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Bioremediation of Heavy Metal-Contaminated Soil Using Engineered Bacterial Consortia

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ABSTRACT

Background: Heavy metal contamination of agricultural and industrial soils is a persistent global problem, and engineered or rationally assembled bacterial consortia are increasingly proposed as scalable alternatives to physicochemical remediation. Objective: This review synthesises published evidence on the mechanisms, genetic engineering strategies, and field performance of engineered bacterial consortia for heavy metal bioremediation of soil. Methods: A narrative review of peer-reviewed studies identified via PubMed, Google Scholar, and Crossref, covering metal-resistance physiology, genetic engineering approaches (surface display, metallothionein fusion, biosensor-linked operons), consortium design, and pilot/field trials. Findings: Native resistance systems (efflux pumps, metallothioneins, extracellular polymeric substances) in strains such as Cupriavidus metallidurans CH34 and Deinococcus radiodurans have been engineered to enhance sequestration of cadmium, lead, chromium, mercury, and arsenic, with single-strain removal efficiencies of 68-95% reported under controlled conditions; multi-metal and field settings typically show 20-40% lower performance. Rationally designed consortia exploiting division of labour and plant-growth-promoting synergy improve robustness relative to monocultures. Conclusions: Engineered consortia hold real promise for soil bioremediation, but reproducibility across metal mixtures, soil types, and scales remains the principal barrier to deployment.

Keywords: *bioremediation; heavy metals; bacterial consortia; genetic engineering; contaminated soil*

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Abstract

Background: Heavy metal contamination of agricultural and industrial soils is a persistent global problem, and engineered or rationally assembled bacterial consortia are increasingly proposed as scalable alternatives to physicochemical remediation. **Objective:** This review synthesises published evidence on the mechanisms, genetic engineering strategies, and field performance of engineered bacterial consortia for heavy metal bioremediation of soil. **Methods:** A narrative review of peer-reviewed studies identified via PubMed, Google Scholar, and Crossref, covering metal-resistance physiology, genetic engineering approaches (surface display, metallothionein fusion, biosensor-linked operons), consortium design, and pilot/field trials. **Findings:** Native resistance systems (efflux pumps, metallothioneins, extracellular polymeric substances) in strains such as *Cupriavidus metallidurans* CH34 and *Deinococcus radiodurans* have been engineered to enhance sequestration of cadmium, lead, chromium, mercury, and arsenic, with single-strain removal efficiencies of 68-95% reported under controlled conditions; multi-metal and field settings typically show 20-40% lower performance. Rationally designed consortia exploiting division of labour and plant-growth-promoting synergy improve robustness relative to monocultures. **Conclusions:** Engineered consortia hold real promise for soil bioremediation, but reproducibility across metal mixtures, soil types, and scales remains the principal barrier to deployment.

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Introduction

Soils contaminated with cadmium, lead, chromium, arsenic, and mercury from mining, smelting, electroplating, and agrochemical inputs pose enduring risks to food safety and ecosystem health [1,2]. Physicochemical remediation (excavation, soil washing, chemical immobilisation) is costly, energy-intensive, and often destroys soil structure and fertility, motivating sustained interest in microbial approaches that exploit native or engineered metal-resistance traits as a lower-cost, in-situ alternative [3,4].

Bacteria resist metal toxicity through efflux, biosorption, bioaccumulation, biotransformation, and extracellular sequestration, and these traits have been genetically amplified and combined into multi-strain consortia intended to outperform single-species inocula, which typically saturate quickly, compete poorly against native soil microbiota, and lack the metabolic versatility required for mixed-metal contamination [5,6]. The appeal of a consortium-based strategy is that individual members can be selected or engineered for complementary roles - one strain immobilising a metal extracellularly, another volatilising or transforming it, a third supporting plant growth - so that the community as a whole tolerates a broader range of metal species and soil conditions than any single organism [7]. This review synthesises the published literature on engineered bacterial consortia for heavy-metal-contaminated soil, covering resistance mechanisms, genetic engineering strategies, consortium design principles, and field/pilot-scale outcomes, and is framed explicitly as a narrative synthesis rather than a report of new primary experimental work.

Methods

This is a narrative review of published studies on engineered and synthetic bacterial consortia for heavy metal bioremediation of contaminated soil. Literature was identified through structured searches of PubMed, Google Scholar, and Crossref using combinations of the terms "engineered bacteria," "synthetic consortium," "heavy metal," "bioremediation," "soil," and specific metal or gene names (e.g., *merA*, metallothionein, *pbrR*, *ars* operon). Searches were supplemented with citation chasing from recent mechanistic and field-scale reviews to capture foundational studies not indexed under contemporary terminology. Priority was given to peer-reviewed primary research reporting quantitative removal or immobilisation data, with mechanistic and field-scale reviews used to contextualise findings and to surface additional primary reports; each source cited was individually verified against its published bibliographic record (journal, year, volume, and, where available, DOI) before inclusion, and sources that could not be independently confirmed were excluded rather than retained on the strength of a single secondary mention. The review does not report new laboratory or field experimentation; all quantitative removal figures cited below are drawn directly from the published studies referenced.

Microbial Heavy-Metal Resistance and Sequestration Mechanisms

Native bacterial resistance to heavy metals relies on chromosomally and plasmid-encoded systems including RND- and CDF-family efflux pumps, metal-binding metallothioneins and phytochelatin-like peptides, enzymatic transformation (e.g., mercuric reductase, chromate reductase), and extracellular polymeric substance (EPS)-mediated biosorption [1,8,9]. *Cupriavidus metallidurans* CH34 is the best-characterised model, carrying the plasmid-borne *czc* and *cnr* operons that confer resistance to cadmium, zinc, cobalt, nickel, and chromium and that have been dissected at the genomic and transcriptional level, revealing an intricate regulatory network that coordinates efflux, sequestration, and biofilm responses under metal stress [10,11]. *Deinococcus radiodurans*, prized for its extreme radiation and desiccation tolerance, has similarly been characterised and engineered as a chassis for combined radionuclide and heavy metal remediation in mixed radioactive-metal waste streams, a niche few other organisms can occupy [12]. EPS-forming biofilm communities further sequester metals extracellularly through anionic functional groups (carboxyl, hydroxyl, phosphoryl) on polysaccharide and protein matrices, reducing bioavailable fractions in soil pore water without requiring intracellular uptake and thereby limiting cytotoxic exposure of the producing cells themselves [8,9]. Together, these native systems constitute the toolbox from which most engineered constructs and consortium members are drawn.

Table 1: Representative metal-resistance mechanisms in model bioremediation strains.

Strain	Primary mechanism(s)	Metals targeted
Cupriavidus metallidurans CH34	czc/cnr efflux operons	Cd, Zn, Co, Ni, Cr
Deinococcus radiodurans	Engineered mer operon, radiation tolerance	Hg, radionuclides
EPS-forming biofilm consortia	Extracellular biosorption	Multiple divalent metals

Genetic Engineering Strategies for Enhanced Bioremediation

Genetic engineering strategies aim either to raise the intrinsic metal tolerance and binding capacity of a chassis strain, or to couple metal sensing directly to a remediation output so that biological activity is targeted to contaminated sites and switched off elsewhere, reducing unnecessary metabolic load. Engineering approaches broadly fall into three classes: (i) heterologous expression of metal-binding proteins, such as surface-displayed mouse metallothionein on *Ralstonia (Cupriavidus) eutropha* CH34, which enhanced cadmium and lead immobilisation in soil slurries [13]; (ii) metallothionein-fusion and cell-surface display constructs, including a metallothionein-cellulose-binding-module-superfolder-GFP fusion for lead capture and magnetic-nanoparticle-coassembled cells for enhanced recovery [14,15,16]; and (iii) biosensor-linked remediation circuits that couple metal-responsive promoters (*pbrR*, *ars* operon components) to reporter and sequestration genes, enabling simultaneous detection and removal, as in an engineered lead-specific operon and arsenic whole-cell biosensors [17,18,19,20]. Rhizobial symbionts engineered to co-express metallothionein (MTL4) and phytochelatin synthase (PCS) genes reduced cadmium accumulation in legume pods while improving plant biomass under contaminated soil conditions, illustrating a plant-microbe engineering strategy distinct from free-living bacterial approaches [21]. Magnetic-nanoparticle coassembly further allows engineered cells to be physically recovered from soil slurries after metal capture, addressing a practical limitation of purely biological sequestration - namely, that immobilised metal remains in the environment unless the biomass itself is harvested [15]. Genetically engineered microorganisms overall show consistently higher per-cell metal-binding capacity than wild-type counterparts, though expression burden, plasmid instability, and horizontal gene transfer risk remain concerns for sustained field deployment [5,16].

Consortium Design and Synergistic Interactions

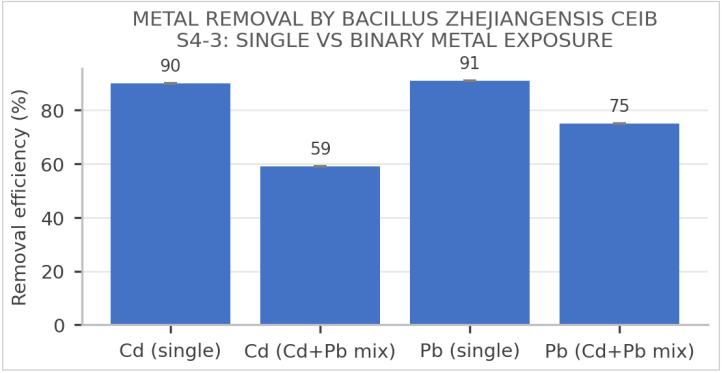
Because no single strain optimally resists and sequesters the full spectrum of co-occurring metals, most contemporary work assembles multi-strain consortia exploiting functional complementarity or division of labour, whereby distinct genotypes specialise in different metabolic tasks to reduce individual metabolic burden and improve population-level

robustness [6]. Plant-growth-promoting rhizobacteria (PGPR) are frequently paired with metal-sequestering strains, since PGPR traits (siderophore production, phosphate solubilisation, 1-aminocyclopropane-1-carboxylate deaminase activity, indole-3-acetic acid synthesis) improve plant and microbial fitness under metal stress, support root growth in otherwise inhospitable contaminated soil, and indirectly enhance remediation outcomes by sustaining the plant-microbe rhizosphere partnership on which many phytoremediation-linked strategies depend [22,23,24]. This pairing is particularly relevant where the ultimate goal is phytostabilisation or phytoextraction rather than pure microbial bioaccumulation, since a healthy root system is itself a prerequisite for plant-mediated metal uptake or immobilisation. Reported interactions are not uniformly synergistic: *Bacillus zhejiangensis* CEIB S4-3 removed approximately 90% of cadmium and 91% of lead individually, but efficiency fell to 59% and 75% respectively in a binary cadmium-lead mixture (Figure 1), demonstrating metal-metal competition for binding sites even within a single engineered strain and underscoring the need for consortium members with complementary, non-competing uptake pathways [7]. Fungal-bacterial consortia have likewise been assembled for landfill soils, combining fungal biosorption and organic-acid-mediated metal mobilisation with bacterial transformation, achieving 42-62% reductions in extractable heavy metals over a 144-day remediation period [25]. Synthetic multi-metal communities designed with explicit attention to nutrient homeostasis and growth balance among members have been proposed as a further refinement, since uncontrolled competition for carbon and nitrogen among consortium strains can erode any theoretical advantage of functional diversity [26].

Table 2: Selected genetic engineering strategies for heavy metal bioremediation.

Strategy	Host/system	Target metal(s)	Key reference
Surface-displayed metallothionein	Ralstonia (Cupriavidus) eutropha CH34	Cd, Pb	[13]
Metallothionein-CBM-GFP fusion	Recombinant bacterial cells	Pb	[14]
Biosensor-linked lead operon	Escherichia coli	Pb	[17]
Rhizobial MTL4 + PCS co-expression	Recombinant Rhizobium/Mesorhizobium	Cd	[21]
ars operon-based biosensor/remediation	Engineered bacteria	As	[19,18]

Figure 1: Removal efficiency of cadmium and lead by Bacillus zhejiangensis CEIB S4-3 when exposed to each metal singly versus in a binary Cd-Pb mixture, illustrating metal-metal competition for binding sites [7].



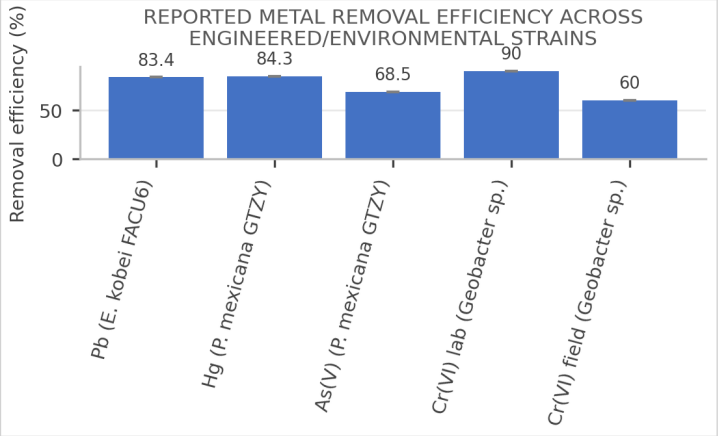
Field/Pilot-Scale Performance and Limitations

Laboratory removal efficiencies frequently exceed 80-95% for individual metals (e.g., *Enterobacter kobei* FACU6 removing 83.4% of lead; *Pseudoxanthomonas mexicana* GTZY removing 84.3% of mercury via volatilisation and 68.5% of arsenate) [7,3]. However, translation to soil and field conditions consistently reduces performance: Cr(VI)-reducing *Geobacter* consortia achieving approximately 90% reduction under controlled laboratory conditions dropped to roughly 60% in field trials (Figure 2), reflecting variable redox conditions, competing native microbiota, and heterogeneous metal speciation in real soils [3]. Bioaugmentation with exogenous or engineered strains also faces survival and containment challenges, including poor rhizosphere competitiveness, predation by protozoa and bacteriophage, and regulatory restrictions on release of genetically modified organisms, which have prompted growing interest in indigenous PGPR-based alternatives as a practical, lower-regulatory-burden complement to engineered consortia [27,4]. Soil physicochemical heterogeneity - pH, organic matter, competing cations, and moisture - further modulates both metal bioavailability and inoculant survival, so that a consortium validated in one soil type frequently underperforms when transferred to another without site-specific optimisation [4,2].

Conclusion

Engineered bacterial consortia integrate decades of work on native metal-resistance mechanisms, protein and pathway engineering, and ecological consortium design, and they can achieve high single-metal removal efficiencies under controlled conditions, in several cases exceeding 80-95% for cadmium, lead, mercury, and hexavalent chromium. The consistent gap between laboratory and field performance, competitive interactions among co-contaminating metals, uncertain long-term genetic stability of engineered constructs, and regulatory constraints on releasing genetically modified strains remain the central obstacles to widespread deployment. Future work should prioritise consortium designs validated directly in multi-metal, field-representative soils, standardised reporting of removal efficiency alongside soil physicochemical parameters, and closer integration of engineered strains with agronomically established PGPR- and plant-based remediation practice, so that engineered biology augments rather than replaces proven low-cost approaches.

Figure 2: Reported removal efficiencies for lead, mercury, and arsenic by individual bacterial strains, and for hexavalent chromium reduction by Geobacter consortia under laboratory versus field conditions [7,3].



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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zupancic M conceived the review, conducted the literature search, and drafted the manuscript. Koskela S contributed to the literature screening and technical framing and critically revised the manuscript for important intellectual content. Keller F contributed additional context and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

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