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Lead-Resistant Bacteria from Contaminated Terrestrial Environments: A Systematic Review of Isolation, Characterization, and Bioremediation Potential

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ABSTRACT

Lead (Pb) is a persistent, non-biodegradable pollutant that accumulates in soils and enters food chains, threatening ecosystems and human health. Indigenous bacteria from lead-polluted sites have evolved ways of tolerating and detoxifying the metal, making them attractive agents for sustainable remediation. We conducted a systematic review following PRISMA 2020 guidelines to synthesize empirical studies published between January 2023 and June 2026 on the isolation, characterization, and bioremediation potential of lead-resistant bacteria. Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar were searched, and 20 of 612 records met the inclusion criteria. Fifteen studies were from Asia, four from Nigeria, and one from Chile. *Bacillus* was the most frequently named genus, followed by *Pseudomonas*, *Kocuria*, *Mesobacillus*, *Sphingobium*, and *Lysinibacillus*. Lead tolerance and removal were attributed to biosorption, intracellular bioaccumulation, biomineralization, extracellular sequestration, biosurfactant production, antioxidative defence, and active efflux. Thirteen studies relied on morphological and biochemical identification alone, whereas seven reported molecular characterization, including 16S rRNA gene sequencing. Almost all work was laboratory-based, and field validation was largely absent. Indigenous lead-resistant bacteria, particularly *Bacillus* and *Pseudomonas*, are promising candidates for lead remediation, but the evidence is limited by non-standardized methods, thin molecular characterization, geographic imbalance, and a lack of field trials. Future work should prioritize standardized reporting, routine genome-based identification, biosafety screening, microbial consortia, and field-scale studies in under-represented regions such as Africa.

Keywords: Lead-Resistant Bacteria; Lead-Contaminated Soil; Lead Bioremediation; Bacterial Characterization; Biosorption; 16S rRNA Gene Sequencing; Systematic Review

INTRODUCTION

Lead (Pb) is among the most toxic and persistent contaminants released by human activity (World Health Organization, 2025). Unlike organic pollutants, it cannot be broken down; once it enters soil, sediment, or water it stays for decades, slowly accumulating and moving into food chains through plants and animals (Kumar and Singh, 2025; World Health Organization, 2025). The consequences for health are well documented. Chronic exposure has been linked to neurological damage, kidney dysfunction, cardiovascular disease, reproductive problems, developmental delay, and reduced cognitive performance, with children and other vulnerable groups bearing the greatest burden (World Health Organization, 2025). The problem is sharpest in low- and middle-income countries. Rapid industrialization, urban growth, mining, battery recycling, and informal waste disposal have pushed lead concentrations in soils well above natural background levels, and environmental monitoring and waste management in many of these settings remain weak (Joseph and Ogunjobi, 2025; Faisal et al., 2025). Lead enters terrestrial systems from many directions. Battery manufacturing and recycling plants, automobile mechanic workshops, mining and smelting operations, electronic-waste dumps, industrial effluents, and petroleum-contaminated land have all been identified as important sources (Harun et al., 2023; Danwanzam et al., 2025; Aguad et al., 2026). Agricultural land can also be affected when it receives contaminated irrigation water or airborne industrial emissions. Once deposited, lead alters soil physicochemical properties, suppresses microbial diversity, and interferes with nutrient cycling, ultimately lowering soil quality and crop productivity (Pal et al., 2024; Li et al., 2026). Its persistence also raises the risk of groundwater contamination and of long-term human exposure through food crops grown on polluted land.

Conventional physical and chemical remediation, such as excavation, soil washing, and chemical stabilization, can be effective but is often costly, disruptive to soil structure, and impractical for large or diffuse sites. Biological approaches offer a gentler alternative, and bacteria are especially attractive because they are abundant, fast-growing, and genetically versatile. Chronic contamination imposes strong selective pressure, and bacteria that survive it often carry a toolkit of adaptive traits. Empirical studies have described biosorption onto the cell envelope, intracellular accumulation, extracellular sequestration, biomineralization and bioprecipitation, biosurfactant production, phosphate-mediated immobilization, antioxidative defence, and active metal efflux (Harun et al., 2023; Kumar and Singh, 2025; Purwasena et al., 2026; Li et al., 2026). The mechanistic basis of surface binding was described earlier in a study of the biosorption mechanism of a lead-resistant *Arthrobacter* strain (Wang et al., 2018). Together these traits lower the

bioavailability and toxicity of lead and form the biological basis of bioremediation.

Recent work has repeatedly recovered a recognizable set of genera from lead-polluted sites, including *Bacillus*, *Pseudomonas*, *Sphingobium*, *Kocuria*, *Mesobacillus*, *Lysinibacillus*, *Klebsiella*, *Enterobacter*, *Proteus*, and *Staphylococcus* (Joseph and Ogunjobi, 2025; Heidari et al., 2025; Aguad et al., 2026). The way lead-resistant bacteria are identified has also changed. Classical morphological and biochemical tests are increasingly complemented by 16S rRNA gene sequencing, MALDI-TOF mass spectrometry, and metagenomic or other genomic approaches, which allow more reliable taxonomic assignment and open a window onto the genes and metabolic pathways behind resistance (Pal et al., 2024; Ehis-Eriakha et al., 2025). Studies that pair sequencing with analytical chemistry, such as ICP-OES quantification of residual lead, can link a named strain directly to a measured remediation outcome (Arasu et al., 2025; Badamasi and Salisu, 2025). Despite many promising laboratory reports, the evidence is fragmented. Studies differ in the bacteria they recover, the way they characterize them, the resistance indicators they report, and the scale at which they test performance. Earlier reviews have mostly addressed heavy-metal bioremediation in general or single contaminated sites, and none, to our knowledge, has brought together the recent empirical evidence specifically on lead-resistant bacteria from contaminated terrestrial environments. A consolidated synthesis is needed to show which taxa dominate, how they work, how they are being studied, and where the gaps lie. This systematic review therefore synthesizes original studies published between 2023 and 2026 on the isolation, characterization, and bioremediation potential of lead-resistant bacteria from battery-waste soils, automobile mechanic workshop soils, mining areas, industrial soils, e-waste sites, agricultural soils, and other lead-polluted environments. The review was designed to answer four questions: which bacterial genera are most frequently recovered, and from which types of contaminated environment; how these bacteria are isolated and characterized, and how widely molecular tools are used; which resistance and remediation mechanisms are reported, and how performance is measured; and which knowledge gaps and methodological weaknesses limit the practical application of the findings.

MATERIALS AND METHODS

Review Design and Reporting Standard

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to keep the process transparent and reproducible. It concentrated exclusively on original empirical studies of lead-resistant bacteria recovered from lead-contaminated terrestrial environments, including battery waste-contaminated soils, battery recycling sites, automobile mechanic workshop soils, mining areas, gold-mine tailings, industrial lead-contaminated soils, e-waste sites, petroleum-contaminated soils, agricultural soils, and other lead-polluted terrestrial settings. Five electronic databases (Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar) were searched for peer-reviewed, English-language articles published between January 2023 and June 2026, using Boolean combinations of terms for lead-resistant bacteria, lead-contaminated terrestrial environments, lead bioremediation, and molecular characterization.

Eligibility Criteria

Studies were eligible if they were original peer-reviewed research articles published in English between January 2023 and June 2026; reported the isolation of indigenous lead-resistant bacteria from lead-contaminated terrestrial environments; characterized the bacteria by morphological, biochemical, molecular, or integrated approaches; and evaluated lead resistance or bioremediation using indicators such as minimum inhibitory concentration (MIC), biosorption efficiency, bioaccumulation capacity, biomineralization, bioprecipitation, extracellular sequestration, active efflux, lead removal efficiency, or related experimental measures.

We excluded review articles, conference abstracts, editorials, book chapters, theses, duplicate publications, and papers without primary experimental data. Studies concerned only with contaminants other than lead, with non-bacterial remediation approaches, or with microbial community analysis without isolation and characterization of lead-resistant bacteria were also excluded. Only studies satisfying every criterion were retained for qualitative synthesis.

Study Selection

All retrieved records were exported to reference management software, and duplicates were removed before screening. Titles and abstracts were then screened against the eligibility criteria, and the full texts of potentially eligible articles were retrieved and assessed. Reasons for exclusion at the full-text stage were recorded, and the whole process is summarized in the PRISMA flow diagram (Figure 1).

Data Collection Process

Data from each eligible article were entered into a standardized extraction form built for this review and held in a structured spreadsheet. The form was designed to keep extraction consistent, reduce error, and allow comparison across studies. The extracted variables are listed in Table 1. Where several publications reported overlapping findings, duplicated information was removed and the most complete dataset retained.

Table 1: Variables Extracted from Each Included Study

Variable	Description
Author(s) and year	Citation of the study
Study location	Country or geographical area
Sample source	Lead-contaminated terrestrial environment (battery waste, battery recycling site, automobile mechanic workshop soil, mining area, industrial soil, e-waste site, petroleum-contaminated soil, agricultural soil, gold-mine tailings, etc.)
Bacterial isolate(s)	Lead-resistant bacterial species identified
Characterization method	Morphological, biochemical, and molecular methods
Molecular technique	16S rRNA gene sequencing or related molecular approaches
Lead resistance	Minimum inhibitory concentration (MIC) or tolerance level
Bioremediation mechanism	Biosorption, bioaccumulation, biomineralization, bioprecipitation, extracellular sequestration, active efflux

Variable	Description
Lead removal efficiency	Percentage or capacity of lead removal
Major findings	Principal outcomes of the study

Data Synthesis

The included studies differed widely in sampling environments, bacterial isolates, experimental designs, lead concentrations, characterization techniques, and outcome measures. This heterogeneity ruled out quantitative meta-analysis, so we used a qualitative narrative synthesis. Findings were tabulated by study characteristics, isolates, characterization methods, and main outcomes (Table 2, built from the variables in Table 1), and similar findings were grouped into themes: dominant genera, analytical techniques, determinants of remediation efficiency, resistance mechanisms, and knowledge gaps. Particular attention was paid to genera with high tolerance (elevated MIC) or efficient lead removal, and to the biological processes underlying detoxification.

RESULTS AND DISCUSSION

Study Selection

The database search returned 612 records: Scopus (n = 185), Web of Science (n = 96), PubMed (n = 74), ScienceDirect (n = 167), and Google Scholar (n = 90). After 124 duplicates were removed, 488 unique records were screened by title and abstract, and 401 were excluded because they were unrelated to lead-resistant bacteria, addressed other contaminants, or were reviews, conference papers, editorials, book chapters, or papers without primary experimental data. The full texts of the remaining 87 articles were assessed. Sixty-seven were excluded for lacking bacterial isolation and characterization, analyzing community composition without evaluating lead-resistant bacteria, focusing on non-bacterial remediation, or not reporting outcomes on lead resistance or remediation performance. Twenty original empirical studies satisfied all criteria and were included in the qualitative synthesis (Figure 1).

Characteristics of the Included Studies

The 20 included studies were published between 2023 and 2026 (Figure 2a; Table 2). Output rose steeply after 2024, with nine studies in 2025 and six in the first half of 2026, which points to growing interest in indigenous microbial solutions for lead pollution. Geographically, the evidence is concentrated in Asia, which accounts for 15 of the 20 studies: India (n = 7), Pakistan (n = 2), Indonesia (n = 2), and one each from China, Iran, Iraq, and Bangladesh (Figure 2b). Africa is represented by four studies, all from Nigeria (Harun et al., 2023; Badamasi and Salisu, 2025; Danwanzam et al., 2025; Joseph and Ogunjobi, 2025), and South America by a single study from Chile (Aguad et al., 2026). The studies sampled a broad range of lead-affected settings (Figure 2c). Battery waste and recycling sites were examined by Faisal et al. (2025) and Joseph and Ogunjobi (2025); agricultural soils by Kaushal and Pati (2024) and Pal et al. (2024); a municipal dumpsite by Badamasi and Salisu (2025); petroleum-contaminated soil by Danwanzam et al. (2025); an e-waste dump yard by Arasu et al. (2025); gold-mine tailings by Aguad et al. (2026); a mining area by Li et al. (2026); and industrial soil by Al-Heety (2026). Three studies drew isolates from aquatic or effluent-associated matrices, namely the Mithi River (Sevak et al., 2025), a marine environment (Joshi et al., 2026), and tannery effluent (Mahmud et al., 2026). The remaining seven described general lead-contaminated soils or environments (Harun et al., 2023; Tahir et al., 2023; Pertiwi et al., 2024; Heidari et al., 2025; Kumar and Singh, 2025; Yadav et al., 2025; Purwasena et al., 2026).

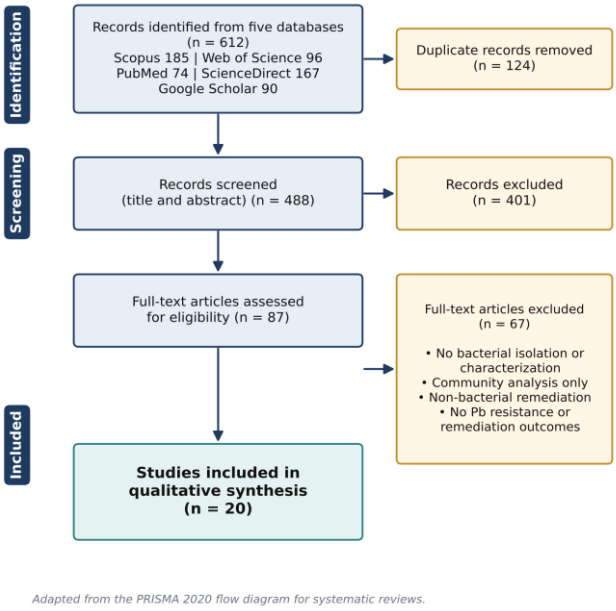


Figure 1: PRISMA 2020 Flow Diagram Showing Identification, Screening, Eligibility Assessment, and Inclusion of Studies

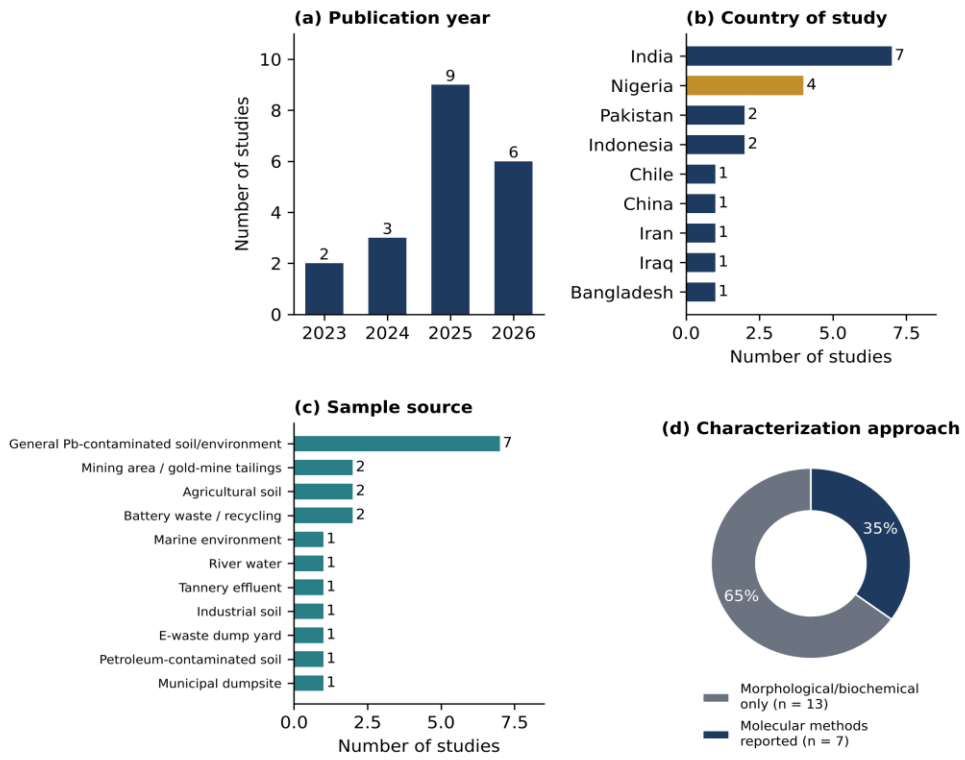


Figure 2: Characteristics of the 20 Included Studies: (a) Publication Year; (b) Country of Study (Nigeria Highlighted); (c) Sampling Source; (d) Bacterial Characterization Approach

Table 2: Empirical Studies on Lead-Resistant Bacteria and Their Bioremediation Potential Included in this Review (2023–2026)

No.	Study	Year	Country	Sample source	Bacterial isolate(s)	Methods used	Major findings
1	Harun et al.	2023	Nigeria	Lead-contaminated environment	*Bacillus cereus* BUK_BCH_BTE2	Morphological, biochemical	High lead tolerance and effective Pb removal.
2	Tahir et al.	2023	Pakistan	Lead-contaminated environment	Indigenous bacterial isolates	Morphological, biochemical	Significant reduction in lead toxicity through bacterial remediation.
3	Kaushal and Pati	2024	India	Lead-contaminated agricultural soil	*Bacillus altitudinis*	Morphological, biochemical	Enhanced rice seedling growth and reduced lead toxicity.
4	Pal et al.	2024	India	Lead-contaminated agricultural soil	Soil-borne Pb-resistant bacteria	Molecular, eco-physiological	Improved plant growth and lead remediation under Pb stress.
5	Pertiwi et al.	2024	Indonesia	Pb-contaminated soil	Lead-resistant bacteria	Morphological, biochemical	Reduced soil Pb concentration while increasing *Brassica chinensis* biomass.
6	Badamasi and Salisu	2025	Nigeria	Municipal dumpsites	Heavy metal-tolerant bacteria (*Bacillus sonorensis*, *Achromobacter mucicolens*, *Bacillus licheniformis*, *Lysinibacillus* sp.)	Morphological, biochemical, 16S rRNA gene sequencing	Isolates exhibited lead tolerance and showed potential for bioremediation of Pb-contaminated soils.
7	Danwanzam et al.	2025	Nigeria	Petroleum-contaminated soil	Hydrocarbon-degrading bacteria	Morphological, biochemical	Remediation of Pb-contaminated soil

No.	Study	Year	Country	Sample source	Bacterial isolate(s)	Methods used	Major findings
							by indigenous bacteria.
8	Faisal et al.	2025	Pakistan	Lead-acid battery recycling units	Multiple bacterial isolates	Morphological, biochemical	Recovered lead-resistant, acidophilic, and antibiotic-resistant bacteria.
9	Heidari et al.	2025	Iran	Lead-contaminated environment	*Kocuria rosea* PH1; *Mesobacillus persicus* DH1	Morphological, biochemical	Excellent Pb removal efficiency.
10	Joseph and Ogunjobi	2025	Nigeria	Battery waste dumpsite	Metal-tolerant bacteria	Morphological, biochemical	Plant growth-promoting bacteria with strong Pb tolerance.
11	Kumar and Singh	2025	India	Lead-contaminated soil	Multiple Pb-resistant bacteria	Morphological, biochemical, molecular	Optimized bacterial growth and confirmed high Pb bioremediation potential.
12	Sevak et al.	2025	India	Mithi River	Indigenous bacteria	Morphological, biochemical	Effective removal of dissolved lead from polluted river water.
13	Yadav et al.	2025	India	Lead-contaminated soil	Plant growth-promoting Pb-tolerant bacteria	Morphological, biochemical	Improved plant growth while reducing lead stress.
14	Arasu et al.	2025	India	E-waste dump yard	Pb-resistant *Bacillus subtilis* (EWB1)	Morphological, biochemical, ICP-OES, 16S rRNA gene sequencing	Strong biosorption capacity for lead bioremediation.
15	Aguad et al.	2026	Chile	Gold-mine tailings	*Sphingobium* sp. RO-01	Molecular characterization	Efficient Pb biosorption and remediation.
16	Al-Heety	2026	Iraq	Industrial lead-contaminated soil	*Pseudomonas* spp.; *Bacillus* spp.	Morphological, biochemical	Indigenous isolates effectively reduced soil lead concentrations.
17	Joshi et al.	2026	India	Marine environment	Marine Pb-resistant bacteria	Molecular characterization	Efficient Pb biosorption and detoxification.
18	Li et al.	2026	China	Mining area	*Bacillus cereus* LSP29	Molecular, biochemical	Lead tolerance mediated through antioxidation, adsorption, biomineralization, and molecular regulation.
19	Mahmud et al.	2026	Bangladesh	Industrial tannery effluent	Lead- and cadmium-tolerant bacteria	Morphological, biochemical	High lead tolerance and bioremediation efficiency.
20	Purwasena et al.	2026	Indonesia	Lead-contaminated soil	*Bacillus licheniformis* F16	Morphological, biochemical	Biosurfactant-assisted soil washing significantly enhanced lead removal.

Diversity and Sources of Lead-Resistant Bacteria

Taken together, the included studies show that lead-polluted sites are rich reservoirs of indigenous resistant bacteria. Prolonged exposure to elevated lead favors populations equipped with physiological, biochemical, and molecular means of coping with the metal, so contaminated soils double as a source of strains with remediation potential. Among isolates identified to genus level in Table 2, *Bacillus* was by far the most common, named in seven studies: *B. cereus* (Harun et al., 2023; Li et al., 2026), *B. altitudinis* (Kaushal and Pati, 2024), *B. subtilis* (Arasu et al., 2025), *B. licheniformis* (Badamasi and Salisu, 2025; Purwasena et al.,

2026), and *Bacillus* spp. (Al-Heety, 2026). Each of the other genera named in the table appeared once: *Pseudomonas* (Al-Heety, 2026), *Kocuria* and *Mesobacillus* (Heidari et al., 2025), *Sphingobium* (Aguad et al., 2026), and *Lysinibacillus* and *Achromobacter* (Badamasi and Salisu, 2025) (Figure 3). Several studies reported isolates only as groups, such as "heavy metal-tolerant bacteria" or "multiple isolates," so Figure 3 understates the true taxonomic breadth.

Our synthesis of the full reports indicates that the community composition tends to track the source of contamination. Battery-waste soils and recycling sites were dominated by *Bacillus*, *Pseudomonas*, *Klebsiella*, and *Proteus*, which fits long-term exposure to lead from spent lead-acid batteries.

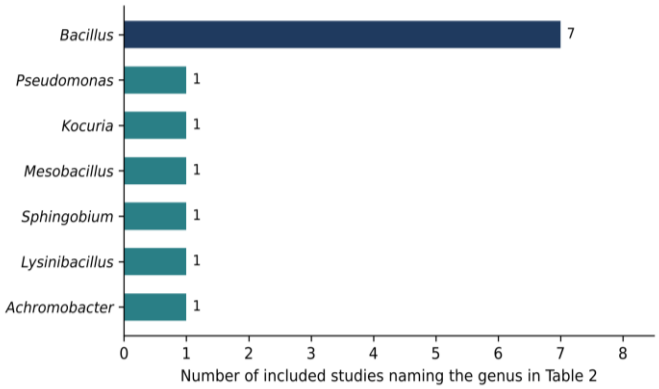


Figure 3: Bacterial Genera Explicitly Named in Table 2, Expressed as the Number of Included Studies Naming Each Genus. Studies Reporting Isolates only as Unspecified Groups are not Counted

Automobile mechanic workshop soils frequently yielded *Bacillus*, *Staphylococcus*, *Klebsiella*, *Proteus*, *Enterobacter*, and *Pseudomonas*, whereas mining areas and gold-mine tailings commonly yielded *Bacillus*, *Sphingobium*, and *Pseudomonas*. Industrial soils and tannery effluents supported *Kocuria*, *Mesobacillus*, *Bacillus*, and *Pseudomonas*, and lead-affected agricultural soils were characterized by plant growth-promoting resistant bacteria able to improve soil fertility while easing lead toxicity (Kaushal and Pati, 2024; Pal et al., 2024; Yadav et al., 2025). Isolates from sites carrying more than one pollutant deserve a separate mention. Strains from e-waste dumps and petroleum-contaminated soils tolerated lead despite living among other contaminants (Arasu et al., 2025; Danwanzam et al., 2025), and bacteria from tannery effluent tolerated both lead and cadmium (Mahmud et al., 2026). This suggests that exposure to mixed pollutants may select for several overlapping resistance mechanisms, an observation that matters for real sites, where lead rarely occurs alone. The study of Zhang et al. (2024), which examined lead, cadmium, and copper uptake together in a *Pseudomonas aeruginosa* strain, points in the same direction. Overall, *Bacillus* and *Pseudomonas* emerge as the central players, probably because of their metabolic versatility and environmental resilience. The presence of *Klebsiella*, *Enterobacter*, *Lysinibacillus*, *Kocuria*, *Mesobacillus*, *Sphingobium*, *Proteus*, *Staphylococcus*, and *Micrococcus* in addition shows that lead tolerance is spread across several phyla.

Isolation and Characterization Approaches

Characterization practice varied considerably. Thirteen of the 20 included studies identified their isolates by morphological and biochemical methods alone, while seven reported molecular approaches (Figure 2d). The molecular studies used 16S rRNA gene sequencing (Badamasi and Salisu, 2025; Arasu et al., 2025) or described molecular characterization more generally (Pal et al., 2024; Kumar and Singh, 2025; Aguad et al., 2026; Joshi et al., 2026; Li et al., 2026). Where it was used, 16S rRNA sequencing served mainly to confirm species identity after preliminary phenotypic screening. Analytical techniques were used to probe how bacteria interact with lead and to quantify remediation. ICP-OES was used to measure lead in solution (Arasu et al., 2025), and, according to our synthesis of the full reports, several studies added surface and structural methods such as FTIR, SEM, EDS/EDX, and XRD, as well as MALDI-TOF mass spectrometry for identification. Studies that combined sequencing with such analytical tools, such as Li et al. (2026) and Joshi et al. (2026), provided the most complete picture of how a named strain handles lead. The reliance on phenotypic identification matters. Morphological and biochemical profiles cannot reliably separate closely related species within genera such as *Bacillus* and *Pseudomonas*, so the taxonomic labels attached to many isolates should be treated as provisional until confirmed by sequencing.

Lead Resistance Mechanisms and Remediation Performance

Across the included studies, indigenous isolates from chronically contaminated sites tolerated lead and, in most cases, lowered its concentration or bioavailability. The mechanisms involved are summarized in Figure 4, and representative evidence from the included studies is given in Table 3. Lead bioremediation is better understood as a set of cooperating processes than as a single pathway.

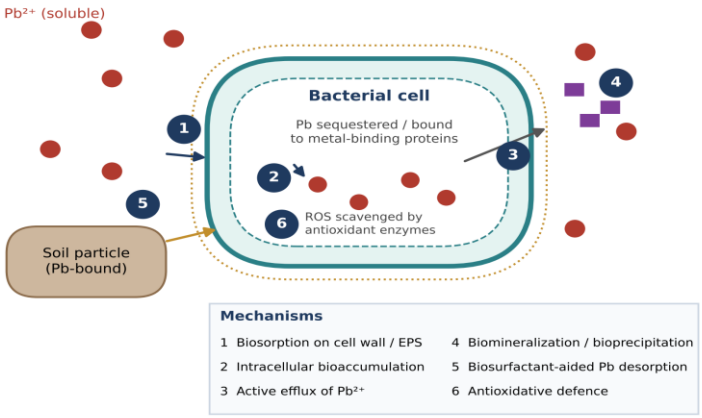


Figure 4: Conceptual Summary of Lead Resistance and Remediation Mechanisms in Indigenous Bacteria: (1) Biosorption, (2) Intracellular Bioaccumulation, (3) Active Efflux, (4) Biomineralization and Bioprecipitation, (5) Biosurfactant-Aided Desorption of Soil-Bound Lead, and (6) Antioxidative Defence.

Biosorption

Biosorption was the most frequently described mechanism. Negatively charged groups on the cell envelope, including carboxyl, hydroxyl, phosphate, amino, and sulfhydryl groups, bind dissolved lead ions. The process is passive and fast (mechanism 1 in Figure 4), and it forms the first line of defence by removing lead from solution before it can enter the cell. Strong biosorption has been reported for *Bacillus subtilis* from an e-waste dump yard (Arasu et al., 2025), *Sphingobium* sp. from gold-mine tailings (Aguad et al., 2026), marine isolates (Joshi et al., 2026), and *Kocuria rosea* and *Mesobacillus persicus* (Heidari et al., 2025). Extracellular polymeric substances (EPS) often amplify the effect by adding binding sites and stabilizing biofilms on contaminated surfaces.

Intracellular Bioaccumulation

Lead that passes the cell envelope can be sequestered inside the cell, where it is compartmentalized or bound to proteins and metal-binding peptides (mechanism 2 in Figure 4). Several isolates accumulated lead while continuing to grow and metabolize, which implies detoxification systems capable of shielding essential cell components from metal damage.

Biomineralization and Bioprecipitation

Some bacteria convert soluble lead into stable, poorly soluble minerals (mechanism 4 in Figure 4). Insoluble lead phosphate and lead carbonate can form through phosphate solubilization, urease activity, or local changes in pH and chemistry around the cell. Because these precipitates are far less mobile and bioavailable than free ions, this route is attractive for the long-term stabilization of lead in soil. Li et al. (2026) found that *Bacillus cereus* LSP29 from a mining area tolerated lead through antioxidation, adsorption, biomineralization, and molecular regulation acting together.

Biosurfactant Production

Biosurfactants can improve remediation indirectly. By helping to release lead from soil particles (mechanism 5 in Figure 4), they raise the amount available for subsequent bacterial binding and removal. Purwasena et al. (2026) showed that biosurfactant from *Bacillus licheniformis* F16 substantially enhanced lead removal in soil washing, compared with conventional washing.

Efflux, Antioxidative Defence, and Metal-Binding Proteins

Active membrane transport can pump excess lead out of the cell (mechanism 3 in Figure 4), while antioxidant enzymes protect cellular components from the oxidative damage that lead exposure triggers (mechanism 6). Table 3 lists representative studies for each mechanism. Molecular work suggests that stress-response genes and metal-resistance pathways are regulated in a coordinated way in chronically exposed bacteria (Pal et al., 2024; Li et al., 2026). The genetic structure of selected lead-resistant isolates has also been examined directly (Ehis-Eriakha et al., 2025).

Measuring Resistance and Removal

Resistance was usually assessed by MIC assays and growth responses, and performance by the percentage or capacity of lead removed. MIC values and removal efficiencies varied widely between species and experiments, and, in the studies we reviewed, isolates from long-contaminated sites generally tolerated more lead than bacteria from uncontaminated soil. Because the studies used different media, lead salts, and exposure conditions, the numbers cannot be compared directly, which is why we do not rank strains by reported efficiency.

Table 3: Lead Resistance and Remediation Mechanisms, with Representative Evidence from the Included Studies

Mechanism	Brief Description	Representative Studies
Biosorption	Passive binding of Pb^{2+} to carboxyl, hydroxyl, phosphate, amino, and sulfhydryl groups on the cell envelope; often enhanced by EPS.	Arasu et al. (2025); Aguad et al. (2026); Joshi et al. (2026); Heidari et al. (2025)
Intracellular bioaccumulation	Uptake and compartmentalization of lead, or binding to proteins and metal-binding peptides.	Zhang et al. (2024); Idrees et al. (2023)
Biomineralization / bioprecipitation	Conversion of soluble Pb into insoluble phosphate or carbonate minerals, reducing mobility and bioavailability.	Li et al. (2026)

Mechanism	Brief Description	Representative Studies
Biosurfactant production	Release of Pb from soil particles, improving contact with bacteria and enhancing soil washing.	Purwasena et al. (2026)
Antioxidative defence and molecular regulation	Enzymatic protection from Pb-induced oxidative stress; coordinated stress-response and metal-resistance gene regulation.	Li et al. (2026); Pal et al. (2024)
Active efflux	Export of excess Pb^{2+} from the cell by membrane transport systems.	Studies of resistance genes and molecular regulation: Ehis-Eriakha et al. (2025); Li et al. (2026)
Plant growth promotion (supporting trait)	Improved plant growth and reduced lead stress in the presence of resistant bacteria.	Kaushal and Pati (2024); Pal et al. (2024); Pertiwi et al. (2024); Yadav et al. (2025); Joseph and Ogunjobi (2025)
Multi-contaminant tolerance	Tolerance to lead together with other metals, hydrocarbons, or antibiotics.	Mahmud et al. (2026); Danwanzam et al. (2025); Faisal et al. (2025); Zhang et al. (2024)

Influencing Factors of Remediation Performance, Integrated Approaches, and Evidence Gaps

Reported removal efficiency depended on bacterial species, initial lead concentration, pH, temperature, contact time, nutrient availability, and inoculum density. These variables interact: pH shapes both the charge of binding sites on the cell surface and the chemical form of lead in solution, so an optimum found for one strain in one medium may not transfer to another. Optimization of growth and remediation conditions, as carried out by Kumar and Singh (2025), is therefore an essential step before any scale-up. A noticeable share of the studies went beyond simple lead removal. In agricultural and pot-based work, lead-resistant bacteria improved plant performance under lead stress: *Bacillus altitudinis* enhanced rice seedling growth (Kaushal and Pati, 2024), resistant bacteria increased *Brassica chinensis* biomass while lowering soil lead (Pertiwi et al., 2024), and plant growth-promoting isolates reduced lead stress in plant systems (Pal et al., 2024; Yadav et al., 2025). Plant growth-promoting properties were also documented in metal-tolerant bacteria from a battery-waste dumpsite in Nigeria (Joseph and Ogunjobi, 2025). Other studies pointed to alternative routes. Hydrocarbon-degrading bacteria from petroleum-contaminated soil showed potential for lead remediation (Danwanzam et al., 2025), which is relevant to sites such as mechanic workshops where oil and metals co-occur, and bacteria recovered from industrial effluent took up lead in a way proposed for wastewater treatment (Idrees et al., 2023). These findings support the idea that microbial remediation works best when integrated with plants, biosurfactants, or other treatments rather than used alone. The encouraging findings above should be read against the setting in which they were obtained. Most studies were conducted under controlled laboratory conditions, and few tested bacterial performance in the field, where soil heterogeneity, competing microorganisms, and fluctuating conditions complicate the picture. Differences in isolation methods, characterization techniques, experimental designs, lead concentrations, and performance indicators further limited comparison between studies. These gaps are examined in the Discussion.

Discussion

This review examined recent evidence on lead-resistant bacteria from contaminated terrestrial environments. The central message is that prolonged contamination selects for indigenous bacteria that not only survive high lead concentrations but also transform, immobilize, or remove the metal. That finding supports the growing view of indigenous microorganisms as a sustainable alternative or complement to physicochemical remediation. At the same time, the evidence is uneven: strong on laboratory proof of concept, weak on identification rigor, standardization, and field validation. The frequent recovery of *Bacillus* can plausibly be explained by several features of the genus. Its members form resistant endospores, tolerate harsh conditions, and secrete EPS that bind lead, and some species also produce biosurfactants, as in *B. licheniformis* F16 (Purwasena et al., 2026). These traits suit survival in battery-waste, mining, and industrial soils, and they also make the genus easy to isolate on standard media, which may inflate its apparent dominance. *Pseudomonas* is the other recurrent genus and is valued for its metabolic flexibility. The appearance of the same genera in geographically distant sites suggests that lead pollution repeatedly selects for organisms with efficient metal-handling machinery. The caveat, discussed below, is that culture-dependent isolation and phenotypic identification favor easily cultured genera and cannot show what is missing. A second consistent finding is that resistance rarely depends on one mechanism. Biosorption removes lead rapidly from solution, but it usually operates alongside intracellular sequestration, mineral formation, biosurfactant activity, efflux, and oxidative defence. For practitioners, this has two implications. First, screening strains by a single assay, such as MIC or biosorption capacity alone, may misrepresent their real value; second, mechanisms differ in permanence. Surface-bound lead can be released again when conditions change, whereas mineralized lead is more likely to stay immobilized, so strains that promote precipitation may be preferable when long-term stabilization is the goal.

The limited use of molecular characterization is a notable weakness, because phenotypic tests cannot reliably resolve species within *Bacillus* or *Pseudomonas*. Sequencing should become routine, and ideally accompanied by deposition of sequences in public databases, as the studies that used 16S rRNA sequencing and genomic characterization demonstrate (Badamasi and Salisu, 2025; Ehis-Eriakha et al., 2025; Li et al., 2026). Heterogeneity in experimental design is the second obstacle. Removal efficiency depended on pH, temperature, contact time, nutrients, inoculum density, and initial lead concentration, and these were set differently from study to study. As a result a 90% removal in one paper and a 60% removal in another cannot be taken to rank the strains involved. A minimum reporting set, such as the one we propose in Table 4, would make future studies comparable and make quantitative meta-analysis possible.

Table 4: Proposed Minimum Reporting Items for Studies of Lead-Resistant Bacteria (Suggested by the Authors of this Review)

Domain	Items to report
Site and sample	Site type, geographic coordinates, total and bioavailable Pb concentration, soil pH, texture and organic matter
Isolation and MIC	Medium, Pb salt, pH, incubation conditions, MIC endpoint definition, replicates
Identification	Phenotypic tests plus 16S rRNA (or genome) sequence, with public database accession numbers
Removal assays	Initial Pb concentration, biomass or inoculum density, contact time, temperature, pH, removal (%) and uptake capacity (mg g^{-1})
Controls and statistics	Abiotic and heat-killed biomass controls, number of replicates, statistical tests
Mechanism evidence	Cell-bound versus intracellular versus precipitated Pb; supporting SEM-EDS, FTIR, XRD, or gene-expression data
Biosafety	Pathogenicity screening and antibiotic-resistance profile of candidate strains
Scale-up and field work	Soil matrix tests, native microbiota effects, plant interaction, duration, and monitoring of Pb speciation

The most important gap is the shortage of evidence beyond the laboratory. Controlled flask experiments remove soil heterogeneity, competition from native microorganisms, seasonal change, moisture variation, and fluctuating lead concentrations, all of which shape performance in real soils. How well laboratory-selected isolates perform under natural conditions therefore remains largely unknown. Closing this gap requires a staged route, from microcosms and greenhouse trials through pilot-scale plots to monitored field applications (Figure 5). The plant-based studies reviewed here (Kaushal and Pati, 2024; Pertiwi et al., 2024; Yadav et al., 2025) are a useful intermediate step, because they test strains in a soil matrix with a living host, but they are still short-term and small-scale. Indigenous strains do have one practical advantage. Because they come from contaminated sites, they are already acclimatized to local conditions and should need less adjustment after application, although this expectation also awaits field confirmation.

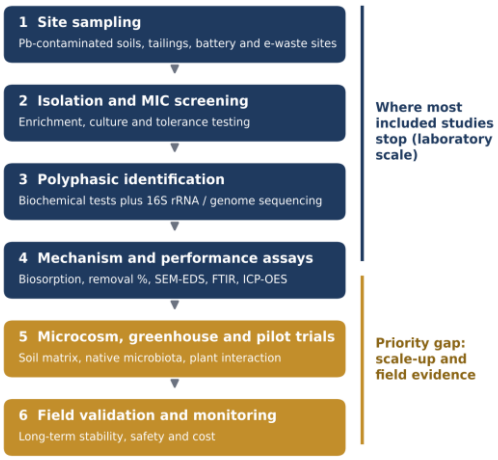


Figure 5: Proposed Research Pathway from Site Sampling to Field Validation, Indicating the Stages Where Evidence is Currently Concentrated and the Priority Gap

An aspect that the literature has barely addressed is biosafety. Several genera that appear repeatedly, including *Klebsiella*, *Proteus*, *Staphylococcus*, and *Pseudomonas aeruginosa*, include opportunistic pathogens, and metal-contaminated environments can co-select for antibiotic resistance, as lead-resistant isolates from battery recycling units have also been antibiotic resistant (Faisal et al., 2025). Releasing such strains into soil would be unwise. Candidate strains for field use should be screened for pathogenicity and transferable antibiotic-resistance genes, and preference should go to organisms with a proven safety record, such as non-pathogenic *Bacillus* species, or to well-characterized consortia.

Research output is heavily skewed toward Asia, with far less work from Africa and South America. This is out of proportion with the burden of exposure: informal battery recycling, artisanal mining, automobile mechanic workshops, and unregulated waste disposal are widespread in many African countries. Existing Nigerian studies show that locally adapted strains are available (Harun et al., 2023; Badamasi and Salisu, 2025; Danwanzam et al., 2025; Joseph and Ogunjobi, 2025). More work across Africa's ecological zones would help identify strains suited to local soils and climates and build the evidence base for locally led remediation. Strengths of the review include its adherence to PRISMA 2020, a predefined search across five databases, explicit eligibility criteria, and a focus on recent empirical studies. It also has limitations. Restricting the search to English-language, peer-reviewed articles from 2023 to June 2026 will have missed older foundational work and studies in other languages. Heterogeneity prevented meta-analysis, so findings are narrative and the studies were not formally

weighted by methodological quality. Searching Google Scholar alongside indexed databases improves coverage but is less reproducible. Some included studies sampled aquatic or effluent-associated matrices, which slightly extend the terrestrial focus, although these systems receive lead from terrestrial sources. Finally, publication bias may favor positive remediation results.

CONCLUSION

Indigenous bacteria from lead-contaminated terrestrial environments, notably *Bacillus* and *Pseudomonas*, are promising agents for lead remediation because they tolerate high lead levels and reduce its mobility and bioavailability through biosorption, bioaccumulation, biomineralization, extracellular sequestration, and related mechanisms. Molecular tools have improved identification and mechanistic understanding, but non-standardized methods, limited field-scale validation, and geographic imbalance still hinder the translation of these findings into practice. Addressing these gaps would bring indigenous lead-resistant bacteria much closer to practical use in restoring contaminated land. Future research should therefore validate promising isolates in microcosm, pilot-scale, and field trials that monitor lead speciation and bioavailability; make molecular identification routine through 16S rRNA gene and genome-based approaches, with sequences deposited in public databases; adopt standardized protocols and reporting; screen candidate strains for pathogenicity and transferable antibiotic-resistance genes before any environmental release; evaluate microbial consortia and integrated strategies that combine bacteria with phytoremediation, biosurfactants, and biochar; and extend studies to under-represented regions, particularly Africa, where mining, battery recycling, industrial activity, and mechanic workshops cause persistent lead contamination.

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