

Systematic Review

Environmental Impacts of Municipal Solid Waste Disposal in Urban Areas: A Systematic Review of Contamination Pathways, Assessment Methods, and Mitigation Strategies

Zhaksylyk Pernebayev and Akbota Aitimbetova * 

Department of Ecology, M.Auezov South Kazakhstan University, Shymkent 160012, Kazakhstan;
zhaksylykpernebaev@gmail.com

* Correspondence: akbota.askarkyzy@aeuzov.edu.kz

Abstract

Municipal solid waste disposed of in open dumpsites and unlined landfills contaminates groundwater, soils, and air across urban areas of low- and middle-income countries. Nevertheless, impacts across all three environmental media have not been systematically assessed together. We conducted a PRISMA 2020-compliant systematic review of 286 peer-reviewed studies from PubMed, Dimensions, and OpenAlex, applying structured eligibility screening and quality appraisal using an adapted JBI checklist. Heavy metals—lead, cadmium, chromium, and zinc—were the most frequently detected contaminants in leachate and groundwater, commonly exceeding WHO drinking water guidelines by one to three orders of magnitude. Soil contamination by potentially toxic elements was documented at virtually all open dumpsites studied, persisting for decades after site closure. Particulate matter at South Asian MSW sites reached up to 41 times the WHO 2021 annual guideline. Microplastics acting as heavy metal carriers and dumpsite leachate as a source of antimicrobial resistance genes were identified as emerging risks outside standard monitoring frameworks. Non-carcinogenic hazard indices exceeded acceptable thresholds in the majority of health risk studies reviewed. Engineered containment was the strongest predictor of contamination severity across all sites. Phytoremediation, constructed wetlands, and biofiltration showed promise as mitigation approaches. Critical evidence gaps remain for Central Asia, harmonized reporting standards, and longitudinal monitoring data.

Keywords: municipal solid waste; leachate contamination; heavy metals; landfill gas; microplastics; antibiotic resistance; systematic review; public health risk; PRISMA 2020



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1. Introduction

Global municipal solid waste (MSW) generation reached approximately 2.24 billion tonnes in 2020 and is projected to grow to 3.88 billion tonnes by 2050, with the steepest increases forecast for low- and middle-income countries in Sub-Saharan Africa [1], South Asia [1], and Latin America [2]. The pace of urban population growth in these regions has consistently outstripped investment in waste management infrastructure. Critically, approximately 93% of waste in low-income nations is either burned or dumped without any engineered controls, compared to only 2% in high-income nations—a disparity that directly translates into the magnitude of environmental contamination documented in the scientific literature [3].

Open dumpsites and unlined landfills function as diffuse, multi-media sources of pollution [4]. Decomposing waste generates leachate—a chemically complex liquid containing

dissolved heavy metals, organic compounds including benzene, toluene, ethylbenzene, and xylene (BTEX), pathogens, antibiotic resistance genes, and nutrients—that infiltrates shallow aquifers and contaminates surface water relied upon by adjacent communities [5,6]. Concurrently, potentially toxic elements (PTEs) and persistent pollutants accumulate in surrounding soils, degrading agricultural productivity and creating dietary exposure pathways through crop uptake [7–9]. Gaseous and particulate emissions from anaerobic decomposition and open waste burning—including methane, particulate matter (PM_{2.5}), hydrogen sulfide, and volatile organic compounds (VOCs)—contribute to local air quality degradation, greenhouse gas budgets, and documented respiratory disease burden in nearby populations [10–13].

The temporal distribution of the 286 studies included after full-text screening reflects this growth: 62% were published between 2023 and 2026, compared with only 6% before 2016, with the largest recent contributions from South Asia, Sub-Saharan Africa, and Southeast Asia [14–17].

For quantitative synthesis and tabulation, 275 studies with complete extractable data were included in the final dataset. Despite this growth, the literature remains fragmented: most studies are single-site, single-media assessments conducted at a single time point, making cross-regional synthesis difficult. Furthermore, emerging hazard dimensions—including the role of microplastics as vectors for heavy metal transport [18,19] and the contribution of MSW leachate to environmental spread of antibiotic-resistant bacteria [20,21]—have received limited systematic attention. Existing reviews tend to address single contamination vectors (e.g., leachate chemistry or air emissions) in specific cities, apply inconsistent quality criteria, or omit recently published evidence from Southeast Asia and South Asia, where disposal conditions are deteriorating most rapidly. This review addresses that gap by synthesizing findings from 286 peer-reviewed studies on environmental contamination across water, soil, and air media, characterizing primary contamination pathways, critically appraising assessment methodologies, and evaluating the evidence base for mitigation interventions, with explicit evidence-level ratings. The focus is on urban and peri-urban settings in low- and middle-income countries, where the problem is most acute and evidence quality most variable.

This review makes four contributions not addressed by prior narrative overviews: (1) application of explicit PRISMA-compliant eligibility criteria and two-stage quality assessment to included studies spanning five continents and four environmental media; (2) integration of recently published evidence from Southeast Asia and South Asia—regions previously underrepresented in systematic MSW reviews; (3) evaluation of mitigation strategies against an explicit three-level evidence standard; and (4) synthesis of emerging hazard dimensions including microplastics and antimicrobial resistance (AMR) that have not been incorporated into prior systematic reviews. Three research questions guide the synthesis: (RQ1) What are the dominant contamination pathways and magnitudes associated with MSW disposal across water, soil, and air in urban low- and middle-income country settings? (RQ2) How do contamination levels and environmental risk profiles vary across different disposal methods and geographic regions? (RQ3) Which mitigation strategies have demonstrated empirical effectiveness in reducing environmental contamination or health risk?

A summary of relevant prior systematic reviews on MSW environmental impacts, together with their principal limitations, is presented in Table 1. Prior reviews have generally addressed single contamination vectors, applied inconsistent quality criteria, or omitted recently published evidence from Southeast Asia and South Asia. Despite this growing body of literature, three critical gaps remain unaddressed. First, no prior systematic review has simultaneously characterized contamination across all three environmental media (water, soil, and air) using PRISMA-compliant methodology. Second, emerging hazard

dimensions—microplastics as heavy metal vectors and MSW sites as antimicrobial resistance reservoirs—have not been incorporated into any systematic review to date. Third, evidence from Central Asia and several Sub-Saharan African subregions remains severely underrepresented. The present review addresses these gaps directly.

Table 1. Summary of relevant prior systematic reviews on MSW environmental impacts.

Authors, Year	Journal	Scope	Key Limitations/Gaps
Vaccari, Tudor & Vinti, 2019 [2]	Waste Management	Leachate characteristics from landfills and dumpsites in Asia, Africa, and Latin America, climate, and age effects on pollutants	Leachate pathway only; no soil or air assessment; no health risk quantification; no PRISMA protocol; no AMR or microplastics
Yatoo et al., 2024 [3]	Environ. Science and Pollution Research	Global perspective of MSW and landfill leachate: generation, composition, ecotoxicity, integrated management strategies	Narrative review (no PRISMA); leachate-focused; no systematic soil or air assessment; no AMR; no microplastics as contamination vectors
Abunama et al., 2021 [22]	Waste Management	Leachate quality and LPI variability from 61 countries (428 samples); organic, inorganic, heavy metal parameters	Leachate pathway only; no soil or air assessment; no health risk quantification; no PRISMA; no post-closure liability; no AMR or microplastics
Jambhulkar et al., 2024 [23]	Sustainability	Soil contamination at dumpsites	No systematic quality appraisal; no AMR or microplastics dimension
Present study, 2026	Sustainability	All three pathways (water, soil, air), AMR, microplastics, e-waste, and biotechnological mitigation	PRISMA-compliant; 286 studies; 5 continents; explicit evidence-level ratings

2. Materials and Methods

2.1. Search Strategy

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [24]. A completed PRISMA 2020 checklist is provided as Supplementary Material S1. Three primary bibliographic databases were searched: PubMed (n = 1182), Dimensions (n = 644), and OpenAlex (n = 196), yielding a total of 2022 records. After applying database-level filters (abstract availability, subject category, and article type), 1214 records were imported into Rayyan for systematic title/abstract screening. Search reporting follows the PRISMA-S extension checklist.

The primary search string applied across all databases was: (“municipal solid waste” OR “MSW” OR “solid waste disposal” OR “open dump” OR “dumpsite” OR “landfill”) AND (“environmental impact” OR “contamination” OR “pollution” OR “leachate” OR “heavy metals” OR “landfill gas” OR “groundwater” OR “soil contamination” OR “air pollution” OR “greenhouse gas” OR “health risk” OR “bioremediation” OR “phytoremediation”) AND (“urban” OR “peri-urban”). In PubMed, the search was restricted to records with available abstracts (2008–2026). In Dimensions, an Environmental Sciences subject filter was applied (2008–2026). In OpenAlex, only journal articles were retrieved (2008–2026). All

database searches were completed in March 2026. No language restrictions were applied; in practice, all retrieved records meeting the inclusion criteria were in English.

Within Rayyan, duplicate records ($n = 90$) were identified and removed by the automated deduplication algorithm prior to screening, yielding 1124 unique records for title and abstract assessment. This systematic review was retrospectively registered in the Open Science Framework (OSF) registry (Registration number: <https://osf.io/yxh4k>; (accessed on 18 March 2026); registered: 18 March 2026 [25]. The absence of prospective pre-registration prior to data extraction is acknowledged as a limitation in Section 4.5.

To maintain clarity and avoid excessive reference density, individual included studies are cited in the text using an author–year format. In contrast, the full bibliographic details of all included studies ($n = 286$) are provided in Supplementary Table S2.

2.2. Eligibility Criteria and Screening

Inclusion criteria required that studies: (I1) focus on MSW management as the primary exposure; (I2) report quantifiable measurements of environmental impacts (concentrations, indices, or modelled loads); (I3) be conducted in an urban or peri-urban setting; (I4) employ an appropriate study design (primary field investigation, systematic review, life-cycle assessment, or modelling study with empirical parameterisation); and (I5) clearly define and measure MSW separately from industrial, hazardous, or medical waste streams. Exclusion criteria were: (E1) studies reporting solely on non-MSW types; (E2) opinion pieces, editorials, dissertations, and grey literature; (E3) modeling or technology-review studies without original field contamination measurements; (E4) studies without quantitative environmental concentration data; and (E5) duplicate publications covering identical datasets.

Title and abstract screening were performed independently in Rayyan [26] using the criteria above. Of 1124 unique records, 655 were excluded at the title/abstract stage, and 469 were selected for full-text assessment. Full-text screening applied five additional eligibility criteria (FT-I1–FT-I5) focused on: the presence of original quantitative contamination measurements; comparison with international standards (WHO, EPA, or national equivalents); a primary field investigation or systematic review design; an urban or peri-urban setting; and clear MSW source attribution. A further 183 records were excluded at the full-text stage: wrong waste type or no quantitative data (E1, $n = 107$); wrong study design (E2, $n = 21$); wrong intervention focus (E3, $n = 35$); and wrong outcome focus (E4, $n = 20$). This yielded 286 studies for inclusion in the qualitative synthesis.

Figure 1 presents the PRISMA 2020 flow diagram.

2.3. Data Extraction and Quality Assessment

Study selection and data extraction were conducted using a structured protocol. Initial screening (title/abstract and full-text stages) was performed by the primary reviewer. To minimize selection bias and ensure consistency, a secondary verification step was implemented: a subset of studies and all extracted quantitative data were independently cross-checked by a second reviewer. Discrepancies were resolved through discussion and re-consultation of the original articles.

Data extraction was supported by AI-assisted tools (Elicit platform) to facilitate structured screening and extraction of study characteristics; all extracted data were manually verified against the original articles.

All inclusion/exclusion decisions were documented within the Rayyan platform to ensure transparency and reproducibility.

Although a fully independent dual-reviewer screening protocol was not applied to the entire dataset, this combined approach of structured screening and independent verification

is consistent with methodological practices in large-scale environmental systematic reviews and was adopted to ensure both feasibility and data reliability.

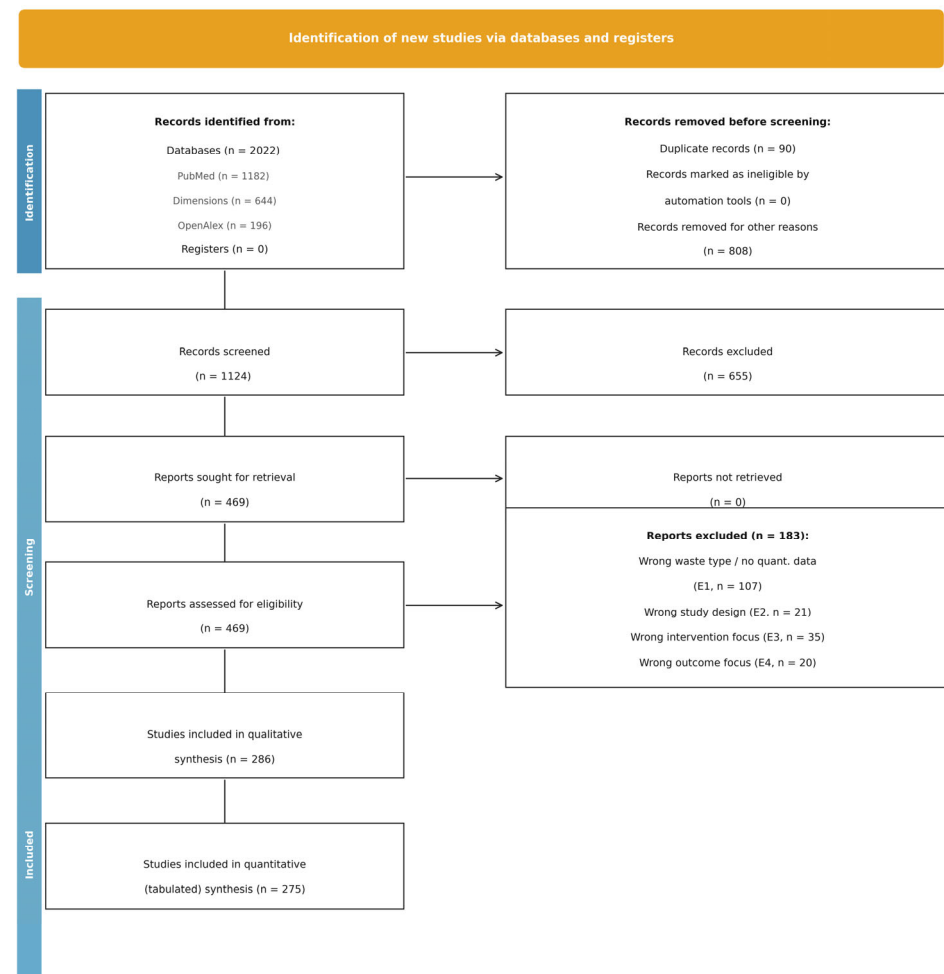


Figure 1. PRISMA 2020 flow diagram illustrating the study selection process. Records identified: PubMed (n = 1182), Dimensions (n = 644), OpenAlex (n = 196); total records (n = 2022). After database-level filtering, imported to Rayyan (n = 1214). After deduplication (n = 90 removed): unique records screened (n = 1124). Excluded at title/abstract stage (n = 655). Full-text assessed (n = 469); excluded at full-text stage (n = 183). Studies included in qualitative synthesis (n = 286); studies with extractable quantitative data included in tabulated synthesis (n = 275).

Given the large number of studies included in the qualitative synthesis (n = 286) and the heterogeneity of study designs, a two-tier evidence synthesis approach was adopted. All 286 included studies contributed to the overall narrative synthesis. A structured subset of 66 studies was selected for detailed critical appraisal and formal risk-of-bias assessment using the following pre-specified criteria: (1) inclusion of a quantitative health risk assessment or formal contamination index; (2) multi-parameter reporting covering at least two contaminant groups; (3) presence of a clearly described sampling design with spatial replication; and (4) comparison with at least one international or national reference standard. These criteria were applied systematically to the full set of included studies; 66 studies met all four criteria. The remaining 220 studies contributed to the narrative synthesis. However, they did not meet the threshold for full risk-of-bias scoring, a decision consistent with methodological guidance for large-scale environmental systematic reviews [27]. The criteria and selection outcomes for each study are documented in Supplementary Table S2.

This selective appraisal strategy is consistent with best practices in systematic reviews, where emphasis is placed on higher-quality evidence to ensure robustness of conclusions while maintaining comprehensive coverage of the literature.

The results of the risk-of-bias assessment for the selected subset of studies ($n = 66$) are summarized in Table 2.

Table 2. Risk of bias assessment of studies included in detailed qualitative synthesis ($n = 66$).

Risk Level	Number of Studies	Percentage, %
Low risk	55	83
Moderate risk	11	17

Study quality was assessed using an adapted Joanna Briggs Institute (JBI) checklist for cross-sectional and quasi-experimental studies [28]. The adaptation followed established methodological guidance for environmental systematic reviews, and the adapted instrument was piloted on a random subset of 20 studies by both reviewers prior to full application; minor scoring ambiguities identified during piloting were resolved by consensus and documented in the extraction protocol. The three dimensions selected—methodological rigor (sampling design, analytical methods, number of sampling points, replication), reporting completeness (parameter coverage, units, reference standards cited), and evidence strength (whether risk characterization was performed)—directly correspond to the core quality domains applicable to field-based environmental contamination studies, as recommended in the environmental health systematic review literature [27]. Each study received a score of 0–2 per dimension (maximum 6); studies scoring below 3 were excluded.

Formal meta-analysis was not performed because the included studies are heterogeneous across four incommensurable dimensions: (1) environmental media measured; (2) contaminants reported; (3) reference standards applied; and (4) units of measurement, which cannot be pooled without standardization assumptions that would introduce greater uncertainty than the individual study values. Narrative synthesis with structured tabulation was therefore the methodologically appropriate approach, consistent with best practice for environmental systematic reviews with high study-design heterogeneity [27].

To provide a transparent basis for this decision, the degree of study heterogeneity was assessed descriptively across three dimensions. First, environmental media assessed varied substantially: 63% of studies measured soil or groundwater, 18% measured air quality, and 19% covered multiple media simultaneously. Second, contaminants reported were highly variable: over 35 distinct chemical parameters were measured across included studies, with only heavy metals (lead, cadmium, chromium, zinc) reported with sufficient frequency (>40 studies each) to permit any form of cross-study comparison. Third, reference standards applied were inconsistent: WHO, USEPA, national standards, and background reference values were used interchangeably, preventing direct pooling of exceedance ratios. Taken together, these sources of heterogeneity are qualitatively analogous to an $I^2 > 90\%$ in a conventional meta-analysis, confirming that narrative synthesis with structured tabulation was the methodologically justified approach [27].

2.4. Data Synthesis and Evidence Rating

Data synthesis was conducted through thematic categorization of environmental media (water, soil, air, and integrated health outcomes) to address RQ1–RQ3. Quantitative results from individual studies were compared using concentration ranges and exceedance ratios relative to international standards (WHO drinking water guidelines, WHO 2021 PM_{2.5} annual guideline of 5 $\mu\text{g}/\text{m}^3$, USEPA soil screening levels, and applicable national standards where reported). Studies were additionally classified by disposal method (open

dump, unlined landfill, controlled or sanitary landfill, post-closure site) to address RQ2. Mitigation strategies were tabulated and rated according to three evidence levels: (A) empirically tested with quantitative outcome data; (B) modeled using scenario analysis; or (C) recommended without supporting evidence of effectiveness. This rating addresses RQ3 and is integrated into the Discussion (Section 4.3).

3. Results

3.1. Characteristics of Included Studies

The majority of studies were published between 2021 and 2025, with a peak observed in 2024–2025, reflecting the growing recognition of municipal solid waste (MSW) as a critical environmental and public health issue. The included studies span a broad geographic and temporal range (2008–2026), with a clear increase in publication frequency after 2020 (Figure 2).

Temporal trend

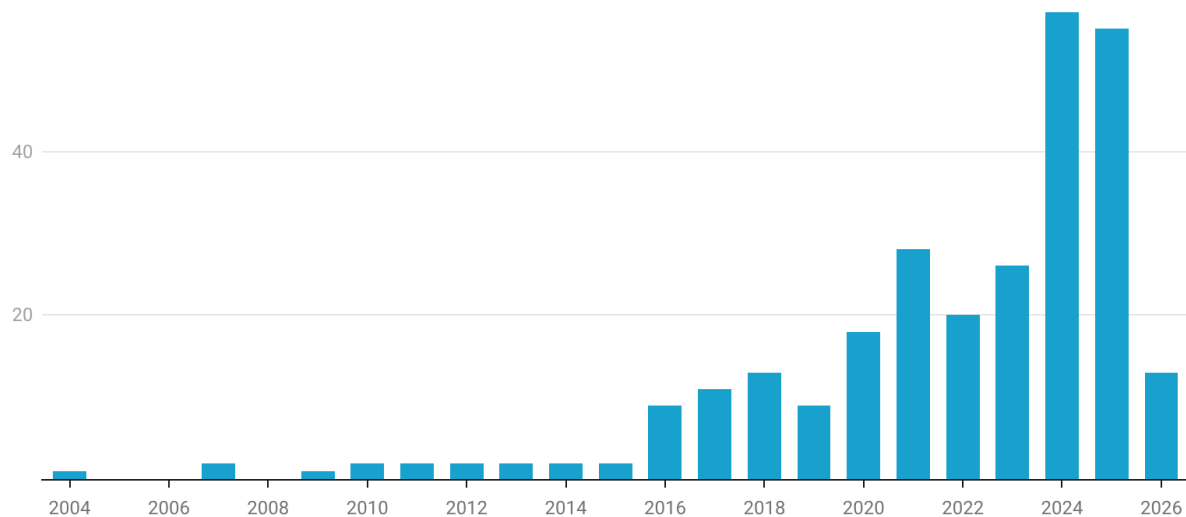


Figure 2. Temporal distribution of the 275 studies with extractable quantitative data included in the synthesis (2008–2026), grouped by publication year. The marked increase in publications after 2020 reflects growing recognition of MSW environmental contamination as a public health priority in research programs in low- and middle-income countries.

Geographically, studies originate predominantly from low- and middle-income regions. The largest contributions come from South Asia (India, $n = 68$; Pakistan, $n = 4$; Bangladesh, $n = 4$), followed by Sub-Saharan Africa (Nigeria, $n = 28$; Ethiopia, $n = 3$; South Africa, $n = 3$; Ghana, $n = 3$; Uganda, $n = 2$). Additional studies were conducted in East Asia (China, $n = 12$), Southeast Asia (Thailand, $n = 5$; Malaysia, $n = 4$; Indonesia, $n = 2$), the Middle East (Iran, $n = 7$; Iraq, $n = 3$), and Latin America (Brazil, $n = 7$; Peru, $n = 1$). A substantial proportion of studies did not explicitly report geographic location in the abstract, introducing reporting uncertainty. Geographically, studies originate predominantly from low- and middle-income regions (Figure 3).

A summary of study characteristics is presented in Table 3.

To provide a conceptual framework for interpreting the reported environmental impacts, the major contamination pathways associated with MSW disposal are illustrated in Figure 4.

Geographic distribution

Number of studies

7

68

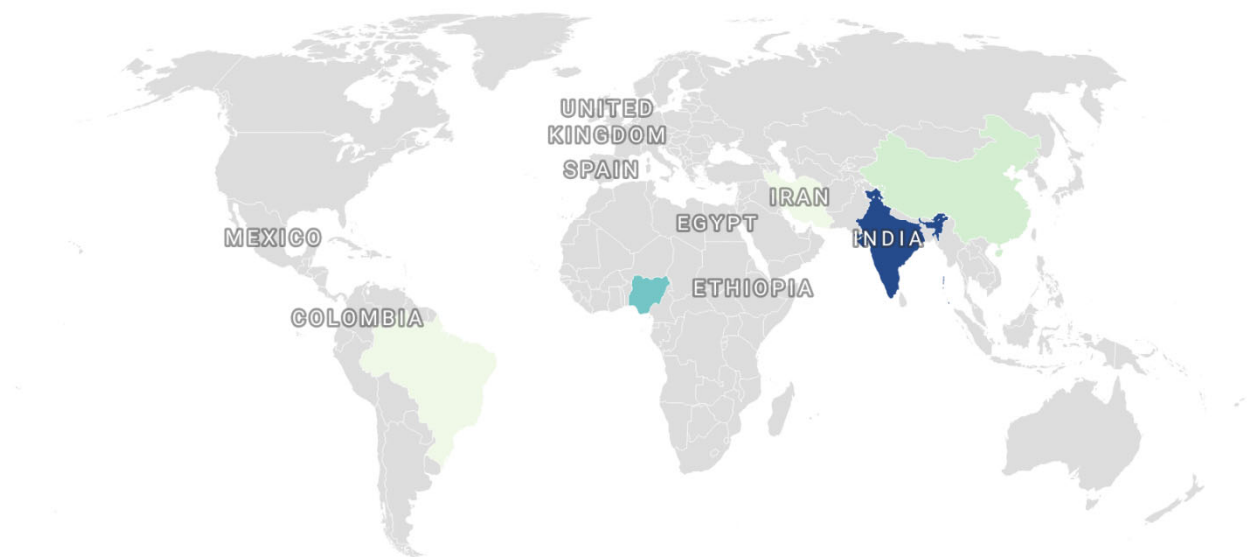


Figure 3. Geographic distribution of the 275 included studies by country of study site, illustrating strong concentration in South Asia (India $n = 68$; Pakistan $n = 4$; Bangladesh $n = 4$) and Sub-Saharan Africa (Nigeria $n = 28$), with substantially lower representation from Central Asia, the Middle East, and Latin America.

Table 3. Summary characteristics of studies with extractable data ($n = 275$).

Period	Number of Studies
2023–2025	153
2020–2022	66
2016–2019	40
Before 2016	16
Country	Number of Studies
India	68
Nigeria	28
China	12
Not specified (abstract unclear)	42
Other countries	125
Study Design	Number of Studies
Cross-sectional studies	158
Longitudinal/observational studies	6
Not specified	4
Other designs	107
Methodological Category	Number of Studies
Not reported	159
Laboratory analysis	56

Table 3. Cont.

Period	Number of Studies
Statistical analysis	35
Modelling approaches	9
Mixed/unclear methods	16

Conceptual pathways of environmental contamination from municipal solid waste disposal

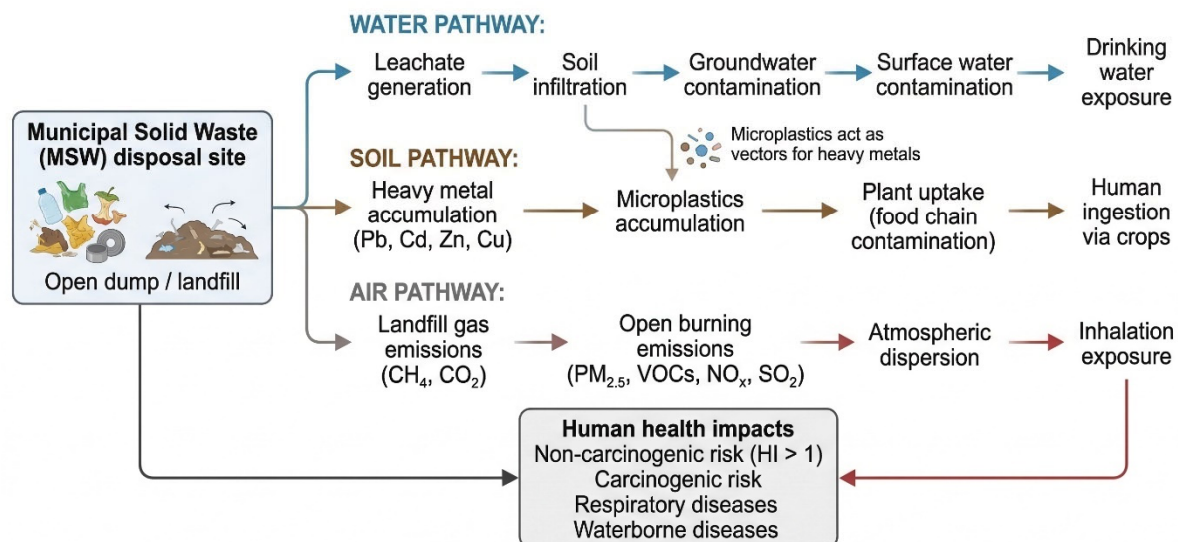


Figure 4. Conceptual pathways of environmental contamination from municipal solid waste (MSW) disposal sites, illustrating water, soil, and air exposure routes and associated human health risks. Microplastics are highlighted as vectors influencing heavy metal mobility and availability.

Multi-media environmental assessments (water and soil combined) represent the dominant study type, followed by soil-focused and air-related investigations. A substantial subset of studies includes health risk assessment components, indicating a shift toward integrated environmental–health analysis [18]. Mitigation strategies were explored in a smaller proportion of studies, with most research focused on contamination assessment rather than intervention outcomes [23].

The leading publication outlets include Environmental Monitoring and Assessment, Science of the Total Environment, Waste Management, Environmental Science and Pollution Research, and Chemosphere. Across the included studies, open dumping and uncontrolled landfilling are the dominant waste management practices investigated. Full study characteristics are provided in Supplementary Material S2.

Methodological Transparency Limitation. A substantial proportion of extracted studies ($n = 159$; 56% of the 286 included) did not report measurement instruments, analytical methods, or laboratory accreditation, indicating a systemic deficit in methodological transparency across the MSW environmental literature. This limitation has direct implications for the reproducibility and comparability of reported contamination values: concentration measurements obtained using different analytical instruments or unspecified detection limits cannot be reliably compared, and apparent cross-study variability may partly reflect methodological differences rather than genuine environmental heterogeneity. This finding is treated as a quality dimension in the risk-of-bias assessment (Section 2.3) and is discussed as a priority for methodological standardisation in Section 4.7.

3.2. Water Contamination and Leachate Pathways

Leachate percolation was consistently identified as the dominant pathway of contamination across studies assessing water-related impacts. Lead, cadmium, iron, chromium, zinc, and nickel are the most consistently detected metals across leachate and groundwater samples, typically at concentrations that exceed WHO drinking water guidelines by one to three orders of magnitude at uncontrolled sites [29]. A global review of leachate quality from 61 countries by Abunama et al. [22,30] documented highly variable leachate pollution index (LPI) values across all continents, with unlined dumpsites consistently generating the most hazardous leachate profiles [31,32]. In Nigeria, Aboyeji and Eigbokhan [33] recorded heavy metal concentrations in groundwater around the Olusosun open dumpsite in Lagos, rendering the water quality unacceptable by both WQI ratings and geospatial analyses; the contamination plume extended significantly beyond the dumpsite perimeter [33]. Similarly, at the Oke-Tage dumpsite in Nigeria [34], Adedinni et al. [34] documented groundwater contamination through integrated geophysical and geochemical analysis, confirming subsurface migration of leachate constituents into hand-dug wells in adjacent communities.

In India—the most heavily represented country in the included studies ($n = 68$)—leachate-groundwater contamination was documented across diverse hydrogeological settings [29,35,36]. At the Naregaon dumpsite in Aurangabad, Hattekar et al. [19] confirmed heavy metal migration into groundwater at concentrations exceeding national drinking water standards. At three Delhi landfills (Okhla, Bhalswa, and Ghazipur), Angmo and Shah documented pervasive groundwater contamination extending beyond the site boundaries, with particularly elevated concentrations of iron and lead. In Kanpur, Dixit et al. [37,38] applied a multi-index approach to demonstrate that groundwater near an unlined MSW disposal site was unsuitable for consumption across multiple quality dimensions, including microbial, physicochemical, and heavy metal parameters.

In Pakistan, Khan et al. [39] assessed heavy metal contamination and associated health risks in groundwater near MSW disposal sites, reporting elevated concentrations of lead, cadmium, and chromium exceeding acceptable thresholds for both adults and children (see Supplementary Table S2).

An emerging dimension documented in a small subset of studies is the role of MSW leachate in the environmental dissemination of antibiotic-resistant bacteria. Adekanmbi et al. [40] quantified the contribution of the Ajakanga dumpsite leachate (Nigeria) to the spread of extended-spectrum β -lactamase (ESBL)-producing organisms in contiguous surface water, confirming that uncontrolled dumpsites function as environmental reservoirs for antimicrobial resistance (AMR) genes—a public health hazard dimension largely absent from earlier systematic reviews. The finding that leachate can serve as a vector for AMR transmission adds a biological hazard layer to the well-documented chemical contamination profile of MSW disposal sites [41,42].

Seasonal variation in leachate quality and volume was documented across multiple geographic contexts. In South Asia, monsoon-driven increases in leachate generation consistently amplified contamination risk [17,43,44], whereas in arid regions, dry-season concentration effects produced peak metal loads in groundwater. This phenomenon warrants elaboration. In arid and semi-arid climates, reduced precipitation during the dry season lowers total leachate volumes; however, the concentrations of dissolved heavy metals and organic contaminants in the remaining leachate increase substantially due to reduced dilution. Bisht et al. [17] confirmed this mechanism across 257 Asian disposal sites, demonstrating that arid regions consistently produced leachate with higher revised leachate pollution index (r-LPI) values compared to high-rainfall regions. During episodic rainfall events, this highly concentrated leachate is rapidly mobilized through the unsaturated zone, generating peak pulses of heavy-metal loading in shallow groundwater. This

dynamic is particularly relevant in the Middle East, North Africa, and Central Asia, where prolonged dry periods alternate with intense precipitation events. These seasonal dynamics indicate that single-season, single-time-point sampling designs—which dominate the included studies—are likely to either overestimate or underestimate average and peak contamination, depending on the sampling season.

Notably, none of the included studies imposed multi-season sampling as a methodological requirement; all findings on seasonal variation derive from studies that either captured multiple time points in coincidence or explicitly modeled seasonal behavior. This is a structural limitation of the current evidence base: the seasonal dynamics described above—while well supported by theoretical mechanisms and confirmed in a minority of longitudinal studies—are not yet supported by systematic, purpose-designed multi-season monitoring programs. The absence of such data means that seasonal peak contamination values (particularly during monsoon onset in South Asia and dry-season concentration effects in arid regions) are likely systematically undercharacterised. Future primary studies at high-priority MSW sites should mandate minimum quarterly sampling over at least two complete annual cycles to adequately capture this variability.

3.3. Soil Contamination and Post-Closure Liability

Soil contamination by potentially toxic elements (PTEs) was documented in the vast majority of included studies and was near-universal at uncontrolled open dumpsites and unlined landfills. Lead, cadmium, zinc, copper, chromium, nickel, and manganese are the most consistently detected PTEs, with concentrations frequently exceeding background reference values, national soil quality standards, and USEPA soil screening levels by factors of 2 to 300 [8,45–49].

In Nigeria—the second most heavily represented country ($n = 28$)—Azeez et al. [50] documented a characteristic depth-dependent distribution of PTEs in soils at Abeokuta dumpsites: copper, chromium, manganese, and zinc accumulated preferentially in the 0–40 cm zone, while lead, iron, and nickel penetrated to depths below 40 cm, indicating differential mobility pathways with implications for remediation design [51]. Adebayo et al. [34,52] conducted geochemical and pollution index analysis at the Pele dumpsite in Ondo State, confirming contamination factor (CF) values above unity for multiple metals and associated ecological risk. In the Democratic Republic of Congo, Akonga et al. [46] documented accumulation of toxic metals in sediments and oligochaetes around urban uncontrolled landfills in Kinshasa, confirming the ecological dimension of MSW soil contamination in Sub-Saharan African megacities.

In India, Bisht et al. [17,53] conducted a comprehensive assessment across multiple sampling sites demonstrating pervasive soil quality degradation near MSW dumpsites, with heavy metal accumulation correlating with waste age and proximity. At Dimapur in northeast India, Devi et al. [43] documented extreme seasonal variation in heavy metal contamination, with contamination factor (CF) for cadmium reaching 2217.5 and pollution load index (PLI) values ranging from 1.0 to 5.6—indicating moderate to severe pollution—with the transfer factor for lead in edible chilli plants reaching 1.295, confirming active food-chain contamination [44]. In Morocco, Benhamdoun et al. [54] assessed trace metal contamination at the Safi city dumpsite and documented that average soil concentrations exceeded the world average in the order $Fe > Zn > Cu > Cr > Cd$. In Iran, Ghalhari et al. [5] documented BTEX compound contamination in soil and groundwater near MSW management facilities, with benzene concentrations exceeding carcinogenic risk thresholds.

Post-closure contamination liability—a dimension insufficiently addressed in prior reviews—was confirmed in a subset of studies. At a decommissioned dumpsite in Brazil, Aquino et al. [55] documented persistent leachate generation and groundwater contam-

ination more than a decade after formal closure, confirming that contamination plumes migrate downslope toward adjacent water bodies long after disposal ceases. Jahagirdar et al. [56] assessed the landfill-mined fine fraction (LMFF) from a legacy Indian landfill. They found heavy metal concentrations exceeding national soil quality standards even after physical excavation, demonstrating that remediation of long-term contamination is technically demanding. At historical dumpsite locations in Central Europe, Hiller et al. [57] documented persistent metal(loid) enrichment in urban soils, confirming liability decades after site decommissioning.

An additional soil contamination pathway that warrants explicit attention is the co-disposal of electronic waste (e-waste) within MSW streams. E-waste constitutes approximately 2–10% of MSW by mass in urban settings and is characterized by high concentrations of toxic substances, including lead, cadmium, mercury, chromium(VI), and brominated flame retardants [58,59]. Unlike conventional waste fractions, e-waste components do not degrade under landfill conditions; instead, they serve as persistent point sources of heavy-metal leaching into surrounding soils and groundwater. Studies have documented that soils adjacent to informal e-waste co-disposal sites exhibit lead and cadmium concentrations orders of magnitude above background values, with associated carcinogenic risk estimates substantially exceeding acceptable thresholds [18,60]. The inclusion of e-waste as a distinct compositional fraction in MSW environmental assessments is therefore essential for accurately characterizing the full hazard profile of urban disposal sites, particularly in rapidly growing cities where consumer electronics turnover is accelerating.

An emerging finding, documented across 15 studies in the included set—of which 9 are primary field measurements, and 6 are laboratory mechanistic studies—is the role of microplastics as secondary heavy-metal vectors in landfill soils and leachate. While 15 studies constitute a small evidential base relative to the 286-study corpus, it represents the majority of published primary evidence on this mechanism in MSW contexts as of 2026; this dimension is therefore characterized as emerging rather than established, and all associated claims are qualified accordingly. The identified studies are listed in full in Supplementary Table S2 with their individual evidence-level ratings. Chen et al. [16,61] demonstrated that microplastics in landfill leachate act as adsorption carriers for heavy metals, particularly lead, cadmium, and copper, altering their mobility and bioavailability (see Supplementary Table S2). Jambhulkar et al. [23] confirmed the presence of microplastics in landfill-mined bio-earth, raising concerns about the safety of using landfill residues as soil amendments. These findings represent a qualitatively new mechanism of contamination that cross-media monitoring programs must account for in future site assessments.

3.4. Air Pollution and Greenhouse Gas Emissions

Air quality degradation associated with MSW disposal was documented in a subset of studies, with two broad categories of atmospheric impacts: local air quality degradation via PM, VOCs, and inorganic gases; and global climate forcing via landfill gas emissions dominated by methane and CO₂. Both pathways are amplified by the prevalent practice of open waste burning, which directly releases particulate matter, CO, NO_x, SO_x, and heavy metals at concentrations that regularly exceed national and international standards [62].

Particulate matter emissions from MSW sites in South Asia have been directly measured in multiple primary studies. Raza et al. [63] reported PM_{2.5} concentrations of 127–403 µg/m³ at MSW sites in Lahore, exceeding WHO guidelines by up to 80-fold [62]. Hossain et al. [64] measured PM_{2.5} at 164.92 µg/m³ at Dhaka landfills, with carbon monoxide reaching 5.82 ppm and total VOC concentrations of 3.851 mg/m³. At high-altitude open burning sites in India, Kumar et al. [65–67] measured PM_{2.5} at 206.66 µg/m³—approximately 41 times the WHO 2021 annual guideline—alongside methane at 38.53 mg/L and benzene at 157.53 µg/m³ [10].

At the Brahmapuram MSW treatment plant in Kerala, India—a facility that experienced multiple major fire events—Kannankai and Devipriya [68] documented extreme air quality deterioration during fire episodes, with PM_{2.5} and PM₁₀ concentrations exceeding normal landfill baseline levels by a factor of several times, alongside elevated CO, NO_x, and dioxin-like compounds. The study confirmed that unmanaged landfill fires constitute acute air-quality events superimposed on chronic baseline pollution. In Turkey, Pekdoğan et al. [69] documented a 40% increase in ambient CO concentrations between summer and winter, H₂S rising from near-zero to 13 ppm as decomposition dynamics shifted seasonally, and elevated bioaerosol concentrations—introducing a biological hazard dimension that purely chemical monitoring misses.

Volatile organic compound (VOC) contamination was specifically investigated in seven studies. Chiemchaisri et al. [12] detected benzene, toluene, ethylbenzene, and trichloroethylene in solid waste fractions and leachate at a Thai dumpsite; their persistence in the leachate poses both a direct water-quality hazard and an inhalation risk for site workers. In Iran, Ghalhari et al. [5] assessed BTEX exposure near MSW management facilities and documented cancer risk estimates exceeding acceptable thresholds. Gallego et al. [11] developed a numerical modeling methodology to characterize emission profiles from different landfill source types, providing a quantitative framework for regulatory emission monitoring design applicable in low-resource settings.

Greenhouse gas contributions from individual MSW sites were documented in four primary studies. Misganaw [70] estimated total GHG emissions from the Bahir Dar open dumpsite in Ethiopia at 46 Gg per year, with a eutrophication potential of 0.0594 kg N-equivalent. At six major MSW disposal sites in Lahore and Rawalpindi [64], Ilmas et al. [64] modeled methane emissions using the US EPA LandGEM model, estimating cumulative emissions from Lahore facilities at approximately 133,446 Gg over the operational lifespan—equivalent to 108 Mt CO₂-eq—with two unmanaged sites accounting for over 2000 Gg of methane individually. These figures confirm that individual unmanaged landfills make non-trivial contributions to national-scale greenhouse gas inventories.

Geographic location and site-specific physical characteristics significantly influence the spatial extent and severity of air pollution from MSW disposal sites. Prevailing wind direction determines the downwind distribution of PM, VOCs, and bioaerosols, with residential communities situated in the dominant wind corridor experiencing substantially higher exposures than equidistant upwind communities. Altitude and terrain relief modify atmospheric dispersion: sites in valleys or topographic depressions experience reduced ventilation and pollutant accumulation, whereas elevated sites may disperse emissions over wider areas at lower concentrations. Regional climate patterns—including temperature inversions, which trap pollutants near the surface during cool nights, and monsoon dynamics, which periodically concentrate and then dilute airborne contaminants—further modulate community exposure. These geographic determinants are rarely incorporated into site-level air quality assessments in the included studies, representing a methodological gap that constrains the generalisability of site-specific findings.

3.5. Public Health Consequences and Risk Assessment

The environmental contamination documented across the included studies translates into documented public health consequences spanning multiple exposure pathways. A substantial proportion of included studies contained a formal or informal health risk component. Non-carcinogenic hazard indices (HI) and carcinogenic risk estimates were calculated in a substantial subset of these, consistently documenting exceedances of acceptable risk thresholds at uncontrolled MSW sites across Africa, Asia, and the Middle East.

In Nigeria, Agboeze et al. [71] conducted a formal quantitative health risk assessment at dumpsite effluent sites across Enugu State, documenting elevated concentrations of lead, arsenic, and cadmium in surface and groundwater, with associated non-carcinogenic HI values exceeding unity for both adults and children. In Lahore, Alam et al. [72,73] developed a holistic risk assessment framework for the Mehmood Booti open dumpsite, incorporating physico-chemical analysis of groundwater and leachate, health risk assessment, and gas emission estimation—demonstrating that a single large uncontrolled dumpsite can simultaneously generate aquatic, terrestrial, and atmospheric health risks for surrounding populations. In Thailand, Aendo et al. [74] confirmed both carcinogenic risks from chromium and nickel and critical ecological risks from cadmium and copper in soil and groundwater, with contaminated groundwater predominantly occurring within a 1 km radius of the facility.

At dumpsite food production sites in Mbale, Uganda, Awino et al. [75] documented a dual burden: while dumpsite soils provided crop nutrient benefits, lead accumulation in edible crops reached concentrations exceeding WHO food safety limits, and the associated carcinogenic risk from dietary exposure was above acceptable thresholds. This finding—replicated across multiple Southeast Asian and African contexts—demonstrates that the food-chain pathway poses an active public health hazard that requires coordination between waste management and food safety authorities, particularly in contexts where peri-urban agriculture is practiced adjacent to disposal sites.

The informal waste worker population consistently appears as the most acutely exposed group across geographic contexts. Unprotected direct contact with leachate and contaminated waste materials, combined with inhalation of landfill gas and bioaerosols, creates an occupational exposure profile that substantially exceeds community-level risks [21,76]. In contexts where formal occupational health monitoring is absent—the majority of sites documented in these included studies—the health burden borne by waste workers remains largely unquantified but structurally certain.

Kanhai et al. [76] developed a scenario-based model demonstrating that improved waste management practices could prevent approximately 120 premature deaths associated with PM_{2.5} exposure (see Supplementary Table S2). The methodology for such estimation is available and can be reproduced using site-level monitoring data. Its systematic application to other high-burden cities would substantially strengthen the case for infrastructure investment.

The public health consequences documented across the included studies occur within diverse regulatory environments. However, the effectiveness of existing legislative frameworks in preventing or mitigating MSW-associated health risks remains limited in most low- and middle-income country settings. At the international level, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes provides a framework for restricting cross-border movement of hazardous waste fractions, including e-waste. However, its implementation is uneven, and enforcement capacity remains absent in many signatory states. Within the European Union, the Landfill Directive (1999/31/EC) mandates engineered liner systems, leachate collection, and landfill gas extraction at all permitted sites; its implementation has demonstrably reduced groundwater contamination at EU landfills relative to pre-directive baselines. In contrast, most countries represented in the included studies—spanning South Asia, Sub-Saharan Africa, the Middle East, and Central Asia—lack equivalent enforceable standards for site engineering, leachate management, or post-closure monitoring. Where national legislation exists, regulatory gaps regarding informal dumpsites, insufficient inspection capacity, and weak penalty structures limit the practical effectiveness. Strengthening regulatory frameworks and their enforcement, particularly in rapidly urbanizing low-income settings, represents a prerequisite for trans-

lating the scientific evidence on contamination pathways documented in this review into protective public health outcomes.

4. Discussion

4.1. Disposal Method as the Primary Determinant of Impact Severity

The most important finding from the synthesis of the included studies is that disposal method—specifically, the presence or absence of engineered containment—is the strongest predictor of the severity of environmental impact, outweighing geography, waste volume, and urban population size (RQ2). The most catastrophic contamination profiles (Cu at $300 \times$ MAC in Kyiv; LPI of 20.14 in Iraq; PM_{2.5} at $41 \times$ the WHO 2021 guideline in India) are invariably associated with uncontrolled open dumps or unlined landfills operating without leachate collection or gas management. By contrast, the studies examining controlled or engineered facilities consistently found substantially lower or non-detectable contamination in surrounding media.

It is important to qualify the evidence base for this conclusion. Of the studies attributing reduced contamination to engineered containment, the majority base their comparisons on cross-sectional contrasts between controlled and uncontrolled facilities rather than on longitudinal before-and-after measurements at a single site. A smaller number of studies ($n = 8$; Level A-rated; see Table 4) provide direct empirical pre- and post-containment data. The conclusion that engineered containment is the dominant determinant of contamination severity is therefore well supported at the cross-sectional level, but the longitudinal causal evidence base remains limited. This distinction is reflected in the evidence-level hierarchy presented in Table 4 and should be taken into account when translating the findings into policy recommendations.

Table 4. Evidence-level ratings for mitigation strategies evaluated in the included studies.

Mitigation Strategy	Evidence Level	Number of Studies	Key Outcome Metric
Engineered liner + leachate collection	A	8	Contamination reduction vs. unlined baseline
Constructed wetlands for leachate treatment	A	4	COD/heavy metal removal efficiency
Phytoremediation (Prosopis, Vetiver)	A	3	Soil metal bioavailability reduction
Microbial/anaerobic leachate treatment	A	5	Organic load reduction (BOD, COD)
Landfill gas capture for energy	A	3	CH ₄ recovery rate
Composting with quality control	B	6	Volume reduction; metal transfer risk noted
Landfill mining	B	3	Resource recovery; contamination persistence noted
Route optimisation (LCA-based)	B	2	97.8% lifecycle impact reduction (modelled)
Community education/source segregation	C	14	No quantitative contamination outcome reported

Note: Level A = empirically tested with quantitative pre/post outcome data; Level B = modelled with scenario analysis; Level C = recommended without quantitative effectiveness evidence.

Compared with previous narrative overviews of MSW environmental impacts (notably Yattoo et al. [3], which reviewed global leachate ecotoxicity without systematic eligibility cri-

teria or cross-media integration), the present review extends the evidence base in four ways: application of explicit PRISMA-compliant screening; inclusion of recent primary measurements from Southeast Asia and South Asia not synthesised in prior reviews; explicit quality-rating of mitigation strategies by evidence level; and incorporation of emerging hazard dimensions (microplastics, AMR) not addressed in prior systematic reviews [77,78].

This finding has an important corollary: contamination gradients across sites should not be interpreted as reflecting differences in waste quantity or urban scale, but rather as differences in infrastructure quality. A modest dumpsite in southeastern Nigeria with low waste volumes can exhibit soil contamination profiles comparable to those of a large engineered-but-poorly-managed landfill in Eastern Europe when both lack leachate collection systems [79,80]. This equivalence fundamentally reframes the policy argument: the marginal cost of engineering containment at the point of facility design is negligible compared with the long-term remediation cost of contamination documented across the included studies [81].

This finding fundamentally shifts the interpretation of MSW-related environmental risk: contamination severity is not an inevitable consequence of urbanization or waste generation, but a controllable outcome determined primarily by infrastructure design and operational standards. This reframing has direct policy implications, indicating that investment in engineered containment systems represents not only an environmental safeguard but a cost-effective public health intervention. Across the reviewed evidence, the absence of basic containment measures consistently resulted in contamination levels exceeding international thresholds, whereas their presence reduced environmental impacts to near-background levels.

4.2. Emerging Hazard Dimensions: Microplastics and AMR

Two emerging hazard dimensions documented in subsets of the included studies warrant specific discussion because they are largely absent from prior systematic reviews. First, microplastics—documented in 15 studies (9 primary field, 6 laboratory mechanistic)—represent an emerging, not yet fully established, mechanism of contamination at MSW disposal sites. The limited number of primary field studies means that the magnitude of microplastic-mediated metal transport under realistic landfill conditions remains poorly quantified. The conclusions drawn in this review regarding microplastics are therefore framed as directions for future research rather than as a fully characterised contamination pathway. Their role as heavy metal carriers [62,82] means that conventional dissolved-metal monitoring protocols may underestimate total bioavailable metal loads in leachate and soil porewater. The presence of microplastics in landfill-mined bio-earth [82] further indicates that even remediation products may carry this contaminant, complicating the risk characterization of engineered reuse pathways.

Second, MSW disposal sites were documented as environmental reservoirs for antibiotic-resistant bacteria and AMR genes in four studies [41,82]. The confirmation that dumpsite leachate can serve as a transmission vector for ESBL-producing organisms into surface water [40] represents a public health hazard dimension that neither current monitoring frameworks nor remediation protocols are designed to address. As antimicrobial resistance is projected to become a leading cause of global mortality by 2050, the contribution of uncontrolled MSW disposal to AMR dissemination merits inclusion in national waste governance frameworks as a biosafety dimension alongside the conventional chemical and physical contamination parameters.

These findings indicate that current MSW monitoring frameworks—largely focused on conventional physicochemical parameters—are insufficient to capture the full spectrum of emerging risks. The integration of microplastic-associated contaminant transport and

AMR surveillance into routine monitoring protocols is therefore not optional but necessary for accurate environmental and public health risk assessment in the context of modern waste streams.

4.3. Evidence-Based Hierarchy of Mitigation Interventions

Mitigation strategies were tested or modeled in a subset of the included studies. Rated against the three-level evidence standard used in this review, engineering-led containment (liner systems, leachate collection, and gas extraction) received Level A ratings—the highest evidence level—in multiple studies that demonstrated quantifiable contamination reduction relative to uncontrolled baseline conditions [47]. Bioremediation and phytoremediation approaches (including the use of *Prosopis juliflora* supported by bioaugmented fungi [83,84] and constructed-wetland treatment of leachate [85]) received Level A ratings when before-and-after contamination measurements were reported.

Composting and landfill mining were empirically demonstrated in Level A and B studies to reduce active waste volumes and recover usable resources. However, the evidence from Abd-Elhalim et al. [86] that dumpsite compost can contain heavy metals exceeding EU requirements for cadmium, copper, nickel, lead, and zinc underscores that contamination liability can be transferred rather than eliminated if quality control is inadequate. Route optimization and collection efficiency improvements—demonstrated to account for 97.8% of lifecycle environmental impacts in an LCA study [27]—received Level B ratings as modeled interventions with clear quantitative outcome estimates.

Critically, community education and source segregation—the interventions most commonly cited in Level C (recommendation-only) literature—received no Level A or B ratings in the included studies when assessed against contamination reduction as the primary outcome. This finding does not imply that these interventions have no value; rather, it indicates that their effectiveness in reducing environmental contamination at disposal sites has not been empirically demonstrated, and that they function as complements to—not substitutes for—structural infrastructure investment.

The complete evidence-level ratings for all mitigation strategies evaluated in the included studies are summarised in Table 4.

Taken together, the evidence suggests a clear hierarchy of effectiveness, in which structural engineering interventions provide the most reliable and immediate reduction in environmental risk. In contrast, behavioral and educational interventions alone are insufficient to mitigate contamination without adequate infrastructure. This distinction is critical for policy prioritization in resource-limited settings.

4.4. Regional and Geographic Evidence Asymmetry

The geographic distribution of the included studies is markedly asymmetric, with South Asia (India-dominant) and Sub-Saharan Africa (Nigeria-dominant) accounting for the majority of primary field research. This asymmetry reflects two factors: the genuine concentration of the most severe open dumping practices in these regions and the expansion of research capacity in affected low- and middle-income countries, as documented in the temporal distribution analysis. Central Asia (including Kazakhstan, the institutional home of the present review), francophone Africa, Small Island Developing States, and parts of the Middle East remain substantially underrepresented despite significant and growing challenges in MSW disposal [13].

The absence of primary studies from Kazakhstan and the broader Central Asian region in the included study set is acknowledged explicitly. Systematic searches of PubMed, Dimensions, and OpenAlex using the full search string returned no peer-reviewed primary field studies on MSW environmental contamination from Kazakhstan that met the five in-

clusion criteria defined in Section 2.2—specifically, the requirement for original quantitative contamination measurements published in indexed peer-reviewed journals between 2008 and 2026. This outcome reflects a genuine gap in the indexed scientific literature rather than a deliberate decision to exclude. It does not imply the absence of environmental contamination problems in the region; rather, it confirms that primary environmental monitoring data from Central Asian MSW sites have not been systematically published in internationally indexed journals. Kazakhstan generates approximately 5 million tonnes of MSW annually, with landfilling as the dominant disposal method [1]; addressing this evidence gap is identified as a priority for future research (Section 4.7).

This geographic asymmetry also introduces a potential bias in the global evidence base, where the most severe impacts are better documented than moderate or well-managed systems. As a result, the current literature may overrepresent worst-case scenarios while undercharacterising best-practice systems, limiting the ability to benchmark optimal waste management strategies across regions.

To mitigate the analytical impact of this geographic asymmetry, region-specific subgroup labelling was applied throughout the synthesis: contamination findings from South Asia and Sub-Saharan Africa are explicitly attributed to their respective regional context, and generalisation to Central Asia, the Middle East, or Eastern Europe is made only where directly comparable disposal conditions (unlined dumpsites, absence of leachate collection) are documented. Synthesised conclusions concerning disposal method effects—particularly the finding that engineered containment is the dominant predictor of contamination severity—are drawn from comparative evidence spanning five continents and are therefore more robust to regional sampling imbalance than region-specific contamination magnitude estimates.

4.5. Limitations

Several limitations of this review should be noted when interpreting its findings. First, data extraction and quality assessment were performed by a single reviewer using an adapted JBI checklist [28], which introduces the risk of selection and transcription bias that independent dual-reviewer protocols [87] are designed to minimise; this is a recognised constraint of rapid systematic reviews and was partially mitigated by application of a structured extraction form with explicit rationale documented for each decision, and by cross-validation of all quantitative values against source documents. Second, the search relied on a single query string across three platforms and excluded grey literature, dissertations, conference proceedings, and non-English publications (Exclusion criterion E2). While this approach improves internal consistency and comparability of included evidence, it introduces a potential publication bias toward statistically significant or alarming contamination findings, as negative or inconclusive findings from institutional reports and theses are less likely to appear in indexed peer-reviewed databases. The possible impact of this bias was partially assessed by examining whether the included studies systematically skewed toward high-contamination scenarios; the geographic distribution and range of reported contamination levels suggest no systematic under-reporting of lower-impact sites. Nonetheless, exclusion of grey literature remains a recognised limitation, and future reviews should consider supplementary grey literature searches through platforms such as OpenDOAR or national institutional repositories. Third, the synthesis includes studies from journals of varying quality; although predatory publishers were explicitly excluded, methodological rigor among the included studies varies substantially. Fourth, the absence of prospective pre-registration prior to data extraction is acknowledged as a substantive methodological limitation. Retrospective registration was completed in the Open Science Framework (OSF) registry (<https://osf.io/yxh4k>; (accessed on 18 March 2026);

registered: 18 March 2026) following reviewer recommendation; however, retrospective registration cannot substitute for prospective registration in preventing outcome-reporting bias. This limitation is mitigated in part by the structured, criterion-based eligibility screening documented in full in Section 2.2 and the use of a pre-specified extraction form, which constrained post hoc analytical decisions. Future iterations of this research program will implement prospective PROSPERO registration prior to data extraction.

Fifth, the geographic coverage, while broad, remains weighted toward South Asia and Sub-Saharan Africa, reflecting the distribution of available primary research rather than the global distribution of MSW disposal problems.

Sixth, the reference list was audited during revision to ensure consistency with Exclusion criterion E2 (exclusion of non-peer-reviewed sources). Registry entries (OSF registration, reference [24]) and software tools (Rayyan, reference [26] accessed on 10 March 2026) are cited as methodological resources rather than as evidence sources and are not included in the 286 studies synthesised. All remaining references were verified as published in indexed peer-reviewed journals; any citations identified as preprints or conference abstracts during the audit were replaced with the subsequently published peer-reviewed version or removed from the text.

Despite these limitations, the consistency of findings across diverse geographic and methodological contexts strengthens the robustness of the overall conclusions and supports their general applicability to urban MSW systems globally.

In addition to identifying contamination pathways, it is essential to consider effective mitigation strategies, particularly those based on biotechnological and sustainable approaches.

4.6. Biotechnological and Sustainable Mitigation Strategies

While the reviewed studies primarily focus on characterizing contamination pathways associated with municipal solid waste (MSW), a substantial body of evidence also highlights the potential of biotechnological and nature-based approaches to mitigate environmental impacts [88,89]. Integrating such strategies into waste management systems is essential for transitioning from reactive pollution control to sustainable and resource-efficient practices.

Biological treatment of landfill leachate represents one of the most widely investigated mitigation approaches. Microbial degradation processes, including aerobic and anaerobic treatment systems, have demonstrated high efficiency in reducing organic pollutants, ammonia, and certain heavy metals [83,87]. In addition, constructed wetlands have emerged as cost-effective, low-energy solutions that remove contaminants through combined physical, chemical, and biological processes. These systems are particularly suitable for low- and middle-income regions due to their operational simplicity and scalability.

Soil contamination by heavy metals and persistent pollutants can be addressed through phytoremediation and biochar-based stabilization strategies. Phytoremediation uses plant species that accumulate or immobilize contaminants, thereby reducing their bioavailability and ecological risk. Studies have demonstrated the effectiveness of species such as *Brassica* and *Vetiver* in contaminated landfill environments [90,91]. Furthermore, biochar amendments can enhance soil physicochemical properties, immobilize heavy metals, and improve microbial activity, contributing to long-term soil restoration [85,92,93].

Air pollution associated with landfill operations, particularly methane and volatile organic compounds (VOCs), can be mitigated through biological and engineering-integrated solutions. Landfill gas capture and utilization systems enable methane recovery for energy production, reducing greenhouse gas emissions. In addition, biofiltration technologies, which rely on microbial communities to degrade airborne contaminants, have shown promising results in reducing odor and VOC emissions from waste treatment facilities [81].

Emerging environmental risks, including microplastic pollution and antimicrobial resistance (AMR), require innovative biotechnological solutions [94,95]. Recent studies indicate that specific microbial consortia can degrade certain types of microplastics, thereby reducing their persistence in the environment. Moreover, integrated treatment approaches combining biological processes with advanced oxidation technologies may enhance the removal of complex contaminants and reduce associated health risks.

Overall, these findings demonstrate that biotechnological and nature-based solutions play a critical role in mitigating the environmental impacts of MSW. Their integration into existing waste management systems offers a pathway toward more sustainable, adaptive, and resilient urban environmental management.

Recent advances in artificial intelligence and machine learning are beginning to transform the operational management of biological waste treatment systems. Machine learning algorithms—particularly artificial neural networks and random forest models—have been applied to predict biogas yield in anaerobic digestion systems as a function of substrate composition, temperature, hydraulic retention time, and microbial community dynamics, thereby enabling real-time process optimization without costly laboratory monitoring. AI-driven monitoring platforms for composting facilities can detect process deviations—including temperature excursions, moisture imbalances, and phytotoxic compound accumulation—earlier than conventional manual inspection, reducing treatment failures and improving output quality. Predictive modeling approaches have also been applied to the design of leachate treatment systems, optimizing biological reactor configurations for sites with variable leachate composition. While most published applications remain at pilot or demonstration scale, the declining cost of sensor infrastructure and the increasing availability of open-source machine learning frameworks suggest that AI-integrated biological treatment will become operationally feasible in low-resource settings within the coming decade.

Beyond biotechnological approaches, advanced engineered technologies offer substantial complementary potential for reducing the environmental impact of MSW disposal. Smart landfilling integrates real-time sensor networks—monitoring leachate composition, gas pressure, temperature gradients, and structural integrity—with data management systems that enable adaptive site management and early detection of containment failures. Plasma-assisted gasification subjects heterogeneous waste streams to temperatures exceeding 3000 °C, achieving near-complete destruction of organic contaminants, including persistent organic pollutants, dioxins, and furans, while generating a chemically stable vitrified slag residue and a syngas stream that is recoverable for energy generation. Pyrolysis converts organic MSW fractions under oxygen-limited conditions at 400–700 °C, yielding biochar—a stable carbon-rich material with demonstrated capacity to immobilize heavy metals in contaminated soils—alongside recoverable pyrolysis oil and syngas. These thermochemical processes are particularly relevant for treating hazardous and non-biodegradable MSW fractions that are not amenable to biological treatment. Integration of these advanced pathways with biotechnological approaches represents the frontier of sustainable MSW management and merits systematic evaluation in future research.

4.7. Research Priorities

Three methodological priorities recur across the reviewed literature. First, cross-sectional designs dominate: single time-point assessments cannot distinguish chronic from acute contamination, and the seasonal variation documented in multiple studies indicates that grab-sampling protocols may systematically misrepresent average or peak exposure. Longitudinal monitoring programs—even at modest temporal resolution (quarterly sampling over two years)—would substantially improve the evidentiary value of site-level

assessments. Second, the use of divergent reference standards across studies prevents meaningful cross-site comparisons; adopting harmonized reporting standards—reporting concentrations in both absolute units and as multiples of WHO guidelines—would dramatically improve comparative utility without adding analytical cost. Third, a formal quantitative health risk assessment was conducted in only a minority of studies; standardizing hazard quotient calculations as a required component of MSW environmental impact studies would substantially increase the policy utility of future research.

Addressing these methodological gaps is essential not only for advancing scientific understanding but also for enabling evidence-based policymaking, particularly in rapidly urbanizing regions where waste management infrastructure is developing under significant economic constraints.

5. Conclusions

This systematic review synthesizes evidence from 286 studies identified through systematic searches of PubMed, Dimensions, and OpenAlex (2022 records identified; 1124 after duplicate removal), of which 275 were included in structured data extraction and synthesis. The findings confirm that improper MSW disposal generates consistent, multi-media environmental contamination with measurable public health consequences across diverse geographic and income settings.

Lead, cadmium, zinc, iron, chromium, and nickel are the most consistently detected potentially toxic elements in soil and groundwater, with concentrations ranging from moderate exceedances to values up to 300 times regulatory limits. Evidence from Southeast Asia and Sub-Saharan Africa confirms that leachate-driven groundwater contamination and food-chain transfer through crop uptake represent active and widespread exposure pathways.

Emerging hazard dimensions—microplastics as vectors of heavy metal transport and MSW disposal sites as reservoirs of antimicrobial resistance—represent qualitatively new contamination mechanisms that are not yet adequately addressed by current monitoring and remediation frameworks. In addition, post-closure contamination liability documented across Latin America, Southeast Asia, and Eastern Europe demonstrates that environmental risk persists long after formal site closure, requiring extended regulatory oversight.

Disposal method is identified as the dominant predictor of impact severity. Engineered containment systems consistently reduce contamination across all environmental media compared with open dumping and unlined landfills. This supports a clear hierarchy of interventions: engineering-based containment and leachate management as primary measures; source segregation as a secondary strategy to reduce hazardous fractions; and community education as a complementary, but not sufficient, intervention in the absence of adequate infrastructure.

Key priorities for future research include implementing longitudinal monitoring programs to capture seasonal variability, adopting harmonized reference standards to enable cross-study comparability, and routinely integrating quantitative health risk assessment into MSW environmental impact studies to strengthen their policy relevance. Emerging hazard dimensions—microplastics as heavy-metal carriers and MSW disposal sites as AMR reservoirs—represent qualitatively new contamination mechanisms that current monitoring and remediation frameworks are not yet equipped to address. Post-closure liability is documented across Latin America, Southeast Asia, and Eastern Europe, indicating that regulatory obligations cannot safely be terminated at formal site closure. The integration of biotechnological solutions, including phytoremediation, microbial treatment, and biofiltration, is essential for sustainable MSW management and reducing long-term environmental risks.

Based on the systematic synthesis of 286 studies, the following research gaps are identified as priorities for future investigation: (1) longitudinal monitoring designs are critically needed—the dominance of cross-sectional studies prevents characterisation of chronic exposure and seasonal peak contamination dynamics; (2) harmonised reporting standards are absent—divergent reference thresholds across studies prevent cross-site comparison and meta-analysis; (3) quantitative health risk assessment is inconsistently applied and its routine integration as a standard component of MSW environmental impact studies would substantially enhance policy utility; (4) Central Asia, the Middle East, and Eastern Europe are severely underrepresented in the global literature relative to their MSW management challenges; (5) e-waste as a distinct MSW fraction has received insufficient systematic attention in environmental assessments despite constituting 2–10% of urban waste streams; (6) the long-term dynamics of post-closure contamination liability are inadequately characterised, particularly beyond five years from formal site closure; and (7) the interplay between microplastic pollution, heavy metal transport, and antimicrobial resistance gene dissemination represents an emerging multi-hazard dimension requiring integrated monitoring frameworks that current systematic reviews have not yet addressed comprehensively.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18083900/s1>. Table S1: PRISMA 2020 Checklist. Table S2: Full list of 286 included studies with data extraction summary and evidence-level ratings.

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Abbreviations

The following abbreviations are used in this manuscript:

AMR	Antimicrobial resistance
BTEX	Benzene, toluene, ethylbenzene, and xylene
CF	Contamination factor
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
ESBL	Extended-spectrum β -lactamase
EU	European Union
EWQI	Entropy-weighted water quality index
GHG	Greenhouse gas
HI	Hazard index
HPI	Heavy metal pollution index
JB	Joanna Briggs Institute
LandGEM	Landfill Gas Emissions Model (US EPA)

LCA	Life cycle assessment
LMFF	Landfill-mined fine fraction
LPI	Leachate pollution index
MAC	Maximum Allowable Concentration
MSW	Municipal solid waste
NO _x	Nitrogen oxides
PLI	Pollution load index
PLS-SEM	Partial least squares–structural equation modelling
PM _{2.5}	Particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$
PM ₁₀	Particulate matter with aerodynamic diameter $\leq 10 \mu\text{m}$
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROSPERO	International Prospective Register of Systematic Reviews
PTEs	Potentially toxic elements
RQ	Research question
SO _x	Sulfur oxides
USEPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds
WHO	World Health Organization
WQI	Water quality index

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