), and lower for immobile ones like Pb (mostly retained in roots) (Dotaniya *et al*., 2018a). In stems and leaves, metals are distributed *via* phloem to some extent, but xylem dominates for most. Accumulation is highest in leaves and stems for phytoextraction, with sequestration in vacuoles *via* tonoplast transporters like HMA (heavy metal ATPases), ABC transporters, or MTP (metal tolerance proteins) to detoxify and store them, often as metal-PC or metal-organic acid complexes (Pasricha *et al*., 2021). For non-essential metals like Cd and As, uptake can occur *via* essential nutrient transporters (e.g., As *via* phosphate transporters), while chelators like EDTA (applied externally) enhance solubility, form stable complexes, and boost root-to-shoot translocation dramatically (e.g., Pb-EDTA complexes). In *B. juncea*, kinetic models describe uptake as first-order (rate proportional to concentration gradient), with time-dependent accumulation peaking in roots early and shifting to shoots over growth stages (Almeaiweed *et al*., 2025). Overall, *B. juncea's* efficiency stems from high root surface area, robust transporter expression, effective chelation, and strong antioxidant defences, enabling significant accumulation (e.g., high Cd/Pb in shoots under enhanced conditions) while maintaining growth—making it ideal for phytoextraction in contaminated soils in most of the industrial/agricultural areas.

Mechanism of heavy metal uptake from soil to mustard plant parts

The uptake and translocation of heavy metals in Indian mustard *Brassica juncea* follow a well-characterized pathway from soil solution to various plant parts, involving root absorption, internal transport, and sequestration. Below is a textual representation of the key steps, followed by relevant diagrams from scientific sources for visual clarity.

i. Soil solution and rhizosphere phase metals (e.g., Cd^{2+} , Pb^{2+} , Zn^{2+} , Cu^{2+}) exist as ions or complexes in soil. Root exudates, microbial activity (e.g., siderophores from PGPR), and amendments (organic acids, chelators like EDTA) increase bioavailability by solubilizing insoluble forms (*via* proton release lowering pH or forming soluble complexes) (Kalyvas *et al*., 2018).

ii. Root uptake (absorption into root cells) metals enter root epidermal/cortical cells mainly *via* plasma membrane transporters (ZIP family for Zn/Cd/Fe, NRAMP for Cd/Fe/Mn, IRT for Fe/

Cd). Non-essential metals like Cd often “hitchhike” on essential nutrient transporters. Pb tends to follow the apoplastic pathway (cell walls) before crossing the Casparian strip into the symplast (Pasricha *et al*., 2021).

iii. Chelation and detoxification in roots inside cells, metals bind to ligands like phytochelatins (PCs), glutathione (GSH), or organic acids to prevent toxicity and enable safe movement.

iv. Xylem loading and translocation to shoots metals are loaded into the xylem (*via* transporters like HMA family) and transported upward by transpiration pull. Translocation factors are often high for Cd/Zn (shoot > root), lower for Pb (mostly retained in roots).

v. Distribution and sequestration in shoots in stems/leaves, metals move to phloem to some extent but primarily accumulate in leaves. Sequestration occurs in vacuoles *via* tonoplast transporters (e.g., MTP, ABC, HMA3), often as metal-PC/GSH complexes, detoxifying and storing them in low-metabolic-activity compartments (Ali and Ahirwar, 2025).

Why mustard crop (Brassica juncea) is commonly using in phytoremediation

Mustard, specifically Indian mustard (*Brassica juncea*), is not the only plant used in phytoremediation—many species like *Thlaspi caerulescens* (Alpine pennycress for Zn/Cd hyperaccumulation), *Pteris vittata* (Chinese brake fern for As), sunflowers, corn, barley, alfalfa, and others serve effectively depending on the metal, soil type, and site conditions (Sheng *et al*., 2008). However, *B. juncea* is one of the most frequently studied, recommended, and applied crops in research and field trials worldwide due to a unique combination of practical advantages that make it highly suitable for phytoextraction and related mechanisms.

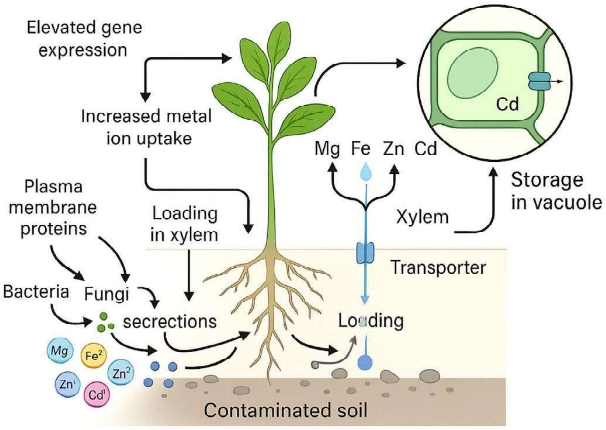

Fig. 2: Heavy metal dynamics in different plant parts (Bhat *et al*., 2025)

Key reasons for its prominence include:

- High biomass production — It grows rapidly with substantial aboveground biomass (leaves and stems), allowing removal of larger total quantities of metals per plant or per hectare compared to low-biomass hyperaccumulators (e.g., many wild Brassicaceae species are slow-growing and small). Average biomass production of the mustard varieties ranged 3-10.3 q/ha including the stalks. However, the biomass production largely depends on the crop climate, cultivar, soil, agronomic management and plant nutrient management (Priyanka *et al*., 2022).
- Fast growth and short life cycle — mustard is a hardy crop and the initial growth is very fast under the proper management of plant nutrients. It reaches maturity in 3–4 months and quicker results than perennial or slower plants.
- Broad metal accumulation capacity — It effectively accumulates and translocates a wide range of heavy metals (Cd, Pb, As, Hg, Cr, Zn, Cu, Ni, Se) from roots to shoots, often with high translocation factors, making it versatile for multi-metal contaminated sites rather than specialists for one metal (Dotaniya *et al*., 2024).
- Good tolerance to moderate contamination — It withstands metal stress without severe toxicity (high tolerance index >90% in many studies), maintains growth, and activates strong antioxidant defences (e.g., SOD, CAT, APX) to counter ROS damage (Saha *et al*., 2017).
- Ease of cultivation and agronomic management — As an agricultural crop (grown for greens, oilseeds, or fodder in regions like India), it is

well-known, with available varieties, seeds, and farming practices; it responds well to enhancements like chelators (EDTA dramatically boosts uptake), sulfur amendments, organic matter, or microbial co-inoculation (Pasricha *et al*., 2021).
- High research backing and proven field success — Extensive studies (e.g., EPA trials showing 13% Pb reduction in one season with EDTA) and genotype screenings (e.g., certain cultivars outperforming others for Cd/Pb) have established it as a reliable model plant, leading to more publications and practical adoption compared to less-studied species (Pasricha *et al*., 2021).

However, in addition above facts not exclusive or always superior (e.g., true hyperaccumulators like *Noccaea caerulescens* concentrate metals at higher tissue levels without chelators, and grasses like barley may tolerate higher concentrations), *Brassica juncea's* balance of biomass, speed, versatility, tolerance, and agricultural feasibility makes it a "go-to" choice for cost-effective, scalable phytoremediation—especially in developing regions or agricultural soils, where it can integrate into farming systems while remediating contaminants from fertilizers, wastewater, or industrial sources. Other plants are chosen when site-specific needs (e.g., extreme hyperaccumulation or wetland conditions) demand them.

Management practices for improving phytoremediation efficiency of Indian mustard

Several agronomic, chemical, biological, and biotechnological management practices can significantly enhance the efficiency of phytoremediation for heavy metal-contaminated soils, addressing limitations like low metal bioavailability, slow plant growth, limited biomass, and poor translocation to shoots. These practices boost metal uptake (especially in phytoextraction), improve plant tolerance to stress, increase biomass production, and accelerate overall contaminant removal while minimizing environmental risks.

- Chemical-assisted approaches (Chelate application) — Adding synthetic chelators like EDTA (ethylenediaminetetraacetic acid) or natural ones like citric acid increases metal solubility and bioavailability by forming soluble metal-chelate complexes, facilitating root uptake and shoot translocation. EDTA is highly effective (often increasing phytoextraction by several folds, e.g., dramatic boosts in Cd, Pb, Zn, and Cu accumulation in plants like *Brassica juncea*), but high doses can harm plant growth or risk groundwater leaching due to persistence. Citric acid (and other organic acids) is biodegradable, eco-friendlier, promotes plant growth under stress, and enhances uptake without severe toxicity—often preferred for sustainable applications, though sometimes less potent than EDTA for certain metals.
- Soil amendments and organic matter addition — Incorporating biochar, compost, manure, humic substances, or crop residues (e.g., sugar beet residue) improves soil structure, nutrient availability, pH adjustment (acidification to mobilize metals in alkaline soils common in Rajasthan), and microbial activity. These enhance root development, reduce metal toxicity to plants, and increase phytoextraction or phytostabilization efficiency (Dotaniya *et al*., 2022a).
- Microbe-assisted (PGPR and mycorrhizal fungi) — Inoculating with plant growth-promoting rhizobacteria (PGPR) (*Pseudomonas, Bacillus*, Azospirillum) or arbuscular mycorrhizal fungi (AMF) promotes plant growth *via* nitrogen fixation, siderophore production, hormone regulation, and antioxidant enhancement, while increasing metal mobilization and tolerance. This bio-augmentation often synergizes with plants like mustard, improving biomass and metal removal without chemical risks (Khawula *et al*., 2025).
- Agronomic and crop management practices — Selecting high-biomass, tolerant varieties (e.g., specific genotypes of *Brassica juncea*); plant genotype and cultivar variation - Significant differences exist among *B. juncea* genotypes (e.g., IM-25, IM-13, IM-65 better for Cd; IM-79, IM-24 for Pb), influencing tolerance, translocation factor (TF), and accumulation

(some show hyperaccumulation traits for specific metals) (Gurajala *et al.*, 2019). In addition, optimizing planting density, intercropping, or co-cropping; applying fertilizers (N, P, S) judiciously to support growth without competing with metals; ensuring proper irrigation and weed control; and timing chelator application (e.g., late growth stage to avoid early toxicity). Multiple cropping cycles per year with fast-growing species accelerate remediation.

- Advanced biotechnological interventions — Genetic engineering (transgenic plants overexpressing metal transporters, chelators like metallothioneins, or stress-response genes) enhances tolerance and accumulation. Mutation breeding (e.g., EMS-induced hyperaccumulators in mustard) or nanoparticle additions can further boost efficiency, though these are more research-oriented (Kumar *et al.*, 2022).
- In regions like alkaline soils, wastewater irrigation, and fertilizer-derived Cd/Pb contamination are common—these practices are particularly relevant: combining *Brassica juncea* with low-dose citric acid or EDTA, organic amendments, and PGPR/AMF inoculation offers a balanced, locally adaptable strategy. Success depends on site-specific testing (soil pH, metal speciation, contamination levels), monitoring plant health, and safe disposal of metal-laden biomass (e.g., incineration or ashing) to prevent re-entry into the food chain (Dotaniya *et al.*, 2018b). Integrated approaches often yield the best results, transforming phytoremediation from a slow process into a more practical, sustainable tool for soil restoration.

CONCLUSION

Metal is an essential for plant growth and when reaches to the threshold level, it will create problems for other nutrients during crop growth. However, discharge of metal contaminated effluent or waste generated material accumulated in natural resources and cause many challenges towards food chain contamination and ecosystem services. Assessment of the metal toxicity by computing the metal indices and execute the remediation strategies either chemical or biological. Over the remediation projects stated that most of the chemical remediation concepts are needed huge investment, which is mostly not preferable in developing countries. However, Indian mustard (*Brassica juncea* L.) is a cost-effective agriculture crop, cultivated on a major part of Indian North states. Huge biomass potential has a curative window to reduce the metal toxicity in soil solution. The transfer factor of root to shoot or further in edible part like oil is almost negligible. In addition, management of Indian mustard by soil and agronomic practices will also improve the phytoremediation potential of major cultivars.

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