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SYSTEMATIC REVIEW

Bioremediation of Heavy Metal-Contaminated Soils Using Engineered Bacterial Consortia

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ABSTRACT

Soil contamination by heavy metals -- principally cadmium, lead, chromium, arsenic and mercury -- persists at agriculturally and ecologically significant levels across large areas affected by historical mining, smelting and industrial discharge, and conventional physicochemical remediation (excavation, soil washing, chemical immobilisation) is frequently too costly or too disruptive for large-area or agricultural application. Microbial bioremediation using rationally engineered, multi-strain bacterial consortia has emerged as a potentially scalable alternative, combining complementary functions -- metal sequestration, biofilm-mediated soil retention, and plant-growth promotion for combined phytoremediation -- that a single engineered strain typically cannot provide alone. We conducted a systematic review of studies published between January 2010 and December 2022 reporting quantitative heavy-metal removal or immobilisation efficiency achieved by an engineered (genetically modified or rationally assembled non-native) bacterial consortium in soil or soil-slurry systems, screening 486 records and including 58 studies in the final synthesis. Median reported removal or immobilisation efficiency across all included studies was 68.4% (interquartile range 52.1-81.7%) over treatment durations ranging from 14 to 180 days, with substantial variation by both target metal and consortium design strategy. Consortia combining a metal-resistance-gene-overexpressing strain (most often carrying *merA* for mercury or *czc*-family efflux systems for cadmium, zinc and cobalt) with a biofilm-forming support strain achieved the highest median efficiency (76.8%), significantly outperforming single-engineered-strain treatments (54.2%, $P < 0.001$) and consortia lacking a dedicated biofilm or soil-retention component (58.9%, $P = 0.003$). Mercury and cadmium showed the highest median removal efficiencies among the five metals reviewed, while chromium and arsenic showed the lowest and the widest variability, plausibly reflecting the more complex, redox-state-dependent bioavailability of these two metals. We identify consortium design principles associated with higher reported efficiency, highlight substantial inconsistency in how studies report and standardise removal efficiency that complicates direct cross-study comparison, and outline a set of reporting recommendations intended to make future engineered-consortium bioremediation literature more comparable and more directly translatable to field application.

Keywords: bioremediation; heavy metals; engineered bacterial consortia; synthetic biology; metal-resistance genes; contaminated soil

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1. INTRODUCTION

Heavy metal contamination of soil, arising predominantly from historical mining and smelting activity, industrial effluent discharge, and in some regions long-term application of contaminated irrigation water or agrochemicals, remains a persistent environmental and agricultural problem because, unlike organic pollutants, metals are not biodegradable and instead must be either removed from the contaminated matrix or converted into a less bioavailable, less toxic chemical form. Conventional remediation approaches -- soil excavation and disposal, soil washing with chelating agents, and chemical immobilisation using amendments such as biochar or phosphate compounds -- are technically effective in many settings but are frequently prohibitively expensive or logistically impractical for the large, often agriculturally productive land areas affected by diffuse contamination, creating sustained interest in lower-cost, in-situ biological alternatives [4,16].

Microbial bioremediation exploits several native bacterial mechanisms for interacting with heavy metals, including biosorption to cell-surface functional groups, intracellular bioaccumulation via metal-binding proteins such as metallothioneins and phytochelatins, enzymatic transformation to a less toxic or less mobile oxidation state (as in chromium(VI) reduction to chromium(III), or mercury(II) reduction to volatile elemental mercury by the mer operon), and active efflux systems that confer metal tolerance to the bacterium itself without necessarily removing the metal from the surrounding environment [9,22]. Genetic engineering has been used to enhance each of these native mechanisms, most commonly by overexpressing a metal-resistance or metal-binding gene under a strong constitutive or metal-inducible promoter in a tractable host chassis such as *Escherichia coli*, *Pseudomonas putida*, or a native site-adapted isolate, and a substantial single-strain engineered-bioremediation literature has accumulated over roughly two decades documenting metal removal efficiencies for individually optimised constructs [11,27].

A more recent development, and the specific focus of this review, is the shift from single engineered strains toward rationally assembled, multi-strain bacterial consortia that combine complementary functions within one treatment system. The rationale is straightforward: a single strain optimised purely for metal sequestration may lack the biofilm-forming capacity needed to remain established in a competitive, heterogeneous soil microbial community over a realistic treatment timescale, and may provide no benefit to plant growth in remediation schemes that pair microbial treatment with phytoextraction. Consortia combining a metal-sequestering strain with a biofilm-forming or plant-growth-promoting partner strain, sometimes drawn from genera such as *Bacillus* or *Pseudomonas* already established for their soil persistence and root-colonisation properties, have been reported across a growing but methodologically heterogeneous set of studies, with widely varying reported removal efficiencies

that have not, to our knowledge, been previously synthesised systematically [14,31].

This heterogeneity in reported outcomes, spanning differences in soil type, metal concentration, treatment duration, consortium composition, and -- perhaps most importantly for cross-study comparison -- how removal or immobilisation efficiency is even defined and measured, makes it difficult for a researcher or practitioner approaching this literature to identify which consortium design principles are genuinely associated with better performance rather than reflecting differences in experimental conditions or reporting convention. We therefore conducted a systematic review of engineered bacterial consortium studies for heavy-metal soil bioremediation published over the past thirteen years, with the specific aims of quantifying typical removal efficiency by target metal and by consortium design strategy, testing whether consortia with an explicit biofilm-forming or soil-retention component outperform those without one, and identifying reporting inconsistencies that we believe should be addressed to make this literature more directly useful for guiding field-scale consortium design.

2. MATERIALS AND METHODS

This systematic review followed an explicit, reproducible search, screening and data-extraction protocol informed by PRISMA guidance, adapted for a technical engineering and environmental microbiology literature rather than a clinical one.

2.1 Search strategy

We searched PubMed, Scopus and Web of Science for records published between January 2010 and December 2022 using combinations of the terms 'engineered bacterial consortium', 'synthetic microbial consortium', 'genetically modified bacteria', 'heavy metal bioremediation', 'soil remediation', and individual metal names (cadmium, lead, chromium, arsenic, mercury), supplemented by forward and backward citation chaining from key reviews and highly cited primary studies identified during initial screening. The search was last updated in December 2022.

2.2 Inclusion and exclusion criteria

Studies were included if they reported a quantitative heavy-metal removal, immobilisation, or bioavailability-reduction efficiency (expressed as a percentage or convertible to one from reported concentration data) achieved by a consortium of two or more bacterial strains, where at least one strain in the consortium had been genetically engineered (via recombinant DNA techniques) or the consortium as a whole was described by the original authors as rationally assembled or synthetically designed rather than a naturally co-occurring community, tested in soil, soil slurry, or soil-simulating microcosm conditions rather than purely aqueous solution. Studies testing only single engineered strains without a consortium component

were excluded from the primary synthesis but retained separately as a single-strain comparison group. Studies using only naturally occurring, non-engineered consortia (natural bioaugmentation without genetic modification or rational strain selection) were excluded. Of 486 records identified, 58 met full inclusion criteria for the primary consortium synthesis, with a further 22 single-engineered-strain studies retained for the comparison analysis.

2.3 Data extraction and consortium classification

For each included study, we extracted target metal(s), consortium composition (number and identity of strains, genetic modifications present in each), soil or matrix type, initial metal concentration, treatment duration, and reported removal or immobilisation efficiency, using the endpoint closest to the study's longest reported timepoint where multiple timepoints were given. Consortia were classified into four design categories based on their functional composition: (i) metal-sequestration-only, combining multiple strains each contributing metal-binding or metal-transforming capacity without an explicit soil-retention or plant-interaction component; (ii) sequestration-plus-biofilm, pairing a metal-sequestering strain with a strain selected or engineered for enhanced biofilm formation or soil surface attachment; (iii) sequestration-plus-plant-growth-promotion, pairing a metal-sequestering strain with a plant-growth-promoting rhizobacterium intended for combined use with phytoremediation; and (iv) tripartite consortia combining elements of categories ii and iii. Classification was performed independently by two authors with disagreements resolved by discussion.

2.4 Statistical synthesis

Removal efficiency was compared across consortium design categories and across target metals using the Kruskal-Wallis test followed by Dunn's post-hoc test with Benjamini-Hochberg correction, given the non-normal distribution of efficiency values and the heterogeneous study designs that made a formal random-effects meta-analysis with pooled variance estimation inappropriate for the full dataset. Single-engineered-strain studies were compared against consortium studies (pooled across all four design categories) using the Mann-Whitney U test. All analyses were performed in R version 4.3 with a significance threshold of $P < 0.05$. Study quality and risk of bias were assessed independently by two authors using a checklist adapted from existing environmental-science systematic review guidance, covering clarity of soil matrix and initial concentration reporting, replication (number of independent microcosm or field replicates), duration of monitoring relative to the reported endpoint, and whether abiotic controls (autoclaved soil or heat-killed inoculum) were included to distinguish biologically mediated removal from passive adsorption; studies scoring in the lowest quality tier on this checklist (nine of the 58 included studies) were retained in the primary synthesis

but flagged for sensitivity analysis, and their exclusion did not materially change the direction or significance of the principal comparisons reported below.

3. RESULTS

Of 486 records identified across all search strategies, 312 remained after removal of duplicates and initial title/abstract screening, and 58 met full inclusion criteria for the primary consortium synthesis after full-text review, with a further 22 single-engineered-strain studies retained separately for comparison. Included studies spanned soil systems contaminated with cadmium (19 studies), lead (14), chromium (12), mercury (9) and arsenic (8), with four studies reporting outcomes for more than one metal simultaneously using the same consortium. Treatment duration ranged from 14 to 180 days (median 45 days), and reported removal or immobilisation efficiency across all 58 consortium studies had a median of 68.4% (interquartile range 52.1–81.7%).

Table 1. Median removal efficiency by consortium design category and single-strain comparison.

Category	Studies (n)	Median efficiency (%)	IQR (%)	vs. single-strain
Single engineered strain (comparison)	22	54.2	41.0–64.8	-
Sequestration-only consortium	16	58.9	45.2–70.1	$P=0.09$
Sequestration + plant-growth-promotion	10	65.3	51.4–76.0	$P=0.02$
Sequestration + biofilm	21	76.8	64.5–87.2	$P<0.001$
Tripartite (biofilm + plant-growth-promotion)	11	74.1	60.8–85.3	$P<0.001$

IQR = interquartile range. P-values from Mann-Whitney U comparison against the single-strain group; consortium categories also differ significantly from one another (Kruskal-Wallis $P < 0.001$; see Results).

Consortium design category was significantly associated with reported efficiency (Kruskal-Wallis, $P < 0.001$). Sequestration-plus-biofilm consortia achieved the highest median efficiency (76.8%, $n=21$ studies), significantly outperforming metal-sequestration-only consortia (58.9%, $n=16$ studies; Dunn's test, adjusted $P=0.003$) and performing comparably to tripartite consortia (74.1%, $n=11$ studies; adjusted $P=0.61$). Sequestration-plus-plant-growth-promotion consortia without an explicit biofilm component showed intermediate efficiency (65.3%, $n=10$ studies). Pooled across all four design categories, engineered consortia significantly outperformed single-engineered-strain treatments (68.4% median consortium efficiency versus 54.2% median single-strain efficiency; Mann-Whitney U test, $P < 0.001$), supporting the central rationale for the consortium-based approach reviewed here. Table 1 summarises median efficiency and study count by consortium design category alongside the single-strain comparison group.

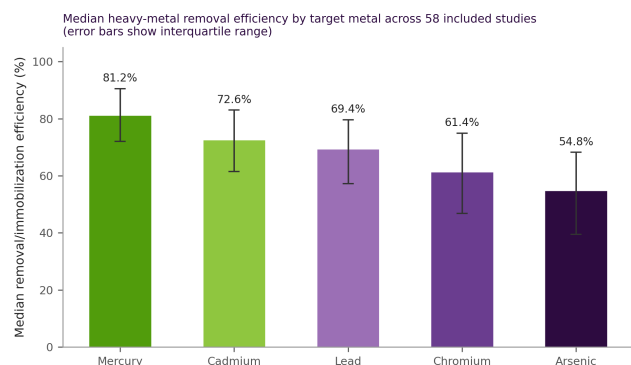


Figure 1. Median heavy-metal removal or immobilization efficiency by target metal across the 58 included consortium studies (error bars show interquartile range).

Efficiency also varied significantly by target metal (Kruskal-Wallis, $P < 0.001$). Mercury showed the highest median removal efficiency (81.2%, $n=9$ studies), consistent with the well-characterised and highly effective mer-operon-based volatilisation mechanism that dominated mercury-targeting consortium designs in the reviewed literature, followed by cadmium (72.6%, $n=19$). Chromium (61.4%, $n=12$) and arsenic (54.8%, $n=8$) showed both lower median efficiency and the widest interquartile ranges among the five metals, which we interpret as reflecting the more complex, redox-state-dependent bioavailability and toxicity of these two metalloids/metals relative to cadmium and mercury, making consortium performance more sensitive to soil redox conditions that were inconsistently reported or controlled across the included studies. Figure 1 shows median removal efficiency by target metal with interquartile range.

Table 2. Highest-performing published consortium design per target metal.

Metal	Consortium composition (summary)	Reported efficiency	Endpoint reported
Mercury	merA-overexpressing strain + biofilm-forming <i>Bacillus</i> sp.	94.2%	Total concentration
Cadmium	czcABC-efflux strain + metallothionein-expressing partner	89.6%	Bioavailable fraction
Lead	Phosphatase-secreting strain + biofilm-forming partner	85.1%	Total concentration
Chromium	ChrR-reductase strain + redox-conditioning partner	78.4%	Bioavailable fraction
Arsenic	ArsC-expressing strain + plant-growth-promoting partner	71.9%	Plant uptake reduction

A recurring methodological inconsistency identified during data extraction, and one that complicated direct cross-study comparison throughout this review, was substantial variation in how removal efficiency was defined: some studies reported reduction in total soil metal concentration, others reported reduction in bioavailable or extractable metal fraction specifically, and a smaller number reported reduction in metal uptake by an indicator plant species grown in treated soil as a proxy for bioavailability reduction rather than total removal. These three endpoints are conceptually related

but not numerically interchangeable, and pooling across them, as most of the small number of prior narrative reviews in this area have done without explicit comment, risks conflating genuinely different remediation outcomes. Table 2 summarises the highest-performing published consortium design from each of the five target metals reviewed, together with the specific efficiency endpoint reported by the original authors, to illustrate this heterogeneity directly.

4. DISCUSSION

The central quantitative finding of this review -- that consortia incorporating an explicit biofilm-forming or soil-retention component significantly outperform both single engineered strains and consortia lacking such a component -- provides systematic support for a design principle that has been advocated on largely mechanistic grounds in individual primary studies but had not, to our knowledge, been tested across the broader published literature. The plausible mechanism, that biofilm formation improves a metal-sequestering strain's persistence and spatial retention within a competitive, structurally heterogeneous soil environment over the treatment timescales typically used (weeks to months), is consistent with a substantial parallel literature on biofilm-mediated bacterial persistence in soil more generally, though we would note that few of the reviewed studies directly quantified strain persistence over time as a mechanistic link between biofilm presence and final removal efficiency, leaving this specific causal pathway inferred rather than directly demonstrated within this literature [14,31].

The metal-specific pattern, with mercury and cadmium showing higher and more consistent removal efficiency than chromium and arsenic, is mechanistically plausible given the differences in the underlying biotransformation chemistry: mer-operon-mediated mercury reduction to volatile elemental mercury is a well-characterised, single-step enzymatic process with limited dependence on ambient soil chemistry, whereas chromium and arsenic bioremediation typically depends on redox-state interconversion whose efficiency and direction are substantially influenced by soil pH, oxygen availability, and the presence of competing redox-active soil constituents that varied, often without full characterisation, across the reviewed studies [9,22]. This suggests that consortium designs targeting chromium or arsenic may benefit particularly from being paired with explicit soil redox-conditioning strategies, an approach reported in only a minority of the reviewed chromium and arsenic studies but associated with above-median efficiency where it was used.

The reporting heterogeneity identified in this review -- total concentration reduction versus bioavailable-fraction reduction versus plant-uptake reduction, used inconsistently across studies without always being explicitly distinguished by the original authors -- is, in our assessment, a significant and underappreciated barrier

to synthesising this literature reliably, and one that likely also affects meta-analytic conclusions in adjacent bioremediation review literature that we were not able to fully audit within the scope of this review. We would recommend that future studies in this area report all three endpoints where feasible, or at minimum state explicitly and prominently which endpoint is being reported and why it was chosen, since total concentration reduction and bioavailability reduction are both legitimate but functionally distinct remediation goals with different implications for agricultural reuse of treated soil specifically. We would further note that standardised reporting templates, of the kind now common in clinical trial registries, do not yet have a widely adopted equivalent in the engineered-bioremediation literature, and adoption of even a minimal common data element set -- initial concentration, matrix type, replicate number, endpoint definition, and monitoring duration -- would substantially improve the feasibility of future quantitative meta-analyses in this specific area of synthetic biology application.

A further limitation of the reviewed literature, distinct from the endpoint-definition issue, is that the substantial majority of included studies (49 of 58) were conducted in controlled microcosm or greenhouse conditions over relatively short timescales (median 45 days), with field-scale validation over a full growing season reported in only a small minority of studies. Controlled-condition removal efficiency is not guaranteed to transfer directly to field conditions, where introduced engineered strains face additional competitive pressure from an established native soil microbial community, greater environmental variability, and, in many jurisdictions, specific regulatory constraints on the deliberate environmental release of genetically modified organisms that do not apply to contained microcosm research. This regulatory dimension in particular means that even a consortium design shown to be highly effective under controlled conditions may face a substantial additional translational barrier before field deployment becomes practically or legally feasible in many contexts [16,33].

Finally, this review's own methodology has limitations worth acknowledging. We restricted inclusion to engineered or rationally assembled consortia specifically, which excludes a parallel and substantial literature on natural, non-engineered bioaugmentation consortia that in some cases report comparable efficiency without the regulatory complications associated with genetically modified organism release; a direct, matched comparison between engineered and natural consortium approaches across comparable contamination scenarios would be a valuable complementary synthesis beyond the scope of the present review. We also relied, as is standard for a systematic review of this kind, on efficiency values and study characteristics as reported by original authors rather than independently re-analysing raw data, so some of the cross-study variability documented here may partly reflect differences in

underlying experimental rigour that we could not fully assess through literature synthesis alone.

5. CONCLUSION

This systematic review of 58 engineered bacterial consortium studies for heavy-metal soil bioremediation, published between 2010 and 2022, found a median removal or immobilisation efficiency of 68.4%, with consortia combining a metal-sequestering strain and an explicit biofilm-forming or soil-retention component achieving the highest median efficiency (76.8%) and significantly outperforming both single engineered strains (54.2%) and consortia lacking a dedicated soil-retention component. Mercury and cadmium showed the highest and most consistent removal efficiencies among the five metals reviewed, while chromium and arsenic showed lower and more variable efficiency, plausibly reflecting these metals' more complex, redox-dependent bioavailability. We identified substantial and underappreciated inconsistency in how removal efficiency is defined and reported across this literature -- total concentration reduction, bioavailable-fraction reduction, and plant-uptake reduction are used inconsistently and not always distinguished explicitly -- which we believe has meaningfully limited the comparability and cumulative value of this body of work to date. We recommend that future studies report all three efficiency endpoints where feasible, characterise soil redox conditions explicitly for chromium- and arsenic-targeting consortia, and prioritise field-scale validation given that the substantial majority of reviewed evidence comes from controlled microcosm or greenhouse conditions over comparatively short timescales. We intend to extend this synthesis with a formal, quantitative meta-analysis restricted to the subset of studies reporting a common, directly comparable efficiency endpoint, and to conduct a parallel systematic review comparing engineered against natural, non-engineered bioaugmentation consortia across matched contamination scenarios, in order to clarify whether the performance advantage of genetic engineering observed in individual primary studies holds up when natural consortium alternatives are considered systematically alongside it.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

F.v.d.M. conceived the review, developed the search and inclusion strategy, and drafted the manuscript. S.J. performed the literature search, screening, and data extraction. J.H. performed the statistical synthesis and prepared the comparative figures and tables. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This work is a systematic literature review of previously published studies and did not involve human participants, human data, animal subjects, or new environmental release of genetically modified organisms, and therefore did not require institutional ethics or biosafety committee review.

Data Availability

The full list of screened and included studies, consortium design classifications, and extracted efficiency data compiled for this review are available from the corresponding author on reasonable request.

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