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Phytoremediation with Ricinus communis L.: A Review of its Potential and Applications

[1] **Kalpana Agarwal;** [2] **Smita Purohit;** [3] **Akshita Khandelwal;** [4] **Vaishali**
[1,2]Associate Professor, [3,4] Research scholar
[1,2,3,4] Department of Botany, IIS (Deemed to be University), Jaipur-302020,
Rajasthan, India

Abstract: Environmental contamination by heavy metals and organic pollutants has intensified with rapid industrialization and unsustainable agricultural practices, posing serious ecological and health risks. Conventional remediation methods are often costly and environmentally disruptive, driving interest in plant-based alternatives. This review focuses on R. communis L. (castor bean) and its microbial associations as promising agents in phytoremediation. The discussion highlights mechanisms such as phytoextraction, phytostabilization, and phytodegradation, alongside the physiological and biochemical responses of R. communis under heavy metal stress. The synergistic role of rhizosphere and endophytic microbes, which enhance pollutant bioavailability, reduces oxidative stress, and improves plant growth and metal uptake. By synthesizing current evidence, this review underscores the relevance of R. communis–microbe partnerships as sustainable tools for remediating contaminated soils and mitigating pollution impacts, and for nanotechnological interventions to optimize remediation efficiency.

Keywords: Phytoremediation, R. communis, heavy metal, Metal toxicity, Microbes, nanoparticles

Introduction: Environmental pollution has become one of the most crucial challenges of the 21st century, threatening human health, biodiversity, and ecosystem stability. Pollution caused by organic xenobiotics such as pesticides, pharmaceuticals, petroleum hydrocarbons, Polycyclic Aromatic Hydrocarbons (PAHs), and Polychlorinated Biphenyls (PCBs)is a global concern (Mahireet al., 2023; Moosavi & Seghatoleslami, 2013).Environmental contaminants of concern encompass both inorganic and organic compounds. These include heavy metals, radionuclides, nitrates, phosphates, inorganic acids, and a range of synthetic organic chemicals. Such pollutants are primarily introduced into ecosystems through anthropogenic activities, including waste disposal, explosive residues, intensive application of pesticides and fertilizers, pharmaceutical discharges, atmospheric acid deposition, and radioactive fallout (Dhiman et al., 2023;

Arthuret al. 2005).In contrast to organic pollutants, heavy metals (HMs) are non-biodegradable and thus persist in the environment, posing significant risks to public health through bioaccumulation in the food chain and contributing to biodiversity loss (Khanet al.,2019). The primary sources of heavy metal contamination are anthropogenic, arising from activities such as mining and smelting operations, sewage irrigation, disposal of municipal sludge, fossil fuel combustion, and the extensive use of pesticides and fertilizers, largely driven by rapid industrialization (Mishra & De 2024; Agoroet al., 2020; Barbosa et al., 2015).Contamination by heavy metals (HMs) is recognized as one of the most severe threats to soil and water quality, with profound implications for ecosystem functioning and human health. Elevated HM concentrations in soils not only impair soil fertility but also enhance their uptake by crops, thereby reducing plant growth and posing risks to food safety (Angon et al., 2024; Schmidt, 2003). Metals such as Cu, Fe, Se, Ni, and Pb are of particular concern due to their high persistence, chemical stability, and bioaccumulative behavior within biological systems (Khanet al., 2019). Importantly, several of these metals exhibit toxicity even at trace levels, adversely affecting plant productivity and crop yield (Yi et al., 2011). Conventional remediation approaches for contaminated soils, such as soil washing, flushing, solidification, electrokinetic stabilization, incineration, and In situ vitrification, are often limited by their high economic cost, labor intensity, and potential to irreversibly alter soil physicochemical properties(Adnan et al., 2022; Ali et al., 2013). Moreover, these methods frequently disrupt beneficial soil microbial communities, thereby reducing long-term soil quality and ecological balance (Wiszniewskaet al., 2016).In contrast, phytoremediationthe utilization of plants and their associated rhizosphere microorganisms for the removal, stabilization, or detoxification of contaminants from soil, water, and airhas emerged as a sustainable and eco-compatible alternative (Sun et al., 2025; Arthur et al. 2005). This strategy allows for the restoration of contaminated soils without compromising soil structure, fertility or chemical integrity(Barbos et al., 2015).Members of the Euphorbiaceae family, including Ricinus, Jatropha, Acalypha, Croton, Phyllanthus, and Euphorbia have been reported as promising plantspecies for the phytoremediation of toxic elements due to their high biomass production and tolerance to metal stress.

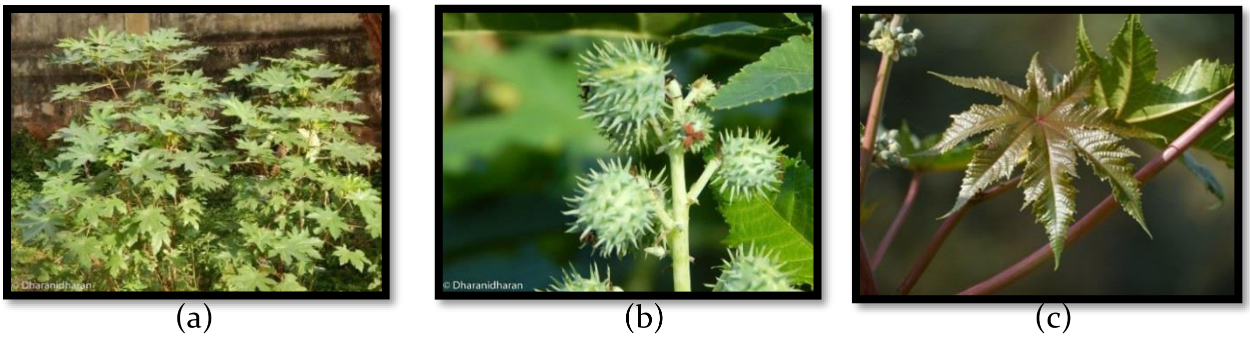
Phytoremediation: Phytoremediation represents a sustainable, In situ remediation technology that utilizes the natural capacity of plants to mitigate environmental contamination through a combination of physiological, biochemical, and enzymatic processes (Sharmaet al., 2023; Raza et al., 2020; Olivares et al., 2013).Plants can absorb, accumulate, stabilize, transform, or degrade a wide spectrum of pollutants directly within the contaminated medium. This approach has gained recognition as a cost-effective and environmentally compatible alternative to conventional physicochemical techniques, which are typically expensive, disruptive, and less acceptable to the public (Phang et al., 2024;Ijaz et al., 2016;Olivares et al., 2013). Beyond toxic metals and metalloids, phytoremediation and related bioremediation strategies have also demonstrated effectiveness in addressing soils contaminated with petroleum hydrocarbons, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, organic solvents, military munition residues,and even radioactive isotopes (Thakur et al., 2025; Patel et al., 2020; Rissatoet al., 2015).Phytoextraction involves the uptake of toxic elements from the soil and concentrates them in harvestable biomass(Mukherjee et al., 2025; Arthur et al. 2005). Phytostabilization reduces contaminant mobility and bioavailability by immobilizing pollutants within the rhizosphere and Phytovolatilization enables the uptake and conversion of contaminants into volatile forms subsequently released into the atmosphere, while phytodegradation employs plant-derived enzymes such as dehalogenases and oxygenases to break down organic pollutants within plant tissues, without reliance on microbial activity (Ogundele et al., 2025; Arthur et al., 2005).

To date, more than 400 plant species, representing at least 45 botanical families, have been identified as hyperaccumulators of trace and heavy metals (Ghosh and Singh, 2005; Lasat, 2000). Notable families with documented hyperaccumulator species include Brassicaceae, Fabaceae, Euphorbiaceae, Asteraceae, Lamiaceaeand Rubiaceae (Vazquez-Marquezet al., 2024; Dushenkov, 2003; Salt et al., 1998). The selection of plant species for phytoremediation is typically guided by their tolerance and accumulation capacity for multiple metals, adaptability to local environmental conditions, high biomass production, extensive root systems, rapid growth, ease of cultivation, and capacity for substantial water uptake(Sharma et al., 2023; Barbosa et al.,2015).Plants are capable of accumulating not only heavy metals such as Cu, Fe, Mn, Ni, Zn, Cr, Cd, Pb and radionuclides, but also a wide spectrum of inorganic pollutants,these include nitrates, phosphates, and other essential micronutrients (Yeboah et al., 2020a; Bauddhet al., 2015). Additionally, they can metabolize or sequester a variety of organic contaminants, including trichloroethylene, trinitrotoluene, gasoline hydrocarbons, benzene, polycyclic aromatic hydrocarbons, methyl tertiary-butyl ether, and polychlorinated biphenyls (Alori et al., 2022; Alkorta & Garbisu, 2001; Newmanet al., 1998). As a result, phytoremediation has emerged as a cost-effective, environmentally compatible, scalable, aesthetically acceptable, and sustainable alternative to conventional remediation technologies (Dixit & Bhatia 2025; Arthur et al., 2005)

Ricinus Communis L.: R. communis L., commonly known as the castor oil plant, belongs to the family Euphorbiaceae. It is referred to by various vernacular names: in English as castor oil plant; in Hindi as Arand, Erand; in Sanskrit as Gandharvahasta; in Gujarati as Erandio or Erando; in Kashmiri as Aran; and in Marathi as Errand(Singh & Geetanjali 2015; Rana et al., 2012).R. communisoriginated in Africa, particularly the Ethiopian region of East Africa and now distributed worldwide, thriving in tropical and subtropical climates(Landoni et al., 2023). It is cultivated extensively in South Africa, India, Brazil, and Russia, and is also naturalized in many regions, including the southwestern United States, where it frequently occurs as a weed. In India, Rajasthan, Gujarat, AP, Karnataka, Maharashtra, Odisha, and castor was conducted in Jodhpur, Jaisalmer and Sirohi districts of Rajasthan. The plant is widely cultivated in gardens and agricultural fields and often grows wild in wastelands (Seitz et al., 2022; Manjunath & Sannappa, 2014). Cytogenetic studies have revealed that R. communis possesses a diploid chromosome number of 2n = 20, with an estimated genome size of approximately 316 Mb containing about 31,000 genes (Yeboah et al., 2020b).Historically, castor oil has been employed as a purgative, as well as in traditional remedies for various ailments. Castor oil has wide industrial applications also It is utilized in the manufacture of paints, enamels, varnishes, linoleum, oiled fabrics, patent leather, flypaper, inks, greases, lubricants, polishes, waxes, hydraulic brake fluids, urethane foams, rubber substitutes, dielectric and condenser oils, and nitrocellulose-based finishes (Kauravet al., 2024; Nangbeset al., 2013; Rana et al., 2012). Castor seeds are rich in oil content, primarily due to the high proportion of monounsaturated fatty acids and other bioactive compounds. This oil is characterized by the presence of ricinoleic acid as its major component, along with oleic acid, palmitic acid, stearic acid, and dihydroxystearic acid (Yeboah et al., 2020c; Nangbeset al., 2013). This unique fatty acid profile contributes to its versatility, allowing modification for use in the food industry as additives, as well as in transportation, cosmetics, and pharmaceuticals (Yeboah et al., 2020b). The oil also finds applications in cosmetics, pharmaceuticals, insecticidal formulations, and as a softening agent in textile industries (Fahmy & Amr 2024;Rana et al., 2012).

Classification of Ricinus Communis

Kingdom:	Plantae
Phylum:	Spermatophyta
Class:	Dicotyledonae
Order:	Euphorbiales
Family:	Euphorbiaceae
Genus:	Ricinus
Species:	communis L.



(a) (b) (c)

Fig. 1: Ricinus communis- (a)Plant, (b)Fruit, (c)Leaf
(source: www.indianbiodiversity.org)

Phytoremediation Potential of R. communis: Ricinus communis L. (castor bean), a C3 plant belonging to the Euphorbiaceae, has been reported as a highly metal-tolerant species capable of growing in heavily polluted soils, making it a valuable resource for phytoremediation (Kiran & Prasad, 2017b; Zhang et al., 2016). Its ability totolerateextreme conditions such as high salinity and drought also demonstrates its potential as aremediator of seashore saline soils. R. communisis a promising species for large-scale remediation of contaminated sites with the additional benefit of oil production (Carrino et al., 2020; Olivareset al., 2013).Research has demonstrated that R. communis can accumulate a wide spectrum of pollutants, including toxic metals such as Cd, Pb, Ni, As, Zn, Cr and Cu,as well as organic contaminants such as pesticides and persistent organic pollutants (POPs)(khan et al., 2019; Zhang et al., 2016; Rissatoet al., 2015). Compared with species such as zucchini, pumpkin, alfalfa, and corn, castor bean exhibits superior efficiency in the remediation of POP-contaminated soils (Rissatoet al., 2015). Its extensive root system allows deeper penetration into contaminated substrates, increasing contact with pollutants, while the relatively high lipid content of its tissues enhances the uptake of hydrophobic organic compounds (Zeb et al., 2022; Aken et al., 2010; Sicbaldiet al., 1997). Chelate-assisted phytoremediation using R. communis has been studied with various chelating agents, including citric acid (CA), ethylenediaminetetraacetic acid (EDTA), and S,S-ethylenediamine disuccinic acid (EDDS) (Jinghua & Shuifeng, 2025; Mohtadiet al., 2013; Luo et al., 2005). EDTA is the most effective and widely applied, as it significantly mobilizes metals into the soil solution and enhances their accumulation in plant tissues (Jinghua & Shuifeng 2025; Cutright et al., 2010; Meers et al., 2005). EDDS proposed as an environmentally safer alternative to EDTA for enhancing Cd phytoremediation, whereas EDTA has been reported to efficiently extract Pb (Anas et al., 2025; Zhang et al., 2016). Castor bean has also been evaluated for its ability to establish on fly ash (FA) disposal sites, which contain high concentrations of toxic metals capable of leaching into surrounding environments (Roychowdhury et al.,2019). While establishment is poor on freshly deposited FA, R. communis grows vigorously on FA-polluted sites and tends to accumulate most metals in its roots rather than aerial tissues. Such a root-dominant accumulation pattern, supported by bioconcentration factor values, indicates that castor bean is highly suitable for phytostabilization and revegetation of FA disposal areas (Pandey 2013).

Castor bean is considered a good plant species for phytoremediation of heavy metal–contaminated soils due to its substantial biomass production, but when exposed to Cd and Pb in culture conditions its growth and root exudation patterns were changed (Niu & Sun, 2017).R. communis has been shown to rapidly extract Cd from soil and higher tolerance of cd, often outperforming well-known phytoremediators such as Brassica juncea (Bauddh and Singh, 2012a). Cd in castor is primarily localized in the cell walls of root tissues there by limiting its translocation to shoots and reducing risks of food-chain transfer (He et al., 2020). Among evaluated genotypes, B09053 was identified as the efficient accumulator of both Cd and dichlorodiphenyltrichloroethanes (DDTs) in co-contaminated soils (Huang et al., 2011). Beyond metals and POPs, castor bean has also been reported as effective in the phytoremediation of distillery sludge, which contains toxic organic acids, mutagenic compounds, and disrupting chemicals (Tripathi et al., 2021; Huang et al., 2011). R. communis is not an efficient Cd phytoextractor; however, it can serve as a potential phytostabilization species by immobilizing and stabilizing Cd in contaminated soils (Kiran & Prasad 2017b; Zhang et al., 2015)

Table 1- The effect of Heavy Metals on Ricinus communis Growth:

Sr. No.	Heavy metal	Treatment level	Experiment	Conclusion	Citation
1	Ni,Cd, Cr, Pb	50ppm,100ppm amended in soil	Pot experiment and plants were harvested after 90 days	castor could be recommended where Ni and Pb are dominant pollutants and Cotton for Cr and Cd contaminated soil.	Ogunshaki net al., 2019
2	pb	0, 100, 200 and 400 µmol Pb L-1	Hydroponics- harvested after 28 days of solutiontreatment	R. communis L is a hyperaccumulator species for Pb and exhibits tolerance to low Pb concentrations	Romeiro et al., 2006
3	cd	(0, 5, 10, 15, 20 and 25 mg/L)	Hydroponics- After 30 days of seedling plant transplant in flask.	Plant height, root length and dry biomass are generally reduced by heavy metals	Hadi et al., 2015
4	Ni	0, 10, 40, 80, 120, 160, 180, 200, 250 mg Ni kg^{-1} in soil	Pot experiment and harvested after 45 days	At the higher Ni levels, beyond 200 mgkg^{-1} Ni in soil, reducedgrowth symptoms of the plant	Adhikari & Kumar 2011
5	Cr	chromium (0, 10, 20 mg kg^{-1}) and citric acid (0, 2.5, 5 mM)	Ripened plants wereharvested in Pot experiment	Cr toxicity reduced the growth, physiological along with oxidant and antioxidant activity of castor bean.	Ali et al., 2022
6	Cd, pb	Cd (0, 1, 2, 4, 8 and 16 mgL-1) Pb (0, 6, 12, 24, 48 and 96 mg L-1),	Hydroponic- Harvested after 30 days	Higher levels in the nutrient medium resulted in lower root and shoot dry matter accumulation, while lead did not noticeably influence plant growth.	de Souza Costa et al., 2012

7	Fe, Zn, Cu, Pb, Co, Cr	BW(borehole water) and industrial waste water (IWW):T1 (100%BW),T2 (75% BW+25 % IWW), T3 (50% BW+ 50% IWW), T4 (25% BW+75% WW) and T5 (100% IWW).	Pot experiment and harvested after 84 days	no toxic effects of the heavy metals on growth parameters of Ricinus communis seedlings.	Akintolaet al., 2022
8	Ni	25, 50, 75, 100, and 150 mg Ni kg^{-1}	Pot experiment-Harvested after 60 days	At every level of contamination, R. communis showed higher biomass production compared to B. juncea.	Bauddh& Singh 2015.
9	cd	0 mg/L, 300 mg/L, 700 mg/L, and 1,000 mg/L Cd solution	Hydroponics-Harvested after 21 days of treatment	Castor plants under Cd stress had reduced growth and biomass.	Huiboet al., 2023

Toxic Impacts of Heavy Metals-Heavy metals are among the most persistent environmental pollutants, exerting severe effects on soil, plants, animals, and humans. According to the Environmental Protection Agency (EPA), elements such as copper (Cu), cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), nickel (Ni), and mercury (Hg) are the most common contaminants of concern. Even at low concentrations, these metals can exert toxicity to plants, soil microorganisms, aquatic organisms, and humans (Tripathi et al., 2021). In soils, heavy metals disrupt the structural integrity of aggregates, reduce organic matter content, and lower water-holding capacity. Their accumulation alters microbial activity, enzymatic processes, and nutrient cycling, ultimately diminishing soil fertility and agricultural productivity(Jaiswal et al., 2018). Soils naturally contain both essential micronutrients such as Fe, Zn, Cu and Mn, which are required for plant growth, as well as non-essential elements such as Cd, As, Hg, Pb and Cr, which serve no biological function and cause toxicity even at trace levels (Bibi et al., 2023; Ali et al., 2013). When present in excess, even essential elements can become toxic, thereby threatening plant health and ecosystem stability (Nieder &Benbi, 2024; Shah et al., 2010). The uptake of heavy metals by plants leads to diverse physiological disorders (Nieder &Benbi, 2024; Yadav et al., 2020). Toxic concentrations interfere with reproductive processes, reduce photosynthetic efficiency, and cause visible symptoms such as chlorosis, leaf rolling, necrosis, and stunted growth (Shukla et al., 2024; Geetha, 2019; Shah et al., 2010). Heavy metals are inert within sediment environments and are often regarded as conservative pollutants. However, under certain disturbances, they can be remobilized into the water column, posing potential threats to aquatic ecosystems (Yi et al., 2011).

Among these pollutants, cadmium is particularly dangerous due to its high mobility and water solubility. Its accumulation leads to severe physiological disruptions, including chlorophyll degradation, carotenoid loss, chlorosis, leaf rolling, and overall growth retardation(Hu et al., 2025; Benavides, 2005).Cadmium-driven reduction of beneficial soil microbes (Zhao et al., 2023). Cd is readily absorbed and translocated within plants, replacing essential nutrients such as K, Ca, Mg, and Fe by competing for the same transporters (Muhammadet al., 2025; Shah et al., 2010).

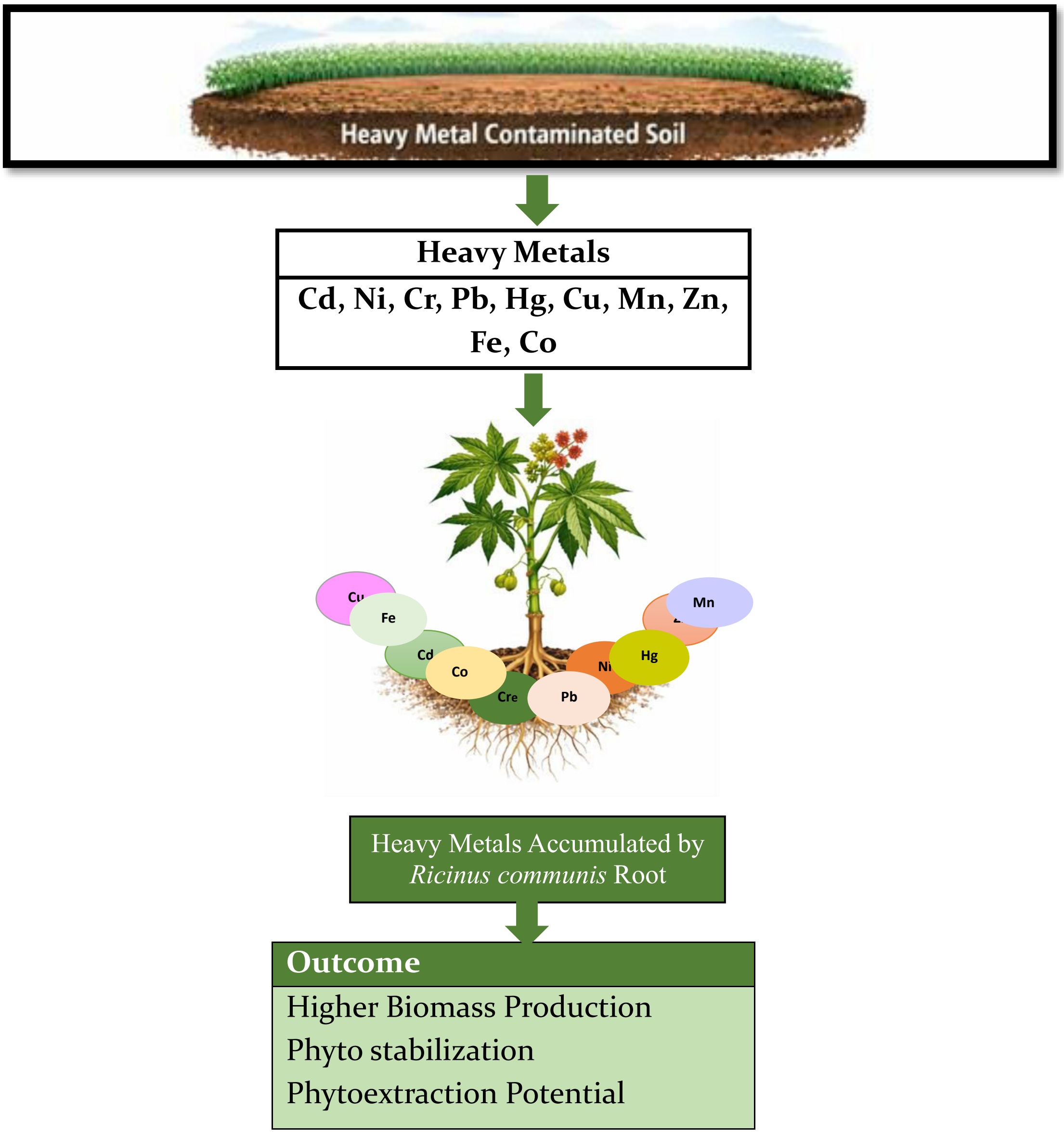


Fig. 2: Heavy Metal Tolerance and Soil Remediation by Ricinus communis (Diagram Supported by AI Tool)

Heavy metals primarily impair plant growth by inducing the generation of free radicals and reactive oxygen species (ROS), which continuously cause oxidative damage by degrading vital cellular components (Mansooret al., 2023; Pandey et al., 2005; Qureshi et al., 2005). Excess copper, although essential in trace amounts, exerts cytotoxic effects when present beyond physiological levels. It induces oxidative stress, interferes with photosynthesis and disrupts peroxidase activity, leading to growth inhibition and chlorotic symptoms (Sameena &Puthur, 2021). Similarly, elevated nickel concentrations alter nutrient balance, impair plasma membrane integrity, and disturb lipid composition and H^+-ATPase activity (Ros et al., 1992), resulting in chlorosis and necrosis in several plant species (Pandey & Sharma, 2002). In R. communis, proline and malondialdehyde (MDA) levels in the leaves increased with rising Ni concentrations, while soluble protein content showed a decline (Dutta et al., 2022; Bauddh& Singh, 2015).Mercury is unique among metals due to its occurrence in multiple forms, including elemental, ionic, and organic states (Clarkson et al., 2003). Mercury is an extensive environmental toxicant and pollutant that induces profound alterations in body tissues and leads to a broad spectrum of adverse health effects (Zafar et al., 2024; Tchounwouet al., 2012). High concentrations of Hg^{2+} are highly phytotoxic, inducing oxidative stress through reactive oxygen species (ROS) generation (Sahu et al., 2012; Tchounwouet al., 2012). Chromium contamination results in growth inhibition, nutrient imbalance, chlorosis in young leaves, root damage, and wilting. It is further recognized as a powerful human carcinogen by the International Agency for Research on Cancer (IARC), the EPA, and the World Health Organization (WHO) (Georgakiet al., 2023;Suhet al., 2019). The toxic effects of chromium (Cr) on plant growth and development include disturbances in seed germination and impairments in root, stem, and leaf growth. Consequently, exposure to elevated Cr levels reduces total dry matter accumulation and overall plant yield(Saud et al., 2022; Shanker et al., 2005). Lead is ranked second in the list of hazardous substances (Roychowdhury et al., 2019). Pb accumulation reduces chlorophyll and carotenoid content, suppresses photosynthesis, disrupts membrane permeability, reduces stomatal conductance, altered metabolism, and induces oxidative damage, which can ultimately lead to cell death (Ashraf & Tang 2017; Kiran & Prasad, 2017a).Zinc, although essential for plant metabolism, is frequently found in excess in contaminated soils, where it restricts root and shoot development (Kaur & Garg, 2021). High Zn levels also induce secondary deficiencies of Mn, Fe and Cu, leading to nutrient imbalance and phytotoxicity (Shukla et al., 2021).

Heavy Metal Stress Responses in Ricinus communis- Exposure to heavy metals significantly influences its physiology, growth, and biochemical processes.Chlorophyll content in R. communis was more adversely affected at elevated pollution levels (Xiong et al., 2018; González-Terreros et al., 2018). Elevated metal concentrations alter biomass production, reduce photosynthetic pigments, and impair nutrient uptake. While low concentrations of metals may not markedly affect plant growth, higher concentrations substantially reduce biomass due to disruptions in physiological and biochemical processes that govern development (Yeboah et al., 2020a; Niu and Sun 2017).One of the earliest responses of R. communis to heavy metal stress is the generation of reactive oxygen species (ROS) (Yeboah et al., 2020; Ashraf et al., 2017). R. communis exhibits tolerance to metal stress through the activation of stress-responsive genes at the molecular level (Yeboah et al., 2020a). Oxidative damage in plants can be evaluated by quantifying malondialdehyde (MDA), a key byproduct of lipid peroxidation (Tsikas2017; Zu et al. 2016).Metal stress can induce the synthesis of proteins involved in energy production and plant defense mechanisms (Singh et al., 2019). To mitigate such stress, plants activate robust antioxidant systems, including elevated levels of glutathione (GSH) and proline, alongside reduced MDA content, which collectively mitigate metal-induced oxidative damage and enhance tolerance to environmental stresses (El-Beltagiet al., 2020; Bauddh & Singh, 2012b).

Several mechanisms contribute to tolerance in R. communis. Organic acids such as citric, malic, oxalic, succinic, and tartaric acids have been shown to reduce metal absorption in roots, thereby improving plant tolerance. Among these, Citric acid (CA) is an effective chelating agent used to enhance heavy metal remediation in soils, including with castor bean (R. communis), and for removing metals from contaminated water (Qureshi et al., 2020; Anwer et al., 2012). Specifically, secretion of CA and MA under Ni stress decreases rhizospheric toxicity and promotes plant survival (Huang et al. 2016; Bauddh and Singh 2015).The adverse effects of HM on photosynthetic pigments (chlorophyll, carotenoid) could inhibit plant growth and yield(Khalid et al., 2019; Kiran and Prasad, 2017b; Hazama et al., 2015). Molecular studies have provided insights into the plant's adaptive strategies. Proteomic and metabolomic analyses suggest that under Cd stress, R. communis limits Cd^{2+} absorption by strengthening cell wall structures and, in severe cases, initiating programmed cell death to restrict systemic toxicity. Cd stress also disrupts antioxidant defenses, ATP synthesis, and ion homeostasis, reflecting its broad physiological impacts (Huiboet al., 2023). Antioxidant responses show a mixed pattern: catalase (CAT) and peroxidase (POD) activities increase, while superoxide dismutase (SOD), ascorbate peroxidase (APX), and glutathione (GSH) levels decline with increasing Pb exposure (Kiran & Prasad, 2019). Seedlings exposed to Pb exhibit impaired development, stunted growth, reduced dry weight, and altered leaf coloration (Luo et al., 2025; Romeiro et al., 2006). R. communis has been identified as a hyperaccumulator of Pb, with retention primarily occurring in roots via cell wall binding and extracellular precipitation, predominantly in the form of lead carbonate deposits (Romeiro et al., 2006). Cadmium stress in R. communis induces oxidative damage by enhancing ROS production, while simultaneously suppressing key antioxidant enzymes (SOD, CAT, POD), leading to impaired defense capacity andenhanced cellular damage (Yeboahet al., 2021; Zhang et al., 2015). A comparative study reported that Cd exposure (100 $mg \cdot kg^{-1}$ soil) reduced root and shoot biomass in R. communis and Brassica juncea L., with a greater decline observed in R. communis (Bauddhet al., 2015).

Microbe-Assisted Phytoremediation by Ricinus communis- Heavy metals also have a crucial role in soil enzymatic activities (Naz et al., 2022). Plants, in association with their microbial counterparts, possess the capacity to remove environmental contaminants and sequester them within their tissues. The activity of Microbial association may alter the mobility and bioavailability of trace metals in soil (Kiran & prasad, 2017). The rhizosphere-associated microbial communities (rhizobiome) are essential for the success of phytoremediation (Rubio-Noguez et al., 2024).Root endosphere-associated fungal communities were more sensitive to heavy metal stress (Yao et al., 2023).Plant growth–promoting bacteria (PGPB) additionally aid phytoremediation by producing beneficial metabolites such as ACC deaminase, siderophores secretion, phytohormones and the release of other chelating substances. These compounds not only enhance nutrient uptake but also indirectly contribute to microbe-mediated removal of pollutants and the overall bioremediation process. within the rhizosphere, microbes mobilize pollutants into bioavailable forms, which can then be absorbed by plant roots (Rabani et al., 2022). Soil microorganisms possess the ability to accumulate, transform, and detoxify heavy metals (Mishra et al., 2017). For instance, Staphylococcus aureus has been shown to exhibit superior tolerance to chromium toxicity compared to Bacillus subtilis, even at high concentrations. Similarly, castor bean has shown strong chromium tolerance and can be efficiently employed in the remediation of metal-polluted soils (Ali et al., 2022). Although elevated metal concentrations often suppress microbial activity, certain metal-tolerant strains adapt to heavy metal stress and increase the bioavailability of metals to plants (Abdu, 2017).Microbes enhance plant tolerance against diverse environmental stresses, in return, plants release root exudates and enzymes that stimulate microbial and biochemical activities in the surrounding soil, thereby reinforcing the remediation cycle (Rabani et al., 2022). Among the diverse microbial communities colonizing the rhizosphere of R. communis, several strains have been identified with remarkable metal resistance. Two endophytic isolates (SS1-E2 and SS1-E9) and four rhizospheric isolates (SS1-R2, SS1-R5, SS2-R4, and SS2-R9) showed strong tolerance to Cu, Cd, and Pb. the endophytesnamely, SS1-E2 and SS1-E9showed positive for ACC deaminase activity. Rhizosphere isolates exhibited differential biosorption capacities for Cd and Pb, with biosorption efficiency increasing alongside the initial metal concentration(Annapurna, 2016). Likewise, endophytic Fusarium strains (F2, F8, and F14), isolated from R. communis roots, displayed co-resistance to Cd, Pb, and Zn. These isolates were capable of producing indole-3-acetic acid (IAA) and 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase, thereby promoting plant growth. Inoculation with these Fusarium strains significantly improved both biomass and metal extraction efficiency of R. communis in multi-metal-contaminated soils(Yao et al., 2023). Environmental pollution acts as a selective pressure, enriching microbial communities with enhanced metabolic capacities for survival (Zhao et al., 2023; Almasiaet al., 2016). Evidence indicates that the rhizobiome of plants growing in heavy metalcontaminated sites is enriched with members of Pseudomonadota, Actinomycetota, and Chloroflexota. Certain members of these phyla enhance metal bioavailability by producing secondary metabolites such as siderophores, which chelate and solubilize heavy metals and produce biosurfactants that facilitate metal translocation within plants (Liu et al., 2022; de Lima et al., 2022).The rhizosphere represents a complex and dynamic microenvironment where microbial communities form unique associations with plant roots, contributing significantly to the detoxification of hazardous compounds (De-Souza et al., 1999). Serratia K120 facilitates the translocation of Al, As, Cu, Pb, Cr, Cd, and Mn into aerial plant parts, while simultaneously reducing oxidative stress in plants by lowering H_2O_2 levels and enhancing the activity of antioxidant enzymes, including SOD, CAT, APX, POX, and GR. Serratia K120 and Pantoea 113 have been proposed as potential bioinoculants to improve phytoremediation efficiency under heavy-metal stress conditions (Mendoza-Hernández et al.,2023). PGPB Pseudomonas sp. PsM6 and P. jessenii PjM15, both enhance phytoextraction efficiency directly by increasing metal accumulation in plant tissues (particularly Zn), and indirectly by stimulating shoot and root biomass production in R. communis (Rajkumar & Freitas, 2008). A total of 44 endophytic bacterial strains were isolated from castor plant tissues, and 42 of them demonstrated three or more plant growth-promoting attributes, most of these isolates also exhibited differential tolerance to copper (Cu) and cadmium (Cd)(Li et al., 2023).

Arbuscular mycorrhizal fungi (AMF) are widespread and abundant, forming symbiotic associations with plants and enhancing their ability to remediate contaminated soils. Root colonization by AMF has been shown to enhance phytoremediation efficiency by increasing soil contact and facilitating nutrient exchange (Bhantanaet al., 2021; Kiran and Prasad, 2017b). Bacterial communities such as Bacillus, Rhodococcus, Paenibacillus, Acidovorax, Alcaligenes, Mycobacterium, and Pseudomonas can also enhance phytoremediation. They facilitate metal availability by secreting polysaccharides and extracellular polymers (Zhang et al., 2020). Higher concentrations of heavy metals generally suppress microbial activity; however, certain microorganisms possess metal tolerance mechanisms and facilitate metal bioavailability to plants. By adjusting soil pH, these microbes influence metal solubility and thereby regulate plant uptake (Abdu et al., 2017). In soils, heavy metals exert toxic effects on microbial communities, often resulting in reduced population density and metabolic activity of microbial communities (Mathivanan et al., 2021; Khan et al., 2010).

Nanotechnology in Environmental Restoration-Recent advancements in nanotechnology have demonstrated that the use of engineered nanomaterials (ENMs) can effectively reduce the harmful impact of heavy metals on plant systems (Ahmed et al., 2023; Tripathi et al., 2015a; Tripathi et al., 2015b). Nanomaterials are increasingly recognized as promising agents for remediation due to their high surface area-to-volume ratio, enhanced reactivity, and rapid penetration of contaminated matrices

(Prakash & S. C., 2023). The integration of nanotechnology with phytoremediation—termed nano-phytoremediation—has emerged as a highly effective and synergistic approach for the decontamination of soil and water (Prakash& S. C., 2023). Among biological systems, fungi have shown exceptional tolerance and absorption capacities during nanoparticle synthesis (Adebayo et al., 2021).According to Khan et al. (2020), phytotechnology and nanobiotechnology are among the most promising modern approaches for environmental restoration. Metallic nanoparticles such as silver (AgNPs), gold (AuNPs), titanium dioxide (TiO_2 NPs), zinc oxide (ZnO NPs), and aluminum oxide (Al_2O_3 NPs) are particularly noteworthy for their environmental applications (Ungureanu et al., 2022; Lin and Xing, 2007).Zhang et al. (2005) observed that TiO_2 nanoparticles enhanced plant dry weight, chlorophyll synthesis, photosynthetic rate, enzymatic activities without causing significant toxicity. Similarly, Gao et al. (2006) and reported that TiO_2 increased Rubisco carboxylase activity, while Doshi et al. (2008) demonstrated that aluminum nanoparticles were taken up and translocated in without adverse effects on growth. Conversely, excessive concentrations of certain nanoparticles, such as copper oxide (CuO NPs), can negatively affect plant growth parameters, including biomass and water content (Abdel-Wahab et al., 2019). Elevated CuO NP levels have been shown to increase malondialdehyde (MDA) accumulation, indicating oxidative stress and cellular damage(Abdel-Wahab et al., 2019). Concentrations exceeding 0.2 mg L^{-1} of Cu and CuO nanoparticles can lead to significant physiological and biochemical disruptions in plants (Javed et al., 2017). Recent studies further highlight the role of TiO_2 nanoparticles in enhancing phytoremediation efficiency. For instance, TiO_2 NPs applied at varying concentrations (0, 100, 250, and 500 mg kg^{-1}) have been shown to improve cadmium (Cd) removal efficiency in hyper accumulator species. TiO_2 NPs not only promote plant growth and increase metal tolerance but also enhance chlorophyll content and photosynthetic performance under metal stress (Bakshi & Kumar 2023). Similarly, TiO_2-assisted phytoremediation has been found effective in managing antimony-contaminated soils by facilitating metal absorption, translocation, and accumulation (Zand& Heir2020). The surface of ZnO nanoparticles is frequently functionalized to improve their colloidal stability, enhance their beneficial interactions with plants, and minimize any potential phytotoxic effects (Šebesta et al., 2022). Collectively, these findings demonstrate that nanomaterial-assisted phytoremediation holds immense potential as a sustainable and efficient strategy for remediation of heavy–metal–contaminated environments. ZnO and TiO_2 both NPs, are only toxic at high concentrations (Šebesta et al., 2022)

Conclusion: Heavy metal contamination remains one of the most critical global environmental concerns due to the persistence, bioaccumulation and toxicity of these pollutants. Conventional remediation approaches are widely employed; they frequently degrade soil quality and pose economic challenges to long-term sustainability. Phytoremediation, by contrast, offers an environmentally compatible and cost-effective solution for the decontamination of soils, waters, and sediments. Ricinus communis L. stands out as a promising phytoremediator, combining high biomass yield, stress tolerance, and non-edible oilseed utility with the ability to accumulate or stabilize a wide range of toxic elements and organic pollutants. Its synergistic interactions with metal-tolerant and growth-promoting microorganisms, enhance its remediation capacity, highlighting the significance of plant–microbe partnerships in restoring contaminated environments. The combined application of R. communis, microbial inoculants, and engineered nanomaterials can significantly enhance remediation efficiency, presenting a sustainable and holistic approach for the ecological restoration of contaminated environments.

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