



REVIEW

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A Comprehensive Review of Landfill Leachate Impact on Groundwater Quality and Public Health

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Abstract

Landfill leachate is one of the major sources of groundwater pollution associated with municipal solid waste dumping. This review discusses the landfill leachate generation, composition, and migration mechanisms, and its environmental impact on the groundwater resources and human health. Usually, landfill leachate has a high level of nutrients, dissolved organic matter, major ions, and emerging contaminants, including pharmaceuticals, microplastics, and heavy metals. The leachate composition is also different depending on the nature of the waste, the age of a landfill, working practices, and climatic conditions. The migration of contaminants in the landfill bodies to the surrounding aquifers and soil systems is controlled by hydrogeochemical processes such as infiltration, dispersion, advection, adsorption, and redox reactions. Many studies performed in Asia, Europe, and North America have indicated degradation in water quality of the groundwater of the regions around landfill sites with the contaminant plumes stretching hundreds of meters around the landfill boundaries. In developing countries, particularly India, unlined landfill sites such as Ghazipur, Bhalswa, and Okhla are major sources of groundwater contamination due to inadequate containment systems. Exposure to contaminated groundwater can result in serious health effects, including methemoglobinemia, kidney dysfunction, neurological disorders, and increased carcinogenic risk. This review further highlights monitoring approaches, remediation technologies, and policy measures aimed at minimizing leachate-induced groundwater contamination. Ensuring groundwater protection in rapidly urbanizing regions requires improved landfill design, integrated monitoring systems, and the adoption of sustainable waste management practices.

Keywords: Landfill leachate; Groundwater contamination; Organic pollutants; Health risk; Environmental monitoring

Introduction

The rapid urbanization and population have highly contributed towards the increase in the municipal solid waste (MSW) produced in the world, hence posing a tremendous strain on the waste management systems, particularly in the developing countries. Landfilling is the most common method of waste disposal since the process is fairly inexpensive to administer and is simple to implement. However, uncontrolled or unplanned landfill locations may constitute severe environmental issues, which are mostly caused by landfill leachate and its possible environmental effects on adjacent soil and groundwater resources (Han et al., 2016; Kurniawan et al., 2006). In most developing countries, a high percentage of municipal waste is deposited in open dumping grounds without engineered liners or leachate collection systems, and this has a high probability of contaminant migration to the subsurface environments (Chatterjee, 2012; Mor & Ravindra, 2023). Landfill leachate is a complex liquid that is created when the precipitation and moisture penetrate through the decomposing waste materials dissolving and mobilizing different chemical components. This complex liquid contains high concentrations of dissolved organic matter, nutrients (ammonia and nitrate), inorganic salts, and heavy metals including lead, cadmium, chromium, and mercury (Abdel-Shafy and Mansour, 2024; Wang et al., 2024).

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Among the major environmental problems that are associated with landfill leachate are the fact that the leakage may contaminate the groundwater resources. The leachate that collects in the landfill bodies can percolate through the vadose zone and flow into the underlying aquifers as a result of advection, dispersion, adsorption and chemical transformations (Burn and Engesgaard, 2002; Regadio et al., 2012). High concentrations of dissolved organic matter, nutrients, including ammonia and nitrate, inorganic salts, and heavy metals, including lead, cadmium, chromium, and mercury, and emerging pollutants, including pharmaceuticals and persistent organic pollutants, are typically found in leachate (Abdel-Shafy and Mansour, 2024; Wang et al., 2024). Hydrogeological parameters like soil permeability, aquifer structure, and the dynamic of groundwater flows play a major role in determining the extent of contaminant movement. Landfill sites have been reported to give rise to contaminant plumes, and these extend hundreds of meters of landfill boundaries in permeable sedimentary settings (Nicholson et al., 1983; Breen et al., 2012). Many studies have been carried out in several parts of the world that reports that the quality of the groundwater has declined in areas surrounding the landfill locations.

The systems of groundwater that were influenced by the landfill leachate were frequently found to have a high level of nitrate, chloride, ammonia, and heavy metals (Jiang et al., 2021; Parvin et al., 2021). Persistent pollutants, in particular, heavy metals and some chemical compounds, are particularly problematic due to their toxicity, environmental persistence and bioaccumulation ability (Hussein et al., 2021; de Oliveira et al., 2020). The problem of contamination of groundwater by landfills is especially serious in developing nations like India where the municipal solid waste management system is not always adequate. Large landfills such as Ghazipur, Bhalswa, and Okhla in Delhi have been reported as the origin of groundwater pollution, and the high concentration of dissolved solids, nitrate, chloride, and heavy metals in the surrounding groundwater (Babbar et al., 2017; Mor et al., 2018; Ahamad et al., 2019; Sharma et al., 2023). These pollutants can be transported via the alluvial sediments of the Yamuna floodplain, which endangers shallow water sources that are utilized as a source of water in the locality. In addition to environmental degradation, the leachate of landfills has a serious social health implication due to contamination of groundwater. The use of contaminated groundwater has been linked to a series of health impacts, which include methemoglobinemia (exposure to nitrates) and chronic toxicity (cadmium, arsenic, and chromium) (Essien et al., 2022; Sharma et al., 2023). Moreover, recent identification of emerging contaminants and antibiotic resistance genes in the landfill leachate introduces additional issues of the ecological and human health risks (Borquaye et al., 2019). Having these issues, it is crucial to know the composition, migration processes, and environmental effects of landfill leachate to protect the groundwater and manage waste materials in a sustainable way. This review is a synthesis of existing literature on the nature of landfill leachate, hydrogeochemical mechanisms that control the movement of contaminants, known case studies of groundwater pollution, and the environmental and population health consequences. Other strategies and policies to control landfill-induced pollution of groundwater are also discussed in the paper, which included monitoring strategies, remediation technologies, and policy frameworks.

Landfill Leachate Composition and Behavior

The chemical composition of landfill leachate is highly variable and reflects the physicochemical processes occurring during waste decomposition. In this process, water that moves through the waste mass dissolves and mobilizes a broad spectrum of organic and inorganic compounds produced during the process of physical, chemical, and biological degradation of waste products (Abdel-Shafy and Mansour, 2024; Wang et al., 2024). Leachate is widely diverse which is explained by its chemical properties based on the age of the landfill, the structure of waste, climate, and practices of landfill.

The leachate in young landfills is usually characterized by high concentrations of biodegradable organic material as indicated by high biochemical oxygen demand (BOD) and chemical oxygen demand (COD). It is caused by high organic loads due to active microbial degradation of organic waste under anaerobic conditions in the initial stages of stabilizing the landfill (Nagarajan et al., 2012). With the advancement of the landfill and the shift to the methanogenic stage of the waste decomposition, the content of easily degradable organic substances decreases gradually, and inorganic compounds such as ammonia, nitrate, chloride, sulphate, are increasingly prevalent in the composition of the leachate (Abdel-Shafy and Mansour, 2024; Wang et al., 2024). Other significant constituents of landfill leachate are the heavy metals. Lead, cadmium, chromium, mercury, and arsenic are often found in discarded batteries, electronics, paints, and industrial materials. Environmental factors such as pH, redox potential, and the complexation of dissolved organic matter have a strong effect on the mobility and persistence of these metals in leachate (Essien et al., 2022; Hussein et al., 2021). In some geochemical conditions, these metals can be transported to the neighboring soils and groundwater systems, which leads to the pollution of the environment in the long term. Another factor that has significance in the regulation of leachate generation and composition is seasonal and climatic conditions. Since a higher level of infiltration is possible during rainy seasons, the leachate can be more productive and dissolved contaminants will be transported more easily to the subsurface. On the other hand, with low water flow, lower dissolved constituent concentrations in the leachate can be observed because of limited dilution (Mor and Ravindra, 2023; Kumar et al., 2023). Besides traditional pollutants, recent landfill leachate

has progressively been reported to have hidden pollutants, such as pharmaceuticals, personal care products, pesticides, and microplastics. Such xenobiotic substances can be relatively resistant to natural degradation and can remain within groundwater systems over a long period of time (de Oliveira et al., 2020; Abdel-Shafy and Mansour, 2024). Their existence emphasizes the increased complexity of landfill leachate chemistry and the need to monitor it continuously and enhance waste management practices.

Table 1. Typical Physicochemical Characteristics of Landfill Leachate

Parameter	Typical Range	Environmental Significance	Source
pH	5.5–9.0	Influences metal mobility and microbial activity	Kurniawan et al., 2006
BOD	200–20,000 mg/L	Indicates biodegradable organic matter	Nagarajan et al., 2012
COD	1,000–60,000 mg/L	Represents total organic pollution load	Abdel-Shafy & Mansour, 2024
Ammonia (NH ₃ -N)	200–3,000 mg/L	Major nitrogen contaminant in leachate	Mor & Ravindra, 2023
Nitrate	10–500 mg/L	Indicator of nitrogen pollution	Parvin et al., 2021
Chloride	200–3,000 mg/L	Conservative tracer of leachate contamination	Han et al., 2016
Heavy metals	Variable	Toxic and persistent pollutants	Hussein et al., 2021

Leachate Migration Mechanisms to Groundwater

The migration of landfill leachates to groundwater is a complex process due to the presence of physical, chemical and biological characteristics that govern transportation of contaminants in subsurface environment. The generation of the leachates starts as precipitations, surface runoffs, or other water bodies enter the landfill body and infiltrate through the waste. In the process, the waste mass is dissolved by water and carried down the unsaturated (vadose) zone to the underlying aquifers (Burn and Engesgaard, 2002; Islam and Singhal, 2004). The conceptual process of landfill leachate generation and its migration through subsurface environments into groundwater systems is illustrated in Figure 1.

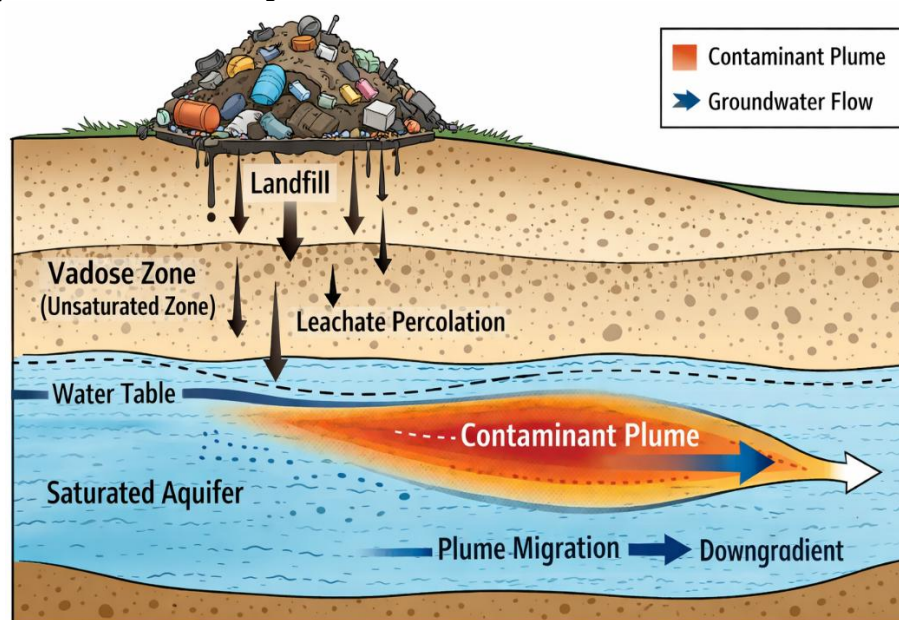


Fig. 1. Conceptual model of landfill leachate migration from landfill sites to groundwater systems

Diffusion, dispersion and advection are the major mechanisms through which contaminant moves in the groundwater systems. Advection is a process that entails the transport of dissolved pollutants by the natural movement of the groundwater, whereas dispersion is associated with the expansion of contaminant plumes owing to the variation in the velocity of the groundwater and the heterogeneity of the subsurface (Dickin, 1979; Regadio et al., 2012). Diffusion can also help in movement of contaminants especially in sediments with low permeability with concentration gradient causing the movement of dissolved substances. The rate and path of transport of the contaminants at landfill sites are strongly influence by the hydrogeological attributes. The speed of migration of leachate through subsurface sediments is depend on factors like soil porosity, hydraulic conductivity and stratigraphic layering. In permeable aquifers like sand and gravel aquifers, the contaminated water can migrate rapidly within groundwater systems. Instead, where the formation contains a lot of clay, it might reduce vertical migration as a result of reduced permeability and higher adsorption capacity (Tsanis, 2006; Watering et al., 2023).

However, even after this, there is the possibility of the lateral contaminating of the plumes over the long stretches of time. The geochemical and biological interactions also affect the behaviour of leachate contaminants in transport process in the subsurface. The processes that may lower the concentration of contaminated substances or change their chemical structure during movement through soil and aquifer substances include adsorption, precipitation, oxidation-reduction reactions and microbial degradation (Lacerda et al., 2014; Nayak et al., 2007). Nevertheless, some conservative ions, especially chloride and nitrate are relatively mobile in groundwater and are usually utilized to indicate contamination of landfills. Leachate migration is also influenced by the existence of engineered containment systems. Contemporary sanitary landfills are generally developed using composite liner programs comprising of compacted clay layers and synthetic geomembranes meant to slow down vertical leachate penetration. There are also leachate collection and treatment systems that collect the contaminated liquid before penetrating the surrounding groundwater systems (Waterloo Hydrogeologic, 2023). However, percolation of limited leakage and migration of contaminant with time may still occur due to degradation of liner materials with time, structural collapse, and natural geological heterogeneity.

Table 2. Major Mechanisms Controlling Landfill Leachate Migration

Mechanism	Description	Effect on Contaminant Transport	Source
Advection	Movement of contaminants with groundwater flow	Controls direction of contaminant plume	Regadio et al., 2012
Dispersion	Spreading of contaminants due to velocity variations	Expands plume size	Dickin, 1979
Diffusion	Movement due to concentration gradients	Important in low-permeability soils	Burn & Engesgaard, 2002
Adsorption	Attachment of contaminants to soil particles	Reduces contaminant mobility	Lacerda et al., 2014
Redox reactions	Chemical transformations during transport	Alters contaminant toxicity and mobility	Nayak et al., 2007

Global Case Studies of Landfill Leachate Impact on Groundwater

Landfill leachate contamination of groundwater has been well reported in various region of the world. Several research works have established that landfills, especially those without engineered containment systems, have the potential to degrade the groundwater quality levels significantly due to the mobility of dissolved organic contents, nutrients, salts and heavy metals to the groundwater. Contamination usually varies with landfill design, composition of waste, hydrogeological setting, and climatic variation (Han et al., 2016; Parvin et al., 2021). Landfill leachate has been reported to be the primary contributor of groundwater pollution in a number of rapidly urbanized parts of Asia. For example, studies carried around landfills in the municipal areas of China have indicated high levels of nitrate, chloride, ammonia and heavy metals in the groundwater systems located in the landfill areas. These studies demonstrate that contaminant plumes can travel hundreds of meters beyond the waste disposal barriers, especially in permeable hydrogeological conditions, caused by landfill locations (Jiang et al., 2021; Jiang et al., 2025). The same has also been observed in other nations of Asia, where lack of control in waste disposal and shortage of landfill engineering have also led to more susceptibility of groundwater resources in these countries. Latin America also provides evidence on the dangers of landfill leachate to the environment. In a study done in Mexico, heavy metals like cadmium and chromium were found in high levels in groundwater around the municipal landfills, and some of the parameters were above the recommended drinking water levels.

These conclusions can indicate that the movement of the leachates can be a source of serious risks in ecological and human health, especially in those areas where groundwater is a source of drinking water (Garcia-Gonzalez et al., 2008). However, in areas where relatively well-developed waste management systems are present, the landfill leachate remains a long-term environmental factor. Research carried out in Europe has reported a constant groundwater contamination along the areas surrounding the aging landfills, several decades after the landfills had been closed. As an example, hydrochemical studies in Italy recorded high levels of nitrate and chloride in groundwater around the old landfill sites, which implies that contaminants migrated over a long period and slow natural rates (De Feo et al., 2017). Other related works in Germany have used hydrochemical monitoring and contaminant transport modelling to evaluate the long-term effects of landfill leachate on the quality of groundwater (Schmidt et al., 2019). The groundwater pollution in the vicinity of the municipal solid waste landfills has also been reported in several of the monitoring studies in North America. According to research, such contaminants as ammonia, nitrate, chloride and volatile organic compounds are often detected at the groundwater of landfill sites, and the contamination plumes may reach several kilometres depending on the hydrogeological conditions and the age of the landfill (Han et al., 2016). All these international case studies point to one thing that landfill leachate is one of the significant environmental challenges of concern even though there has been an improvement in landfill engineering and waste management operations. The continued presence of contaminant plumes and their ability to migrate through the subsurface environment highlight the need for regular groundwater

monitoring, effective leachate management strategies and improved landfill design, to minimize long-term environmental impacts.

Table 3. Global Case Studies of Landfill Leachate Impact on Groundwater

Country	Landfill Site	Major Contaminants	Key Findings	Source
China	Zunyi landfill	Nitrate, heavy metals	Groundwater contamination observed near landfill	Jiang et al., 2025
Mexico	Municipal landfill	Cd, Cr, organic pollutants	Water quality standards exceeded	Garcia-Gonzalez et al., 2008
Italy	Old landfill	Nitrate, chloride	Long-term groundwater contamination	De Feo et al., 2017
Germany	Municipal landfill	Nutrients, metals	Hydrochemical changes in groundwater	Schmidt et al., 2019
India	Ghazipur landfill	Nitrate, chloride, metals	Groundwater deterioration near landfill	Babbar et al., 2017
India	Bhalswa landfill	Heavy metals, nutrients	Leachate infiltration into aquifer	Ahamad et al., 2019

Indian Landfill Case Studies and Groundwater Impacts

India is experiencing significant threats in the municipal solid waste management because of rapid rates of urbanization, population, and insufficiency in waste processing facilities. This has led to many cities depend on open dumping grounds or poorly constructed landfill facilities to manage their waste. Such sites usually do not have engineered liners and leachate collection systems, so contaminated leachate can enter the soils and groundwater systems around them and is a serious environmental and health hazard (Babbar et al., 2017; Mor et al., 2018).

Ghazipur landfill in East Delhi is one of the most well-researched landfill site in India because it has environmental effects and is located near residential communities. Research done surrounding the landfill has reported high levels of nitrate, chloride, ammonia and heavy metals in the groundwaters sampled in and around the landfill. A number of studies have shown that such parameters often exceed the recommended drinking water limits, implying that the quality of groundwater is often highly degraded because of the leachate infiltrations (Babbar et al., 2017; Mor et al., 2018; Sharma et al., 2023). Hydrogeological studies also show that the highly permeable alluvial sediments of the Yamuna floodplain promote the downward migration of leachate into shallow aquifers. Similar, groundwater pollution issues have been reported at the Bhalswa landfill in North Delhi. This landfill operated from several decades and it receives large volume of municipal solid waste. Studies that are carried out around the landfill have identified high levels of dissolved solids, nutrients, and heavy metals in groundwater samples collected around the landfill boundary. These findings indicate that leachate generated within the landfill body may infiltrate surrounding sediments and affect nearby groundwater systems (Ahamad et al., 2019). The fact that the landfill has residential settlements further poses a greater risk of being exposed to the contaminated groundwater resources. Environmental pollution and degradation of groundwater have also been linked to the Okhla landfill in South Delhi. Several investigations reported that this landfill have high levels of physicochemical parameters such as total dissolved solids, chloride, nitrate and organic pollutants in groundwater systems. Mixed municipal waste and lack of proper waste segregation practices lead to the formation of highly complex leachate composition which may move nearby environmental compartments.

Similar patterns of groundwater contamination have been observed in the vicinity of open dumping sites and landfills in other regions of India. As per the research that has been carried out in Tamil Nadu has reported that chloride, nitrate, sulphate, and heavy metal elements like cadmium, chromium and copper are present in high levels in samples of the groundwater around municipal dumping grounds. These studies have shown that the level of contaminants usually declines as the distance increases around the landfills, which reflect influence of leachate penetration and its effects on the nearby groundwater systems (Nagarajan et al., 2012).

Environmental Impact Assessment and Risk Evaluation of Landfill Leachate

Environmental impact assessment (EIA) can be quite significant in the assessment of risks that landfill leachate can have on the soil and groundwater systems around landfill area. Without any control, the generation of leachates can spread a broad array of the pollutant in the environment such as organic compounds, nutrients, heavy metals, and emerging contaminants and many more. Thus, this requires systematic monitoring and risk assessment methods that will allow to identify the contamination pathways, measure the pollutant loads, and determine the possible effects on the environment and human health (Teng et al., 2021). Assessment of landfill leachate typically involves the analysis of key physicochemical parameters such as pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia, nitrate, chloride, sulphate, and heavy metals. These parameters give significant data concerning the pollution potential of leachate and the potential impact of the same on the neighbouring

environmental compartments. Periodic changes in rainfall, temperature, and microbial activity may have a profound impact on leachate production and the level of contaminants, so periodic monitoring is a vital consideration to learn the actual effect on the environment (Nagarajan et al., 2012; Singh et al., 2022). A number of quantitative measures have been established in order to determine landfill leachate pollution potential. A tool used is the Leachate Pollution Index (LPI), which incorporates various chemical parameters in one numerical value that forms the overall pollution potential of a landfill site. Higher LPI values, indicate higher environmental risk, and thus better leachate management and treatment systems should be required (Kumar and Alappat, 2014; Mukherjee et al., 2014). The differences in values of LPI among different landfill sites are usually signs of the difference in the waste composition, age of the landfill, and operational practice (Vashisht et al., 2022). Hydrogeological modelling and groundwater monitoring are also common in assessing the transport of the contaminants from landfill sites. Numerical models that incorporate parameters such as hydraulic conductivity, groundwater flow velocity, and soil porosity can help predict contaminant transport and identify potential risk zones around landfill sites (Regadio et al., 2012; Lacerda et al., 2014).

These modelling techniques offer useful data to develop monitoring networks and carry out mitigation measures. The ecological risk assessment also may be a part of environmental risk assessment as the evaluation of the possible effects of landfill leachate on aquatic environment and soil. The leachate contaminants may settle in soils and the surface waters, which impact plant growth, microbial activity and biodiversity. Moreover, the existence of antibiotic-resistance genes and other emerging contaminants in landfill leachate has brought up the issue of long-term ecological and overall population health effects (Borquaye et al., 2019; Essien et al., 2022).

Ecological and Health Impacts of Landfill Leachate

Landfill leachate is a complex liquid which is a combination of organic matter, nutrients, heavy metals, and emerging contaminants, and is considered as a serious threat to the ecological and human health. The leachate flowing into soil, groundwater or surface water systems can disturb environmental quality and interfere with the ecological processes. Such effects are especially intense in those locations, where landfill facilities do not have engineered liner and sufficient leachate control system (Teng et al., 2021; Al-Yaqout and Hamoda, 2020).

Impacts on Water and Soil Ecosystems

Leakage of landfill leachate into the surface water bodies and groundwater may cause serious loss of water quality and disturb aquatic life. The leachate is usually rich in ammonia, organic compounds, and heavy metal, i.e., cadmium, mercury and lead. These pollutants may lead to the reduction of oxygen, physiological distress, and mortality in aquatic life (Hussein et al., 2021; Essien et al., 2022). Persistent organic pollutants and metals may accumulate in sediments and aquatic organisms, changing the food webs and leading to the ecological pollution in the long term (Teng et al., 2021; de Oliveira et al., 2020). Landfill sites can also alter soil environments by leaching. High salts, nutrient and heavy metals may alter physicochemical properties of soils, disturb microbial communities, as well as lower soil fertility. In agricultural areas near landfill sites, crops may absorb pollutants from contaminated soils or groundwater, facilitating the transfer of toxic substances into the food chain (Mor & Ravindra, 2023).

Biodiversity Loss and Habitat Disruption

Landfill leachate may pollute soil and water systems that support the loss of habitats and biodiversity. The pollutants can decrease the supply of a favorable habitat to plants and animals and have adverse impacts on wildlife by causing physiological stress and decreasing their reproductive success (Essien et al., 2022; Sharma et al., 2023). The changes in the soil chemistry and nutrient cycling can also promote the growth of invasive species that can successfully grow in the disturbed conditions (Njoku et al., 2019; Vaverkova et al., 2018). Wetlands and riparian areas are sensitive ecosystems that can be significantly affected by ongoing contamination and negatively impact the ecological integrity and ecosystem services (Mor and Ravindra, 2023, Teng et al., 2021).

Human Health Hazards

Human exposure to landfill-derived contaminants typically occurs through the consumption of contaminated groundwater or agricultural products grown in polluted soils. Elevated nitrate levels in drinking water are linked to methemoglobinemia disease and long-term exposure to heavy metals including cadmium, arsenic, and chromium can lead to kidney damage, neurological diseases, and risk of cancer (Essien et al., 2022; Sharma et al., 2023). There is concern about long-term impacts on human health by landfill leachate too due to the presence of antibiotic resistant microorganisms and emerging organic pollutants (Borquaye et al., 2019; Teng et al., 2021). Also, the communities living near landfills, report respiratory irritation and other symptoms related to landfill gas emissions (Njoku et al., 2019; Vaverkova et al., 2018).

Long-Term Risks and Emerging Pollutants

According to recent research, the occurrence of emerging contaminants in landfill leachate has been reported which include polycyclic aromatic hydrocarbons, microplastics and endocrine-disrupting compounds. These pollutants are very difficult to degraded by natural processes (de Oliveira et al., 2020; Hussein et al., 2021). With

time, they accumulate in soils, groundwaters, crops, and animal tissues, and enhance the bioaccumulation and biomagnification possibilities in the food chains. Such long-term environmental persistence emphasizes the necessity of ongoing environmental monitoring, efficient leachate management and improved waste treatment techniques.

Remediation and Management Strategies for Landfill Leachate

Landfill leachate should be properly controlled and treated to avoid groundwater pollution and reduce ecological and population health risk. Because leachate composition significantly varies with the age of the landfill, the characteristics of waste, and climate conditions, a variety of treatment technologies were developed at international level to manage and eliminate contaminants in the landfill leachate (Teng et al., 2021; Al-Yaqout and Hamoda, 2020).

Physico-Chemical Treatments

In leachate treatment, physicochemical treatment techniques are frequently employed as preliminary or intermediate processes. Techniques like chemical precipitation, coagulation–flocculation, advanced oxidation processes and adsorption are commonly utilized to remove heavy metals, suspended solids and refractory organic compounds (Abdel-Shafy & Mansour, 2024; Magalhães et al., 2020). Adsorbent materials, including ion exchange resins and activated carbon, have shown considerably effective in eliminating organic dissolved metals and contaminants from leachate (El Batouti et al., 2021). In addition, electrocoagulation has gained increasing attention as an efficient treatment approach capable of removing ammonia, chemical oxygen demand (COD), and other dissolved pollutants with comparatively low operational costs (Yasa Ltd., 2022; Magalhães et al., 2020).

Biological Treatment Processes

Biological treatment processes are widely used for degrading biodegradable organic matter present in landfill leachate. Membrane bioreactors (MBR), sequencing batch reactors (SBR), and activated sludge, have been shown to have high removal efficiency of organic chemicals and nitrogen species (Srivastava et al., 2022; Chen et al., 2021). Advanced biological processes such as anaerobic ammonium oxidation (ANAMMOX) provide an energy-efficient way of removing nitrogen by converting ammonium directly to nitrogen gas without requiring external carbon sources. However, the application of ANAMMOX to landfill leachate containing high concentrations can be limited because of their complexity in operation (Feria-Diaz et al., 2021).

Membrane Technologies

The treatment of landfill leachate is progressively being achieved by membrane filtration technologies. Processes such as nanofiltration, ultrafiltration and Reverse osmosis (RO) are highly effective for removing heavy metals, persistent organic pollutants and dissolved solids (Magalhaes et al., 2020; Srivastava et al., 2022). Among these methods, reverse osmosis, which is most commonly considered effective treatment techniques, capable of reaching a contaminant removal efficiency equal to or greater than 99%. However, the problem of concentrated brine created during the membrane filtration process is also a severe operation problem that requires further treatment or safe disposal (Odabasi et al., 2022; El Batouti et al., 2021).

Hybrid and Integrated Approaches

Leachate generated at the landfills is often a complex mixture of organic and inorganic contaminants, so combined systems of processes are traditionally used. Hybrid approaches involving biological pre-treatment followed by physico-chemical treatment or membrane filtration have been shown to significantly improve overall contaminant removal efficiency (Teng et al., 2021; El Batouti et al., 2021). With such integrated systems the biodegradable organic matter, nutrients and refractory compounds that are found in landfill leachate can easily be removed.

Sustainable Management and Policy Integration

Besides the treatment technologies, sustainable landfill management practices are very essential when it comes to minimizing the generation of leachate and environmental contamination. The contemporary designs of sanitary landfills include the use of engineered liner systems, leachate collection networks, and drainage layers that reduce the movement of contaminated liquid to the adjacent groundwater systems. Continuous environmental monitoring and regular performance evaluation are essential to identify potential leakage and ensure proper landfill functioning (Veolia Water Tech, 2020). It is, therefore, necessary to have effective regulatory models and policy interventions that will enhance waste minimization, recycling, and enhanced landfill design to protect groundwater resources and human health for long term protection (Al-Yaqout and Hamoda, 2020; Magalhaes et al., 2020).

Policy Recommendations and Future Directions

International Policy Benchmarks

Effective landfill leachate management requires strong regulatory frameworks, consistent enforcement, and the adoption of advanced treatment technologies tailored to site-specific risks (Dagwar et al., 2024; Wang et al., 2024; EEA, 2024). The European Union's Landfill Directive has established strict requirements for engineered liners,

leachate collection systems, and groundwater monitoring, significantly reducing uncontrolled leachate discharge across member states (EEA, 2024). Other countries have also strengthened their regulatory frameworks, for example China's "Standard for Pollution Control on the Landfill Site of Municipal Solid Waste" (GB 16889-2008) defines discharge limits and monitoring requirements for landfill leachate (Wang et al., 2024) and in India, Hazardous and Other Wastes (Management and Transboundary Movement) Rules (2016) impose the duty to manage the leachate by using leachate containment, controlled landfills, and regular monitoring of the groundwater under the supervision of the Central Pollution Control Board (Sadala et al., 2023). Risk-based landfill siting supported by hydrogeological mapping is increasingly recommended to prevent landfill development in vulnerable aquifers (EPA Ireland, 2024).

Integrated Waste Management and Circular Economy

Circular economy strategies that emphasize waste reduction, recycling, and composting can significantly reduce landfill volumes and subsequent leachate generation (Igwegbe et al., 2024). Energy recovery from landfill gas and organic waste also contributes to improved resource efficiency and environmental sustainability. In addition, innovative treatment approaches such as constructed wetlands, advanced oxidation processes, and automated monitoring technologies are being explored as cost-effective solutions for complex landfill leachate (Igwegbe et al., 2024; Wang et al., 2024).

Monitoring, Public Engagement, and Enforcement

Effective management of landfills requires comprehensive environmental monitoring. The routine groundwater and surface water monitoring in the areas around landfills must be part of regulative processes, to make sure that contamination can be detected early (EEA, 2024; EPA Ireland, 2024). When the environmental information is reported transparently and there is an active community communication, the involvement of the community can enhance trust among people and help discover possible health hazards posed by landfill leachate in time (Sadala et al., 2023).

Research Priorities and Technology Innovation

The research of the future should be directed towards development of effective technologies of monitoring and treatment that would be capable to handle the complicated structure of landfill leachate. Nanotechnology application in a treatment system such as sensor-based monitoring network, and machine learning models to predict transport of present contaminants to enhance the landfill management system (Dagwar et al., 2024). There is also a necessity to conduct long-term investigation of rising contaminants, antibiotic resistance genes, and chronic health effects to improve the understanding of the environmental risk of landfill leachate (Sadala et al., 2023).

Conclusion

Landfill leachate remains a significant environmental challenge because of its complex composition and its potential to contaminate groundwater systems. It usually consists of organic matter, nutrients, heavy metals, and emerging contaminants, the behaviour of which varies depending on waste type, landfill age, management practices, and climatic conditions. Hydrogeochemical processes control the migration of such pollutants in the soil and aquifer systems, which often leads to the degradation of groundwater quality that surpasses the drinking water norms and is hazardous to the ecological system and human health. Although substantial progress has been made in characterizing leachate and developing treatment technologies, important research gaps remain. Long-term monitoring programs integrating hydrogeochemical analysis with environmental health data are needed to better understand the chronic impacts of landfill contamination. Further research should also be carried out to ascertain the environmental performance of the new pollutants, such as pharmaceuticals, microplastics, and antibiotic resistance genes in the landfill-affected environments. Improved landfill engineering, efficient leachate collection systems, and advanced treatment technologies combining biological, physico-chemical, and membrane processes are essential for reducing environmental risks. Strengthening regulatory frameworks, promoting circular waste management strategies, and expanding environmental monitoring programs will play an important role in protecting groundwater resources and minimizing the long-term impacts of landfill leachate.

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FAM and SSA conceived the concept, wrote and approved the manuscript.

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