Landfill Leachate Generation, Migration and Impacts on Soil and Groundwater Systems: A Review of Global, African and Nigerian Perspective

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Abstract
Municipal solid waste generation is rising rapidly worldwide, and in many low- and middle-income countries disposal remains dominated by open dumping without engineered containment, creating persistent conditions for the generation and uncontrolled migration of landfill leachate. This review synthesises global, African and Nigerian evidence on the composition, environmental behaviour and public health implications of landfill leachate, with particular attention to humid tropical and Niger Delta settings. Leachate composition is shown to evolve with waste age, climate and landfill design, shifting from organically dominated, high-BOD acidogenic-phase leachate towards ammonia- and chloride-dominated methanogenic-phase leachate over time. Once generated, contaminant transport is governed by the interaction of climate-driven infiltration, subsurface lithology and groundwater flow, conceptualised through the Source-Pathway-Receptor framework and explained mechanistically by Darcy's Law, Toth's groundwater flow system theory and the water balance concept. Empirical studies from Europe, North America, Asia, Africa and Nigeria consistently associate unlined dumpsites with elevated heavy metals, nutrients, organic loading and microbial contamination in soil and groundwater, with health consequences ranging from methemoglobinemia and gastrointestinal disease to chronic heavy-metal toxicity, alongside socio-economic impacts including declining property values and disproportionate exposure of low-income communities. Within the Niger Delta and Port Harcourt specifically, high rainfall, unconsolidated sandy aquifers and shallow groundwater tables create conditions of especially high intrinsic vulnerability. The review identifies persistent gaps in the integration of hydrogeophysical, geotechnical, hydrochemical and public health evidence within a single analytical framework, and in the treatment of seasonal variability, and argues that closing these gaps is essential for developing context-specific groundwater protection strategies in rapidly urbanising tropical cities.

Keywords: *landfill leachate; municipal solid waste; groundwater contamination; aquifer vulnerability; Source-Pathway-Receptor model; Niger Delta; Nigeria*

1. Introduction

Municipal solid waste management has become a critical global environmental challenge, driven by accelerating urbanisation, industrial expansion and changing consumption patterns; the World Bank projects substantial future growth in global waste generation, with low- and middle-income countries accounting for a disproportionate share of this increase because of rapid urban growth and limited waste infrastructure (Kaza *et al.,* 2018). In many developing regions, including much of sub-Saharan Africa, disposal remains dominated by open dumping and uncontrolled landfilling that lack engineered liners, leachate collection systems and treatment facilities, creating persistent conditions for environmental contamination (Ferronato & Torretta, 2019). A central environmental concern associated with such disposal systems is the generation of landfill leachate, a chemically complex liquid formed when precipitation and intrinsic waste moisture percolate through decomposing refuse. Leachate composition varies substantially with waste age, climatic conditions, landfill design and moisture availability (Kjeldsen *et al.,* 2002), and its capacity to mobilise dissolved organic matter, heavy metals, nutrients and pathogenic organisms into soil and groundwater systems has been documented across highly varied geographical and regulatory contexts. In Port Harcourt and the wider Niger Delta, this concern is amplified by rapid urbanisation, extensive reliance on groundwater for domestic supply, and hydrogeological conditions, high rainfall, shallow water tables and unconsolidated sandy aquifers, which are particularly conducive to rapid contaminant migration. Despite an expanding body of research, existing studies remain unevenly distributed: comparatively sophisticated, multi-contaminant and long-term monitoring studies dominate the literature from Europe, North America and parts of Asia, while investigations in tropical developing regions, including Nigeria, more frequently rely on isolated water-quality assessments that do not adequately capture subsurface transport mechanisms, seasonal dynamics or public health outcomes. This review therefore synthesises global and regional evidence on landfill leachate generation, environmental and health impacts, and the hydrological and theoretical basis of contaminant migration, with the specific aims of: (i) situating leachate contamination within global and African solid-waste management trends; (ii) reviewing evidence on the environmental, health and socio-economic consequences of leachate contamination; (iii) outlining the conceptual and theoretical basis of hydrological contaminant transport; and (iv) identifying persistent gaps in the literature that constrain evidence-based groundwater protection in rapidly urbanising tropical cities such as Port Harcourt. The remainder of this review is organised as follows. Section 2 situates landfill leachate contamination within global municipal solid waste management trends. Section 3 reviews evidence on the environmental, health and socio-economic consequences of leachate contamination, covering soil and groundwater impacts, human health outcomes and socio-economic dimensions in turn. Section 4 sets out the conceptual and theoretical basis of hydrological contaminant transport, including the Source-Pathway-Receptor model and the hydrogeological theories that underpin it. Section 5 synthesises empirical evidence from Europe and North America, Asia, Africa, Nigeria, and Port Harcourt and the Niger Delta specifically, before Section 6 draws these strands together to identify persistent research gaps and future directions, and Section 7 concludes.

2. Global Perspectives on Municipal Solid Waste Management and Leachate Dynamics

Global waste generation continues to rise sharply, with low- and middle-income countries facing the steepest increases due to rapid urban growth outpacing infrastructure development (Kaza *et al.,* 2018). Where open dumping and uncontrolled landfilling persist, the resulting leachate is highly variable in composition: younger waste deposits typically generate leachate with high biochemical oxygen demand and elevated organic loading, whereas mature systems are dominated by inorganic constituents, ammonia and more persistent chemical species (Kjeldsen *et al.,* 2002; Christensen *et al.,* 2011). Landfill leachate has also been shown to contain heavy metals such as lead, cadmium, chromium and nickel, alongside emerging contaminants including pharmaceuticals and synthetic organic compounds (Mor *et al.,* 2006;

Eggen *et al.,* 2010).

Even engineered sanitary landfills equipped with liners, leachate collection systems and monitoring wells are not entirely free of long-term risk. Persistent organic pollutants, endocrine-disrupting compounds, antibiotics and microplastics have increasingly been detected in leachate and surrounding groundwater from engineered facilities, indicating that liner degradation and prolonged decomposition can sustain contaminant release for decades after closure (Zhang *et al.,* 2020; Nghiem *et al.,* 2021). Climate variability further complicates management: increased rainfall intensity, flooding and rising groundwater levels have been shown to accelerate leachate generation and enhance contaminant mobility, with these effects amplified in tropical coastal environments characterised by shallow aquifers and highly permeable soils (IPCC, 2021; *Odukoya et al.,* 2019; Adeyemi *et al.,* 2022).

While substantial progress has been made in understanding landfill leachate processes in developed regions, the literature demonstrates persistent knowledge gaps in tropical urban environments, particularly regarding coupled hydrogeophysical characterisation, seasonal plume behaviour and integrated geotechnical controls on migration. Addressing these gaps is essential for developing context-specific waste management strategies and improving groundwater protection in rapidly urbanising cities of the Global South.

3. Environmental and Health Impacts of Landfill Leachate

3.1 Soil and Groundwater Contamination

In engineered landfills, protective liners and collection systems are designed to minimise downward contaminant migration; in open dumpsites, however, leachate infiltrates directly into the soil profile, dissolving and mobilising heavy metals, dissolved salts, nutrients, hydrocarbons and persistent organic compounds as it percolates through subsurface layers. Heavy metals such as cadmium, lead, chromium, arsenic and mercury are of particular concern because, unlike biodegradable pollutants, they do not readily decompose and may persist in soils and aquifers for extended periods, altering soil physicochemical properties, reducing microbial activity and impairing plant growth, with potential indirect transfer into the human food chain in agricultural areas near dumpsites. Groundwater contamination represents perhaps the most critical risk associated with landfill leachate, since groundwater serves as the principal source of potable water in many developing countries. Numerous studies reports that boreholes and wells located near dumpsites exceed WHO or national guideline values for electrical conductivity, total dissolved solids, nitrate, chloride and heavy metals, with contamination intensity generally declining with increasing distance from the waste source, confirming the influence of leachate migration pathways (Mor *et al.,* 2006).

The rate and extent of soil contamination is further modulated by soil texture, organic matter content and cation exchange capacity, since fine-grained, organic-rich soils generally exhibit greater sorptive capacity for metals than coarse sandy materials typical of deltaic and coastal environments. In such permeable settings, adsorption and ion exchange provide only limited retardation, so that contaminants introduced at the surface can reach the water table relatively quickly once the unsaturated zone becomes saturated with infiltrating leachate. This textural control on attenuation capacity is a recurring theme across the empirical literature reviewed in Section 5 and helps explain why groundwater contamination is consistently more severe in sandy coastal aquifers than in clay-dominated inland settings.

3.2 Human Health Implications

Human exposure to landfill leachate occurs through multiple pathways, including ingestion of contaminated groundwater, inhalation of polluted air, dermal contact with contaminated soils and water, and indirect exposure through the food chain; populations near open dumpsites in

sub-Saharan Africa are particularly vulnerable because of continued dependence on untreated borehole and well water (Mor *et al.,* 2006; Christensen *et al.,* 2011). Nitrate and ammonia are of particular concern in drinking water because elevated nitrate interferes with oxygen transport in infant blood, causing methemoglobinemia (blue baby syndrome), and has been linked to gastrointestinal disorders, thyroid dysfunction and increased cancer risk with long-term exposure (Ward *et al.,* 2018; Temkin *et al.,* 2019).
Heavy metals present severe long-term concerns because of their persistence and bioaccumulative toxicity: lead exposure is associated with neurological impairment and developmental delays in children, cadmium with kidney dysfunction and skeletal demineralisation, and mercury and arsenic with immune suppression and carcinogenic outcomes (Tchounwou *et al.,* 2012). Studies around the Olusosun dumpsite in Lagos and dumpsites in southeastern Nigeria have documented elevated lead and cadmium in surrounding environmental media, alongside significant microbial contamination linked to waterborne disease risk, including cholera, typhoid and gastroenteritis (Bakare *et al.,* 2012; Ogbonna *et al.,* 2009; Ezeronye & Ubalua, 2005). Open burning of waste, common where engineered disposal is unavailable, further releases particulate matter, methane, hydrogen sulphide and dioxins, contributing to respiratory illness in nearby communities (Nriagu *et al.,* 2016). More recently, attention has shifted towards emerging contaminants, pharmaceuticals, endocrine-disrupting compounds, antibiotic-resistant organisms and microplastics, which are persistent, resistant to conventional treatment and increasingly implicated in hormonal and immune disruption (He *et al.,* 2019; Masoner *et al.,* 2020).
Despite these advances, research gaps remain substantial in tropical developing countries, where studies have concentrated primarily on groundwater chemistry while giving comparatively little attention to epidemiological outcomes, chronic exposure pathways, or the combined effects of mixed contaminant exposure on vulnerable populations, and where the interaction between seasonal flooding, shallow groundwater and contaminant mobility remains under-examined.

3.3 Socio-Economic Dimensions

Beyond direct health risks, poorly managed dumpsites have documented socio-economic consequences, including declining property values, social stigmatisation and reduced investment in surrounding areas because of odour nuisance, visual pollution and perceived health risk (Kimani, 2007; Adewumi *et al.,* 2020); in Port Harcourt and other expanding Nigerian cities, communities near waste disposal facilities frequently exhibit slower infrastructural development than other urban districts (Nwankwoala *et al.,* 2014). Environmental justice scholarship argues that such exposure reflects underlying social and political inequality rather than random environmental process, with low-income and socially marginalised groups disproportionately exposed because of weak institutional protection (Bullard, 2000). Informal waste-picking economies further complicate this picture: while providing livelihoods for large numbers of urban poor across Africa, Asia and Latin America, waste pickers are routinely exposed to contaminated materials, toxic fumes and untreated leachate without occupational protection (Wilson *et al.,* 2006), reflecting broader tensions between economic survival and environmental health protection. Existing research nonetheless continues to treat leachate contamination primarily as a technical problem, with comparatively little empirical quantification of the cumulative economic costs, healthcare expenditure or property value impacts borne by affected communities.
A further dimension increasingly recognised in the literature concerns gendered and intergenerational burdens of exposure, since women and children in many affected communities bear a disproportionate share of water-collection duties and are therefore more

frequently and directly exposed to contaminated sources, while children face heightened physiological vulnerability to nitrate and heavy-metal toxicity. Despite this recognition, few empirical studies from Nigeria or the wider Niger Delta have systematically disaggregated exposure or health outcome data by gender or age group, representing a further specific gap that limits the design of targeted protective interventions.

4. Hydrological Processes and Theoretical Framework For Contaminant Migration

4.1 Conceptual Framework: The Source-Pathway-Receptor Model

The conceptual basis for understanding landfill impacts recognises waste disposal sites as dynamic biogeochemical systems rather than static storage areas, within which decomposition, water movement and contaminant transport occur simultaneously and leachate composition evolves over time in response to changing redox conditions and microbial activity (Kjeldsen *et al.,* 2002). A widely adopted framework for structuring this understanding is the Source-Pathway-Receptor (SPR) model (Figure 1), extensively applied in landfill impact assessment (DEFRA, 2004; WHO, 2017), in which the Source is the landfill or dumpsite generating leachate through decomposition, the Pathway comprises the soil layers, fractures and aquifer systems transmitting contaminants, and the Receptor includes humans, ecosystems and water resources exposed to contamination. Evidence from rapidly urbanising regions shows that, in the absence of engineered barriers, the pathway component is rarely interrupted, permitting direct hydraulic connection between waste sources and groundwater-dependent communities (Adewumi *et al.,* 2015; Longe & Balogun, 2010), reinforcing the conceptual position that landfill pollution becomes a public health issue specifically when hydrogeological pathways remain open.

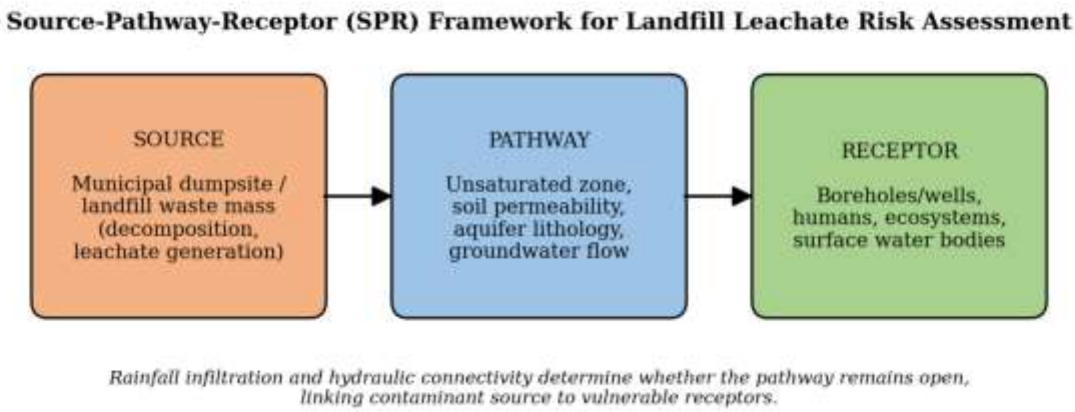

Figure 1: Source-Pathway-Receptor (SPR) conceptual framework applied to landfill leachate risk assessment (adapted from DEFRA, 2004; WHO, 2017).

4.2 Hydrological Drivers and Subsurface Vulnerability

Rainfall is the primary driver of leachate generation in humid tropical environments, where high precipitation rates sustain continuous infiltration and leachate production throughout the year (Fatta *et al.,* 1999). Research in West African coastal cities confirm that extreme rainfall events simultaneously enhance contaminant mobilisation and groundwater recharge, reducing the protective thickness of the unsaturated zone and thereby increasing aquifer vulnerability because contaminants travel shorter vertical distances before reaching the water table

(Adewumi *et al.,* 2015; Odukoya & Abimbola, 2010). Subsurface lithology exerts a further major control: unconsolidated sandy formations, such as those dominant in the Niger Delta, exhibit high hydraulic conductivity and low natural filtration capacity, allowing rapid vertical and lateral contaminant migration once leachate enters the formation, in contrast to clay-rich aquitards that retard movement through low permeability and sorptive capacity (Todd & Mays, 2005; Freeze & Cherry, 1979; Appelo & Postma, 2022).

Groundwater contamination transport is commonly explained through Darcy's Law combined with advection-dispersion theory, in which discharge is proportional to hydraulic conductivity and hydraulic gradient (Freeze & Cherry, 1979; Fetter, 2018), while Toth's groundwater flow system theory conceptualises movement as hierarchical local, intermediate and regional systems controlled by topography and recharge, providing a framework for explaining contaminant migration distances and vertical penetration depth (Toth, 1963; 2009). The water balance concept, linking precipitation, evapotranspiration, runoff and infiltration, further explains how positive water balance conditions in humid tropical climates enhance both groundwater recharge and leachate generation simultaneously, increasing subsurface vulnerability (Chow *et al.,* 1988). Field studies show that natural subsurface systems rarely conform to idealised homogeneous conditions: heterogeneity in grain size and soil structure creates preferential flow pathways that accelerate transport and produce non-uniform plume development, while sorption moderates the mobility of heavy metals such as lead, cadmium and chromium relative to highly soluble, weakly sorbing species such as nitrate and chloride, which migrate further down-gradient (Bear, 1972; Sharma & Reddy, 2004; Freeze & Cherry, 1979; Rivett *et al.,* 2008). Collectively, these theoretical and empirical strands demonstrate that contaminant migration is a coupled system of physical flow, chemical interaction and biological transformation, and that in high-rainfall, shallow-aquifer settings such as the Niger Delta these factors combine to produce conditions of persistent groundwater vulnerability.

5. Empirical Evidence from Global and Regional Studies

5.1 Evidence from Europe and North America

Research in Europe and North America provides some of the earliest and most detailed evidence on landfill leachate migration, initially motivated by groundwater pollution incidents from poorly designed disposal systems in the mid-twentieth century, which prompted regulatory reforms and the development of engineered sanitary landfills with liners, collection systems and monitoring wells (Rowe, 2012). Despite these advances, long-term studies show that landfill systems continue to pose risks long after closure: Christensen et al. (2001) reported persistent ammonium, dissolved organic carbon, chloride and trace-metal contamination around closed European landfills decades after waste deposition ceased, while Bjerg et al. (2013) observed continued ammonium and chloride migration beneath Danish landfills despite engineered containment, attributable to gradual liner deterioration. In the United States, Slack et al. (2005) documented elevated volatile organic compounds, chlorinated hydrocarbons and heavy metals near municipal landfills, and more recent work has detected per- and polyfluoroalkyl substances, microplastics and pharmaceutical residues in leachate-affected groundwater, reflecting a widening focus toward emerging contaminants (Benskin et al., 2012; Propp et al., 2021).

5.2 Evidence from Asia

Rapid industrialisation and urban expansion across Asia have intensified waste management challenges where infrastructure has not kept pace with waste generation. In Punjab, India, Mor *et al.* (2006) reported high total dissolved solids, chloride, nitrate, cadmium and chromium in groundwater around municipal dumpsites, frequently exceeding WHO standards, with contamination declining with distance from the landfill. In Malaysia, Akinbile and Yusoff (2011) linked elevated BOD, ammonia, iron and microbial contamination near uncontrolled sites to heavy monsoonal rainfall and highly permeable subsurface materials, while Naveen *et al.* (2018) used combined hydrochemical and geophysical surveys to identify extensive contaminant plumes migrating through sandy aquifers in southern India. Research in China has additionally linked leachate-polluted irrigation water to heavy metal accumulation in agricultural soils and food crops (Li *et al.,* 2020), while a persistent debate concerns whether existing landfill engineering can withstand increasing rainfall intensity associated with climate change without exceeding design capacity (Mukherjee *et al.,* 2020).

5.3 Evidence from Africa

Across Africa, empirical studies consistently associate groundwater contamination with unlined dumpsites, shallow aquifers, weak regulation and rapid urbanisation, reflecting continued dependence on open dumping due to inadequate waste infrastructure and institutional weakness (Ferronato & Torretta, 2019). In Ghana, Abiye *et al.* (2019) integrated electrical resistivity imaging with hydrochemical analysis to reveal low-resistivity contaminant plumes and elevated nitrate, iron, manganese and coliform concentrations in wells near an urban dumpsite. In Kenya, Kiptum *et al.* (2016) documented elevated lead, cadmium, ammonia and faecal coliform levels near Nairobi's Dandora dumpsite alongside increased diarrhoeal disease and skin infection prevalence among nearby residents, while in South Africa, Ololade *et al.* (2019) showed that contamination extended beyond groundwater into wetlands and river systems, with associated heavy-metal bioaccumulation in aquatic organisms. A consistent theme across African studies is strong local dependence on untreated groundwater amplified by shallow water tables, weathered soils, seasonal flooding and the absence of groundwater monitoring systems (Nwankwoala *et al.,* 2014).

5.4 Evidence from Nigeria

Nigerian studies reveal widespread groundwater contamination associated with municipal dumpsites across major urban centres, driven by rapid population growth, poor waste segregation, inadequate landfill engineering and high rainfall. Ipeaiyeda and Onianwa (2002) reported elevated lead, cadmium, zinc, nitrate and total dissolved solids around dumpsites in Ibadan, concluding that nearby shallow wells were unsuitable for domestic use. Odukoya *et al.* (2019) combined hydrochemical analysis with electrical resistivity techniques in Lagos, finding strong correlations between low subsurface resistivity and elevated dissolved contaminants, confirming active leachate migration through permeable sandy formations, while similar patterns of microbial and heavy-metal contamination were reported in Benin City and Akure (Ihenyen *et al.,* 2018; Adesina & Akinyemi, 2021). Recent Nigerian investigations increasingly combine geophysical imaging with hydrochemical assessment, although many remain limited to localised water-quality analysis without fully integrating geotechnical properties, hydrological modelling or public health risk evaluation into a single framework.

5.5 Evidence from Port Harcourt and the Niger Delta

Within Port Harcourt and the wider Niger Delta, landfill contamination studies consistently highlight the vulnerability of shallow aquifer systems to leachate infiltration under conditions of high rainfall, unconsolidated sandy formations, shallow groundwater and extensive urbanisation. Ehirim *et al.* (2009) reported that the Benin Formation aquifer underlying Port Harcourt possesses high permeability and limited natural protection, permitting rapid migration of surface-introduced pollutants into shallow groundwater. Nwankwo *et al.* (2014) documented elevated iron, nitrate, cadmium, lead and microbial contaminants in borehole water near Rivers State dumpsites, with contamination intensity strongly influenced by proximity to disposal sites, while Obafemi *et al.* (2020) found that Port Harcourt dumpsite leachate exhibited high organic strength, elevated conductivity and substantial heavy-metal concentrations, and Weli and Adekunle (2022) detected faecal coliforms and elevated nitrate in wells near open dumpsites within Obio/Akpor and Port Harcourt metropolis. A growing trend within Niger Delta studies is the application of Electrical Resistivity Tomography and Vertical Electrical Sounding for delineating subsurface contaminant plumes, offering improved understanding of migration pathways relative to water chemistry alone; nevertheless, relatively few studies integrate hydrogeophysical data with geotechnical characterisation and structured public health risk assessment within a single investigative framework. Taken together, the Port Harcourt and Niger Delta evidence base indicates that intrinsic hydrogeological vulnerability in this region is generally higher than in many of the international case studies reviewed in Sections 5.1-5.3, since the combination of high annual rainfall, shallow water tables and unconsolidated sandy aquifers removes several of the natural attenuation mechanisms, thick unsaturated zones, low-permeability confining layers, that have been shown to moderate contaminant transport elsewhere. This regional context underscores why findings from temperate, engineered-landfill settings cannot be directly extrapolated to inform groundwater protection policy in the Niger Delta without independent, site-specific hydrogeophysical and hydrochemical verification.

6. Synthesis, Research Gaps and Future Directions

This review demonstrates broad international consensus that unlined or poorly managed landfills generate leachate capable of significantly degrading soil and groundwater quality, with severity governed by the interaction of waste characteristics, climate, subsurface lithology and regulatory context. Several unresolved debates nonetheless persist. First, the relative contribution of geogenic versus anthropogenic sources of elevated groundwater metal concentrations near dumpsites remains contested, particularly in sedimentary basins where baseline hydrochemical data are limited (Freeze & Cherry, 1979; Bear, 1988). Second, the effectiveness of natural attenuation in tropical soils is debated: some researchers emphasise that high rainfall and permeable sandy soils facilitate rapid, minimally filtered contaminant transport, while others highlight meaningful roles for adsorption, dilution and microbial degradation under certain conditions, underscoring the need for site-specific investigation rather than generalised assumptions. Several structural gaps in the literature limit current understanding, particularly in rapidly urbanising tropical cities. Most studies from developing regions rely on isolated water-quality assessments that do not adequately capture subsurface transport mechanisms, in contrast to the comparatively few investigations that integrate subsurface imaging, geotechnical analysis and hydrochemical data within a single framework. Seasonal variability in leachate generation and migration remains under-explored despite its evident importance in monsoonal and humid tropical climates, and limited attention has been given to the interaction between soil structure, aquifer vulnerability and contaminant transport under high-rainfall, shallow-groundwater conditions. Finally, a persistent gap exists in linking environmental contamination data with structured, spatially resolved public health risk assessment frameworks capable of informing policy and mitigation strategies, and in quantifying the socio-economic costs borne by communities living near contaminated sites. Addressing these gaps requires future research that combines hydrogeophysical, hydrochemical, geotechnical and epidemiological methods within unified, site-specific investigative frameworks, incorporates seasonal and multi-year monitoring designs capable of capturing dynamic plume behaviour, and translates technical contamination data into practical tools, such as groundwater vulnerability registers and evidence-based discharge standards, that can directly inform landfill siting, regulatory enforcement and community protection in rapidly urbanising tropical settings such as the Niger Delta. A further point of convergence across the reviewed literature is that resistivity-based geophysical techniques, where applied, consistently correlate with independently measured hydrochemical indicators of contamination, lending credibility to their use as a scalable, cost-effective screening tool for plume delineation in data-scarce tropical settings. However, the reviewed studies also show that geophysical anomalies alone cannot distinguish contamination from natural lithological variation without corroborating water-quality or geotechnical evidence, reinforcing the case for multi-method integration rather than reliance on any single investigative technique, however sophisticated.

From a methodological standpoint, the reviewed literature suggests that future site investigations in the Niger Delta would benefit from a standardised, replicable protocol combining seasonal hydrochemical sampling of both leachate and groundwater, geotechnical characterisation of receiving soils, and geophysical imaging using VES and ERT, interpreted jointly rather than sequentially. Establishing such a protocol as a regional standard would improve comparability across studies, strengthen the evidence base available to regulators, and support the development of locally calibrated aquifer vulnerability indices better suited to humid tropical, unconsolidated sedimentary settings than vulnerability indices originally developed for temperate or semi-arid aquifer systems.

7. Conclusion

Landfill leachate remains a significant global environmental and public health challenge, and the evidence reviewed here shows that its severity is disproportionately borne by rapidly urbanising, poorly regulated tropical cities where open dumping persists in hydrogeologically vulnerable settings. Global and regional evidence, from Europe and North America through Asia, Africa, Nigeria and the Niger Delta specifically, consistently links unlined waste disposal to elevated heavy metals, nutrients, organic pollutants and microbial contaminants in soil and groundwater, with attendant risks to human health and community wellbeing. The Source-Pathway-Receptor model, together with Darcy's Law, Toth's groundwater flow theory and the water balance concept, provides a coherent theoretical basis for understanding how climatic, geological and hydraulic factors combine to determine aquifer vulnerability. However, the literature also reveals that methodological integration, particularly the combination of hydrogeophysical, geotechnical, hydrochemical and public health evidence within unified frameworks, remains limited in tropical developing contexts. Closing this gap is essential for developing scientifically robust, context-specific groundwater protection strategies capable of safeguarding vulnerable communities in Port Harcourt and comparable rapidly urbanising settings across the Global South.

Ultimately, the value of this body of research lies not only in documenting contamination after it has occurred, but in providing the theoretical and empirical foundation needed to anticipate and prevent it. As Nigerian cities such as Port Harcourt continue to expand and existing dumpsites approach or exceed their operational lifespans, the evidence synthesised in this review offers a basis for shifting from reactive contamination assessment towards proactive, hydrogeologically informed landfill siting, design and regulation, an approach that would materially reduce the long-term burden of groundwater contamination on vulnerable urban and peri-urban communities across the region.

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