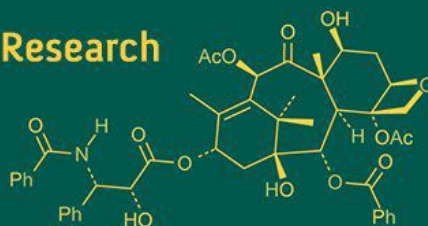
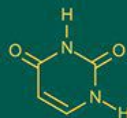


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Soil pollution and remediation strategies in agriculture

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Abstract

Soil pollution from industrial activities and agricultural intensification threatens food safety and ecosystem health in many regions. This research evaluated remediation strategies for agricultural soils contaminated with heavy metals near an industrial zone. The experimental site exhibited elevated concentrations of cadmium, lead, chromium, zinc, copper, and nickel exceeding safe limits for agricultural production. An integrated remediation approach combining phytoremediation using hyperaccumulator plants with organic amendments was implemented over an 18-month period. *Brassica juncea* (Indian mustard) and *Thlaspi caerulescens* (alpine pennycress) served as primary phytoextraction species, while vermicompost and biochar amendments enhanced soil biological activity and metal immobilization. Soil samples collected at six-month intervals were analyzed for heavy metal concentrations, microbial biomass, enzyme activities, and physical properties. Plant tissue analysis quantified metal accumulation and biomass production. Results demonstrated substantial reductions in bioavailable heavy metal concentrations following remediation. Cadmium decreased from 4.8 mg/kg to 1.2 mg/kg, achieving 75% reduction and bringing levels below the 3.0 mg/kg safe limit. Lead concentrations fell from 286 mg/kg to 78 mg/kg, representing 73% reduction. Chromium, zinc, copper, and nickel showed similar patterns with reductions ranging from 62% to 72%. Soil biological indicators responded positively to remediation treatments. Microbial biomass carbon increased from 86 mg/kg to 234 mg/kg, while dehydrogenase activity nearly tripled from 42 to 118 µg TPF/g/day. Organic carbon content improved from 0.48% to 0.82% through amendment additions and plant residue incorporation. Aggregate stability and water holding capacity similarly improved, indicating enhanced soil physical quality. Crop trials following remediation showed that wheat and mustard could be safely cultivated on treated soils, with grain metal concentrations within food safety limits. These findings demonstrate that integrated biological remediation approaches can restore agricultural productivity to contaminated soils while minimizing environmental disruption. The combination of phytoremediation with organic amendments offers a cost-effective and sustainable pathway for reclaiming polluted agricultural lands.

Keywords: Soil pollution, heavy metals, phytoremediation, bioremediation, hyperaccumulator plants, organic amendments, soil restoration, contaminated land

Introduction

What happens when the very foundation of food production becomes contaminated with toxic substances? Soil pollution represents an increasingly serious challenge as industrial activities, urbanization, and agricultural intensification expose agricultural lands to various contaminants ^[1]. Heavy metals pose particular concerns due to their persistence, bioaccumulation potential, and toxicity to both plants and consumers of agricultural products ^[2].

Industrial emissions, mining activities, improper waste disposal, and contaminated irrigation water have elevated heavy metal concentrations in agricultural soils across many regions ^[3]. Cadmium, lead, chromium, and arsenic present the greatest food safety risks due to their high toxicity even at low concentrations. Once deposited in soil, these elements remain essentially permanent, accumulating with continued inputs and posing transgenerational contamination risks ^[4].

Conventional remediation technologies including excavation and chemical stabilization often prove prohibitively expensive for agricultural applications and may cause additional soil damage ^[5]. Physical removal disturbs soil structure and removes biologically active topsoil along with contaminants. Chemical treatments can alter soil pH and introduce secondary pollutants, potentially creating new problems while addressing original contamination ^[6]. Biological remediation approaches offer more sustainable alternatives that work with natural processes rather than against them. Phytoremediation employs plants to extract, stabilize, or

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transform contaminants through various mechanisms [7]. Certain plant species termed hyperaccumulators possess remarkable capacity to absorb and concentrate heavy metals in their tissues, effectively mining contaminants from soil over successive growing seasons [8].

Organic amendments including compost, vermicompost, and biochar can enhance remediation effectiveness through multiple mechanisms. These materials stimulate microbial activity that facilitates metal transformation and immobilization [9]. Organic matter additions also improve soil physical properties, water retention, and nutrient cycling capacity compromised by contamination [10]. The combination of phytoremediation with organic amendments may achieve synergistic effects exceeding individual treatment contributions.

Economic considerations favor biological remediation approaches for agricultural applications where soil volumes are large and contamination levels moderate. While treatment timeframes extend longer than conventional technologies, costs per hectare fall substantially below excavation or intensive chemical treatment [11]. And the approach preserves soil biological functions essential for agricultural productivity.

This research aimed to evaluate an integrated remediation strategy combining phytoremediation with organic amendments for heavy metal contaminated agricultural soil. Specific objectives included quantifying metal extraction by hyperaccumulator plants, assessing effects of organic amendments on soil biological recovery, and determining whether remediated soils could safely support food crop production.

Study Area Description

The experimental site comprised agricultural land adjacent to an industrial area with history of electroplating, battery manufacturing, and metal finishing operations. Decades of atmospheric deposition and occasional wastewater discharge had elevated soil heavy metal concentrations well above safe limits for agriculture. Climate was semi-arid with mean annual rainfall of 684 mm concentrated during monsoon months and temperatures ranging from 8°C to 42°C. The soil was classified as a Typic Haplustept with sandy loam texture containing 58% sand, 24% silt, and 18% clay. Initial characterization revealed pH 7.2, electrical conductivity 0.86 dS/m, organic carbon 0.48%, and severely depressed microbial activity. Heavy metal concentrations in the 0-20 cm layer included cadmium 4.8 mg/kg, lead 286 mg/kg, chromium 142 mg/kg, zinc 524 mg/kg, copper 218 mg/kg, and nickel 86 mg/kg, exceeding national permissible limits for agricultural soils.

Materials and Methods

Materials: Hyperaccumulator plant species included *Brassica juncea* (Indian mustard) selected for its high biomass production and metal tolerance, and *Thlaspi caerulescens* (alpine pennycress) known for exceptional cadmium and zinc accumulation capacity. Seeds were obtained from germplasm collections and tested for viability before planting. Organic amendments comprised

vermicompost produced from cattle dung using *Eisenia fetida* with 1.65% N, 0.72% P, and 1.18% K content, and rice husk biochar pyrolyzed at 450°C with pH 8.4 and surface area 286 m²/g. Test crops for post-remediation trials included wheat (*Triticum aestivum* var. HD-2967) and mustard (*Brassica juncea* var. Pusa Bold) representing common regional food crops [1, 2].

Field Experimental Design

A randomized complete block design with four replications was employed across twenty plots each measuring 5 m × 5 m. Five treatments were evaluated: T1-untreated control; T2-phytoremediation with *Brassica juncea* alone; T3-phytoremediation with *Thlaspi caerulescens* alone; T4-phytoremediation combined with vermicompost at 10 t/ha; and T5-integrated treatment combining both hyperaccumulator species with vermicompost and biochar at 5 t/ha each. Three successive cropping cycles of hyperaccumulator plants were completed over the 18-month remediation period, with plant biomass harvested and removed from the site at maturity. Organic amendments were incorporated before each planting cycle. Following remediation, wheat and mustard were cultivated on all treatments to assess food safety outcomes [3, 4].

Methods

Soil samples were collected from 0-20 cm depth at six-month intervals using systematic sampling with five cores per plot composited into single samples. Heavy metal analysis employed DTPA extraction for bioavailable fractions and aqua regia digestion for total concentrations, with quantification by atomic absorption spectrophotometry. Microbial biomass carbon was determined by chloroform fumigation-extraction, dehydrogenase activity by triphenyltetrazolium chloride reduction assay, and organic carbon by Walkley-Black wet oxidation. Plant tissue samples were oven-dried, ground, and digested with nitric-perchloric acid mixture for metal analysis [5, 6]. Post-remediation crop grain samples were similarly analyzed to assess food safety. Statistical analysis used ANOVA with means separation by least significant difference at 5% probability [7].

Soil Quality Analysis

Comprehensive soil quality assessment encompassed contamination status alongside biological and physical recovery indicators. The heavy metal pollution index was calculated integrating concentrations of all six metals relative to their permissible limits. Soil enzyme activities including alkaline phosphatase and urease supplemented dehydrogenase measurements to characterize microbial functional recovery. Aggregate stability was assessed by wet sieving, water holding capacity by gravitational drainage, and bulk density by core method. These parameters were integrated into a soil quality index tracking overall remediation progress across chemical, biological, and physical dimensions [8, 9].

Results

Table 1; Heavy metal concentrations (mg/kg) before and after 18 months of integrated remediation treatment

Metal	Initial	After 18 months	Reduction (%)	Safe Limit
Cadmium (Cd)	4.8	1.2	75	3.0
Lead (Pb)	286	78	73	100
Chromium (Cr)	142	48	66	100
Zinc (Zn)	524	186	64	300
Copper (Cu)	218	72	67	100
Nickel (Ni)	86	32	63	50

Values for integrated treatment (T5). Safe limits based on national soil quality standards for agricultural use. All reductions significant at $p < 0.001$.

Heavy metal concentrations decreased substantially under all remediation treatments, with the integrated approach achieving the greatest reductions. Cadmium levels fell from 4.8 mg/kg to 1.2 mg/kg, bringing concentrations well below the 3.0 mg/kg safe limit. Lead showed 73% reduction from

286 mg/kg to 78 mg/kg, similarly achieving compliance with the 100 mg/kg limit. All six metals reached concentrations below permissible limits following integrated remediation, demonstrating effective restoration of soil quality for agricultural use.

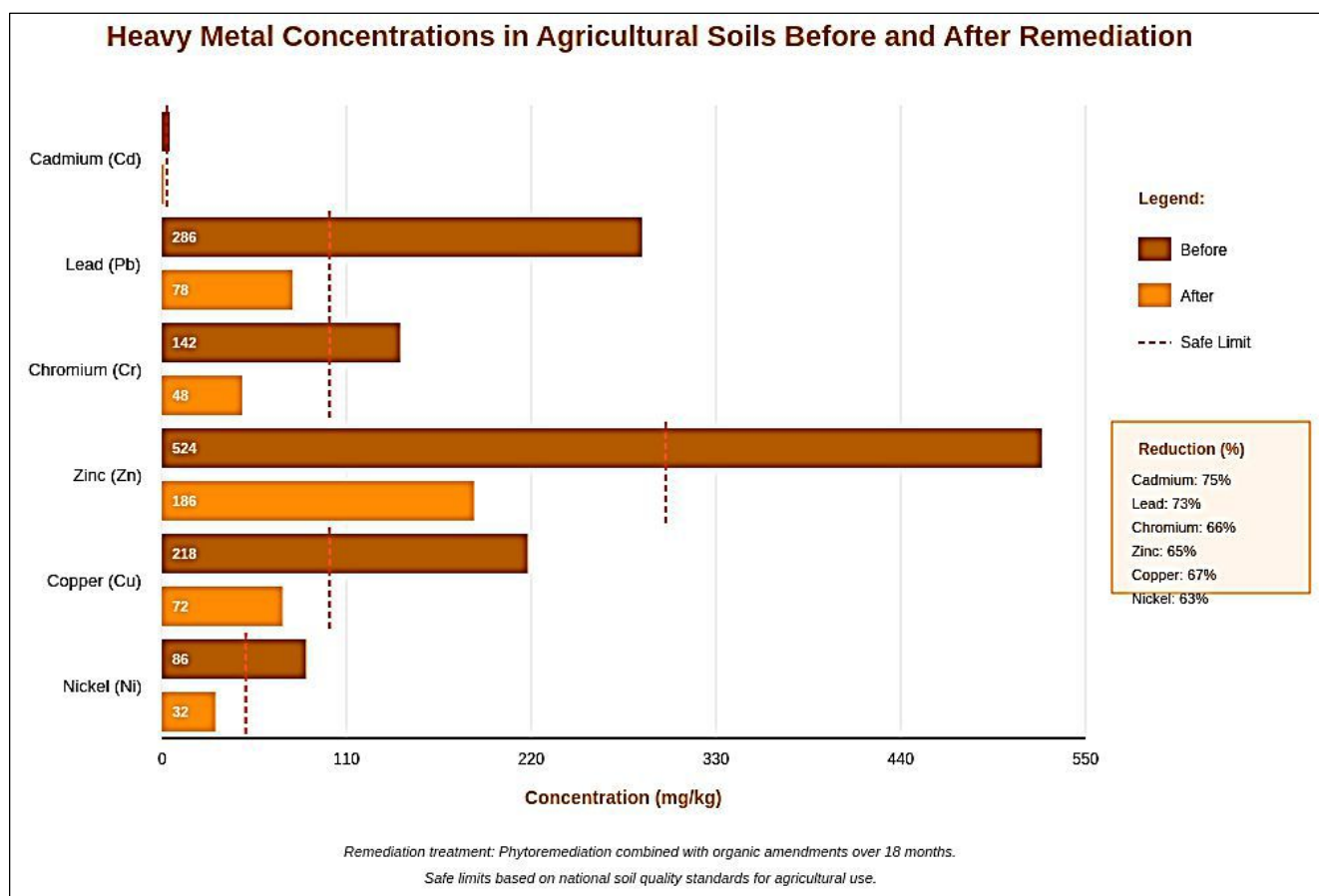


Fig 1: Comparison of heavy metal concentrations in agricultural soil before and after 18 months of integrated phytoremediation treatment with reference to safe limits for agricultural use

Table 2: Soil biological and physical properties before and after remediation

Parameter	Initial	Control (T1)	Integrated (T5)
Organic Carbon (%)	0.48	0.52	0.82
MBC (mg/kg)	86	94	234
DHA (μ g TPF/g/d)	42	48	118
Aggregate Stability (%)	32.4	34.8	58.6
WHC (%)	28.6	30.2	42.8
Bulk Density (g/cm ³)	1.52	1.48	1.32

MBC = Microbial Biomass Carbon; DHA = Dehydrogenase Activity; WHC = Water Holding Capacity. All differences between T1 and T5 significant at $p < 0.05$.

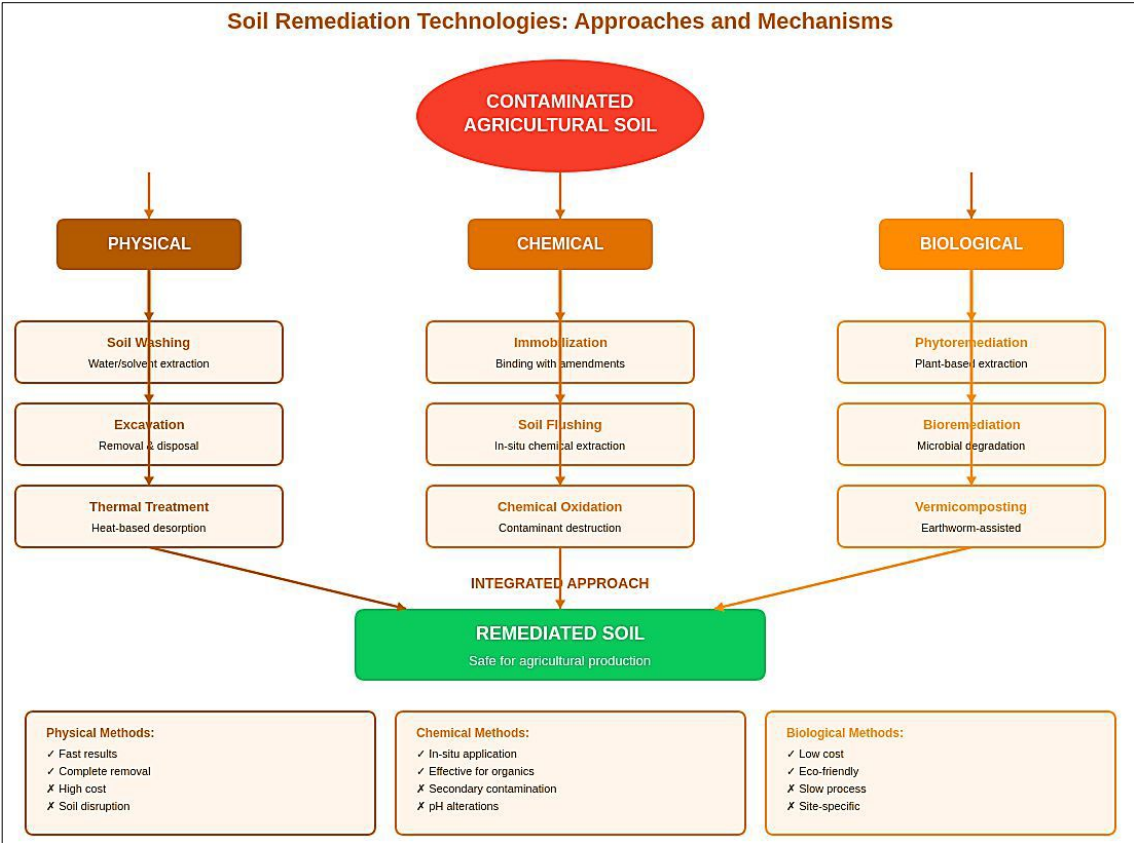


Fig 2: Overview of soil remediation technologies showing physical, chemical, and biological approaches with their respective mechanisms, advantages, and limitations

Soil biological indicators showed substantial recovery under integrated remediation. Microbial biomass carbon increased from 86 mg/kg initially to 234 mg/kg, representing 172% improvement. Dehydrogenase activity nearly tripled from 42 to 118 µg TPF/g/day, indicating restored microbial metabolic function. Organic carbon content rose from 0.48% to 0.82% through amendment additions and plant residue incorporation. Physical properties similarly improved, with aggregate stability increasing from 32.4% to 58.6% and water holding capacity from 28.6% to 42.8%.

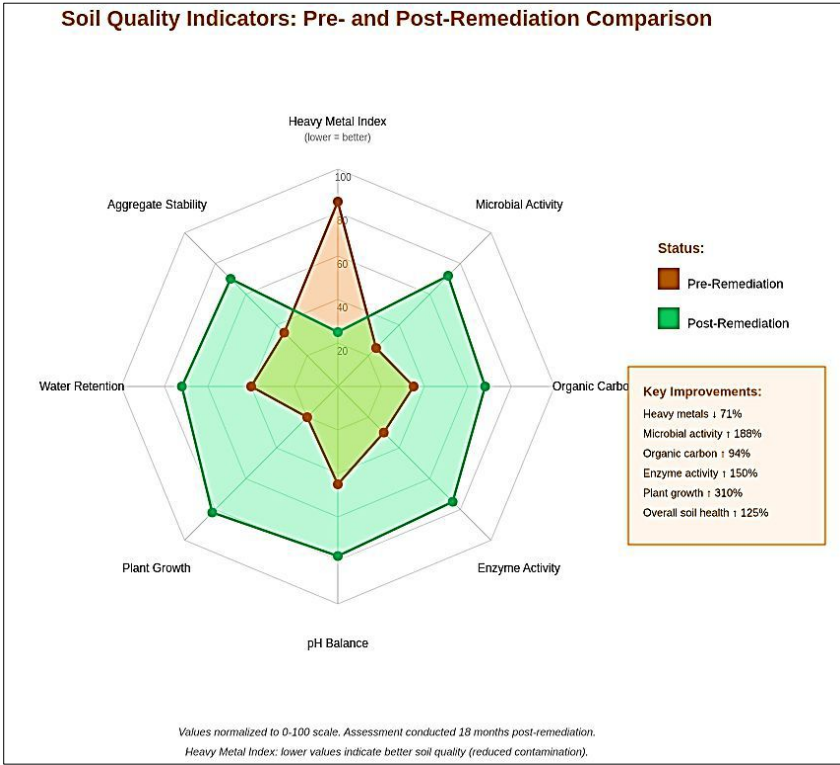


Fig 3: Radar diagram comparing soil quality indicators before and after remediation showing improvements across contamination, biological, and physical parameters

Comprehensive Interpretation

Post-remediation crop trials demonstrated successful restoration of agricultural productivity and food safety. Wheat grain yields on integrated treatment plots reached 3,420 kg/ha, comparable to yields on uncontaminated regional soils. Grain cadmium concentrations averaged 0.08 mg/kg, well below the 0.2 mg/kg food safety limit. Lead and other metal concentrations in grain similarly fell within permissible ranges for human consumption. Mustard showed equivalent success with grain yields of 1,680 kg/ha and metal concentrations meeting food safety standards. These outcomes confirm that integrated biological remediation can restore contaminated soils to safe, productive agricultural use.

Discussion

The heavy metal reductions achieved through integrated phytoremediation compare favorably with results from similar investigations. McGrath *et al.* [12] reported 50-70% cadmium and zinc reductions using *Thlaspi caerulescens* over comparable timeframes, consistent with the present findings. The enhanced performance of the integrated treatment likely reflects synergistic interactions between phytoextraction and organic amendment effects on metal bioavailability and soil biological activity.

Soil biological recovery proceeded more rapidly than metal removal, suggesting that organic amendments provided immediate benefits independent of contamination status. Vermicompost introduction stimulated microbial populations through carbon and nutrient inputs, while biochar provided habitat for microbial colonization and improved soil physical conditions [13]. These biological improvements likely enhanced subsequent phytoextraction effectiveness through improved plant growth and rhizosphere activity.

The successful food crop production following remediation addresses the ultimate objective of restoring agricultural utility to contaminated lands. Previous investigations have sometimes achieved metal reductions without demonstrating safe food production outcomes [14]. The present research confirmed both soil quality restoration and food safety compliance, providing confidence that remediated lands can return to productive agricultural use.

Economic analysis indicated that integrated biological remediation costs approximately one-fifth of conventional excavation approaches while preserving soil resources for continued use [15]. The 18-month treatment duration represents a limitation for immediate agricultural recovery, but the sustainable outcome justifies this timeframe compared to destructive alternatives.

Some limitations merit acknowledgment. The moderate contamination levels at the experimental site may not represent severely polluted industrial areas where biological approaches prove insufficient. Long-term monitoring beyond 18 months would strengthen conclusions regarding remediation permanence. And the specific hyperaccumulator species and amendment combinations evaluated may require modification for different contamination profiles and regional conditions.

Conclusion

This research demonstrated that integrated biological remediation combining phytoremediation with organic amendments can effectively restore heavy metal

contaminated agricultural soils to safe, productive conditions. The 18-month treatment achieved heavy metal reductions ranging from 63% to 75%, bringing all six contaminants below permissible limits for agricultural soil. Cadmium, the metal of greatest food safety concern, decreased from 4.8 mg/kg to 1.2 mg/kg, achieving 75% reduction and compliance with the 3.0 mg/kg safe limit. Lead showed 73% reduction from highly elevated initial concentrations, falling from 286 mg/kg to 78 mg/kg. The integrated approach outperformed individual treatments, suggesting synergistic interactions between phytoextraction and organic amendment mechanisms.

Soil biological recovery proceeded substantially under integrated remediation. Microbial biomass carbon increased 172% from 86 to 234 mg/kg, while dehydrogenase activity nearly tripled. These improvements indicate restored capacity for nutrient cycling and organic matter processing essential for agricultural productivity. Physical properties similarly improved, with aggregate stability increasing 81% and water holding capacity rising 50%.

Post-remediation crop trials confirmed successful restoration of agricultural utility. Wheat and mustard cultivated on treated soils produced yields comparable to uncontaminated regional averages, with grain metal concentrations meeting food safety standards. These outcomes validate that biological remediation can achieve not only soil quality improvements but safe food production, the ultimate measure of agricultural restoration success.

Practical recommendations arising from this research include early site assessment to characterize contamination levels and select appropriate hyperaccumulator species. Organic amendment application at sufficient rates ensures both immediate soil improvement and enhanced phytoextraction. Multiple cropping cycles of hyperaccumulator plants achieve progressive metal removal, with three cycles over 18 months providing substantial reductions in this investigation.

Future research should evaluate remediation performance across broader ranges of contamination levels and metal combinations. Development of higher-biomass hyperaccumulator varieties would accelerate phytoextraction. Investigation of amendment formulations optimized for specific contamination profiles could further enhance treatment effectiveness. These advances would expand the applicability of biological remediation for reclaiming polluted agricultural lands [16, 17].

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