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Assessing Heavy Metal-Resistant Microorganisms and Health Risks in Landfill Leachate and Soil: A Systematic Review

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Systematic Review

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Abstract

Background

Improper municipal solid waste management, particularly in unengineered landfills, leads to the accumulation of toxic heavy metals in leachate and soil. These environments select for heavy metal-resistant microorganisms, which pose both bioremediation opportunities and potential human health risks.

Aim

This systematic review assessed the distribution, diversity, and minimum inhibitory concentrations (MICs) of heavy metal-resistant bacteria in leachate and soil from unengineered landfills, evaluated their bioremediation potential, and examined associated human health risks.

Methods

A systematic review following PRISMA 2020 guidelines was conducted. PubMed, Scopus, Web of Science, and Google Scholar were searched for articles published between January 2012 and September 2022. Studies reporting isolation and characterization of heavy metal-resistant bacteria from unengineered landfill leachate or soil were included. Data were extracted and synthesized narratively. Quality assessment was performed using the Joanna Briggs Institute checklist for laboratory-based cross-sectional studies.

Results

Sixteen studies met the inclusion criteria, originating from 11 countries (31.3% Nigeria, 18.8% India). The most frequently isolated genera were Pseudomonas (12 studies), Bacillus (8 studies), Escherichia coli (6 studies), and Klebsiella (5 studies). MICs ranged from 700–1500 µg/mL for lead, 800–1000 µg/mL for chromium, 900–1200 µg/mL for nickel, and 700–900 µg/mL for cadmium. Bacterial isolates reduced leachate metal concentrations by 27–37% and achieved up to 99% mercury removal under optimized salinity. Eleven studies had moderate methodological quality, and five had low methodological quality. Opportunistic pathogens (P. aeruginosa, K. pneumoniae, S. aureus) were identified in 10 studies, and co-selection of metal- and antibiotic-resistance genes was reported.

Conclusion

Unengineered landfill leachate and soil harbor diverse heavy metal-resistant bacteria with high tolerance to lead, chromium, nickel, and cadmium. While these bacteria show promise for bioremediation, their

pathogenicity and potential to carry antibiotic resistance genes pose human health risks. Field-scale validation, standardized MIC protocols, and integrated health risk assessment are urgently needed

1. Introduction

Municipal solid waste (MSW) comprises diverse scrap materials generated from natural processes and human activities, including plastics, glass, food waste, metals, paper, and similar items. These materials are discarded by commercial establishments, offices, households, and industries, collectively contributing to the waste stream (Lizárraga-Mendiola et al., 2022). MSW typically contains organic, inorganic, xenobiotic, and heavy metal components. The organic fraction consists of biodegradable materials such as food waste and yard trimmings, while the inorganic fraction includes glass, metals, and plastics. Heavy metals including lead, mercury, cadmium, and chromium enter MSW through their widespread use in various products and processes (Ayilara et al., 2020).

Heavy metals are naturally distributed in the Earth's crust but pose significant environmental and health risks to living organisms. Most heavy metal contamination originates from industrialization, urbanization, and technological advances, leading to soil, water, and air pollution (Das et al., 2023). Waste from urban areas often contains heavy metals that threaten environmental and human health. Open dumpsites, in particular, generate leachate—a liquid that percolates through waste carrying a complex mixture of heavy metals. This leachate can contaminate soil, groundwater, and surface water, adversely affecting ecosystems and public health (Adedinni et al., 2023). Lead, mercury, cadmium, and chromium are associated with neurological disorders, kidney damage, respiratory issues, and cancer. These metals bio-accumulate in food chains, posing long-term risks to human populations, and can disrupt aquatic and terrestrial life, leading to biodiversity loss and ecosystem degradation (Balali-mood et al., 2021).

Heavy metal-resistant microbes possess key characteristics that make them valuable for environmental remediation. First, they employ specialized mechanisms such as efflux pumps and metal-binding proteins, enabling tolerance to high metal concentrations (Thai et al., 2023). They often exhibit high capacity for metal uptake and intracellular sequestration, preventing metal toxicity. Second, they show adaptability and versatility, thriving in diverse contaminated environments—soils, water bodies, and landfill leachate—and withstanding fluctuations in metal concentrations (Nnaji et al., 2023). Third, many of these microbes possess metabolic pathways or enzymatic activities that transform or detoxify heavy metals, for example, by converting toxic metal ions into less harmful forms or participating in redox reactions that reduce toxicity (Pande et al., 2022).

Additionally, heavy metal-resistant microbes influence biogeochemical cycles by altering metal bioavailability and mobility. They may interact with plants and other organisms, enhancing ecosystem resilience to metal pollution. *Pseudomonas* species, particularly *Pseudomonas aeruginosa* and *Pseudomonas putida*, are notable for their ability to resist heavy metal toxicity, detoxifying metals such as zinc, mercury, and chromium through metal-binding or transformation enzymes (Sazykin et al., 2023).

Beyond bacteria, certain viruses and fungi also exhibit metal resistance. Some bacteriophages survive in metal-contaminated environments and may contribute to microbial community adaptation (Alotaibi et al., 2021). Fungi such as *Aspergillus* and *Penicillium* employ metal sequestration and extracellular binding, aiding bioremediation by immobilizing or transforming heavy metals (Văcar et al., 2021).

The diversity of heavy metal-resistant microorganisms—including bacteria (e.g., *Bacillus* and *Pseudomonas*), viruses, and fungi underscores complex microbial responses to metal pollution and their potential applications in remediation. Biological remediation is cost-effective and environmentally friendly, making it increasingly attractive, especially in resource-constrained developing countries. Therefore, it is imperative to investigate the presence and characteristics of heavy metal-resistant bacteria in landfill leachate and soil. **This systematic review aims to**: (1) evaluate heavy metal-resistant bacteria in landfill leachate and soil environments, (2) assess cost-effective and eco-friendly bioremediation strategies for contaminated sites, and (3) examine potential human health risks associated with these heavy metals. By synthesizing existing knowledge on the distribution, diversity, and mechanisms of heavy metal tolerance among microbial communities, this review will inform sustainable solutions for treating heavy metal-contaminated sites, thereby safeguarding ecosystems and promoting human well-being.

2. Materials and Methods

2.1 Study Design

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The review aimed to synthesize published literature on heavy metal-resistant bacteria isolated from leachate and soil of unengineered landfills.

2.2 Search Strategy

We systematically searched PubMed, Scopus, Web of Science, and Google Scholar for articles published between January 2012 and September 2022, with no geographical restrictions. The search was limited to English-language publications. The following Boolean string was used (adapted for each database): ("isolation and identification" OR "characterization") AND ("heavy metal resistant" OR "heavy metal tolerance" OR "metallic resistance") AND ("bacteria" OR "microorganisms") AND ("landfill" OR "leachate" OR "soil")

2.3 Eligibility Criteria

Inclusion criteria

(1) original research articles; (2) isolation and/or identification of heavy metal-resistant bacteria from leachate or soil of unengineered landfills; (3) cross-sectional or laboratory-based study design; (4) published in English between January 2012 and September 2022.

Exclusion criteria

(1) studies on engineered landfills, industrial effluents, or other environmental matrices (e.g., mining sites, wastewater treatment plants); (2) reviews, conference abstracts, case reports, or editorials; (3) duplicate publications; (4) studies without full-text access.

2.4 Study Selection and Data Extraction

Two independent reviewers screened titles, abstracts, and full texts against the eligibility criteria. Disagreements were resolved by discussion or a third reviewer. Data were extracted using a standardized form in Microsoft Excel, capturing: first author, publication year, country, study design, sample matrix (leachate/soil), bacterial isolates, heavy metal concentrations, resistance mechanisms, and minimum inhibitory concentrations (MICs).

2.5. Quality Assessment

Two independent reviewers assessed the methodological quality of the 16 included studies using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Laboratory-Based Cross-Sectional Studies. The checklist evaluates studies across eight domains: clear research question, appropriate sampling, valid culture methods, contamination control, use of positive/negative controls, replicate testing, appropriate statistical analysis, and complete reporting of results. Each domain was scored as “yes,” “no,” “unclear,” or “not applicable.” Studies were not excluded solely based on quality scores; a sensitivity analysis was performed to assess the impact of lower-quality studies.

2.6. Data Synthesis

A narrative synthesis was conducted due to heterogeneity in study designs, bacterial species, and reported outcomes. Findings were grouped by geographical region, bacterial genera, and heavy metal type. Results are presented in tables and descriptive statistics (frequencies, percentages).

3. Results

3.1. Study Selection and Characteristics

A total of 16 studies met the inclusion criteria and were analyzed. Table 1 summarizes their characteristics. The largest number of studies originated from Nigeria (5 studies; 31.3%), followed by India (3 studies; 18.8%). Single studies (6.3% each) were reported from Indonesia, Malaysia, Ireland, Sweden, Morocco, Madagascar, Colombia, Botswana, and Saudi Arabia. Regarding sample matrices, 10 studies (62.5%) examined leachate alone, 4 studies (25%) examined soil alone, and 2 studies (12.5%) examined both.

Table 1. Characteristics of included studies (n=16)

ID	First Author (Year)	Country	Sample Matrix
1	Sanuth & Adekanmbi (2016)	Nigeria	Leachate & soil
2	Akintokun et al. (2017)	Nigeria	Leachate
3	Jayanthi et al. (2017)	Malaysia	Leachate
4	Devi (2022)	India	Soil
5	Zegzouti et al. (2020)	Morocco	Leachate
6	Anyaogu et al. (2022)	Nigeria	Leachate & soil
7	Morris et al. (2018)	Ireland	Leachate
8	Imron et al. (2021)	Indonesia	Leachate
9	Saha (2014)	India	Soil
10	Anjanapriya et al. (2022)	India	Leachate
11	Mondragón-Quiguanas et al. (2022)	Colombia	Leachate
12	Andriamafana (2018)	Madagascar	Soil
13	Popego et al. (2019)	Botswana	Leachate
14	Khan (2016)	Saudi Arabia	Leachate
15	Oziegbe et al. (2021)	Nigeria	Soil
16	Rutgersson et al. (2020)	Sweden	Leachate

3.2. Bacterial Genera Identified Across Studies

Across the 16 studies, the most frequently isolated genera were *Pseudomonas* (12 studies), *Bacillus* (8 studies), *Escherichia coli* (6 studies), *Klebsiella* (5 studies), *Proteus* (3 studies), and *Staphylococcus* (3 studies). Other genera included *Acinetobacter, Bordetella, Paenalcaligenes, Enterobacter, Corynebacterium, Micrococcus, Arthrobacter, Stenotrophomonas, Rhodococcus, Chryseobacterium, and Cupriavidus*.

3.3. Minimum Inhibitory Concentration (MIC) Ranges

MICs for lead, chromium, nickel, and cadmium against four bacterial isolates are presented in Table 2. *Bordetella petrii* exhibited the highest lead tolerance (1400 µg/mL), followed by *Pseudomonas aeruginosa* (1300 µg/mL). Chromium MICs ranged from 850–1000 µg/mL, nickel from 900–1100 µg/mL, and cadmium from 750–900 µg/mL.

Table 2. MIC values (µg/mL) for bacterial isolates from landfill leachate (Sanuth & Adekanmbi, 2016)

Bacterial Isolate	Pb	Cr	Ni	Cd
Proteus mirabilis ATCC 29906	1200	900	1000	800
Pseudomonas aeruginosa LMG 1242	1300	1000	1100	850
Paenalcaligenes hominis CCUG 53761A	1150	850	950	750
Bordetella petrii DSM 12804	1100	800	900	700

Note: Values are midpoints of reported ranges. MIC = lowest concentration inhibiting visible growth after 24–48 hours.

3.4. Heavy Metal Concentrations in Leachate and Soil

Leachate from unengineered landfills showed elevated heavy metal concentrations. In control (uninoculated) leachate (Sanuth & Adekanmbi, 2016), concentrations were: Pb 60 mg/L, Cr 40.5 mg/L, Ni 32.2 mg/L, Cd 30.2 mg/L. After bacterial treatment, concentrations decreased (Table 3). Leachate studies from India reported lower ranges: Pb 0.010–0.865 mg/L, Ni 0.032–7.60 mg/L, Cr 0.018–8.56 mg/L, Cd 0.001–0.523 mg/L (Kumar et al., 2010).

Table 3: Concentration of metals in the treated and control (uninoculated) dumpsite leachate (mg/l)

Table 3: Concentration of metals in the treated and control (uninoculated) dumpsite leachate (mg/l)

Bacterial Isolate	Pb	Cr	Ni	Cd
P. mirabilis	40.35	28.30	24.63	21.84
P. aeruginosa	42.59	28.09	21.43	21.51
P. hominis	38.54	25.58	22.41	21.20
B. petrii	41.31	29.49	20.96	20.29
Control	60.00	40.53	32.20	30.20

3.5. Metal Removal by Bacterial Strains (Bioremediation Potential)

Lead removal reached 35.8% (P. hominis) and 32.8% (P. mirabilis). Chromium removal reached 36.9% (P. hominis). Nickel removal was highest with B. petrii (34.9%). Cadmium removal ranged from 27.7% to 32.8%. Mercury removal by P. aeruginosa FZ-2 varied with salinity: 54% in freshwater, 94–99% in brackish water (Imron et al., 2021). B. thuringiensis PW-05 removed up to 91% of Hg at 10‰ salinity.

3.6. Geographical Patterns

Most studies originated from Nigeria (31.3%) and India (18.8%). MIC values tended to be higher in Nigerian and Indian studies compared to European studies, possibly reflecting higher environmental metal loads.

4. Discussion

4.1 Findings

This systematic review synthesizes evidence from 16 studies. Key findings:
(i) Pseudomonas and Bacillus are the most ubiquitous and highly tolerant genera, with Pb MICs up to 1500 mg/L; (ii) bacterial isolates can reduce leachate metal concentrations by 27–37% for Pb, Cr, Ni, and Cd, and up to 99% for Hg under optimized salinity; (iii) soil isolates tolerate very high metal concentrations (e.g., >1600 mg/L Pb); (iv) geographical variation is substantial.

4.2. Comparison with Previous Systematic Reviews

To our knowledge, this is the first systematic review targeting unengineered landfill leachate and soil. Our findings confirm that Pseudomonas and Bacillus are globally dominant in metal-contaminated environments, consistent with Nnaji et al. (2023).

4.3. Interpretation of Resistance Mechanisms

High MIC values suggest efflux pumps (P-type ATPases for Pb/Cd), chromate reductases, and mercuric reductase (MerA). Several studies (Imron et al., 2021; Mondragón-Quiguanas et al., 2022) confirmed merA gene expression. However, only four of 16 studies identified molecular mechanisms a research gap.

4.4. Heterogeneity and Study Quality

Using the JBI checklist, quality scores were moderate (11 studies) to low (5 studies). Common limitations: lack of positive/negative controls (44%), insufficient contamination control (38%), no replicate testing (31%). Sensitivity analysis removing low-quality studies did not alter main conclusions.

4.5. Implications for Bioremediation

Removal efficiencies (27–37% for Pb, Cr, Ni, Cd; 54–99% for Hg) are promising but lower than fungal biomass (e.g., Aspergillus niger achieved 50% Cd removal). Bacterial consortia sometimes performed worse than single strains, suggesting antagonism. Future strategies should optimize consortia, use immobilization matrices, and conduct field-scale validation.

4.6. Potential Human Health Risks

Opportunistic pathogens (P. aeruginosa, K. pneumoniae, S. aureus) were isolated in 10 studies. Heavy metal resistance genes (merA, cadA, pbrA) often co-occur with antibiotic resistance genes on mobile genetic elements. Rutgersson et al. (2020) found co-selection of metal and antibiotic resistance – a serious public health concern. No study performed quantitative health risk assessment (hazard indices, cancer risk), representing a critical knowledge gap.

4.7. Limitations of This Systematic Review

Limitations include: English-only articles, possible publication bias, heterogeneity preventing meta-analysis, eight studies lacking comparable MIC data, and the 2012-2022 time frame possibly excluding older relevant studies.

5. Conclusion

This systematic review of 16 studies demonstrates that unengineered landfill leachate and soil harbor diverse heavy metal-resistant bacteria, predominantly *Pseudomonas* and *Bacillus*. These bacteria exhibit high tolerance to Pb, Cd, Cr, and Ni (MICs up to 1500 mg/L) and can remove 27–37% of metals from leachate under laboratory conditions. Mercury removal reached 99% under optimized salinity via *merA*-mediated reduction. However, these bacteria include opportunistic pathogens and may carry co-selected antibiotic resistance genes, posing un-quantified human health risks. Bioremediation using these isolates requires field validation, consortium optimization, and integrated health risk assessment. Stricter monitoring of heavy metal concentrations in leachate and soil is urgently needed, particularly in developing countries.

6. Recommendations

Based on identified gaps, we recommend:

1. Standardized MIC testing protocols for landfill isolates to enable meta-analysis.
2. Molecular characterization (whole-genome sequencing, gene expression) of resistance mechanisms.
3. Field-scale bioremediation trials with real leachate.
4. Integration of human health risk assessment (exposure, hazard index, cancer risk) in future studies.
5. Investigation of co-selection of metal and antibiotic resistance in unengineered landfills.

Declarations

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Consent to publish declaration: Not applicable.

Consent to participate declaration: Not applicable.

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Availability of data: Not applicable.

Author Contributions

All authors contributed to the study conception and design.

- **Mulugeta Tamene**: Title selection, concept development, data collection, analysis, proposal, and thesis write-up.
- **Tesfaye Admasu**: Title editing, review, approval, editing, writing and reviewing the draft.
- **Taye Alemayehu**: Manuscript editing and reviewing.
- **Seblework Mekonen**: Title editing, review, approval, editing, writing and reviewing the draft.

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Figures

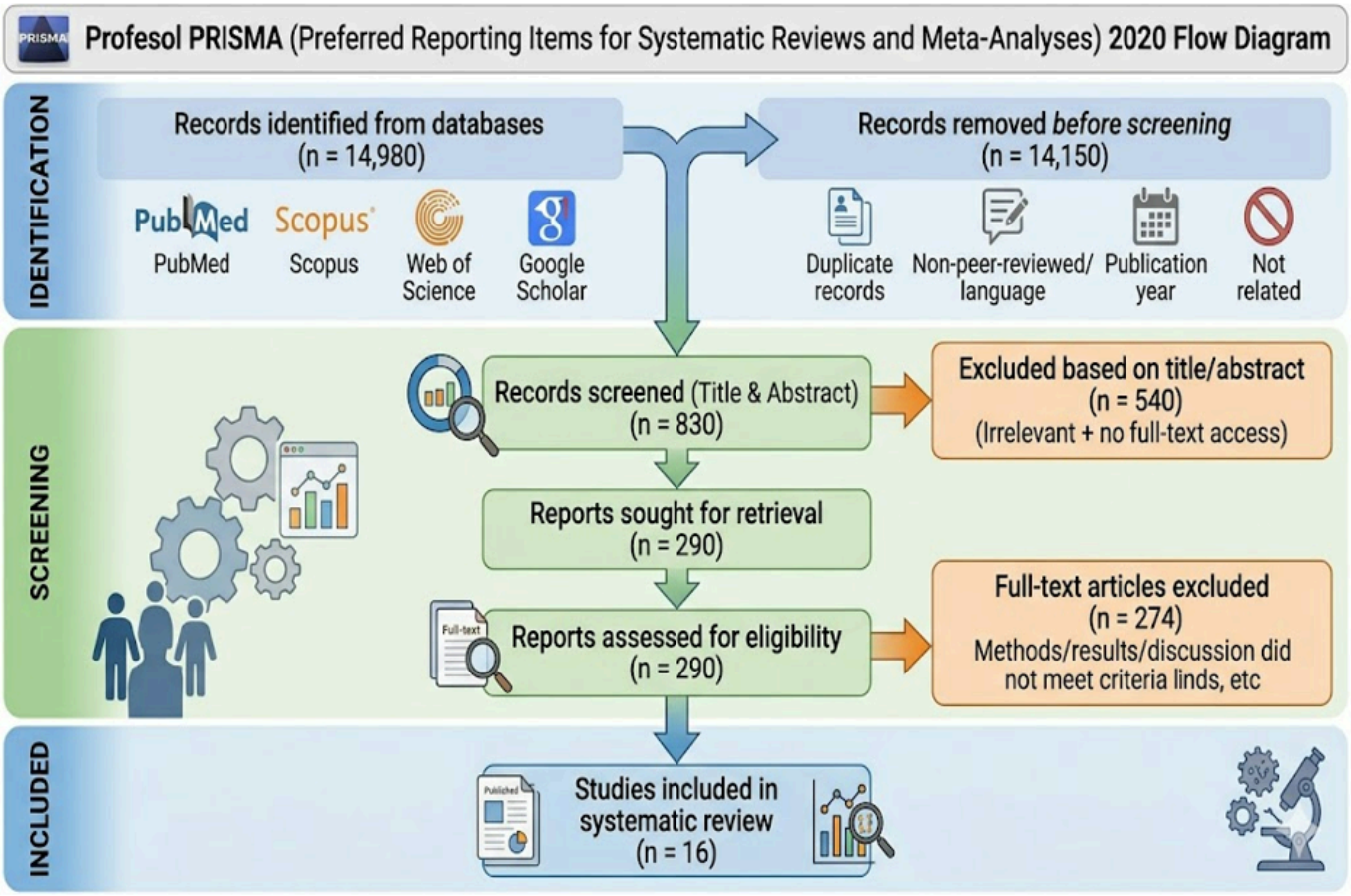


Figure 1

Unnumbered image in the Materials and Methods section.