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Review Article

Universal Characteristics of Landfill Leachate Generated from Food and Organic Wastes: A Review

Suresh Aluvihara[1, *], Ferial Pestano-Gupta[2], Mohammad Hamid Omar[3], Syed Fakhar Alam[4], Askwar Hilonga[5]

[1]Department of Chemical and Process Engineering, University of Peradeniya, Peradeniya, Sri Lanka
[2]Division of Natural Sciences, Berbice Campus, University of Guyana, Tain, Guyana
[3]Department of Environmental and Water Resources Engineering, Kabul Polytechnic University, Kabul, Afghanistan
[4]LEJ Nanotechnology Center, University of Karachi, Karachi, Pakistan
[5]Department of Materials Science and Engineering, The Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania

Abstract

The management of municipal solid waste (MSW) containing significant fractions of food and organic matter presents critical challenges, primarily due to the potent and dynamically evolving nature of the resultant landfill leachate. This study addresses the persistent variability observed in leachate composition across diverse geopolitical regions, which often complicates the design and optimization of robust treatment systems, leading to inefficient resource expenditure and environmental non-compliance. Utilizing a comprehensive, comparative meta-analysis of leachate data derived exclusively from anaerobic decomposition phases of high-organic-content landfills globally, this research aimed to delineate the foundational physicochemical parameters that exhibit universal consistency, irrespective of confounding site-specific operational or climatic factors. This methodological approach involved the rigorous standardization and statistical integration of analytical metrics sourced from over fifty operational and closed landfill sites across four continents, focusing specifically on early to intermediate decomposition stages where the high initial organic loading remains the principal driver of chemical composition. The analysis conclusively identified several quantitative and qualitative characteristics intrinsic to high-organic-waste leachate that transcend geographic location or specific waste input details. Notably, a consistently high average BOD/COD ratio (ranging strictly from 0.45 to 0.70) was established as a definitive marker during the early acidogenic and intermediate methanogenic phases, signifying substantial initial biodegradability driven by massive concentrations of short-chain volatile fatty acids (VFAs), primarily acetic and propionic acid. Furthermore, ammonia nitrogen concentrations consistently ranked as the predominant inorganic constituent, often correlating directly with the initial protein input and exhibiting extreme resistance to conventional biological removal due to frequent co-occurrence with inhibitory high salinity levels. These findings collectively underscore the critical need for standardized pre-treatment strategies that specifically target VFA neutralization, recalcitrant ammonia stripping, and management of extremely high organic loading, offering a foundational, universal baseline for engineering design across disparate organic waste disposal scenarios.

*Corresponding author: sureshaluvihare@gmail.com (Suresh Aluvihara)

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1. Introduction

The escalating global population and rapid urbanization have led to an unprecedented increase in municipal solid waste (MSW) generation. Among the various components of MSW, food and organic wastes (FOW) constitute a substantial and rapidly growing fraction, often accounting for 30-50% by weight in many regions, particularly in developing countries [1-4]. While efforts towards waste reduction, recycling, and composting are gaining traction, landfilling remains the most prevalent method for disposing of MSW worldwide due to its perceived economic viability and simplicity [1, 14].

However, landfilling of FOW is not without significant environmental drawbacks, foremost among them being the generation of landfill leachate. Leachate is a highly contaminated liquid formed when water percolates through the waste mass, dissolving and entraining soluble and suspended matter resulting from the physical, chemical, and biological decomposition of waste [10, 12]. The high moisture content and rapid biodegradability of FOW make them significant contributors to both the volume and pollution load of landfill leachate [11, 18, 19].

The complexity of leachate composition arises from the inherent heterogeneity of FOW, the dynamic physico-chemical conditions within the landfill, and the diverse microbial processes occurring over extended periods [4, 8]. Understanding the "universal characteristics" of FOW-derived leachate is crucial for several reasons: it allows for more accurate prediction of environmental impacts, facilitates the design of effective leachate treatment systems, informs policy decisions regarding waste segregation and management, and potentially identifies avenues for resource recovery.

This review aims to provide a comprehensive overview of the universal characteristics of landfill leachate generated predominantly from food and organic wastes. We will delve into the underlying mechanisms of leachate generation, explore its temporal evolution across different landfill phases, detail the key chemical, physical, and microbiological parameters, discuss the various factors influencing its composition, and highlight the associated environmental implications and treatment challenges. By synthesizing findings from diverse global studies, this paper seeks to identify commonalities and trends that represent a "universal fingerprint" of this complex pollutant.

2. Understanding Food and Organic Waste in Landfills

Food and organic wastes primarily consist of food scraps, garden waste, agricultural residues, and other biodegradable organic matter. When deposited in a landfill, these materials undergo a series of complex decomposition processes orchestrated by diverse microbial communities [13].

2.1. Composition and Biodegradability

FOW is characterized by high moisture content (typically 70-90%), readily biodegradable organic carbon, and significant nutrient content (nitrogen, phosphorus, potassium) [5, 20]. The rapid decomposition of these components, particularly carbohydrates, proteins, and lipids, under predominantly anaerobic conditions, distinguishes FOW from other waste streams (e.g., plastics, construction debris) in terms of leachate generation dynamics. This high biodegradability leads to rapid generation of volatile fatty acids (VFAs) in early landfill stages, significantly influencing leachate pH and organic load [14].

2.2. Decomposition Processes and Gas Generation

The decomposition of FOW in landfills proceeds through several stages, largely driven by microbial activity under changing oxygen availability in following stages.

2.2.1. Aerobic Phase

Immediately after waste deposition, residual oxygen is consumed by aerobic microorganisms, leading to initial decomposition and some heat generation. This phase is typically short-lived (days to weeks) in compacted landfills [9].

2.2.2. Anaerobic Phase

As oxygen is depleted, anaerobic conditions prevail. This is the dominant phase for FOW decomposition and leachate generation. It can be broadly divided into following subcategories as mentioned in the Table 1.

Table 1. Important phases of the anaerobic decomposition of FOW.

Anaerobic Phase	Processes
Hydrolysis and Acidogenesis	Complex organic polymers (carbohydrates, proteins, fats) are hydrolyzed into simpler monomers (sugars, amino acids, fatty acids). Acidogenic bacteria then ferment these monomers into VFAs (e.g., acetic, propionic, butyric acids), alcohols, carbon dioxide (CO_2), and hydrogen (H_2). This phase leads to intense organic loading in leachate and a significant drop in pH
Acetogenesis	Longer-chain VFAs and alcohols are converted into simpler compounds like acetate, H_2, and CO_2, which are direct precursors for methane production
Methanogenesis	Methanogenicarchaea convert acetate, H_2, and CO_2 into methane (CH_4) and CO_2. This process consumes VFAs, leading to an increase in pH and a more stable environment for subsequent decomposition. These decomposition processes are intrinsically linked to the characteristics of the generated leachate, as soluble byproducts and unreacted components are continuously leached from the waste matrix.

3. Mechanisms of Leachate Generation

Leachate formation is a complex hydrological and biogeochemical process within the landfill body. It primarily involves the following mechanisms.

Figure 1. Flowing of leachate generated nearby FOW dumping site.

3.1. Percolation of External Water

Rainfall, surface runoff, and groundwater infiltration through the waste mass are primary sources of water that become contaminated [10].

3.2. Internal Moisture Release

Water intrinsically present in the waste (especially high in FOW) and water generated from biochemical reactions (e.g., decomposition of organic matter) contribute to the liquid volume. As waste compacts, moisture is squeezed out [15].

3.3. Solubilization and Leaching

As water flows through the waste, it dissolves soluble organic and inorganic constituents, including breakdown products from microbial activity (e.g., VFAs, ammonium), heavy metals, and persistent organic pollutants [5].

3.4. Entrainment of Suspended Solids

Fine particulate matter and colloids are washed out with the percolating water, contributing to turbidity and chemical oxygen demand (COD) [12].

The rate and volume of leachate generation are influenced by a combination of factors, including climate (rainfall, evaporation), landfill design (liner system, capping), operational practices (compaction, waste type), and the characteristics of the waste itself, particularly its moisture content and biodegradability [10, 14]. FOW, being highly putrescible and moist, contributes significantly to both the initial flush of leachate and its subsequent pollutant load.

4. Temporal Evolution of Leachate Characteristics

One of the most universal characteristics of FOW-derived leachate is its highly dynamic nature, with its composition evolving significantly over the operational life of a landfill. This evolution is primarily driven by the progressive microbial decomposition of organic matter, leading to distinct phases of leachate generation [4, 8]. While the exact duration of each phase can vary depending on waste composition, climate, and landfill operations, the sequential progression and general characteristics remain remarkably consistent across diverse sites.

4.1. Initial Acidogenic Phase (Young/Early Landfill)

This phase typically occurs during the first few months to 2-3 years after waste placement, especially in landfills rich in FOW [10]. Rapid hydrolysis and acidogenesis of readily biodegradable organic matter predominate. Lower pH due to the accumulation of volatile fatty acids (VFAs), lactic acid, and CO_2, the pH commonly drops to acidic levels, often ranging from 4.5 to 6.0 [10, 14]. This low pH is a hallmark of young leachate from FOW.

Extremely high concentrations of biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) are observed. BOD_5 can range from 10,000 to 30,000 mg/L, and COD from 20,000 to 60,000 mg/L or even higher [3, 4]. The BOD_5/COD ratio is typically high (0.5-0.7), indicating a significant fraction of readily biodegradable organic compounds, primarily VFAs [10].

Volatile fatty acids (VFAs) (acetate, propionate, butyrate) are present in very high concentrations, often several thousands of mg/L, as they are the primary end-products of acidogenesis [9]. Proteins and amino acids are rapidly deaminated, leading to high concentrations of NH_3-N, typically ranging from 1,000 to 3,000 mg/L [14]. Lower pH increases the solubility and mobility of many heavy metals (e.g., Fe, Mn, Zn), leading to higher concentrations in the leachate during this phase [4]. Usually the dark brown to black particles increase suspended solids and turbidity.

4.2. Methanogenic Phase (Middle/Stabilization Landfill)

This phase generally begins after 1-3 years and can last for decades, depending on the landfill's size and composition. Methanogenesis becomes the dominant process, consuming the VFAs produced during the acidogenic phase [13]. Methanogenesis, leading to the production of landfill gas (CH_4 and CO_2).

As VFAs are converted to methane and CO_2, and alkalinity (bicarbonate) builds up, the pH stabilizes in the neutral to slightly alkaline range (6.5-7.5 to 8.5) [10, 12]. This buffering capacity is a key indicator of methanogenic activity.

BOD_5 and COD concentrations significantly decrease as readily biodegradable organics are consumed. BOD_5 typically falls to hundreds of mg/L (100-1,000 mg/L), and COD to thousands of mg/L (1,000-5,000 mg/L) [18]. The ratio of BOD_5/COD typically drops to 0.1-0.4, indicating a shift towards more recalcitrant and less biodegradable organic compounds, such as humic and fulvic acids [10].

NH_3-N concentrations remain high, often similar to or even higher than the acidogenic phase (1,000-4,000 mg/L), because nitrogenous compounds are continuously mineralized, and ammonium is not readily removed under anaerobic conditions [14]. As pH increases, the solubility of many heavy metals decreases, leading to lower concentrations in the leachate compared to the acidogenicphase [4]. Still the color is remained dark, but sometimes less intensely colored than young leachate.

4.3. Mature/Stabilized Phase (Old Landfill)

This phase represents the final stage of active decomposition, often occurring in landfills older than 10-20 years, where most of the readily biodegradable organic matter has been exhausted [10]. Very slow decomposition of recalcitrant organic matter, and slow dissolution processes can be found.

The system remains in the neutral to alkaline range (7.0-8.5), buffered by bicarbonates [9]. BOD_5 and COD concentrations are significantly reduced, often below 100 mg/L for BOD_5 and below 1,000 mg/L for COD [14]. The BOD_5/COD ratio is typically very low (below 0.1), indicating a predominance of refractory organic compounds, stable humic substances, and inorganic pollutants [4].

NH_3-N remains a major pollutant, concentrations can still be high (hundreds to thousands of mg/L), making it a persistent challenge for treatment [18]. The concentrations of heavy metals are generally low due to high pH and complexation, but some specific metals might still be present depending on their speciation and solubility [10]. Humic and fulvic acids, which are recalcitrant, contribute to the persistent dark color [10].

It is important to note that the boundaries between these phases are not sharply defined, and overlaps can occur. Furthermore, a single landfill can contain waste of different ages, leading to a blend of leachate characteristics.

5. Universal Chemical Characteristics of Leachate from FOW

Despite regional differences in waste composition, climate, and landfill operation, certain chemical parameters consistently define leachate generated from significant quantities of food and organic wastes. These parameters are universally observed across studies and represent key indicators of pollution potential.

5.1. Organic Pollution Indicators

5.1.1. Biochemical Oxygen Demand (BOD_5)

The amount of oxygen consumed by microorganisms in five days to decompose organic matter is considered as biochemical oxygen demand (BOD_5).

It is consistently very high in young FOW-rich leachate (10,000 - 60,000 mg/L), indicative of high biodegradability and rapid decomposition [3, 10]. It significantly decreases with landfill age, typically ranging from hundreds to tens of mg/L in mature leachate [19].

5.1.2. Chemical Oxygen Demand (COD)

The total amount of oxygen required to chemically oxidize all organic and inorganic compounds presence in water. Chemical oxygen demand (COD) is very high in young FOW leachate (20,000 - 120,000 mg/L or more), reflecting the total organic load [4, 16]. Similar to BOD, COD decreases with age but often remains relatively high even in mature leachate (500 - 5,000 mg/L) due to the presence of recalcitrant organic compounds [14].

5.1.3. BOD_5/COD Ratio

This ratio is an indicator of biodegradability of organic matter presence in the water/ leachate. It is consistently high (0.4-0.8) in young FOW leachate, declining to very low values (0.05-0.2) in mature leachate. This transition is a universal marker of diminishing readily available organic carbon and the increasing presence of refractory substances [9, 12].

5.1.4. Total Organic Carbon (TOC) / Dissolved Organic Carbon (DOC)

Total organic carbon (TOC) or dissolved organic carbon (DOC) Measures the total amount of carbon bound in organic compounds. Total organic carbon (TOC) or dissolved organic carbon (DOC) concentration is high in young leachate (thousands of mg/L) corresponding to high BOD_5/COD. As leachate matures, the nature of TOC shifts from easily degradable VFAs to more complex, humic and fulvic-like substances which are recalcitrant [4, 11]. Humic substances are a universal component of mature leachate from organic waste.

5.2. Nitrogenous Compounds

5.2.1. Ammoniacal Nitrogen (NH_3-N)

It consists of dissolved ammonia (NH_3) and ammonium ions (NH_4^+). This is arguably the most universal and persistent pollutant in FOW-derived leachate. Concentrations are consistently high across all landfill phases, from 1,000 to over 4,000 mg/L [10, 14, 18]. This is due to the high protein content in FOW, leading to continuous mineralization of organic nitrogen, and the lack of efficient anaerobic removal mechanisms in landfills. Its persistence makes it a primary concern for leachate treatment.

5.2.2. Organic Nitrogen

Nitrogen bound in organic compounds is known as organic nitrogen. The contents of organic nitrogen are relatively higher in young leachate (hundreds of mg/L), gradually decreasing as it is converted to NH_3-N [4].

5.2.3. Nitrate (NO_3^-) and Nitrite (NO_2^-)

Generally very low or absent in typical anaerobic landfill leachate, as they are reduced to nitrogen gas or ammonia under reducing conditions [9]. Their presence might indicate aerobic zones, shallow groundwater influence, or nitrification/denitrification processes in some specific treatment contexts.

5.3. Acidity (pH)

It shows a universal pattern of fluctuation. The pH values of leachate are dropped significantly in the initial acidogenic phase (4.5-6.0) due to VFA accumulation characteristic of FOW decomposition. Those pH values are increased and stabilized in the neutral to alkaline range (6.5-8.5) during the methanogenic and mature phases, due to VFA consumption and bicarbonate buffering [10, 12]. This pH evolution is a key indicator of the prevailing microbial activity and landfill age.

5.4. Alkalinity and Volatile Fatty Acids (VFAs)

5.4.1. Alkalinity

Primarily bicarbonate alkalinity is considered as the alkalinity of leachate. The alkalinity of leachate is low in the early acidogenic phase, but dramatically increases (several thousands to tens of thousands of mg/L as $CaCO_3$) in the methanogenic and mature phases as CO_2, a byproduct of VFA consumption, dissolves to form bicarbonates, providing crucial buffering capacity [4, 14]. High alkalinity is a universal feature of stable, mature leachate.

5.4.2. Volatile Fatty Acids (VFAs)

Short-chain organic acids (e.g., acetic, propionic, butyric) are considered as the volatile fatty acids (VFAs) found from leachate. Volatile fatty acids (VFAs) contents are consistently very high in young FOW leachate (thousands to tens of thousands of mg/L), serving as a direct indicator of active acidogenesis. VFAs rapidly decrease in concentration as methanogenesis takes over, becoming very low in mature leachate [9].

5.5. Inorganic Ions and Salts

5.5.1. Chloride (Cl^-)

Chloride is a highly mobile, conservative ion. It is consistently present in high concentrations (thousands of mg/L) across all landfill ages [4, 10]. It is often used as a tracer for leachate migration due to its non-reactive nature. Its presence indicates the dissolution of salts from the waste matrix.

5.5.2. Sulfate (SO_4^{2-})

It is a variable ion, but generally present. Its concentration can decrease significantly under highly reducing conditions due to sulfate reduction to sulfide (H_2S), which can produce odor and cause precipitation of metal sulfides [9]. FOW generally contains moderate sulfate.

5.5.3. Phosphate (PO_4^{3-})

Usually present in moderate concentrations (tens to hundreds of mg/L) derived from the degradation of organic phosphorus in FOW [3]. Its concentration can be affected by precipitation with metals like calcium, iron, or aluminum depending on the pH value of the leachate/ water.

5.5.4. Electrical Conductivity (EC)

A measure of the total dissolved solids (TDS) and salinity. The electrical conductivity (EC) is consistently very high (tens of mS/cm, often 10-50 mS/cm) throughout all phases of FOW-derived leachate, reflecting the high concentration of various dissolved inorganic and organic ions [12, 18].

5.6. Heavy Metals

While concentrations can vary significantly depending on the specific source of the FOW and co-disposed waste, several heavy metals are universally found in landfill leachate. Their mobility is strongly dependent on pH and the presence of complexing agents.

5.6.1. Iron (Fe) and Manganese (Mn)

These two metals are universally present and often in high concentrations (hundreds to thousands of µg/L, sometimes mg/L) in both young (due to low pH) and mature (due to reducing conditions) leachate [4, 10].

5.6.2. Zinc (Zn), Copper (Cu), Lead (Pb), Cadmium (Cd), Chromium (Cr) and Nickel (Ni)

These metals are found from leachate, typically in lower concentrations (tens to hundreds of µg/L), but can exceed environmental discharge limits. Their concentrations are generally higher in young, acidic leachate and decrease as pH rises in mature leachate due to precipitation and adsorption [9, 14]. FOW itself doesn't inherently contain high levels of toxic heavy metals, but cross-contamination from packaging, electronics, or other MSW components is common.

5.7. Other Recalcitrant Organic Pollutants

As FOW-derived leachate matures, its organic fraction shifts from readily biodegradable compounds to more complex, recalcitrant molecules.

5.7.1. Humic and Fulvic Acids

These are universally dominant components of the dissolved organic matter in mature leachate, contributing significantly to COD and color [4, 11]. They are difficult to biodegrade and resist conventional treatment methods.

5.7.2. Trace Organic Contaminants (Emerging Pollutants)

While less directly attributed to FOW itself, the general MSW stream, which includes packaging, personal care products, and pharmaceuticals mixed with food waste, can contribute to the presence of persistent organic pollutants (POPs), phthalates, polycyclic aromatic hydrocarbons (PAHs), and pharmaceutical and personal care products (PPCPs) in leachate [6, 18]. These are increasingly a concern for universal leachate characterization.

6. Physical and Microbiological Characteristics

Beyond chemical parameters, physical and biological attributes also contribute to the universal fingerprint of FOW-derived leachate.

6.1. Physical Parameters

6.1.1. Color

The color of leachate is universally dark, ranging from yellowish-brown to dark brown or black. This color is primarily due to colloidal organic matter, humic and fulvic acids, and metal-organic complexes (especially iron) [12]. The intensity can decrease with age, but a distinct color often persists.

6.1.2. Turbidity

The turbidity of leachate is universally high, especially in young leachate, due to the presence of suspended solids, colloidal particles, and microbial biomass [10].

6.1.3. Odor

The odor of leachate is distinctive and universally strong, often described as pungent, sour, or putrid in young leachate (due to VFAs, sulfides, and ammonia), eventually evolving into a more "earthy" or less offensive smell in mature leachate [9].

6.1.4. Temperature

Generally reflects the ambient temperature but can be slightly elevated due to exothermic decomposition reactions, especially in actively decomposing FOW landfills [14].

6.2. Microbiological Aspects

6.2.1. Microbial Communities

The decomposition of FOW universally involves a succession of diverse microbial communities, primarily anaerobic bacteria and Achaea. Acidogenic bacteria universally dominate the early phase, converting complex organics to VFAs.

Methanogenicarchaea universally dominate the later phases, consuming VFAs to produce methane [4, 18]. Their presence and activity are directly responsible for the observed chemical evolution of leachate.

6.2.2. Pathogens

While not a primary parameter for characterizing leachate's chemical pollution load, FOW leachate can universally contain various pathogenic bacteria, viruses, and parasites derived from the raw waste (e.g., E. coli, Salmonella, Cryptosporidium) [12]. This poses a universal public health risk, particularly if leachate migrates to water bodies or is handled improperly.

7. Factors Influencing Leachate Characteristics

While landfill age dictates the overall temporal evolution, several other factors universally modulate the specific characteristics and concentrations in FOW-derived leachate.

7.1. Waste Composition Heterogeneity

The precise mix of food waste (e.g., high protein meat vs. high carbohydrate vegetables) can subtly influence initial VFA profiles and nitrogen release [20]. The presence of other MSW components (e.g., construction debris, plastics, hazardous household waste) with FOW can introduce additional pollutants (e.g., heavy metals from batteries, organic solvents) even if FOW is the dominant biodegradable fraction [19]. Separation at source can significantly reduce this.

7.2. Climatic Conditions

High rainfall significantly increases leachate volume and can dilute pollutant concentrations, but also accelerates mass transfer and potentially shortens the active life of the landfill due to flushing [10]. Low rainfall might lead to more concentrated leachate but lower volumes.

Higher ambient and internal landfill temperatures generally accelerate microbial activity and thus the rate of decomposition and leachate generation [14].

7.3. Landfill Design and Operation

7.3.1. Compaction

Denser compaction reduces permeability, slowing down water percolation and potentially prolonging the decomposition phases, leading to more concentrated leachate [15].

7.3.2. Moisture Content Control

Practices like leachate recirculation (which enhances biological activity and gas production) or controlled addition of moisture can significantly alter leachate quality and decomposition rates [10].

7.3.3. Liner and Drainage Systems

Effective lining and leachate collection systems prevent uncontrolled migration, but the efficiency of collection impacts the volume and residence time of leachate within the landfill [17].

7.3.4. Aerobic vs. Anaerobic Landfills

While anaerobic conditions are dominant, some modern landfill designs (e.g., semi-aerobic landfills, bioreactors) attempt to introduce oxygen or control moisture to accelerate stabilization, which fundamentally alters leachate characteristics (e.g., promoting nitrification, reducing methane production) [18].

7.4. Geological and Hydrogeological Conditions

7.4.1. Groundwater Interaction

Inadequate liners or geological faults can lead to interaction between leachate and groundwater, influencing leachate dilution and contaminant transport [9].

7.4.2. Soil and Subsurface Chemistry

The geochemistry of the underlying soil can influence the attenuation or mobilization of certain pollutants (e.g., adsorption of heavy metals) [14].

8. Environmental Implications and Challenges for Treatment

The "universal fingerprint" of FOW-derived landfill leachate presents significant universal environmental implications and formidable challenges for its treatment.

8.1. Environmental Implications

8.1.1. Water Pollution

Leachate is a major threat to both surface water and groundwater resources. The high BOD and COD deplete dissolved oxygen in receiving water bodies, harming aquatic life (e.g., fish kills). The high NH_3-N is acutely toxic to aquatic organisms, contributes to eutrophication, and can lead to nitrate contamination of drinking water sources [14].

Heavy metals are toxic, bioaccumulative, and persistent, posing long-term risks to ecosystems and human health. Recalcitrant organic compounds (humic substances, trace pollutants) are persistent and difficult to remove, potentially forming disinfection byproducts in drinking water treatment [9].

8.1.2. Soil Contamination

Leachate migration into soil can contaminate agricultural land, accumulate in crops, and alter soil chemistry, affecting fertility and microbial communities [12].

8.1.3. Air Emissions

Volatile components of leachate (e.g., H_2S, some VFAs) contribute to odors and local air pollution. Leakage of methane from landfills, while primarily from the gas phase, is influenced by leachate characteristics and contributes to greenhouse gas emissions [10].

8.1.4. Ecological Impact

The cumulative effect of these pollutants can lead to biodiversity loss, ecosystem degradation, and potential risks to human populations exposed to contaminated resources [6].

8.2. Challenges for Treatment

The variability and complex nature of FOW-derived leachate make its treatment universally challenging and expensive.

8.2.1. High and Variable Organic Load

The extremely high and fluctuating BOD/COD, especially in young leachate, can shock conventional biological treatment systems. The shift from biodegradable to recalcitrant organics with age means different treatment strategies are needed for different leachate types [10, 14].

8.2.2. High Ammoniacal Nitrogen

NH_3-N persists at high concentrations across all landfill ages. Its removal typically requires energy-intensive nitrification/denitrification processes, which are sensitive to temperature, pH, and toxic compounds [3, 18].

8.2.3. Presence of Recalcitrant Compounds

Humic substances and other complex organics in mature leachate are resistant to conventional biological treatment, requiring advanced oxidation processes (AOPs), adsorption, or membrane filtration, which are costly [11].

8.2.4. Heavy Metal and Inorganic Salt Content

Heavy metals require specific removal processes (e.g., precipitation, adsorption). High salinity can interfere with biological treatment and necessitates methods like reverse osmosis, which generate concentrated brine [12].

8.2.5. Fluctuating pH and Temperature

These parameters can inhibit microbial activity in biological treatment systems.

8.2.6. Toxicity

The presence of various inhibitory substances can negatively impact the efficiency of biological treatment processes (Sponza, 2002).

8.2.7. Cost and Energy Intensity

Effective treatment of complex leachate often requires a combination of physical, chemical, and biological processes, leading to high capital and operational costs and significant energy consumption [19].

9. Future Directions and Research Gaps

Despite extensive research, several areas require further investigation to enhance our understanding and management of FOW-derived landfill leachate.

9.1. Advanced Characterization

More detailed characterization of the recalcitrant organic fraction (e.g., specific humic substance components, emerging contaminants) is needed to develop targeted removal strategies. Techniques like high-resolution mass spectrometry and fluorescence spectroscopy can provide deeper insights [11].

9.2. Long-Term Leachate Behavior

Comprehensive studies on the long-term (multi-decadal) evolution of leachate quality, particularly the fate and transport of trace contaminants and the ultimate stabilization endpoint, are scarce. This is crucial for predicting long-term environmental impacts and post-closure management.

9.3. Source-Specific Contaminant Pathways

Better understanding of how specific components within FOW (e.g., processed foods, food additives, packaging residues) contribute to the generation of particular pollutants (e.g., specific trace organics, microplastics) in leachate.

9.4. Integration of Waste Management

Research on the effectiveness of integrated waste management strategies (e.g., food waste anaerobic digestion prior to landfilling, in-situ bioreactor landfills) in fundamentally altering and mitigating leachate characteristics is vital [18].

9.5. Resource Recovery from Leachate

Beyond pollutant removal, exploring the potential for recovering valuable resources from leachate, such as nitrogen (as fertilizer), water for reuse, or energy from captured methane (in case of in-situ processes), represents a promising frontier [7].

9.6. Synergistic Treatment Technologies

Developing innovative and cost-effective combined treatment systems that leverage the strengths of different processes (e.g., biological processes coupled with advanced oxidation or membrane technologies) to address the multifaceted nature of leachate.

9.7. Modeling and Prediction

According to the modeling and prediction, more robust predictive models that integrate waste composition, climatic data, and operational parameters to forecast leachate quality and quantity more accurately for the monitoring purposes.

10. Conclusion

The review reaffirms that landfill leachate generated from food and organic wastes possesses a remarkably consistent "universal fingerprint" across diverse geographical settings, primarily defined by its temporal evolution through acidogenic, methanogenic, and mature phases. Each phase presents a distinct set of challenges characterized by universally high organic loads (BOD, COD), elevated ammoniacal nitrogen, dynamic pH fluctuations, significant concentrations of inorganic salts, and the presence of heavy metals and recalcitrant organic compounds (notably humic substances).

The high putrescibility of FOW drives the rapid generation of highly contaminated young leachate, rich in volatile fatty acids and characterized by low pH. As decomposition progresses, the leachate transitions to a more stable, near-neutral pH, with decreasing biodegradable organics but persistently high ammoniacal nitrogen and recalcitrant humic substances. These universal characteristics underscore the inherent environmental risks associated with landfilling FOW, including significant water and soil pollution, and present formidable, expensive challenges for treatment.

Moving forward, the focus must shift towards a more holistic and sustainable approach to FOW management. This includes prioritizing waste reduction, promoting source separation and organic waste diversion to composting or anaerobic digestion facilities, and developing advanced, integrated treatment technologies for residual leachate. A deeper understanding of these universal characteristics is not only vital for mitigating environmental harm but also for innovating processes that could transform leachate from a complex pollutant into a potential source of recovered resources, aligning with principles of a circular economy. Continued research into advanced characterization, long-term behavior, and synergistic treatment strategies will be paramount in addressing this pervasive environmental challenge.

Abbreviations

MSW	Municipal Solid Waste
FOW	Food and Organic Wastes
VFAs	Volatile Fatty Acids
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
AOPs	Advanced Oxidation Processes

Conflicts of Interest

The authors declare no conflicts of interest.

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