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Landfill Leachate and Water Resources: An Evaluation of Chemical and Microbiological Characterization, Contamination Pathways, and Risk-Oriented Monitoring

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ABSTRACT

Landfill leachate is a persistent threat to water resources, yet few reviews follow its constituents across media to the receptors exposed or translate that evidence into design and monitoring decisions. This review characterizes landfill leachate chemically and microbiologically, traces its migration pathways, and consolidates the evidence into a risk-oriented monitoring framework aligned with multi-barrier landfill design. A structured narrative review synthesized 75 sources published mainly between 2020 and 2025. Leachate composition evolves predictably with landfill age, from acidogenic leachate rich in biodegradable organics and mobile metals to methanogenic leachate dominated by refractory humic material and persistent ammoniacal nitrogen; climate modifies this signature, shifting the monitoring priority from loads in humid settings to peak concentrations in arid ones. Treatment trains frequently fail to remove per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, microplastics, pathogens, and antibiotic resistance genes (ARGs), and contaminants migrate into groundwater plumes, surface waters, soils, and food chains. The framework is a rule set that assigns a site to a risk tier based on containment, hydrogeological vulnerability, and receptor proximity and it prescribes parameters, sampling frequency, well-network density, and escalation triggers, supported by a tiered analytical strategy. Source control, multi-barrier treatment, and mandatory surveillance emerge as more defensible than aquifer remediation.

1. INTRODUCTION

Despite significant progress in recycling development, composting, and waste-to-energy technologies, landfill remains the primary means of waste disposal globally. Municipal solid waste (MSW) generation has increased significantly in recent years because of rapid urbanization, industrialization, population growth, and changing consumption patterns, especially in developing and low-income states where MSW infrastructure is still lacking [1, 2]. Many existing landfills are not engineered and are simply open dumps. This is often a simple, low-cost option compared to a sophisticated waste-treatment facility. However, the long-term effects of indiscriminate waste are now a major concern worldwide. Among the many environmental issues posed to ecosystems, the generation and migration of landfill leachate are primary concerns [3, 4].

Landfill leachate is the liquid waste formed when rainwater percolates through the waste and mixes with entering groundwater, especially in poorly sealed sites. The native moisture in the waste percolates through it, picking up dissolved, colloidal, and suspended substances through dissolution, desorption, and physical entrainment. The composition is highly heterogeneous because of the waste's characteristics, the landfill's age and stabilization phase, climatic and hydrological conditions, operational and containment methods, and the series of biogeochemical changes occurring in the waste mass [5, 6]. Leachate is also rich in biodegradable and refractory organic matter, ammoniacal nitrogen (NH_4^+-N), chloride, sulfate, heavy metals, and xenobiotic organic substances, as well as an increasing number of contaminants of emerging concern (CECs), including pharmaceuticals, endocrine disruptors, per- and polyfluoroalkyl substances (PFAS), and microplastics [2, 7, 8]. Poor landfill lining or regulation can allow leachate to percolate through the soil profile and, ultimately, reach the groundwater aquifer, causing contaminated plumes to drift via groundwater [9, 10]. The groundwater around the landfill has high concentrations of ammonium, nitrate, heavy metals, and total dissolved solids (TDS). Concentrations above international drinking-water guideline values are widely reported [11, 12]. Figure 1 shows the principal pathways by which landfill leachate infiltrates from the waste body to groundwater and surface water, and the human and ecological receptors ultimately exposed through them.

Landfill leachate threatens public health, ecosystems, and water quality. When leachate enters receiving waterways, its normally high nutrient load may cause eutrophication, and the resulting oxygen depletion can put considerable stress on aquatic ecosystems [1]. Toxic metals and persistent organic pollutants (POPs) act quite differently. Rather than being flushed out of the system, they partition into sediments and are

taken up by crops and aquatic creatures. Transport of toxins along the food chain leads to contaminant accumulation with subsequent increases in cancer and other adverse health effects among communities exposed to these contaminants [13, 14].

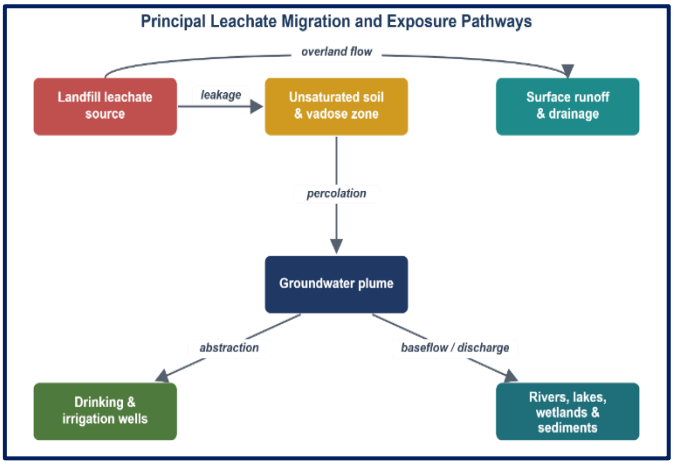

Figure 1. Routes of primary leachate migration and exposure [15]

In addition to chemical hazards, leachate can be a pool for pathogens, antibiotic-resistant bacteria (ARB), and antibiotic resistance genes (ARGs), adding a microbiological dimension to the ecological and health problems mentioned above [16]. The heightened awareness of CECs and the slow, cumulative impacts of conventional pollutants further strengthen the case for implementing leachate management systems that are more robust and sustainable than those currently in common use.

Understanding leachate generation, composition, transport, environmental impacts, and treatment is therefore central to solid waste management (SWM) and protecting water resources. Recent reviews have advanced this field considerably, yet most address its components separately: some concentrate on chemical characterization and treatment performance [3, 17], others on ecological and public-health consequences [1, 14], and others on individual contaminant classes such as emerging pollutants or nitrate [7, 11]. Global syntheses of leachate chemistry and microbiology have also been published [2, 8], but these characterize the source rather than trace it to receptors, and none translates the resulting evidence into monitoring guidance applicable at a specific site or connects it to the design and governance decisions that determine whether contamination occurs at all.

This review is designed to fill this gap. It follows leachate constituents through all affected media (groundwater, surface water, soil and vadose zone, biota, and atmosphere) within a single source–pathway–receptor framework rather than treating groundwater in isolation, and it combines the microbiological signature of leachate (the leachate microbiome and the antibiotic resistome) with conventional physicochemical characterization, because microbial guilds regulate pollutant attenuation and are themselves health hazards. The source–pathway–receptor sequence is deliberately aligned with the multi-barrier logic of landfill design: waste acceptance and source control, engineered containment, leachate collection and treatment, the natural attenuation capacity of the vadose zone and aquifer, and monitoring coupled to institutional response form successive barriers, and each pathway described here corresponds to the failure of one of them. The review therefore asks not only what leachate does to receptors but which barrier should carry the monitoring and investment effort at a given site. To that end, it consolidates the evidence into a risk-oriented monitoring framework (Section 8), converts it into a rule set that links risk tier to monitoring design (Section 8.1), specifies a tiered analytical strategy that separates low-cost routine indicators from specialist analyses (Section 8.4), provides an indicator–medium interpretation guide (Section 8.5), and compares prevention, treatment, and remediation strategies as management choices (Section 9).

2. REVIEW METHODOLOGY

2.1 Review design and questions

This study was conducted as a structured narrative review with transparent, replicable procedures for search, screening, and synthesis. The review questions were: (i) how do landfill age, waste composition, climate, and hydrogeology control leachate characteristics; (ii) through what pathways does leachate affect groundwater, surface water, soil, ecosystems, and human health; and (iii) what prevention, treatment, monitoring, and remediation strategies are supported by current evidence? Given the diversity of study designs, analytical methods, climatic settings, landfill types, and reporting units, a structured narrative approach was selected because the evidence does not support a defensible quantitative meta-analysis.

2.2 Search strategy

The search strategy was conducted in Scopus, Web of Science Core Collection, ScienceDirect, PubMed, and Google Scholar. The strategy used three concept blocks: (A) the source, limited to the title field (leachate*), combined with landfill, dumpsite, open dump, or MSW in the title, abstract, and keyword fields; (B) the receiving medium or receptor (groundwater, aquifer, surface water, river, stream, lake, wetland, soil, vadose zone, sediment, drinking water, crops, food chain); and (C) contaminant classes, outcomes, and management responses (heavy and trace metals, potentially toxic elements, ammonium and ammoniacal nitrogen, nitrate, PFAS, microplastics, pharmaceuticals, CECs, ARGs, pathogens, ecotoxicity, toxicity, health risk, risk assessment, pollution index, plume, attenuation, monitoring, treatment, remediation, composition, and characterization). Blocks A, B, and C were combined as A AND (B OR C), and truncation was used where the database syntax allowed. We deliberately limited the source block to the title field to improve precision, in keeping with the exclusion of studies that did not present leachate-specific evidence (Section 2.3). The main evidence window was January 2020 to December 2025, and results were limited to research articles and reviews published in English. Table 1 summarizes the search strategy and the number of records retrieved, and Appendix A provides the search strings for each database.

Because ScienceDirect limits a query to eight Boolean operators, block C was divided into five sub-queries (SD-1 to SD-5). Google Scholar was used as a supplementary source with six short queries anchored on intitle: leachate; its results were screened for relevance to identify records not retrieved from the bibliographic databases, and because the depth of that screening was not recorded during the original review, no

fixed record cut-off is reported. Because retrieval counts from the original searches were not archived, the complete strategy was re-executed on 20 September 2026 to document the counts in Table 1; institutional access to Web of Science was unavailable at the time of re-execution, so its count is not reported.

Table 1. Search design, retrieval counts, and characterization of the evidence base

(a) Search design and retrieval (searches re-executed on 20 September 2026)

Database	Fields	Query Design	Filters	Records Retrieved
Scopus	TITLE; TITLE-ABS-KEY	A AND (B OR C)	2020–2025; English; article, review	2,532
Web of Science Core Collection	TI; TS	A AND (B OR C)	2020–2025; English; article, review	n/a[1]
PubMed	[ti]; [tiab]	A AND (B OR C)	2020–2025; English	1,023
ScienceDirect	Title, abstract, keywords	Five sub-queries SD-1 to SD-5	2020–2025; research and review articles	305; 398; 245; 303; 1,174
Google Scholar	Full text, in title: leachate	Six queries GS-1 to GS-6	2020–2025; patents and citations excluded	≈2,250; 3,090; 3,350; 1,100; 612; 4,250[2]
Update search (Scopus; PubMed)	As above	A AND C′ (PFAS, microplastics, antibiotic resistance)	2026	50; 24 (52 unique; 8 added)

(b) Evidence base retained for synthesis

Item	Value
Full texts assessed	177
Sources retained	75 (49 published 2020–2025; 16 pre-2020 landmark studies; 10 published 2026)
Evidence type	31 reviews and global syntheses; 43 primary field, laboratory, or modeling studies; 1 guideline document
Topic domain, primary[3]	Groundwater contamination and subsurface transport 22; leachate chemistry and characterization 18; treatment, remediation, and engineered controls 7; ecotoxicity and human-health risk 9; PFAS, microplastics, and pharmaceuticals 7; monitoring tools, indices, and guidelines 4; microbiology, pathogens, and ARGs 6; surface water, soil, and ecosystems 2

Notes: Concept blocks: A = source (leachate* in the title AND landfill*, dumpsite*, "open dump*", or "municipal solid waste"); B = medium or receptor; C = contaminant classes, outcomes, and management; C′ = PFAS, microplastics, and antibiotic resistance only. Full query strings are given in Appendix A. [1] Institutional access unavailable at re-execution. [2] Approximate totals reported by the engine; Google Scholar served as a supplementary source screened by relevance, without a recorded cut-off. [3] "Primary" assigns each source to one domain (sum = 75).

The 2020–2025 window was selected because it spans the period in which multi-country syntheses of leachate chemistry and microbiology became available [2, 8] and in which the literature on PFAS, microplastics, and ARGs in leachate expanded rapidly; the review therefore reflects current characterization and monitoring practice rather than a historical account. Earlier landmark studies were retained where they provide foundational definitions, long-term field observations, analytical frameworks, or widely used indicators that recent publications have not replaced [5, 9]. Because PFAS, microplastics, and antibiotic resistance are fast-moving topics, articles published online ahead of print during screening but subsequently assigned to 2026 issues were retained (two sources, e.g., [14]); these were retrieved by the main search and are distinct from the sources added by the update search described below. A supplementary update search restricted to these three topics was executed on the same date (Scopus, n = 50; PubMed, n = 24; 52 unique records). These records were screened by title and abstract, and eight further sources published in 2026 were added through this update search (these eight, together with the two retained ahead-of-print sources, make up the ten 2026 sources reported in Table 1): a global synthesis of leachate composition and its groundwater impacts [18]; a global compilation of PFAS in leachate [19] and a multi-regional study of PFAS in raw and treated leachate [20]; multi-plant evidence on the persistence of ARGs through treatment [21]; reviews of ARG transfer to groundwater [22], of microplastics in leachate [23], and of leachate pathways in tropical urban aquifers [24]; and a study of PFAS sorption onto aquifer media [25].

2.3 Eligibility and screening

Peer-reviewed research articles and reviews published in English that reported leachate composition, contaminant transport, environmental or health effects, treatment performance, risk assessment, or monitoring and management practice were eligible. Studies were excluded when they addressed general solid-waste management without leachate-specific evidence, consisted of non-scholarly web material, were inaccessible in full text, or duplicated other records. Studies were also excluded for insufficient methodological or contextual information, defined as the absence of one or more of the following: (i) the location of sampling points relative to the landfill and a description of the hydrogeological or hydrological setting; (ii) sampling dates, frequency, or number of samples; (iii) the analytical methods used and any quality-assurance information; (iv) the units and reporting basis of concentrations (for example, NH_4^+ versus NH_4^+-N, or NO_3^- versus NO_3^--N); and (v) a background, control, or reference value against which the reported concentrations could be interpreted. Titles and abstracts were screened first, followed by full-text assessment, and the reference lists of major reviews were examined to identify additional foundational and recent studies. In a final relevance screening, sources that were only tangentially related to the review questions or that duplicated stronger evidence were removed. Consistent with narrative-review practice, flow counts in the style of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were not recorded during the original screening; the evidence base is instead characterized in Table 1 by the number of full texts assessed, the number of sources retained for synthesis, and their distribution across topic

domains and evidence types.

2.4 Data extraction and synthesis

For each retained source, data were extracted on research location and climate, landfill type and age, environmental media sampled, target contaminants, analytical or modeling approach, key findings, reported limitations, and management implications. Evidence was organized in five subject domains: leachate formation and composition; age- and climate-related variation; subsurface and surface-water movement; ecological and human-health impacts; and prevention, treatment, and remediation. Greater interpretive weight was given to multi-site investigations, studies with upstream or background controls, seasonal or long-term monitoring, validated analytical procedures, and explicit uncertainty or statistical evaluation. Because concentration ranges, detection limits, sampling techniques, exposure assumptions, and units varied among studies, the synthesis was qualitative: stronger evidence came from independent sites that agreed, whereas isolated or context-dependent findings are discussed with caution. Throughout the review, concentrations are reported together with the environmental medium and the chemical basis used in the source study, and ranges are not compared directly across media or reporting bases (Section 4).

2.5 Limitations

The review is limited by its restriction to English-language sources, potential publication bias, uneven reporting in the primary studies, and the absence of a registered protocol and a full database export. Retrieval counts in Table 1 derive from a re-execution of the search strategy rather than from the original searches; overlap between databases was not quantified, Google Scholar totals are the engine's approximate estimates, and the Web of Science count could not be re-established. The conceptual curves of leachate evolution with landfill age presented in Section 4 are normalized rather than measured concentrations.

3. LEACHATE OF LANDFILLS

Inappropriate SWM is one of the greatest ecological problems worldwide, especially in low- and middle-income nations where open dumping or bare landfills are still frequent. Most of these sites lack leachate liners, leachate collection systems (LCSs), or treatment plants. This allows water to seep through the waste, picking up contaminants that can then transfer into soil, groundwater, streams, ponds, and rivers [4]. With the increasing population and waste accumulation in cities, unregulated leachate is a severe hazard to drinking and aquatic resources, agriculture, and ecosystems [2, 11].

Figure 2 illustrates the interacting hydrological, biochemical, climatic, and waste-related processes that generate landfill leachate.

Leachate is usually rich in dissolved organic matter (DOM), which is usually quantified as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), and inorganic salts (ammonium, nitrate, chloride, sulfate, sodium, and potassium), as well as numerous other chemicals, including polycyclic aromatic hydrocarbons and halogenated organics [2, 3]. The recent world synthesis, which has summarized the information on 1,251 leachate samples in 51 countries, revealed particularly high levels of COD, BOD, ammonium, and heavy metals in developing countries and in warmer and wetter climate regions, indicating the impacts of waste composition (high fraction of food waste) and climatic factors on leachate formation [2].

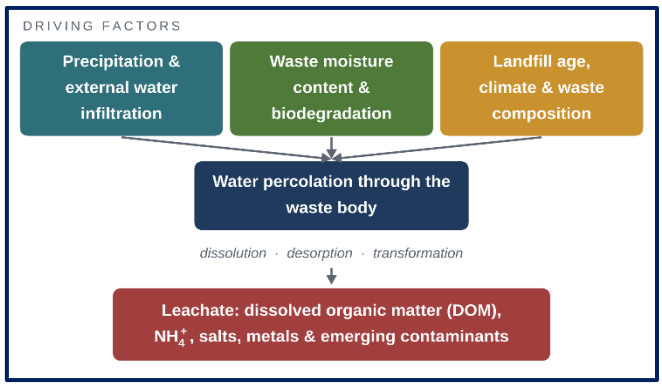

Figure 2. Mechanism of landfill leachate generation [5]

A case study across different geographical areas supports this argument and shows that leachate from unregulated landfills significantly degrades groundwater and surface water quality. In Bangladesh, non-engineered locations such as Amin Bazar have a high pollution index, comparable to that reported in highly polluted regions of India and Malaysia [12, 26]. In groundwater and surface water near these sites, toxic metals—lead, cadmium, nickel, manganese, and chromium—often exceed World Health Organization (WHO) drinking-water guideline values, posing carcinogenic and non-carcinogenic risks of consuming crops irrigated with contaminated water [12, 27, 28].

Even engineered landfills with composite liners and LCSs may pose long-term risks once the containment components start to degrade due to aging, differential settlement, root penetration, or chemical attack on the geomembrane [29]. Comparative monitoring studies indicate that contaminant loads in groundwater adjacent to sanitary landfills are much lower than those reported near open dumps, but down-gradient groundwater concentrations of dissolved organic matter, ammonium, chloride, sulfate, and trace metals frequently exceed regulatory thresholds, thus necessitating continued post-closure surveillance. For example, Abd El-Salam and Abu-Zuid [30] assessed the Alexandria sanitary landfill in Egypt by detecting statistically significant elevations in electrical conductivity (EC), TDS, NH_4^+-N, iron, and manganese in down-gradient groundwater wells compared with up-gradient controls. Furthermore, contemporary landfills are increasingly acknowledged as point sources of CECs, such as pharmaceuticals, endocrine-disrupting compounds, PFAS, and microplastics, which resist the physicochemical and biological processes commonly used to treat leachate [31, 32], and ARB and resistance genes are likewise detected in leachate and in hydraulically connected groundwater [16]; short-chain perfluoroalkyl acids dominate raw and treated leachate alike, so that treated effluents from 17 Chinese landfills still contained 6–7,390 ng/L of PFAS [20], and across 30 leachate treatment plants treatment reduced plasmid-borne resistance genes while chromosomally encoded multidrug and aminoglycoside resistance genes increased in the effluent [21]. Nitrate concentrations in groundwater near engineered and unlined landfills regularly exceed the WHO guideline value of 50 mg/L expressed as NO_3^- (equivalent to

11.3 mg/L as NO_3^--N) [28], an exceedance epidemiologically linked to infantile methemoglobinemia ("blue-baby syndrome") and, in chronic exposure scenarios, to elevated risk of gastric and colorectal cancers [11, 33], and are of particular public-health concern.

General tests that combine physicochemical analysis and toxicity testing indicate that, despite being contained within landfill structures, leachate exhibits high inherent toxicity [34]. For example, biological assays with white mustard and duckweed showed increasing growth inhibition as leachate levels increased, further supporting leachate phytotoxicity, even in the absence of groundwater leakage [26]. The presence of constituents that are especially toxic to aquatic organisms (e.g., chromium, copper, and high NH_4^+-N) has prevented direct discharge or co-treatment with municipal sewage without prior specialized treatment [35, 36].

4. CHARACTERIZATION OF LANDFILL LEACHATE

Throughout this review, concentrations are reported on the environmental medium (raw leachate, groundwater, surface water, soil, or sediment) and the chemical basis used in the source study. Nitrogen species are expressed as nitrogen (NH_4^+-N, NO_3^--N) except where a guideline value is defined as the ion, as for the WHO nitrate guideline of 50 mg/L as NO_3^- (11.3 mg/L as NO_3^--N) [28]; "ammonium" denotes the chemical species in process descriptions, whereas NH_4^+-N denotes the measured concentration. Ranges from different media or reporting bases are placed side by side only to indicate orders of magnitude and are not compared directly, because sampling points, detection limits, and units differ among studies.

When industrial waste is added, leachate tends to contain more heavy metals, xenobiotic organic compounds, and salts than landfill leachate, which receives only municipal waste. It also affects metal bonding in the liquid state [17, 37]. Organic waste decomposed in landfills, particularly food or household organic waste, creates leachate that is rich in biodegradable organic matter and ammonium. Adding industrial or electronic waste [31, 38] pollutes the mixture with solvents, PFAS precursors, metals, and pharmaceuticals. Worldwide, landfills that receive more food waste tend to generate leachate with higher organic strength and ammonium concentration because easier-to-hydrolyze materials decompose rapidly in the waste matrix, but food waste contributes only a small part of this variability [2].

Young leachate (<5 years old) is generally quite acidic [5, 6, 39]. It contains high BOD, COD, volatile fatty acids (VFAs), and heavy metals owing to extensive organic decomposition in the early stage [3]. As the landfill ages for ten years and enters the methanogenic phase, the BOD-to-COD ratio drops, indicating reduced biodegradable content. The main concern, however, is ammonium, which tends to be independent of landfill age [2, 3, 11].

Leachate volume and concentration are greatly affected by climatic factors, particularly temperature and rainfall. In tropical regions, heavy rainfall increases COD, five-day biochemical oxygen demand (BOD_5), NH_4^+-N, and metal leaching [40], whereas in arid regions, low leachate volume is associated with high pollutant concentrations [2, 13]. Ammonium and chloride are common and dangerous macro elements in aquifers, but emerging pollutants such as PFAS, microplastics, and pharmaceuticals are a current concern [19, 23]. These compounds are typically stubborn and difficult to treat, and DOM may further complicate their mobility by adsorbing onto metals, enabling their entrance into groundwater [5, 41].

Table 2 presents the major pollutant groups in landfill leachate, their representative constituents, associated risks, monitoring approaches, and potential control measures for direct comparison.

Table 2. Major landfill leachate pollutant groups, risks, monitoring indicators, and control options

Pollutant Group	Representative Constituents	Principal Concern	Monitoring Approach	Potential Controls	References
Dissolved organic matter	BOD, COD, VFAs, humic/fulvic substances	Oxygen depletion, color, odor, mobilization of co-contaminants	BOD_5, COD, TOC, UV_{254}, fluorescence	Biological treatment; coagulation; adsorption; AOPs	[2, 9]
Inorganic macro-components	NH_4^+-N, Cl^-, SO_4^{2-}, Na^+, K^+, TDS	Toxicity, salinization, eutrophication, and drinking-water impairment	Ion chromatography, spectrophotometry, EC/TDS	Nitrification–denitrification; stripping; ion exchange; membranes	[2, 9]
Potentially toxic elements	Cd, Cr, Pb, Ni, Cu, Zn, Fe, Mn	Aquatic toxicity, bioaccumulation, and chronic health risk	ICP-MS/ICP-OES; speciation analysis	Precipitation; coagulation; adsorption; reactive barriers	[2, 9]
Emerging contaminants	PFAS, pharmaceuticals, PPCPs, bisphenol A (BPA), flame retardants, microplastics	Persistence, mobility, endocrine/ecotoxic effects, and mixture toxicity	LC-MS/MS, GC-MS, particle spectroscopy	Activated carbon; membranes; AOPs; source control	[8, 32]
Biological hazards	Pathogens, ARB, and ARGs	Infection risk and dissemination of antimicrobial resistance	Culture, qPCR/metagenomics, bioassays	Disinfection and multi-barrier treatment	[8, 16, 42]

Notes: BOD, biochemical oxygen demand; COD, chemical oxygen demand; VFAs, volatile fatty acids; BOD_5, five-day biochemical oxygen demand; TOC, total organic carbon; UV_{254}, ultraviolet absorbance at 254 nm; EC, electrical conductivity; TDS, total dissolved solids; ICP-MS, inductively coupled plasma mass spectrometry; ICP-OES, inductively coupled plasma optical emission spectrometry; AOP, advanced oxidation process; ARB, antibiotic-resistant bacteria; ARGs, antibiotic resistance genes; qPCR, quantitative polymerase chain reaction.

Landfill leachate has become a global phenomenon, a diverse yet systematically ordered complex of pollutants. In raw leachate, global compilations report COD of 3,700–75,900 mg/L and NH_4^+-N of 300–8,100 mg/L (as N) [8]. Major inorganic ions (Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}) occur at hundreds to thousands of milligrams per liter, far above domestic

wastewater levels [5, 43]. Dissolved heavy metals in raw leachate are typically at or below the mg/L level, yet leachate-impacted groundwater frequently exceeds drinking-water and groundwater standards for individual metals [9]. Recent global surveys indicate that leachate is a primary source of PFAS, bisphenol A, *N*,*N*-diethyl-3-methylbenzamide (DEET), and other pharmaceuticals and personal care products (PPCPs), which occur in raw leachate at ng/L to µg/L concentrations but remain persistent and toxic [8, 32]. A 2026 compilation of 1,416 leachate samples from 539 facilities in 22 countries reported total PFAS of 1 to 5,542,000 ng/L, with industrial landfills averaging 56–101 times the concentrations of other landfill types and PFAS levels correlated with TOC, COD, and ammonium [19]. These ranges refer to different media and reporting bases and are presented to indicate orders of magnitude, not for direct comparison.

Figure 3 summarizes the conceptual evolution of leachate characteristics with landfill age, and Table 3 compares the principal changes in leachate chemistry across young, transitional, and mature landfill phases, along with their treatment implications.

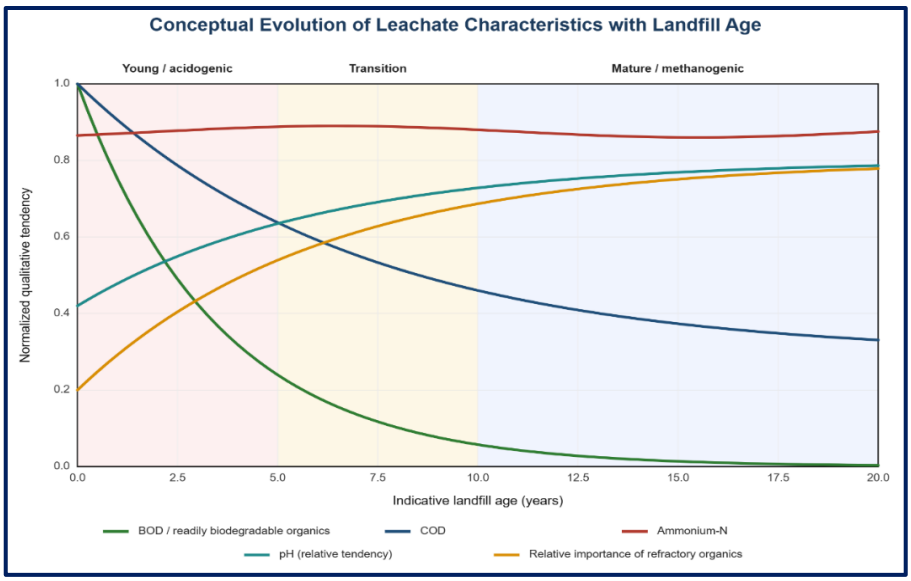

Figure 3. Conceptual evolution of leachate characteristics with landfill age [39]

Table 3. Comparative characteristics of landfill leachate by landfill age and biochemical phase

Phase	Indicative Age	Typical pH Tendency	Organic Fraction	Inorganic/Metal Tendency	Management Implication	References
Young/acidogenic	<5 years	Acidic to near-neutral	High BOD, COD, and VFAs; BOD/COD is often >0.3	Greater dissolved metal mobility; variable ammonium	Biological treatment is comparatively feasible; pH and metal toxicity may require control.	[3, 5, 39]
Intermediate / transition	5–10 years	Rising toward neutral	Declining biodegradable fraction; mixed humic material	Ammonium and salt become increasingly persistent.	Combined biological and physicochemical treatment is often required.	[5, 6, 39]
Mature/methanogenic	>10 years	Neutral to alkaline	Lower BOD, refractory COD, and humic substances; BOD/COD is often less than 0.1	Persistent NH_4^+-N, chloride, and TDS; many metals decline but may remain relevant.	Advanced oxidation, adsorption, membranes, stripping, or integrated trains may be needed.	[2, 5, 6]

Notes: VFAs, volatile fatty acids; TDS, total dissolved solids. Boundaries are indicative and vary with climate, waste composition, and operational conditions.

4.1 Global trends and driving forces

Patterns associated with development status, climate, and waste composition are evident in a database of 51 countries. Sites in developing countries in dry temperate and moist-to-wet tropical zones have significantly higher concentrations of COD and BOD_5 than sites in industrialized countries, as these landfills receive a higher proportion of food and other easily biodegradable materials [2, 8, 40, 44]. Food waste has a positive correlation with COD, BOD_5, NH_4^+-N, and some macro-ions, but accounts for a small proportion of the variance (R^2 = 0.07–0.18), indicating that the food-waste content is a minor contributor [2].

However, the statistical and machine-learning data show that the size and age of a landfill can have a large effect on the volume and composition of the leachate. Larger facilities produce more leachate and higher total nitrogen and ammonium; hotter areas have higher COD but lower BOD_5, indicating more but weaker biological processing [45]. Cluster analysis distinguishes among anaerobic, early and intermediate, and later methanogenic stabilization, showing that the degradation phase is a major organizing variable in leachate chemistry [45]. The same age-related patterns appear in the regional surveys: Fe/Mn and organic pollution are prevalent in young cells, ammonium in intermediate locations, and refractory organics and salts in older facilities [45, 46].

4.2 Age and biogeochemical phase of landfill

Research indicates that leachate composition follows a predictable pattern that undergoes acidogenic, acetogenic, and methanogenic stages (Figure 3). During the first five years, COD and BOD_5 are typically an order of magnitude higher than in mature leachate; pH is acidic to near neutral, and VFAs and soluble metals are pre-eminent [5, 39]. As decomposition continues, methanogenic bacteria consume the VFAs generated during the acid phase, and the leachate shifts from acidogenic to methanogenic conditions. This transition is accompanied by a major decline in leachate biodegradability; BOD/COD ratios are typically >0.3 in fresh leachate but <0.1 in aged, methanogenic leachate [5, 39, 43]. By contrast, NH_4^+-N is not attenuated under methanogenic conditions and persists in raw leachate at concentrations commonly in the range of 500–2,000 mg/L (as N) with no decreasing trend over time, making it the dominant long-term contaminant [5].

Long-term reviews and field studies confirm that most heavy metals decrease or precipitate into insoluble species over time and that ammonium is the prevailing long-term pollutant [9]. Other metals such as Cd and Pb may decrease but remain above regulatory levels in old landfills, particularly in warmer regions where the decomposition process is not fully complete [46]. Over the multi-year monitoring period, the leachate pollution index (LPI) indicates a steady decrease in total pollution scores as the landfills stabilize. However, the main parameters of COD, NH_4^+-N, and chloride are usually not optimal [47].

5. CHEMICAL COMPOSITION AND SPECIATION

5.1 Organic matter

A broad range of dissolved organic matter, including small VFAs and sugars to macromolecules resembling humic in nature, is covered by dissolved organic material in leachate. Analyses always separate the organic fraction into three categories: (i) easily biodegradable organics measured by BOD and VFAs; (ii) slowly biodegradable humic-like compounds, which COD measures; and (iii) xenobiotic organics that include phenols, chlorinated solvents, plasticizers, and pesticides [5, 43, 48]. Fourier-transform infrared (FTIR) and thermogravimetric analyses show numerous carboxyl (COOH) and hydroxyl (OH) groups, providing multiple binding sites for multivalent metal cations [49]. Potentiometric titrations indicate that the leachates possess distinct spectra of acidity constants, which govern the acid-binding capacity of metal-sequestering agents [49].

Surveys of emerging contaminants report hundreds of low-concentration CECs that are persistent in landfill leachates, such as PFAS and flame retardants [8, 31, 32]. Mixture effects are becoming an increasing cause of ecotoxicity because CECs tend to sorb to DOM [32, 37].

5.2 Inorganic macro components

Typically, inorganic macro-ions constitute the major fraction of landfill leachate mass. Major ions such as Cl^-, SO_4^{2-}, HCO_3^-, Na^+, K^+, Ca^{2+}, and Mg^{2+} occur at relatively high concentrations and contribute significantly to elevated EC of leachate [5, 50]. NH_4^+-N, formed by protein mineralization, recurs as a major long-term hazard in leachate and impacted groundwater [9, 46]. Nitrate levels in the landfill body are low due to the reducing environment, but it can accumulate down-gradient if nitrification occurs in oxygenated areas [46].

The landfill and its surrounding aquifer systems contain varying amounts of inorganic macroconstituents, which the landfill's hydrogeochemical conditions strongly influence. Chloride and sodium are commonly assumed to be highly conservative ions that can be extensively transported from landfill sources and are likely to be good markers for leachate contamination of groundwater [13, 30, 43]. These ions, along with bicarbonate, calcium, magnesium, and potassium generated by waste decomposition and mineral dissolution, are considered responsible for the high EC and TDS observed near landfills [5]. Carbonate minerals can dissolve, and carbon dioxide can be produced during anaerobic biodegradation, significantly increasing bicarbonate concentration in mature methanogenic leachates and thereby increasing the alkalinity and buffering capacity [5, 6].

The most difficult macro-component of leachate to treat is probably ammonium, mainly because the anaerobic core of a landfill does not constitute an efficient avenue for its natural attenuation [2]. Long-term monitoring operations documenting high ammonium concentrations for decades after closure provide well-established evidence of the persistence, with the pattern most prominent at older MSW sites with organic-rich waste inventories [40, 46]. The implications stretch far beyond the groundwater body itself. When contaminated groundwater is discharged to rivers, wetlands, or lakes, ammonium oxidation drives high dissolved-oxygen consumption and ensuing hypoxia, exacerbated by the nutrient enrichment provided by ammonium, which damages aquatic organisms [1, 51]. Under oxygenated conditions, ammonium is converted to nitrate, a much more mobile species that can easily move with groundwater flow and has been frequently found above drinking-water limits in wells near landfill sites [11, 12].

Sulfate also has a complex role, and its fate is controlled mainly by the redox conditions and the activity of the resident microbial community. Under reducing conditions, sulfate-reducing bacteria reduce sulfate to sulfide species, with three practical consequences: odor production, corrosion of engineered infrastructure, and precipitation of dissolved metals as insoluble sulfides [9, 14]. However, partial re-oxidation and seasonal oxygen ingress may reverse these transformations at the local scale, which explains the strong spatial heterogeneity of sulfate concentrations across landfill plumes [13, 45, 46]. Macro-ion concentrations are also greatly influenced by climatic conditions. In general, leachate volume and dissolved-salt mobilization are higher in tropical and humid environments [2, 40], whereas in arid environments leachate volume is lower but salinity and ionic strength are higher [2, 13].

5.3 Heavy metals and metal partitioning

The critical toxicological component is heavy metals. Common examples include Cd, Cr, Cu, Ni, Pb, Zn, Mn, and Fe [9, 49]. Most metals are present in suspended solids, and dissolved concentrations are more sensitive to redox state and pH [41]. Unlined dumps with shallow waste layers show higher dissolved metal levels because they are more subject to oxidizing conditions [5, 52].

Thermodynamic research indicates that leachate DOM can chelate Cd^{2+}, Zn^{2+}, and Cu^{2+}, thereby promoting metal mobility

in soils [49]. MSW and e-waste co-disposal indicate high levels of Cd, Cr, and Pb not only in leachate but also in neighboring sediments, where they accumulate over long periods of time [27, 53].

Partitioning of heavy metals in landfill leachates results from adsorption-desorption reactions, precipitation-dissolution equilibria, complexation with dissolved organic matter, and redox-driven transformations [6, 41]. In general, acidic conditions typical of young landfill leachates will increase the dissolution of Cd, Zn, Ni, and Pb, thereby increasing their mobility and bioavailability in the surrounding soil and groundwater [5, 27, 39]. During stabilization of the landfill towards methanogenic conditions and increasing pH, many metals will precipitate as sulfides, carbonates or hydroxides, thus decreasing dissolved concentration, but often increasing sediment or suspended particulate matter [9, 37]. However, contaminated sediments can be secondary sources of pollution by releasing metals bound in the sediments when dissolved quantities decline, redox conditions change, or the pH regime is modified.

In contaminant transport, special emphasis should be paid to the interaction between heavy metals and DOM. The humic and fulvic fractions of landfill leachate are rich in carboxylic and phenolic functional groups that coordinate metals such as Cu, Pb, Cd, and Zn to form soluble organo-metallic complexes. Such complexation reduces the activity of free metal ions and their affinity for sorption on mineral surfaces and organic coatings, resulting in less retardation during advective transport and sustaining metal mobility in the subsurface much further than predicted from inorganic speciation alone [48, 49]. The co-disposal of e-waste complicates the problem because batteries, printed circuit boards, and plastic additives introduce trace metals that are highly toxic and resistant to natural degradation [1, 7]. These elements enter aquatic and terrestrial food chains, bioaccumulate, and threaten ecosystem integrity and the health of populations that depend on affected water resources [54, 55].

6. MICROBIOLOGICAL AND BIOGEOCHEMICAL SIGNATURES

More recent surveys focus on the leachate microbiome as a source and indicator of decay. Proteobacteria, Bacteroidota, Firmicutes, and Chloroflexi were the most common phyla identified globally [8]. The fate of inorganic nitrogen is determined by functional guilds essential to nitrogen cycling, including anammox bacteria (*Candidatus Brocadia*) and nitrifying bacteria such as *Nitrosomonas* [8, 56]. Time-series surveillance correlates declining VFAs with the emergence of methanogens, providing indirect evidence of landfill stabilization [5, 39].

The LPI combines parameters such as COD, NH_4^+-N, and heavy metals. LPI values decline with stabilization but remain above optimal levels over decades [47, 57]. As regional-scale studies point out, hydrogeological environments buffer the expression of leachate characteristics in groundwater effects [46]. Groundwater exceedance rates are lower in landfills in mountainous regions with thick, fine-grained vadose zones than in coarse-gravel aquifers, supporting the idea that leachate characterization should be accompanied by site-specific transport evaluation [44, 52].

Microbial succession drives the biochemical evolution described in Section 4.2: fermentative bacteria dominate the hydrolytic and acidogenic phases, breaking readily biodegradable organic matter down to VFAs, alcohols, hydrogen, and carbon dioxide and producing acidic leachate with high COD and BOD [5], whereas methanogenic archaea dominate the subsequent strictly anaerobic phase, converting these intermediates to methane and carbon dioxide, reducing organic strength and raising pH [9, 58]. Recent breakthroughs in molecular sequencing have revealed that microbial diversity and metabolic activity in landfills vary widely depending on site age, waste content, temperature, moisture regime, and oxygen availability [16, 58, 59]. Metagenomic and microbiome studies over the past few years have revealed that landfill leachate harbors remarkably diverse microbial assemblages that mediate the cycling of carbon, nitrogen, sulfur, and metals [8, 58]. The functional guilds responsible for nitrification, denitrification, sulfate reduction, methanogenesis, and anaerobic ammonium oxidation are crucial to this process, influencing contaminant conversion and, ultimately, the degree to which they are attenuated in the landfill environment. For example, sulfate-reducing bacteria can precipitate dissolved metals as insoluble sulfides, while methanogenic communities can stabilize organic matter under decreased circumstances [9]. At the same time, microbial degradation can generate intermediate chemicals that affect leachate toxicity and mobility. Environmental parameters such as pH, dissolved oxygen (DO), temperature, and salinity substantially regulate microbial activity and the fate of contaminants in landfill plumes [6, 60]. Another area receiving increasing scientific attention is the presence of pathogenic microorganisms, ARB, and ARGs in landfill leachate, particularly at sites receiving commingled municipal, medical, and industrial waste streams [16, 42]. Metagenomic surveys of landfill leachates and hydraulically connected groundwater have recovered hundreds of distinct ARG subtypes encoding resistance determinants to tetracyclines, sulfonamides, and β-lactams, along with genes mediating multidrug efflux [16]. These findings indicate that landfill environments may serve as reservoirs and active sites of horizontal gene transfer, where sustained exposure to sub-inhibitory concentrations of pharmaceuticals, heavy metals, and other toxicants exerts co-selective pressure that favors the maintenance and dissemination of resistance determinants. Recent reviews of ARG transfer from leachate to groundwater, and the biotic and abiotic factors that govern it, conclude that groundwater near landfills remains comparatively understudied and lacks a standardized ARG methodology [22].

7. MECHANISMS OF ENVIRONMENTAL CONTAMINATION

Most pollutants enter groundwater through downward-flowing water that reaches the unsaturated zone above the aquifer. Where the liner is absent or defective, leachate leaks through the soil and weathered rock, and ammonia, salts, small organics, and metals reach the water table and spread as a plume [4, 10, 12]. Imaging and chemical analysis field studies indicate that these plumes manifest as areas of low electrical resistance and high dissolved solids, occurring between 0 and 10 m deep in the shallow aquifers. This indicates that the downward movement occurs where liners are missing or broken [10, 61, 62]. The second major route is surface runoff and lateral flow. During rain or monsoon storms, leachate and polluted stormwater may overflow ponds or slide downslope

along the landfill to adjacent lowlands, streams, and ponds [27, 44]. In Bangladesh and other monsoon-season areas, studies have shown that leachate-contaminated waters are released directly into adjacent surface waters during floods, thereby increasing the extent of the region exposed to contamination [52, 63]. Increases in BOD, COD, nitrate, chloride, and metal levels in downstream surface waters during the dry and wet seasons confirm that this surface relationship is real [1, 15, 63].

7.1 Environmental impacts

Leachate entering an aquifer alters the water chemistry. It changes the pH and the redox potential (Eh). These forms stratify plumes that flow up and down as well as sideways. Near the source, microbial communities rapidly consume DO and other electron acceptors, creating a highly reducing aqueous environment. This process reductively dissolves iron (Fe) and manganese (Mn) oxides, releasing sorbed heavy metals and nutrients into the water [1, 64]. Oxidizing conditions return as the plume moves down-gradient and mixes with oxygenated groundwater or surface water. When this occurs, the metals reprecipitate or adsorb onto mineral surfaces, and contaminant distribution is neither simple nor uniform [1].

High EC and elevated levels of TDS, NH_4^+-N, chloride, and sulfate, along with trace amounts of Fe, Mn, and Pb, typically indicate these plumes [61, 65]. They are typically several-fold greater than background levels [61, 66]. Without effective control, plumes persist for decades and extend for hundreds of meters, occasionally beyond a kilometer, in the direction of groundwater flow [9, 46, 61].

When discharged into surface water, leachate with high nitrogen and phosphorus content usually causes eutrophication [1, 51].

BOD and COD in streams and ponds surrounding landfills are often above acceptable levels, and as such, the water is unsafe until treated [51].

Ammonia, heavy metals, and harmful organic chemicals are also acute toxicants. In contaminated water, aquatic vegetation halts growth, and fish experience oxidative stress and DNA damage [14, 26].

Chemical and biological breakdown of soil is a common feature in areas surrounding landfill sites. In areas where salts, metals, and other constituents accumulate to high concentrations, they induce measurable changes in soil pH, redox status, and cation exchange capacity—parameters that together determine how readily nutrients become available and how the microbial community is structured [35, 53, 56]. Field studies at open dumpsites in Bangladesh and Nigeria provide a useful illustration. In such places, lead, cadmium, chromium, and other elements accumulate in topsoil and enter growing vegetation; reported effects include reduced soil fertility and metal concentrations in plant tissue that exceed established safety limits [14].

7.2 Risks to human health and ecosystems

The overall impact of landfill leachate on potable waters, food safety, air quality, soil stability, ecological diversity, and the spread of antimicrobial resistance is multifaceted.

7.2.1 Drinking water and groundwater contamination

Poorly lined or otherwise uncontrolled landfills often allow leachate to penetrate the subsoil, thereby contaminating groundwater used for domestic and irrigation purposes [10, 61]. Monitoring studies in Bangladesh [12], India [54, 64], and China [60, 67] show that NO_3^-, NH_4^+-N, Cl^-, TDS, and heavy metals in wells close to landfills frequently exceed WHO guideline values or national limits, with nitrate the most consistently reported exceedance [11]. Comparable exceedances have been recorded well beyond South and East Asia, including Mexico [51], Morocco [68], Ethiopia [44], Zambia [69], and Ghana [70], indicating that the pattern recurs wherever containment and monitoring provisions are limited. In several case studies from Asia and Africa, groundwater nitrate levels exceed the WHO guideline value of 50 mg/L as NO_3^-, increasing the risk of methemoglobinemia and long-term oncogenic effects [11, 33].

Field studies show that iron, manganese, lead, cadmium, chromium, and nickel concentrations in groundwater below dumpsites and sanitary landfills are usually above drinking-water standards, and hazard indices exceed unity for susceptible populations, including children [15, 61, 66]. Risk-based corrective action models indicate that manganese and nitrate concentrations are likely to pose non-carcinogenic health risks and expand risk zones without remedial action [10].

7.2.2 Food-chain transfers and agricultural effects

Groundwater and surface water affected by leachate are often used to irrigate vegetables and staple crops, leading to the bioaccumulation of heavy metals and other pollutants in edible tissues [12, 15, 65]. In Bangladesh, calculated health-risk indices for lead, cadmium, nickel, and manganese in leafy vegetables and rice grown near landfill sites indicate an unacceptable lifetime carcinogenic risk to the local population through pathways involving nickel, lead, and cadmium [12, 27]. Similar enrichment of cadmium, lead, zinc, and copper in soil and crops has been observed worldwide around open dumps [65, 66].

Saline intrusion and heavy metals negatively affect soil structure and fertility, reducing yields and nutrient uptake, altering microbial communities and enzymatic activity, and inhibiting essential nutrient cycling [53, 65]. Long-term leachate exposure has been linked to declines in organic matter, microbial biomass, and macrofaunal abundance in soils of semi-arid rangelands, indicating a serious deterioration of soil health and ecosystem productivity [53].

7.2.3 Chemical toxicity and long-term health effects

Special attention should be paid to non-threshold heavy metals such as lead, cadmium, arsenic, mercury, and hexavalent chromium due to their bioaccumulating properties and carcinogenic, neurotoxic, and developmental effects at relatively low levels [1, 14]. Lead is a common contaminant of surface water and groundwater around landfill sites, and its occurrence is strongly associated with neurodevelopmental impairment and renal damage; arsenic, however, increases the risk of several types of cancer and cardiovascular disease [1, 33, 71]. Quantitative health risk evaluations support these concerns. Incremental lifetime cancer risks (ILCR) calculated for consuming contaminated water or foodstuffs are reported, in study after study, to exceed thresholds conventionally regarded as acceptable [12, 14, 66]. Organic contaminants (phenols, polycyclic aromatic hydrocarbons, pharmaceutical residues) are very common in waters affected by leaching, and genotoxicity and endocrine disruption have been reported [1, 33, 71]. Cytotoxicity methods have determined DNA damage

and oxidative stress after exposing samples to raw or diluted leachates [33, 72].

7.2.4 Risks of pathogens, antibiotic resistance, and infectious diseases

Leachate routinely contains a range of pathogenic bacteria, viruses, protozoa, and helminths, and this range increases when municipal and hospital wastes are co-disposed [1, 17].

Landfill leachate shows a high prevalence of ARB and ARGs [16, 42, 65]. Metagenomic surveys have identified over 300 different ARGs, and these genes can affect neighboring groundwater [16]. Medical or livestock waste in landfills can act as crucibles for resistance evolution, complicating the treatment of community-acquired infections [16, 65].

7.2.5 Loss of biodiversity and degradation of ecosystems

Leachate alters the physical, chemical, and biological properties of aquatic and terrestrial ecosystems, leading to ecosystem simplification [1, 2, 53]. Lasting exposure to a mixture of contaminants causes plants and fish to experience DNA damage and reproductive deficits [1, 14, 71].

Even with partial leachate treatment, ecotoxicological trials have reported reduced survival and growth of soil-dwelling organisms [14, 72]. Standardized earthworm bioassays quantified the adverse effects of landfill leachate on *Eisenia fetida* using undiluted and diluted leachate [34, 55, 73]. Wetlands downstream or downslope of disposal sites are at particular risk, and regular leachate discharges can alter them and reduce species variety [1, 2].

7.2.6 Air quality, odor, and greenhouse-gas effects

Landfill sites release a variety of airborne pollutants such as methane, hydrogen sulfide, and bioaerosols [1, 14, 33]. Sulfur compounds are often linked to unpleasant odors and respiratory discomfort [33, 71]. Methane, with its high global warming potential, contributes to climate change and indirectly increases health risks such as heat stress and the spread of disease vectors [14, 33].

7.2.7 Disproportionate inequality of burdens and research gaps

In developing nations, marginalized groups suffer the greatest health and ecological consequences as open dumps and uncontrolled groundwater extraction have become the norm [12, 62, 65]. Although numerous studies report contamination, many are limited by a lack of direct epidemiological evidence of disease effects, and the toxicity of chemical combinations remains poorly understood [1, 14, 71]. To address these gaps, specific attention must be paid to metals, nitrates, and ARGs in human groups and the environment [1, 12, 16].

8. RISK-ORIENTED MONITORING FRAMEWORK

Table 4 presents a risk-oriented framework that integrates environmental media, sampling design, core monitoring parameters, sampling frequency, and interpretive objectives. The surface-water category requires hydraulic consideration. DO levels are affected not only by oxygen demand from organic and ammoniacal loads in leachate but also by re-aeration processes, which are influenced by channel geometry, turbulence, and flow over drops, weirs, and stepped structures. These factors can greatly increase the DO concentration [74]. Downstream monitoring stations must therefore be placed in such a way that the load signal from the landfill is not masked by hydraulic re-aeration.

Table 4. Risk-oriented monitoring framework for landfill-affected environments

Medium	Sampling Design	Core Parameters	Suggested Frequency	Interpretive Objective	References
Groundwater	Wells up-gradient and down-gradient of the landfill	NH_4^+-N, NO_3^-, Cl^-, EC/TDS, COD/TOC, major ions, metals, selected CECs	Quarterly (semi-annual at low-risk or aftercare sites, Table 5); increase after wet seasons or incidents	Background comparison, trends, plume delineation, and drinking-water screening	[9, 46, 75, 76]
Surface water	Upstream/downstream stations and sediment	DO, BOD/COD, nutrients, EC, metals, toxicity, and microbial indicators	Wet and dry seasons; event-based runoff sampling	Load and ecological-impact evaluation	[15, 63, 75]
Leachate	Collection sumps, cells of different ages, outlets	Flow, pH, EC, BOD/COD, NH_4^+-N, metals, PFAS/selected CECs	Monthly to quarterly during operation (semi-annual in aftercare, Table 5), linked to rainfall and operations	Treatment loading, age trends, and source attribution	[2, 5, 39, 75]
Soil/vadose zone	Transects beneath/down-gradient; lysimeters where feasible	Moisture, pH, EC, organic carbon, metals, and selected organics	Annual/biannual plus incident response	Attenuation capacity and early leakage warning	[13, 27, 53]
Ecological/health evidence	Biota, crops, and exposure-relevant populations	Bioassays, tissue residues, water-use pathways, and risk indices	Risk-based and site-specific	Link chemical occurrence to meaningful exposure and effects.	[12, 14, 34, 66]

Notes: Adapt the proposed framework to landfill design, hydrogeology, climate, regulatory requirements, and receptor vulnerability. BOD, biochemical oxygen demand; CECs, contaminants of emerging concern; COD, chemical oxygen demand; DO, dissolved oxygen; EC, electrical conductivity; PFAS, per- and polyfluoroalkyl substances; TDS, total dissolved solids; TOC, total organic carbon. Compiled by the authors (Section 8.1); references indicate the principal sources on which each row is based.

8.1 Derivation of the framework and the risk-tier rule set

The framework in Table 4 was derived from three lines of evidence, not precedent alone. First, the core parameters are those that are elevated by one to three orders of magnitude in leachate relative to natural waters irrespective of climate,

waste composition, or landfill age [2, 5, 8] and that behave predictably along the plume: chloride and EC are conservative tracers of dilution; NH_4^+-N is the persistent long-term contaminant; nitrate, dissolved iron and manganese, and sulfate map the redox zonation of the plume; and COD or TOC quantifies the organic load [9, 46]. Multivariate analyses of leachate datasets consistently identify pH, EC, NH_4^+-N, TDS, Cl^-, Fe, and Mn as the most discriminating variables [35, 36]. The parameter set is therefore transferable across settings; what differs between sites is monitoring intensity, not the indicators themselves. Second, the sampling frequency is anchored on the seasonal recharge cycle that drives leachate generation and plume loading [2, 40, 67] and on regulatory practice. The EU Landfill Directive prescribes quarterly monitoring of leachate composition and surface water during the operational phase and six-monthly monitoring during aftercare, with groundwater composition sampled at a site-specific frequency set by groundwater velocity and the time needed for remedial action between two samplings, and with trigger levels verified by repeat sampling [75]. The US Subtitle D criteria require detection monitoring of up-gradient and down-gradient wells at least semi-annually throughout the active life and post-closure period, with statistical comparison to background and escalation to assessment monitoring when a significant increase is confirmed [76]. The "quarterly minimum" in Table 4 is thus the operational-phase frequency of the Directive and the coarsest interval at which wet- and dry-season contrasts can be resolved; semi-annual sampling is the regulatory floor appropriate to low-risk or aftercare sites. Third, station density follows the same regulatory logic of background comparison and plume interception (Section 8.3).

Table 5. Risk-tier rule set for monitoring design (risk tier = highest rating of the three factors)

Element	Low-Risk Tier	Moderate-Risk Tier	High-Risk Tier	References
Containment and source control	Composite liner, functioning leachate collection, final cover; municipal waste only	Single or aged liner, partial collection, or unverified integrity	Unlined or open dump; failed or degraded containment; co-disposal of industrial, medical, or e-waste	[17, 29, 75]
Hydrogeological vulnerability	Thick, fine-grained vadose zone; deep water table; low-permeability aquifer	Intermediate vadose thickness or moderate-permeability aquifer	Shallow water table (<~5 m), coarse or fractured/karst aquifer, high recharge, or flood-prone site	[13, 46, 52]
Receptor proximity and use	No supply wells or supply-used surface water within plausible plume travel distance (~1 km)	Supply wells, irrigation, or streams within ~1 km down-gradient	Drinking-water or irrigation wells, or supply-used surface water, within a few hundred meters down-gradient	[9, 10, 61]
Parameter priority	Tier A core set every round	Tier A every round; Tier B annually and when triggered	Tier A and B every round; Tier C at baseline and when triggered	[2, 5, 9]
Groundwater frequency	Semi-annual (wet and dry season)	Quarterly	Quarterly full suite; monthly field indicators; event-based sampling	[67, 75, 76]
Leachate frequency	Semi-annual composition; monthly volume	Quarterly composition; monthly volume	Monthly composition and volume, linked to rainfall	[75]
Groundwater station density	≥1 up-gradient background well; ≥1 near-field down-gradient; ≥1 far-field control	≥1 up-gradient; ≥2 down-gradient on the plume axis; ≥1 lateral; nearest supply well as compliance point	≥1 up-gradient; ≥3 down-gradient including lateral wells; multi-level wells at ≥2 depths; all supply wells within travel distance as compliance points	[9, 61, 76]
Surface water and other media	Upstream and downstream stations, wet and dry season	Plus sediment sampling annually and runoff sampling during events	Plus continuous flow or DO at discharge points, sediment, crops or biota, and receptor exposure survey	[15, 27, 63]
Triggers for intensification	EC or Cl^- in a down-gradient well >2× the up-gradient value in two consecutive rounds; NH_4^+-N above background in any down-gradient or supply well; upward trend over ≥4 rounds; any drinking-water guideline exceedance at a receptor well; leachate head rise or collection-flow decline indicating containment failure	Same	Same, plus immediate resampling and receptor protection	[9, 28, 76]
Regulatory analogue	RCRA detection-monitoring floor; EU aftercare phase	EU operational phase	EU trigger-level response; RCRA assessment monitoring	[75, 76]

Notes: Tier A, B, and C analytical sets are defined in Table 6. Trigger values are indicative and should be replaced by site-specific background statistics (mean plus three standard deviations, or a prediction limit) once sufficient baseline data exist. DO, dissolved oxygen; EC, electrical conductivity; RCRA, Resource Conservation and Recovery Act (US).

Table 5 converts the framework into a rule set. Three factors are rated low, moderate, or high: containment and source control, hydrogeological vulnerability, and receptor proximity and use. The site tier is the highest rating of any single factor. This precautionary "maximum rule" is deliberate: an unlined cell above a shallow gravel aquifer with wells down-gradient supply is a high-risk site regardless of how favorably the other factors score, and a scoring scheme that averages the factors would understate such cases. Each tier then specifies parameter priority (the analytical tiers A, B, and C defined in Section 8.4), sampling frequency, station density, and the conditions that trigger intensified monitoring. The trigger

values are indicative and should be replaced by site-specific background statistics once four or more rounds of data exist; the verification principle, however, is general: a trigger is confirmed only when it recurs in a consecutive sampling round, after which the site moves up one tier and adds wells or analytes as specified. Where eight consecutive rounds pass without a confirmed trigger, the site may step down one tier.

8.2 Climate-conditioned monitoring design

Climate enters the framework as a modifier of timing and parameter emphasis rather than as a separate tier. In arid and semi-arid settings, leachate generation is episodic and evaporative concentration raises salinity and ionic strength, so the plume is small in volume but highly concentrated [2, 13, 53]. Elevated ionic strength and abundant dissolved organic matter alter sorption and metal complexation, so that mobility rather than load governs risk [41, 48, 49]; for short-chain PFAS, leachate DOM and coexisting ions have been shown to modify sorption onto aquifer media, with low-molecular-weight DOM fractions increasing adsorption by about 32% and Cl^{-}–Mg^{2+} pairs exerting a stronger effect than SO_4^{2-}–Na^{+} [25]. Monitoring should therefore target peak concentrations: sampling of leachate sumps and near-field wells should be timed to the weeks following rainfall or irrigation-driven recharge above a site-defined threshold; EC, Cl^{-}, and Na^{+} should serve as first-line tracers; and vadose-zone monitoring beneath cells (suction lysimeters or moisture sensors) justifies its cost because travel times to deep water tables are long and no other early warning exists [13]. In humid, tropical, and monsoon settings, leachate is generated continuously, concentrations are diluted, but loads are high, and storm runoff and pond overflow create direct surface-water pathways [27, 40, 63]; in a tropical urban aquifer, isotopic tracers indicated leachate-infiltration fractions of 1–33% of local groundwater, with nitrate-driven health risk peaking after the monsoon [24]. Here the priority is load rather than concentration, so continuous flow or level measurement at leachate outlets and surface-water stations adds more information than additional analytes; event-based sampling during and immediately after storms, paired wet- and dry-season campaigns, and DO, BOD, nutrient, and microbial indicators in receiving waters take precedence [67]. In temperate settings with seasonal recharge, paired campaigns before and after the recharge season are the minimum, and the quarterly interval of Table 5 resolves the annual cycle. In all climates, concentration must be reported together with the flow condition under which it was sampled.

8.3 Monitoring network design: Well placement, depth, and rapid plume checks

The framework assumes a network that can establish background, detect a release as early as possible, and verify whether the plume reaches a receptor. The conceptual minimum (Figure 4) is therefore one up-gradient background well, one near-field down-gradient well at the waste boundary or compliance line, and one far-field control well between the landfill and the nearest receptor, or the receptor well itself sampled as a compliance point. Because transverse dispersion in most aquifers is small and plumes are narrow relative to their length [9], lateral wells on both flanks of the flow axis are added in the moderate and high tiers to bound the plume width.

Leachate plumes occupy the uppermost aquifer and, at the sites reviewed here, were typically imaged within roughly the upper 10 m of the shallow aquifers [10, 61, 62]; with distance they may sink beneath fresh recharge, and density differences can cause sinking close to the source [9]. Near-field wells should therefore be screened with short intervals (about 2–3 m) straddling the seasonal range of the water table, where the first arrival of a release is detected; far-field wells should be screened in the expected plume core or, preferably, constructed as multi-level nested wells with screens at two or more depths. Long screens that span both clean and contaminated water blend the sample and can dilute a plume signal below detection. In layered or multi-aquifer settings, nested piezometers in each unit with measured vertical gradients are needed because perched water and leaky aquitards can route leachate downward, and borehole annuli must be sealed so that the monitoring wells do not themselves become pathways.

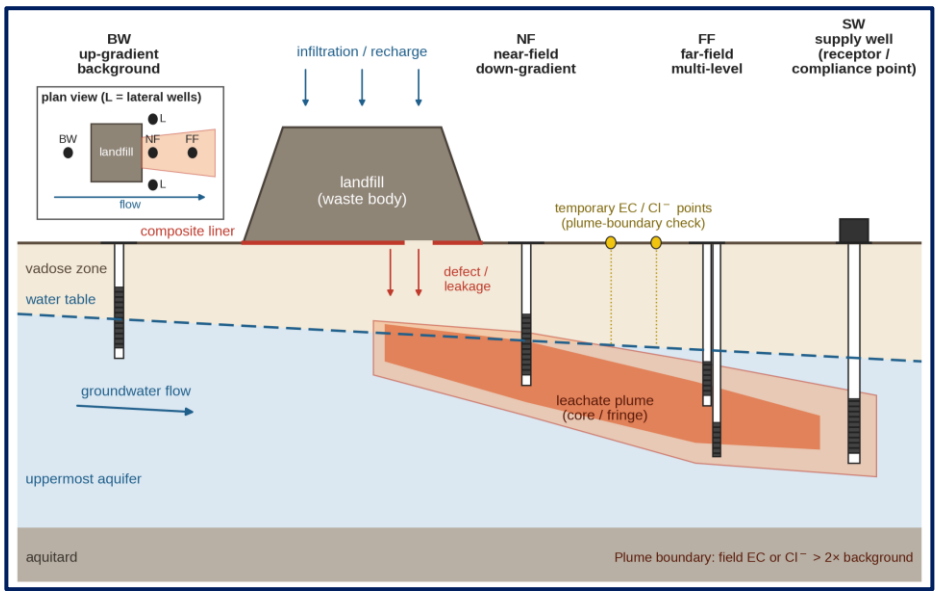

Figure 4. Conceptual minimum groundwater monitoring network in cross-section with a plan-view inset (schematic, not to scale; present study, based on study [9])

The background well must be hydraulically up-gradient and outside the zone of influence of the landfill, beyond the leachate mounding that can locally reverse gradients beneath unlined sites and beyond gas migration, while being screened in the same hydrostratigraphic unit as the down-gradient wells and unaffected by other sources such as agriculture, septic systems, or road salt. Flow direction should be established from at least three water-level points and re-checked seasonally, because directions can reverse near rivers, under pumping, or during monsoon flooding [27, 63].

EC and chloride provide a quick, low-cost delineation before or between full sampling rounds. Field EC measured in wells, springs, drains, and temporary hand-augered or direct-push points, together with chloride by titration or test strip, identifies the plume where the down-gradient value exceeds roughly twice the up-gradient value; the boundary is traced by stepping laterally and down-gradient until values return to background (Figure 4). Because chloride is neither retarded nor degraded, its boundary marks the outer limit of leachate influence, and retarded constituents such as NH_4^+-N lie inside it [9]. Ratios of Cl^- to Br^- or of Na^+ to Cl^- help distinguish leachate from other salinity sources. Where available, electrical resistivity imaging maps the low-resistivity plume within a day and is the most efficient guide to permanent well placement [10, 61]. Where the budget is tight, the order of priority is: first, inventory and sample every existing down-gradient supply well, spring, drain, and stream, because these are the receptors and cost nothing to install; second, install the three-well minimum with short screens across the water table; third, run field EC, Cl^-, NH_4^+-N, NO_3^-, and water level quarterly (Tier A, Section 8.4); fourth, add lateral and multi-level wells only where the EC/Cl^- survey or resistivity imaging shows the plume leaving the axis or sinking.

8.4 Tiered analytical strategy and practical feasibility

Table 2 lists monitoring approaches for each pollutant group but not what they cost, what they detect, or what they require in the field. Table 6 therefore organizes the parameters into three analytical tiers. Tier A comprises routine, low-cost field and basic-laboratory indicators that detect and delineate a plume and can be run at every station in every round. Tier B comprises confirmatory analyses available in regional or university laboratories that quantify hazard. Tier C comprises specialist analyses for PFAS, pharmaceuticals, microplastics, and ARGs that characterize hazards Tier A cannot detect but do not change the plume delineation; they are run at baseline and when triggered. The rationale is that the leachate signature in EC, Cl^-, and NH_4^+-N lies one to three orders of magnitude above natural variability, so Tier A alone suffices to detect and delineate a release in any setting [2, 5, 9], whereas the higher tiers answer different questions, namely how hazardous the release is and to whom, and are justified once a pathway to a receptor is plausible or confirmed. The practical constraints of low- and middle-income settings, including holding times relative to the distance to the laboratory, the availability of reference materials, and specialist analyses that often require shipment abroad, are addressed in the preservation and access columns of Table 6.

8.5 Indicator interpretation by medium

The same constituent carries different information in each medium. Table 7 supplements Table 4 by stating, for each core indicator, what a measurement means in leachate, groundwater, and surface water, and what to do next.

Table 6. Tiered analytical strategy: Parameters, methods, detection capability, sample handling, and escalation triggers

Tier and Purpose	Parameters	Methods	Typical LOQ	Preservation and Field Requirements	Cost and Access	When
A– Routine screening: detect and delineate the plume; trends [2, 5, 9, 46]	Field: EC, pH, T, DO, ORP, water level or flow. Laboratory: Cl^-, NH_4^+-N, NO_3^-, COD or TOC, Fe, Mn, alkalinity, TDS	Portable multiparameter meters; argentometric titration or IC (Cl^-); colorimetry or ion-selective electrode (NH_4^+-N); UV/colorimetric or IC (NO_3^-); closed-reflux dichromate COD with chloride masking; FAAS or colorimetric kits (Fe, Mn)	EC 1 µS/cm; Cl^- ≈ 1 mg/L (titration); NH_4^+-N ≈ 0.02–0.1 mg/L; NO_3^- ≈ 0.1–0.5 mg/L; COD ≈ 5–10 mg/L (low range); Fe, Mn ≈ 0.02–0.05 mg/L	Field parameters measured on site; samples cooled to 4 °C; NH_4^+-N and COD acidified (H_2SO_4, pH < 2) if not analyzed within 24–48 h; Fe and Mn filtered (0.45 µm) for the dissolved fraction and acidified (HNO_3, pH < 2); leachate COD requires dilution or mercuric-sulfate masking of chloride	Low; portable meters and basic wet chemistry available to most municipal, water-authority, and university laboratories	Every station, every round, at all tiers
B– Confirmatory: quantify hazard; guideline screening [28, 34, 41, 49]	Trace metals (Cd, Cr, Cu, Ni, Pb, Zn, As, Hg); major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^-); BOD_5, TSS; total coliforms and *E. coli*; screening bioassays (seed germination, *Daphnia*, earthworm)	ICP-OES or ICP-MS (hydride or cold-vapor AAS for As and Hg where ICP-MS is unavailable); IC; standard BOD_5 and TSS; membrane filtration or defined-substrate MPN; ISO/OECD bioassays	ICP-OES ≈ 1–10 µg/L; ICP-MS ≈ 0.01–0.1 µg/L; IC ≈ 0.1 mg/L; BOD_5 ≈ 2 mg/L; coliforms 1 CFU/100 mL	Metals filtered and acidified; microbiology in sterile bottles at 4 °C with analysis within 6–24 h; BOD within 48 h	Moderate; regional or university laboratories; microbiology limited by holding time and transport distance	Annually at the moderate tier and whenever Tier A triggers; every round at the high tier

C– Specialist: characterize hazards invisible to Tiers A and B [16, 19, 23, 31, 71]	PFAS (targeted suite); pharmaceuticals and PPCPs; microplastics; ARG markers (e.g., *sul1*, *tetW*, *bla*TEM, *ermB*, *intI1*) and pathogens; resistome by metagenomics; genotoxicity assays	LC-MS/MS with isotope dilution (standardized PFAS methods such as ISO 21675 and US EPA 1633); density separation and oxidative digestion with μ-FTIR or Raman (microplastics); qPCR normalized to 16S rRNA; shotgun metagenomics	PFAS ≈ 1–10 ng/L; PPCPs ≈ 1–50 ng/L; microplastics reported as particles per volume with a stated size cut-off (reported leachate concentrations span 0.16 to 33,213 items/L [23]); qPCR ≈ 10–100 gene copies per reaction	PFAS-free sampling train (HDPE or polypropylene, no PTFE or fluorinated materials, field and equipment blanks); PPCPs in amber glass at 4 °C with extraction within 48 h; microplastics with glass or metal equipment and procedural blanks; ARGs filtered on site or within 24 h, filters frozen at −20 to −80 °C	High; usually external or international laboratories with turnaround of weeks; contamination control is the principal quality risk	Baseline once, then annually while any trigger holds: Tier B confirms the plume reaching or approaching a receptor; waste inventory includes industrial, medical, e-waste, or fire-fighting foam; drinking-water receptor within plume travel distance; treated leachate discharged to supply-used surface water; regulatory requirement

Notes: LOQ values are indicative orders of magnitude for water samples and depend on matrix and laboratory; leachate matrices generally require dilution. AAS, atomic absorption spectrometry; CFU, colony-forming unit; FAAS, flame atomic absorption spectrometry; IC, ion chromatography; LOQ, limit of quantification; MPN, most probable number; ORP, oxidation–reduction potential; PTFE, polytetrafluoroethylene; HDPE, high-density polyethylene; EC, electrical conductivity; TDS, total dissolved solids; ICP-MS, inductively coupled plasma mass spectrometry; ICP-OES, inductively coupled plasma optical emission spectrometry; qPCR, quantitative polymerase chain reaction. Compiled by the authors (Section 8.4); references in the first column indicate the sources on which each tier is based; analytical methods follow the standards named in the cells (ISO 21675, US EPA Method 1633, ISO/OECD bioassay guidelines).

Table 7. Indicator–medium–interpretation guide: What is measured, what it means, and what to do next

Indicator	In Leachate	In Groundwater	In Surface Water	Next Step
EC/TDS	Bulk strength; rises with age as salts persist and in arid climates through evaporative concentration; falls with rainfall dilution [2]	First-line plume detection by ratio to the up-gradient well; vertical EC profiles locate the plume depth [61]	Dominated by dilution; informative only near a discharge or at low flow [15, 63]	If >2× background, confirm with Cl^- and NH_4^+-N and delineate laterally and with depth
Cl^-	Conservative; defines the source term [5]	Neither retarded nor degraded: defines plume extent, dilution factor, and travel time; other constituents are interpreted relative to it [9, 13, 43]	Rapidly diluted; useful for mass balance only with measured flow [9, 63]	Separate leachate from road salt, seawater, or irrigation return using Cl^-/Br^- or Na^+/Cl^- ratios; adjust the well network to the Cl^- boundary
NH_4^+-N	Dominant nitrogen form; persists for decades irrespective of landfill age [5, 46]	Marks the anoxic plume core; sorption retards its front relative to Cl^-, so detection in a supply well indicates a mature, poorly attenuated plume [9]	Exerts nitrogenous oxygen demand; toxicity depends on pH and temperature through the un-ionized NH_3 fraction; drives eutrophication [1, 51]	Pair with NO_3^- and DO to map redox zonation; screen supply wells; place river stations upstream of re-aeration structures [74]
NO_3^-	Low, because the waste body is reducing [46]	Appears at the oxic fringe where NH_4^+ is nitrified; compare with 50 mg/L as NO_3^- (≈11.3 mg/L as NO_3^--N) [28]; may also derive from agriculture [11]	Nutrient contributing to eutrophication; low direct toxicity [1, 51]	On exceedance, assess health risk and alternative supply; use co-tracers if the source is ambiguous
DO, ORP with BOD/COD	BOD/COD ratio indicates age and biodegradability (>0.3 young, <0.1 mature) and treatment choice [5, 39]	DO depletion and low ORP near the source define the reducing zone that releases Fe and Mn [9]	DO sag downstream of a discharge; re-aeration by turbulence and drops can mask the load [74]	Select biological versus physicochemical treatment from BOD/COD (Table 8); site surface stations before hydraulic re-aeration
Fe, Mn	Variable; often high in young leachate [5]	Reductive dissolution of aquifer oxides inside the plume: an indicator of redox impact even where the landfill contributes little Fe or Mn; taste, staining, and guideline concerns [9, 30]	Re-oxidize and precipitate at the discharge; accumulate in sediment [1, 9]	Report filtered and total fractions; compare with drinking-water guidelines [28]; sample sediment; expect release of sorbed trace metals
SO_4^{2-}	Depleted in methanogenic leachate by sulfate reduction [9]	Depleted in the plume core and rebounding at the fringe; with Fe, Mn, and CH_4 delineates redox zones; sulfide odor and corrosion [9, 14]	Quasi-conservative; low toxicity [9]	Interpret jointly with Fe and Mn; never use as a sole tracer

Trace metals (Cd, Cr, Cu, Ni, Pb, Zn, As)	Mostly particulate or DOM-complexed; dissolved fraction pH- and redox-dependent [41, 49]	Usually attenuated by sorption and sulfide precipitation but mobile as DOM complexes; exceedances near unlined and e-waste sites [15, 38, 77]	Partition to sediment; bioaccumulate in crops and biota [12, 27]	Analyze filtered and unfiltered samples; speciate where feasible; sample sediment, crops, and biota; compute hazard indices for receptors
Fecal indicators, pathogens, ARGs	Reservoir, particularly with medical or mixed waste [16, 42]; treatment reduces but does not eliminate ARGs [21]	Presence signals a fast pathway (fractured, karst, or shallow) or direct leakage, and a public-health risk beyond chemistry [16, 22, 77]	Direct exposure hazard; dissemination of resistance determinants [65]	Escalate to Tier C (qPCR markers); point-of-use disinfection; well-head protection
PFAS and other CECs	Persist through conventional treatment; source inventory needed [19, 31, 32]	Short-chain PFAS highly mobile and may travel with the Cl^- front, with sorption modulated by leachate DOM and ions; drinking-water limits are in the ng/L range [7, 20, 25, 31]	Effluent-discharge pathway; long-chain PFAS bioaccumulate [32]	Waste-acceptance control; treatment upgrade (activated carbon, reverse osmosis); advisories for supply wells

Notes: Tier C refers to Table 6. EC, electrical conductivity; TDS, total dissolved solids; CECs, contaminants of emerging concern; DOM, dissolved organic matter; ORP, oxidation–reduction potential; qPCR, quantitative polymerase chain reaction. Compiled by the authors (Section 8.5); bracketed numbers give the supporting studies for each statement, and the 'Next step' column is the authors' recommendation derived from Sections 8.1–8.4.

9. MITIGATION AND MANAGEMENT STRATEGIES

Aquifer remediation relies mainly on pump-and-treat systems, which are energy-intensive and may need years of operation for large, diffuse plumes, and on permeable reactive barriers (PRBs) filled with reactive media such as activated carbon, compost, or zero-valent iron that remove nitrate, heavy metals, and selected organics as groundwater passes through; PRBs suit narrow plumes and combine well with source control [4, 29].

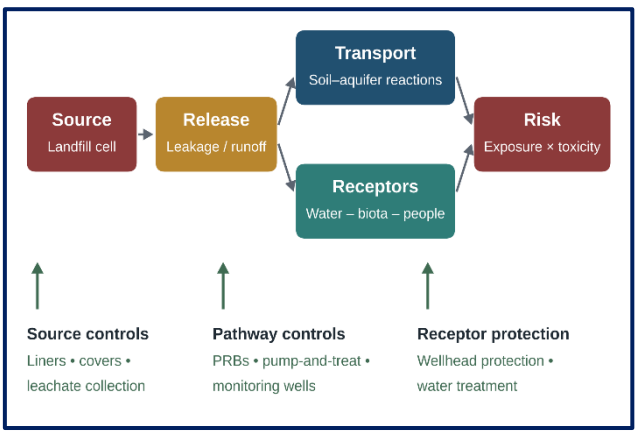

Figure 5. Integrated source–pathway–receptor model and principal control points (present study, based on study [4])

Engineering controls installed at landfill sites are a major line of defense against the incipient generation of new contamination. These controls include composite liners comprising clay and geomembrane, LCS, protective covers to reduce infiltration, and specific gas collection schemes. Still, in the long run, landfill performance depends on construction and maintenance quality and on close attention to liner integrity [3, 4, 17]. Figure 5 illustrates the integrated relationship between the contaminant source, migration pathways, environmental receptors, resulting risk, and available control points.

Read as a multi-barrier system, Figure 5 also organizes the management choices that follow this review. Waste acceptance and source control, engineered containment, leachate collection and treatment, the natural attenuation capacity of the vadose zone and aquifer, and monitoring coupled to institutional response are successive barriers, and each contamination pathway described in Section 7 corresponds to the failure of one of them. Three implications follow. First, for new facilities, the first two barriers dominate: liner and cover integrity, leachate collection, and the exclusion of industrial, medical, and e-waste streams cost a fraction of aquifer remediation and are the only measures that prevent the persistent constituents, NH_4^+-N, chloride, and the emerging contaminants, from entering the subsurface at all [4, 29]. Second, at existing unlined or degraded sites, the containment barrier is already lost, so the risk-tier rule set (Table 5) directs effort to the attenuation and monitoring barriers: plume delineation with the minimum well network (Figure 4), Tier A indicators at the frequency the tier prescribes, and receptor protection by supply substitution, well-head protection, or point-of-use treatment where a plume reaches a well. Third, monitoring data protect receptors only when they are tied to trigger levels and mandated responses; the European and United States regimes achieve this through defined verification and escalation steps [75, 76], and the tiered analytical strategy (Table 6) makes an equivalent regime affordable where laboratory capacity is limited. Sustainable landfill management, in this reading, is the allocation of investment to the barrier that still stands, informed by monitoring designed to reveal when it is failing.

Table 8 compares the relative strengths, limitations, and best-fit applications of source prevention, biological and physicochemical treatment, advanced treatment, and plume remediation.

Table 8. Comparative evaluation of leachate prevention, treatment, and remediation strategies

Strategy	Representative Methods	Main Strength	Principal Limitation	Best-Fit Context	References
Source prevention	Composite liners, final covers, stormwater diversion, leachate collection	Reduces generation and initial release	Long-term integrity, construction quality, and maintenance	All facilities; highest priority for new landfills	[29]

Biological treatment	Aerobic/anaerobic processes, nitrification–denitrification	Effective for biodegradable organics and nitrogen under suitable conditions	Inhibition by toxicity/salinity; weak for refractory compounds	Young/intermediate leachate; pretreatment or integrated trains	[43, 56, 59]
Physicochemical treatment	Coagulation, precipitation, adsorption, stripping, ion exchange	Targets color, metals, ammonium, and selected organics	Chemical use, sludge/residuals, and variable selectivity	Polishing or pretreatment according to target contaminants	[43]
Advanced treatment	AOPs, nanofiltration, reverse osmosis, membrane bioreactors	High removal of refractory and emerging contaminants	Energy, concentration/by-products, fouling, and cost	Mature leachate or stringent discharge/reuse standards	[56, 59]
Plume remediation	Pump-and-treat, PRBs, monitored natural attenuation	Controls or removes contaminants after release	Slow restoration, plume heterogeneity, and long-term operation	Selected groundwater plumes following site characterization	[29]

Notes: AOP, advanced oxidation process; PRB, permeable reactive barrier.

10. CONCLUSIONS

Uncontrolled and aging landfills remain persistent sources of contamination for decades after disposal ceases. Leachate composition depends on waste characteristics, landfill age, and climate, and its migration to groundwater and, through runoff and lateral flow, to surface water generates plumes that alter redox conditions, degrade water quality and soil functions, and expose people through drinking water, crops, and aquatic food webs.

Effective risk reduction requires thorough leachate collection and groundwater-monitoring programs. Engineered containment systems and multi-barrier treatment trains are just as important but will only have the desired effect when linked with strong regulatory enforcement. These initiatives need to be coupled with the closure or safe rehabilitation of existing disposal sites and the phasing out of open dumping. Tracing constituents across groundwater, surface water, soil and the vadose zone, biota, and the atmosphere within a single source–pathway–receptor sequence showed that the same constituent carries different significance according to the medium in which it is measured and the receptor it reaches; risk therefore cannot be inferred from source composition alone. Within that sequence, the microbiological signature proved inseparable from physicochemical characterization: microbial guilds govern the attenuation of nitrogen, sulfur, and metals, while pathogens, ARB, and ARGs are hazards that conventional determinants do not detect. The resulting risk-oriented monitoring framework links environmental medium, sampling design, core parameters, frequency, and interpretive objective. The framework is expressed as a rule set in which containment, hydrogeological vulnerability, and receptor proximity assign a site to a risk tier that prescribes parameter priority, sampling frequency, well-network density, and triggers for intensified monitoring; a tiered analytical strategy confines costly PFAS, microplastic, and resistome analyses to sites where a pathway to a receptor is plausible or confirmed; and an indicator–medium guide translates each measurement into its meaning and the action that should follow. Because the source–pathway–receptor sequence maps onto the barriers of landfill design, the framework also indicates which barrier should carry investment at a given site. Read alongside the comparative evaluation of prevention, treatment, and remediation options, it allows monitoring effort to be allocated by receptor vulnerability rather than uniform routine sampling.

Future studies should focus on the transport, persistence, and toxicity of PFAS, microplastics, and pharmaceutical residues in legacy landfill plumes. More attention is needed on long-term exposure to contaminant mixtures and antibiotic resistance. Research is also needed to evaluate the long-term performance of landfill liners. At the same time, heterogeneous leachate constituents should be treated using low-cost nature-based and advanced technologies.

Environmental policies should be focused on pollution prevention, not remediation. Protecting groundwater and surface-water resources from landfill contamination must be central to sustainable environmental governance and public-health protection.

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NOMENCLATURE

AAS atomic absorption spectrometry

AOP	advanced oxidation process
ARB	antibiotic-resistant bacteria
ARG	antibiotic resistance gene
BOD	biochemical oxygen demand, $mg \cdot L^{-1}$
BOD_5	five-day biochemical oxygen demand, $mg \cdot L^{-1}$
BPA	bisphenol A
CECs	contaminants of emerging concern
CFU	colony-forming unit
COD	chemical oxygen demand, $mg \cdot L^{-1}$
DEET	*N,N*-diethyl-3-methylbenzamide
DNA	deoxyribonucleic acid
DO	dissolved oxygen, $mg \cdot L^{-1}$
DOM	dissolved organic matter
EC	electrical conductivity, $\mu S \cdot cm^{-1}$
Eh	redox potential, mV
FTIR	Fourier-transform infrared spectroscopy
GC-MS	gas chromatography–mass spectrometry
HDPE	high-density polyethylene
IC	ion chromatography
ICP-MS	inductively coupled plasma mass spectrometry
ICP-OES	inductively coupled plasma optical emission spectrometry
ILCR	incremental lifetime cancer risk, dimensionless
LC-MS/MS	liquid chromatography–tandem mass spectrometry
LCS	leachate collection system
LOQ	limit of quantification
LPI	leachate pollution index, dimensionless
MPN	most probable number
MSW	municipal solid waste
ORP	oxidation–reduction potential, mV
PFAS	per- and polyfluoroalkyl substances
POP	persistent organic pollutant
PPCP	pharmaceutical and personal care product
PRB	permeable reactive barrier
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PTFE	polytetrafluoroethylene
qPCR	quantitative polymerase chain reaction
RCRA	Resource Conservation and Recovery Act (US)
SWM	solid waste management
TDS	total dissolved solids, $mg \cdot L^{-1}$
TOC	total organic carbon, $mg \cdot L^{-1}$
TSS	total suspended solids, $mg \cdot L^{-1}$
UV_{254}	ultraviolet absorbance at 254 nm, cm^{-1}
VFAs	volatile fatty acids
WHO	World Health Organization

Chemical Species

Ca^{2+}	calcium ion, $mg \cdot L^{-1}$
Cd^{2+}	cadmium ion, $mg \cdot L^{-1}$
Cl^-	chloride ion, $mg \cdot L^{-1}$
K^+	potassium ion, $mg \cdot L^{-1}$
Mg^{2+}	magnesium ion, $mg \cdot L^{-1}$
Na^+	sodium ion, $mg \cdot L^{-1}$
NH_4^+-N	ammoniacal nitrogen ($NH_4^+ + NH_3$, expressed as N), $mg \cdot L^{-1}$
NO_3^-	nitrate ion (reported as NO_3^- unless stated as NO_3^--N), $mg \cdot L^{-1}$
SO_4^{2-}	sulfate ion, $mg \cdot L^{-1}$
Zn^{2+}	zinc ion, $mg \cdot L^{-1}$

APPENDIX

Database Query Strings

A.1 Scopus (advanced search; executed 20 September 2026)

TITLE (leachate*) AND TITLE-ABS-KEY (landfill* OR dumpsite* OR "dump site*" OR "open dump*" OR "municipal solid waste") AND TITLE-ABS-KEY (groundwater OR "ground water" OR aquifer* OR "surface water" OR river* OR stream* OR lake* OR wetland* OR soil* OR "vadose zone" OR sediment* OR "drinking water" OR crop* OR "food chain" OR "heavy metal*" OR "trace metal*" OR "potentially toxic element*" OR ammoni* OR nitrate OR PFAS OR perfluor* OR polyfluor* OR microplastic* OR pharmaceutical* OR "emerging contaminant*" OR "emerging concern" OR "antibiotic resistan*" OR "resistance gene*" OR resistome OR pathogen* OR ecotoxic* OR toxicity OR "health risk" OR "risk assessment" OR "pollution index" OR plume* OR attenuation OR monitoring OR treatment OR remediation OR composition OR characteri*) AND PUBYEAR > 2019 AND PUBYEAR < 2026 AND (DOCTYPE (ar) OR DOCTYPE (re)) AND LANGUAGE (english)

A.2 Web of Science Core Collection (equivalent field-tagged form of the three-row search; count not re-established)

TI=(leachate*) AND TS=(landfill* OR dumpsite* OR "dump site*" OR "open dump*" OR "municipal solid waste") AND TS=(groundwater OR "ground water" OR aquifer* OR "surface water" OR river* OR stream* OR lake* OR wetland* OR soil* OR "vadose zone" OR sediment* OR "drinking water" OR crop* OR "food chain" OR "heavy metal*" OR "trace metal*" OR "potentially toxic element*" OR ammoni* OR nitrate OR PFAS OR perfluor* OR polyfluor* OR microplastic* OR pharmaceutical* OR "emerging contaminant*" OR "emerging concern" OR "antibiotic resistan*" OR "resistance gene*" OR resistome OR pathogen* OR ecotoxic* OR toxicity OR "health risk" OR "risk assessment" OR "pollution index" OR plume* OR attenuation OR monitoring OR treatment OR remediation OR composition OR characteri*) AND PY=(2020-2025) AND LA=(English) AND DT=(Article OR Review)

A.3 PubMed (executed 20 September 2026)

leachate*[ti] AND (landfill*[tiab] OR dumpsite*[tiab] OR "dump site"[tiab] OR "open dump"[tiab] OR "municipal solid waste"[tiab]) AND (groundwater[tiab] OR "ground water"[tiab] OR aquifer*[tiab] OR "surface water"[tiab] OR river*[tiab] OR soil*[tiab] OR sediment*[tiab] OR "drinking water"[tiab] OR crop*[tiab] OR "food chain"[tiab] OR "heavy metal"[tiab] OR "heavy metals"[tiab] OR "trace metals"[tiab] OR "potentially toxic elements"[tiab] OR ammoni*[tiab] OR nitrate[tiab] OR PFAS[tiab] OR perfluor*[tiab] OR polyfluor*[tiab] OR microplastic*[tiab] OR pharmaceutical*[tiab] OR "emerging contaminants"[tiab] OR "emerging concern"[tiab] OR "antibiotic resistance"[tiab] OR "antibiotic resistant"[tiab] OR "resistance genes"[tiab] OR resistome[tiab] OR pathogen*[tiab] OR ecotoxic*[tiab] OR toxicity[tiab] OR "health risk"[tiab] OR "risk assessment"[tiab] OR "pollution index"[tiab] OR plume*[tiab] OR

attenuation[tiab] OR monitoring[tiab] OR treatment[tiab] OR remediation[tiab] OR composition[tiab] OR characteri*[tiab]) AND ("2020/01/01"[dp] : "2025/12/31"[dp]) AND english[la]

A.4 ScienceDirect (field: title, abstract or author-specified keywords; years 2020–2025; research and review articles; executed 20 September 2026)

SD-1: ("landfill leachate" OR "dumpsite leachate") AND (groundwater OR aquifer OR "surface water" OR soil OR sediment)

SD-2: ("landfill leachate" OR "dumpsite leachate") AND ("heavy metals" OR ammonium OR nitrate OR "pollution index" OR plume)

SD-3: ("landfill leachate" OR "dumpsite leachate") AND (PFAS OR microplastics OR pharmaceuticals OR "emerging contaminants")

SD-4: ("landfill leachate" OR "dumpsite leachate") AND ("antibiotic resistance" OR pathogens OR ecotoxicity OR toxicity)

SD-5: ("landfill leachate" OR "dumpsite leachate") AND ("health risk" OR "risk assessment" OR monitoring OR treatment OR remediation)

A.5 Google Scholar (custom range 2020–2025; patents and citations excluded; supplementary source screened by relevance; executed 20 September 2026)

GS-1: intitle:leachate landfill groundwater OR aquifer contamination

GS-2: intitle:leachate landfill "surface water" OR soil OR sediment

GS-3: intitle:leachate landfill "heavy metals" OR ammonium OR nitrate

GS-4: intitle:leachate landfill PFAS OR microplastics OR pharmaceuticals

GS-5: intitle:leachate landfill "antibiotic resistance" OR pathogens OR ecotoxicity

GS-6: intitle:leachate landfill OR dumpsite "health risk" OR monitoring OR treatment OR remediation

A.6 Update search for 2026 records (Scopus; the equivalent PubMed form used [ti]/[tiab] fields and a 2026 publication-date filter)

TITLE (leachate*) AND TITLE-ABS-KEY (landfill* OR dumpsite* OR "open dump*") AND TITLE-ABS-KEY (PFAS OR perfluor* OR polyfluor* OR microplastic* OR "antibiotic resistan*" OR "resistance gene*" OR resistome) AND PUBYEAR = 2026