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A Review of Landfill Leachates and Its Effects on the Receiving Plants and Soil

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ABSTRACT
Landfill leachate is a complex and potentially toxic aqueous solution that is produced by the decomposition of municipal solid waste and the percolation of water through landfill deposits. The chemical composition of landfill leachate is dependent on the characteristics of the waste, the age of the landfill, climatic conditions, and the prevailing biological and physicochemical processes. This review discusses the mechanisms, composition, properties, and environmental impacts of landfill leachate, especially on soil properties and plant growth and development. The leachate is mainly formed by rainfall infiltration, moisture contained in waste materials, and water produced during microbial decomposition. In addition to organic matter, nutrients, dissolved salts, ammonia, heavy metals, and other potentially harmful compounds, the leachate may contain high concentrations of organic matter, nutrients, dissolved salts, ammonia, heavy metals, and other potentially hazardous compounds, which can change soil pH, electrical conductivity, and the availability of other soil nutrients when it is discharged into surrounding soils. While diluted leachate may occasionally stimulate plant growth by the enrichment of nutrients, higher concentrations are generally inhibitory. In summary, landfill leachate can have a severe impact on soil quality, vegetation, and ecosystem functioning, and the proper collection, treatment, monitoring, and environmentally sound management of landfill leachate is imperative.

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INTRODUCTION

Due to its complex chemical composition and its ability to transport contaminants into other environmental media, landfill leachate is considered one of the most environmentally significant by-products of municipal solid waste disposal (Teng et al., 2021; Ma et al., 2022). Leachate is generated when soluble substances released by the physical, chemical, and biological transformations of waste materials are mobilized by infiltrating water (Teng et al., 2021; Ma et al., 2022). The generation of leachate is a major problem in landfill management because the liquid often contains high levels of organic matter, nutrients, dissolved salts, heavy metals, ammonia nitrogen, and other organic and inorganic contaminants that can negatively impact soil quality, vegetation, groundwater resources, and aquatic ecosystems (Siddiqua et al., 2022; El-Saadony et al., 2023). Consequently, understanding the processes responsible for leachate formation, its chemical composition, and its physicochemical characteristics is essential for assessing environmental risks associated with landfill operations. Landfill leachate is the liquid produced when precipitation, surface runoff, groundwater intrusion, and moisture trapped in the waste materials percolate through landfill deposits and dissolve organic and inorganic substances in the waste mass (Teng et al., 2021; Al Raisi, 2022). This liquid contains the dissolved constituents of the landfill waste, including dissolved organic and inorganic compounds formed from the degradation of waste materials and chemical and biological reactions, and inorganic constituents that are physically leached out from the waste mass (El-Saadony et al., 2023). Landfill waste is a mixture of heterogeneous materials from various sources, and the chemical composition of leachate is usually variable and can vary significantly between landfill sites and even within various locations in a landfill (Ma et al., 2022; Lindamulla et al., 2022). This variability makes the characterization of landfill leachate particularly important when evaluating its potential environmental impacts.

Formation of Landfill Leachates

Leachate formation starts immediately after waste deposition and continues during the operational and post-closure periods of the landfill (Lindamulla et al., 2022). One of the main factors causing leachate generation is rainfall infiltration, especially in tropical and humid areas where large amounts of rainfall can infiltrate into the waste (Ma et al., 2022). When rainwater seeps into landfill cells, it dissolves soluble compounds found in the waste material and carries contaminants down through the landfill. Besides precipitation, moisture within the waste itself is another major contributor to leachate production. Water-balance investigations of active municipal solid waste landfills in recent years have shown that the moisture contained in incoming waste can be a significant source of landfill moisture in addition to precipitation and leachate recirculation (Gen et al., 2023). Biological degradation processes can further contribute to moisture availability through the production of metabolic water during microbial decomposition of organic matter (Teng et al., 2021).

A number of environmental and operational factors affect the amount of leachate produced in landfills, including climatic conditions (e.g., precipitation, evaporation, surface runoff, temperature) that can affect water infiltration and moisture availability in waste deposits (Lindamulla et al., 2022; Ma et al., 2022), as well as temperature, which affects microbial activity and the rate of organic matter degradation within the landfill, both of which can influence leachate production and its chemical composition (Teng et al., 2021). Another critical factor that affects leachate production and quality is the composition of the waste. Leachates from municipal solid wastes can be high in dissolved organic matter and nutrients if the wastes contain a large fraction of biodegradable materials, but the leachates may also contain heavy metals and other potentially toxic contaminants if the wastes include hazardous materials, electronic components, batteries, metals, plastics, and other synthetic materials (El-Saadony et al., 2023; Ma et al., 2022).

Teng et al. (2021) noted that another important factor in determining leachate characteristics is landfill age, as waste decomposition proceeds through distinct biochemical phases with time. Young landfills typically produce leachates high in biodegradable organic matter because of the active decomposition of readily degradable substrates, and leachates at this stage are often high in BOD and COD, and the pH can be relatively acidic due to the accumulation of organic acids during decomposition (Ma et al., 2022). As the landfill stabilizes, the microbial processes evolve and the fraction of readily biodegradable organic matter generally declines, leading to corresponding changes in leachate composition and biodegradability (Luo et al., 2020).

Composition of Landfill Leachates

The composition of landfill leachate evolves with the biochemical stages of waste degradation within landfills; first, an aerobic phase takes place shortly after waste deposition, during which time aerobic microorganisms degrade easily degradable organic materials and produce carbon dioxide, heat, and water (Teng et al., 2021). As oxygen is depleted, anaerobic conditions are established, complex organic materials are further biologically degraded, and organic acids and other intermediate products are produced, which contribute significantly to the organic load and dynamic physicochemical properties of the resultant leachate (Teng et al., 2021; El-Saadony et al., 2023).

Methanogenic microorganisms play an important role in waste decomposition, converting organic acids and other intermediate products into methane and carbon dioxide. The shift to methanogenic conditions is typically accompanied by an increase in leachate pH and a decrease in readily biodegradable organic matter (Luo et al., 2020; Ma et al., 2022). As the landfill ages, the composition of leachate changes, with young leachate typically containing higher concentrations of biodegradable organic compounds, and mature leachate containing greater proportions of refractory and relatively less biodegradable organic substances (Teng et al., 2021).

Landfill leachate is a complex solution containing a wide variety of organic and inorganic constituents resulting from the breakdown, dissolution, and transport of disposed materials. The major constituents include dissolved organic matter, volatile fatty acids, ammonia nitrogen, dissolved salts, inorganic ions, and heavy metals; xenobiotic organic compounds and other potentially hazardous substances may also be present, and their relative concentrations depend on the composition of the waste and landfill conditions (Teng et al., 2021; El-Saadony et al., 2023). The relative concentrations of these constituents are affected by factors such as the nature of the waste deposited, climatic conditions, the age of the landfill, operational practices, and the prevailing biochemical processes within the landfill (Ma et al., 2022; Lindamulla et al., 2022).

Inorganic wastes tend to have high concentrations of dissolved organic compounds and nutrients, while wastes with hazardous materials, batteries, electronic components, industrial residues, plastics, and metal-containing products can have high concentrations of heavy metals and synthetic organic contaminants (El-Saadony et al., 2023). Landfill leachate also contains a growing list of emerging contaminants such as pharmaceuticals and personal-care-related compounds, further adding to the environmental importance of uncontrolled leachate release (Yu et al., 2020).

Characteristics of Landfill Leachates

The physicochemical properties of landfill leachate are closely related to the degree of decomposition of the waste and environmental conditions in the landfill (Teng et al., 2021; Ma et al., 2022). Young leachates generally have high concentrations of easily biodegradable organic matter, as indicated by high BOD and COD values, and relatively low pH due to the production of organic acids during the early stages of landfill development (Luo et al., 2020; Ma et al., 2022). As the landfill becomes more stable, the properties of the leachate dramatically change. When the landfill becomes methanogenic, organic acids are converted into methane and carbon dioxide, which increases the pH and decreases the readily biodegradable organic matter (Luo et al., 2020; Ma et al., 2022).

Leachates from mature landfills tend to be less biodegradable and often have high concentrations of ammonia nitrogen, humic substances, fulvic substances, dissolved salts, and refractory organic compounds (El-Saadony et al., 2023; Teng et al., 2021).

Leachate quality may also vary significantly spatially and temporally within landfill deposits because landfill deposits are heterogeneous and the processes controlling contaminant release are not uniform throughout the waste mass, resulting in significant variability in leachate quality between different landfill sites and even between different locations within the same landfill (Ma et al., 2022; Lindamulla et al., 2022). In particular, studies of landfill leachate from tropical regions have shown that climate, landfill age, waste characteristics, and operating conditions can all have significant impacts on leachate quality (Lindamulla et al., 2022). The complex and dynamic physicochemical properties of landfill leachate govern the mobility, persistence, and potential toxicity of the contaminants released into the surrounding soil, vegetation, groundwater, and aquatic ecosystems (Siddiqua et al., 2022; El-Saadony et al., 2023). Consequently, comprehensive characterization of landfill leachate is crucial for assessing its environmental risks and for developing effective management and treatment strategies.

Effects of Landfill Leachate on Soil Properties

Soil is an essential part of terrestrial ecosystems and is an environmental compartment that landfill leachate comes into contact with as it moves from disposal sites to surrounding areas. While soils have natural abilities to attenuate pollutants via physicochemical and biological processes, chronic or excessive contact with landfill leachate can result in the degradation of soil quality and ecosystem function (Kooch et al., 2024; Islam et al., 2024). For example, long-term studies have shown declines in soil organic matter, porosity, aggregate stability, available nutrients, microbial biomass, enzyme activities, and soil fauna in soils that have been affected by landfill leachate (Kooch et al., 2024).

The effect of landfill leachate on soil is highly dependent on the chemical composition of the leachate, contaminant concentration, exposure time, soil properties, climatic conditions, and leachate movement through the soil profile (Islam et al., 2024; Ma et al., 2022). Since landfill leachates are typically rich in dissolved organic matter, nutrients, salts, heavy metals, ammonium, and other potentially toxic substances, their introduction into soil systems can result in substantial alterations in both physicochemical and biological soil characteristics (Teng et al., 2021; Dagwar and Dutta, 2024).

Global characterization of landfill leachates has shown the presence of organic contaminants, ammonium, dissolved salts, heavy metals, and emerging contaminants, which are ubiquitous in landfill leachates but differ in concentrations across landfill sites (Teng et al., 2024). Wydro et al. (2022) stated that the presence of these contaminants can alter soil fertility and nutrient cycling, affect microbial communities, and impact ecosystem functioning. Research on leachate-contaminated soils has shown that prolonged leachate exposure can alter microbial composition and ecological functions (Gu et al., 2022). Another major impact of landfill leachate contamination is to change the soil pH, a key soil property that affects nutrient availability, microbial activity, biochemical processes, and the transport of several contaminants in soil (Maurya et al., 2020). Leachate impact on soil pH will depend on the composition and characteristics of the leachate as well as the properties of the receiving soil. Soil pH has been shown to be altered by leachate and waste-derived contaminants in landfill-affected soils, with measurable differences between contaminated and control locations (Nta et al., 2020; Islam et al., 2024). For example, the degradation of organic wastes and the accumulation of organic acids as a result of anaerobic degradation of the waste may contribute to lowering soil pH, while the presence of alkaline constituents and other dissolved ions may contribute to increases in soil pH under certain conditions (Teng et al., 2021; Dagwar and Dutta, 2024).

By contrast, mature leachates may contain significant concentrations of ammonia, bicarbonate, dissolved salts, and other inorganic constituents, which can make them relatively neutral or alkaline, depending on the characteristics of the receiving environment (Ma et al., 2022; Teng et al., 2021). Soil pH changes are environmentally significant as they can affect the mobility, solubility, and bioavailability of heavy metals and other contaminants (Kooch et al., 2024; Islam et al., 2024). Therefore, changes in soil pH may alter the environmental behaviour and potential ecological impacts of contaminants introduced through landfill leachate. Another parameter impacted by landfill leachate infiltration is soil electrical conductivity, which is a measure of the amount of dissolved ions in the soil solution and is a primary parameter used to describe soil salinity and accumulation of soluble salts (Maurya et al., 2020). Landfill leachates typically contain high levels of dissolved salts and inorganic ions, including sodium, potassium, calcium, magnesium, chloride, sulfate, and ammonium (Teng et al., 2024). Prolonged leachate infiltration can thus raise the concentration of soluble ions in the receiving soil and result in soil salinity. Field studies near municipal waste disposal sites have demonstrated that soil electrical conductivity is higher in soils near waste disposal areas than at more distant or control sites (Nta et al., 2020; Islam et al., 2024).

Leachate also has a significant impact on soil organic matter, which is responsible for maintaining soil fertility, nutrient retention, water-holding capacity, aggregation, and biological activity (Teng et al., 2021; Teng et al., 2024). Therefore, adding leachate to the soil could alter soil organic matter and carbon dynamics. Yet, the direction and intensity of this impact vary with the properties of the leachate, application rates, exposure duration, and the properties of the receiving soil. Leachate exposure has been shown to modify soil organic matter and other physicochemical properties in experimental work, while long-term field observations have reported significant decreases in soil organic matter and particulate organic carbon in landfill-impacted ecosystems (Wydro et al., 2022; Kooch et al., 2024), which can alter decomposition processes, microbial activity, nutrient cycling, and soil function.

Leachate can also significantly alter nutrient dynamics in soil; landfill leachates contain high concentrations of dissolved nutrients, especially nitrogen, in the form of ammonium from the decomposition of organic wastes (Teng et al., 2024), and can introduce large amounts of nutrients into soils into which they are infiltrated; however, nutrient enrichment does not always lead to enhanced soil fertility because high levels of nutrients (especially nitrogen and soluble salts) can also disrupt nutrient balance and soil biological processes. Leachate application changed soil nutrient properties, reducing nitrogen but increasing phosphorus and potassium in the experimental conditions. Likewise, landfill contamination over longer periods has been linked to decreases in available nutrients, ammonium, and nitrate, as well as decreases in microbial biomass and soil enzyme activities (Kooch et al., 2024), indicating that the impact of landfill leachate on soil nutrients is not always a simple enrichment process, but also can result in depletion or alteration of nutrient cycling, depending on the conditions of exposure.

Effects of Landfill Leachate on Plant Growth and Development

Plants are the most significant biotic component of terrestrial ecosystems and are frequently among the first organisms to display detectable effects when environmental contamination occurs. As plants absorb water and nutrients directly from soil, they can be especially sensitive to pollutants that enter soil via landfill leachate, which is a complex solution containing a mixture of organic compounds, inorganic ions, nutrients, heavy metals, salts, ammonia, and other potentially toxic components that can affect plant growth and development (Anand and Palani, 2022; Wdowczyk et al., 2026). Thus, plant responses to landfill leachate have become an important aspect of environmental toxicity testing, as plant bioassays can provide a holistic measure of biological effects resulting from exposure to complex leachate mixtures.

Many factors influence the impact of landfill leachate on plants, such as the concentration of the contaminant, the length of exposure, the species and developmental stage of the plant, and the chemical composition of the leachate itself (Palm et al. 2022; Wdowczyk et al. 2026). Although low levels of some leachate constituents may represent nutrients that stimulate plant growth for a short time, high levels often have inhibitory or toxic effects on plant development (Palm et al. 2022), for example, low proportions of municipal solid waste leachate stimulated some growth responses in Sinapis alba, whereas higher concentrations strongly inhibited root growth and adversely affected physiological parameters. Wdowczyk et al. (2026) found that untreated landfill leachate was highly phytotoxic to Sinapis alba, Lepidium sativum, and Sorghum saccharatum, but treated leachate with longer hydraulic retention times exhibited significantly lower toxicity. Thus, plant responses to landfill leachate may vary from growth stimulation at low concentrations to severe inhibition at higher concentrations.

Germination and early seedling development are especially relevant endpoints for phytotoxicity testing because they are among the earliest and most sensitive stages of plant development (Bożym, 2020; Vaverková et al., 2020). Many studies have shown that landfill leachate can inhibit seed germination and, in particular, root development due to the combined effect of ammonia, salts, heavy metals, organic compounds, and other contaminants (Anand and Palani, 2022; Wdowczyk et al., 2026). Lower germination indices were observed for both active and closed landfill leachates, and leachate from closed landfills was more phytotoxic (Anand and Palani, 2022). The inhibition of seed germination by landfill leachate is typically attributed to both osmotic stress and chemical toxicity: high levels of dissolved salts can raise the osmotic pressure of the germination medium and limit the supply of water needed for seed imbibition and subsequent metabolic activation, while toxic components such as heavy metals and ammonia can disrupt cellular processes during germination and early seedling development (Bożym, 2020; Wdowczyk et al., 2026). As a result, prolonged exposure to contaminated leachate may lead to reduced germination, impaired root elongation, and abnormal seedling development.

Another plant function sensitive to landfill leachate contamination is root development. Roots are the primary organs for water and nutrient acquisition, and are the plant organs exposed to contaminants in soil solutions. Experiments with Sinapis Alba, Lepidium sativum, and other test plants have shown that root elongation is especially sensitive to landfill leachate exposure (Vaverková et al., 2020; Palm et al., 2022; Wdowczyk et al., 2026). In many studies, root growth was inhibited at higher leachate concentrations, and diluted leachate sometimes showed a stimulatory response (Palm et al., 2022; Wdowczyk et al., 2026).

Many studies have thus described decreases in root length and root growth after exposure to landfill leachate. The presence of heavy metals and other toxic constituents in leachate can inhibit root growth by disrupting cellular processes that promote root elongation (Bożym 2020) and can lead to strong inhibition of root growth following direct exposure to high concentrations of municipal solid waste leachate (Palm et al. 2022). Reduced root development can then lead to reduced water and nutrient uptake, causing further physiological stress in the plant. Contamination of landfill leachate also affects shoot growth. The shoot system includes stems and leaves that are involved in photosynthesis, resource allocation, biomass production, and reproduction. Landfill leachate can contain a variety of toxic constituents that can impair shoot elongation and overall plant biomass accumulation, especially at relatively high exposure concentrations (Palm et al., 2022). For example, municipal solid waste leachate affected growth responses in Sinapis alba and Triticum aestivum, with high leachate concentrations producing inhibitory effects (Wdowczyk et al., 2026). These responses could relate to water relations, nutrient acquisition, cellular metabolism, and other physiological processes that are disrupted by contaminant exposure.

Landfill-leachate contamination can also impact leaf development and morphology, since changes in water availability, nutrient balance, and contaminant exposure can alter plant physiological functioning; leaves are the primary sites of photosynthesis and carbon assimilation, so disturbances in leaf development can affect overall plant productivity. Phytotoxicity studies have shown that leachate exposure can alter plant growth and physiological responses, and the magnitude of the response can depend on leachate concentration and plant species (Palm et al. 2022; Wdowczyk et al. 2026); for example, Palm et al. (2022) found that responses in photosynthetic performance and carbon assimilation varied with leachate concentration, and thus, even when effects on visible growth are relatively minor, physiological responses can occur.

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CONCLUSION

Landfill leachate is a complex environmental pollutant that can have a negative impact on soil quality and plant growth and development, depending on the physicochemical composition of the leachate, contaminant concentration, exposure time, landfill age, and properties of the receiving environment. The infiltration of leachate can change critical soil properties, such as pH, electrical conductivity, organic matter and nutrient dynamics, and the accumulation of heavy metals, salts, ammonia and organic contaminants can further disrupt soil biological functioning. Landfill leachate can also impact plants, inhibiting seed germination, root and shoot growth, biomass accumulation and photosynthetic performance; although diluted leachate may occasionally supply nutrients that stimulate some growth responses, higher concentrations are usually phytotoxic. Therefore, efficient collection, treatment and controlled disposal of landfill leachate are important to reduce soil contamination and protect vegetation and ecosystem health.

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