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Characterization And Treatment of Landfill Leachate in South Indian Metropolitan Cities: A Review of Regional Challenges and Sustainable Solutions

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Abstract:- Landfill leachate is a major environmental concern in rapidly urbanizing cities. The composition of leachate varies from region to region due to differences in waste generation patterns, landfill age, climatic conditions and waste management practices. This review paper provides a comprehensive analysis of landfill leachate characterization in metropolitan cities of South India, focusing on key physicochemical and biological parameters. Furthermore the study reviews on various landfill leachate treatment technologies including conventional methods like coagulation- flocculation and biological treatment as well as advanced techniques such as membrane filtration, electrochemical process and phytoremediation. The challenge posed by high organic loads, ammonia concentration are discussed in the context of local climatic and regulatory conditions. The review highlights the need for region-specific, integrated treatment strategies with sustainability to mitigate the environmental impact of landfill leachate.

Keywords*: landfill leachate, organic pollutants, biological treatment, physical-chemical treatment.*

1. Introduction

The exponential increase in municipal solid waste (MSW) over time has predominantly resulted from the expansion of industrial activities, population growth, and shifts in lifestyle (Mohamad et.al (2014)). According to the "Manual on Solid Waste Management" by the Central Public Health & Environment Engineering Organisation (CPHEEO), Ministry of Urban Development, Government of India, the waste produced in Indian cities typically falls within the range of 0.2-0.6 kg per capita per day. The amount of waste generated is greatly influenced by the lifestyle of the population (As of CPHEEO). Municipal solid waste generation is persistently increasing on both an individual and collective scale (Renou et.al (2008)). Ensuring sustainability poses a greater challenge in metropolitan regions, where effective waste management is a top priority. Solid waste management encompasses the comprehensive management of solid waste, including its generation, collection, storage, transfer, and transportation (Abuabdou et.al (2020)). At present, sanitary landfilling stands as the most practical approach to municipal solid waste management due to advantages such as affordability, straightforward disposal processes, land reclamation opportunities, and reduced environmental consequences (Ahmad et.al (2022)).

Landfill sites encounter significant challenges, notably the production of leachate. The composition of leachate generated at each landfill site primarily relies on seasonal fluctuations. During the summer, leachate concentrations tend to be higher due to lower moisture content. Conversely, in the rainy season, increased water percolation from the surrounding areas dilutes the leachate, resulting in reduced concentration. Achieving stabilization of municipal solid waste typically necessitates 20 years or more (Yaqout et.al (2003)).Waste deposited in landfills can undergo a sequence of biological and physiochemical changes, leading to the creation of highly contaminated wastewater known as leachate. This leachate has the potential to contaminate adjacent groundwater, surface water and soil, contributing to waste stabilization. (mojiri et.al (2021)).

Leachate primarily originates from the reactive percolation of rainwater passing through the solid waste layer within landfills, alongside water produced by various biochemical reactions within the waste (Ahmad et.al (2022)). Landfill leachate exhibits elevated levels of chemical and biological oxygen demand and frequently contains significant concentrations of organic contaminants, heavy metals, toxic substances, ammonia, inorganic materials, and refractory compounds like humic substances, along with emerging contaminants. The specific characteristics of landfill leachate can vary based on degradation processes, climate, hydrological conditions, and the age of the landfill. Insufficient treatment of landfill leachate is often associated with ecological contamination and health concerns (Chavez et.al (2019).

The significant pollution potential of leachate, environmental regulatory agencies faced societal pressure to establish stricter discharge parameters for leachate. The objective of this article is to conduct a comprehensive literature review focusing on various leachate characteristics and treatment technologies. This review aims to assess their suitability, functionality, merits, drawbacks, and uncertainties, with the intention of offering a clearer perspective on the subject and aiding in the informed selection of leachate treatment methods.

2. Leachate generation

Estimating leachate generation is crucial for preventing potential leachate leakage, especially into groundwater systems. Leakage could occur if the leachate head in the bottom liner exceeds 30 cm, a measure easily monitored with a pressure transducer in the leachate collection well. Higher rates of leachate generation significantly increase leachate accumulation at the bottom liners due to the downward, vertical flow, thus raising the risk of leakage into groundwater aquifers (Ayub et.al 2011).

Leachate is primarily produced from external water inputs, mainly rainwater infiltration, in addition to the moisture already present in the waste and a small amount generated by various reactions within the landfill. Sanitary landfills are typically designed to prevent or minimize water infiltration through various strategies, depending on the landfill owner or contractor. Therefore, accurate modeling of leachate generation requires considering factors such as the type of waste disposed, land filling practices, landfill cover methods, leachate collection systems, and leachate recirculation (Mojiri et.al 2021).

3. Leachate characterization

The interaction of waste with water that percolates through the landfill produces a highly polluted wastewater known as leachate. The components of landfill leachate can vary based on characteristics of the landfill, such as; the type of waste received at the disposal site and its degree of decomposition, as well as variations in weather during waste disposal, affect leachate composition. Additionally, factors related to the landfill environment, such as the waste degradation phase, humidity, precipitation, and temperature also play significant roles [Shah M et.al (2019)].

The quality of leachate is influenced by various factors such as the age of the landfill, precipitation, seasonal weather variations, and the type and composition of waste. The composition of landfill leachate varies greatly depending on the landfill's age and the type of waste it contains. Landfills can be classified by age as young (less than 5 years), medium-aged (5-10 years), and old (more than 10 years). Table 1 represents the varience of characteristics of leachate with different landfill ages. Highly toxic leachate contains numerous organic compounds such as Chemical Oxygen Demand (COD) and Total Organic Carbon (TOC), as well as inorganic compounds like calcium, magnesium, sodium, and iron. It also includes heavy metals such as chromium, nickel, and copper, along with pathogens and suspended particles [Shah M et.al (2019)].

TABLE 1: Variance of Characteristics of leachate with Different Landfill Ages

PARAMETERS	CHARACTERISTICS			References
	Recent (0-5)	Medium (5-10)	Old (>10)	
pH	<6.5	6.5-7.5	>7.5	Naveen et al., (2017)
COD (mg/L)	>10000	5000-10000	<5000	Powrel K et.al (2022)
BOD5/COD	>0.3	0.1-0.3	<0.1	Bhalla.B et.al (2012)
Organic Compounds	Volatile fat acids (80%)	Humic and Fulvic acids + (5-30% Volatile fat acids)	Humic and Fulvic acids (80%)	Mojiri A et.al (2021)
Heavy Metals (mg/L)	Low-Medium (>2.0)	Low (<2.0)	Low (<2.0)	Shah M et.al (2019)
Biodegradability	High	Medium	Low	Abbas A et.al (2009)
NH3-N (mg/L)	<400	400	>400	Mojiri A et.al (2021
TOC/COD	<0.3	0.3-0.5	>0.5	Renou S et.al (2007)
TDS(mg/L)	2500-14000	4000-55000	1100-6400	Zakaria S et.al (2017)

As the landfill ages, the concentration of organic compounds (COD) in the leachate decreases, while the concentration of ammonia nitrogen increases. Leachate from older landfills typically contains high levels of ammonia, which results from the hydrolysis and fermentation of nitrogen-containing biodegradable waste materials. Leachate may contain significant amounts of organic matter, including both biodegradable and non-biodegradable (refractory) substances, with humic-type constituents forming a key group. It also often contains ammonia nitrogen, heavy metals, chlorinated organic compounds, and inorganic salts [Abbas A et.al (2009)]. The pH value is frequently utilized to indicate the aggressiveness of leachate and the biochemical conditions within solid waste (Emenike et al. (2012). pH levels below 7 typically signify softer waters, with the acidity primarily resulting from carbonic, humic, fulvic, and other organic acids. Conversely, pH levels above 7 can carry a higher load of dissolved substances. The alkaline nature of leachate at this stage reflects the maturity of the dumping site (Naveen et al., 2017). Electrical conductivity (EC) and total dissolved solids (TDS) are influenced by the total amount of dissolved organic and inorganic materials in the solution, and they are used to indicate the salinity and mineral content of leachate. The total mineral content reflects the strength and overall pollutant load of the leachate. The salt content in the leachate arises from the presence of potassium, sodium, chloride, nitrate, sulfate, ammonia, and other substances. Extremely high conductivity values are due to high levels of cations and anions. High TDS can reduce water clarity, which limits light penetration, decreasing photosynthesis and increasing water temperature. This can impact the leachate biota, as high TDS can inhibit the growth and potentially cause the death of many aquatic organisms (Naveen et al., 2017).

The ratio aligns with the pH observations, indicating acidic conditions in the landfill. Both hardness and alkalinity were highest in the fresh leachate. The level of inorganic elements in the leachate mainly depends on how easily inorganic constituents from the municipal solid waste (MSW) leach out and the stabilization process within the landfill (Naveen et al., 2017). Multivalent cations, especially Mg2+ and Ca2+, are often found in significant concentrations in natural waters. These ions readily precipitate and can react with soap, making it difficult to remove scum. Total hardness (TH) is typically expressed as the combined concentration of Ca^{2+} and Mg^{2+} in mg/L, as equivalent CaCO3. A high concentration of Na+ may pose risks to individuals with cardiac, renal, and circulatory diseases (Teng .C et.al (2021)). Heavy metals remain in the waste or at the waste–rock interface due to redox-controlled precipitation reactions. Additionally, metal mobility is regulated by physical sorptive mechanisms, and landfills inherently possess the capacity to minimize the mobility of toxic heavy metals. Leachate is typically a strongly reducing liquid formed under methanogenic conditions. When it comes into contact with aquifer materials, it can reduce sorbed heavy metals in the aquifer matrix. The most significant reactions involve the reduction of Fe and Mn to more soluble forms, leading to increased concentrations of these components near the landfill under favorable conditions, which may pose a serious toxic risk (Naveen et al., 2017).

4. Case studies

An important facet of urbanization in India is the notable clustering of people, exemplified by the increase in the number of metropolises from 35 to 46 over the past decade, with a population exceeding one million in Class1 and urban cities. Table 2 represents the Per Capita Waste Generation in Metropolitan cities of South India. As per reports, it is approximated that urban India is producing around 68.8 million tons of solid waste annually (Dantre et.al (2017)).

TABLE 2: Per Capita Waste Generation in South Indian States

States	Metropolitian City	Population	MSW (Tons/Day)	Per Capita Waste Generated (Kg/Day)	Referances
Karnataka	Bengaluru	8.8 million	4500 MT/day	0.5 kg/capita/day	Naveen et.al (2019)
Telangana	Hydrabad	7.75 million	3000 T/day	0.6 kg/capita/day	Kamble.S (2016)
Kerala	Tiruvananthapuram	1.68 million	300 T/day	0.2 kg/capita/day	Menon et.al (2022)
Tamilnadu	Chennai	9 million	4500MT/day	0.7 kg/capita/day	Nair V et.al (2016)
Andhra Pradesh	Vishakapatnam	2.3 million	1150 T/day	0.4 kg/capita/day	Praveena G et.al (2016)

In most Indian cities, the management of municipal solid waste (MSW) typically comprises only four main activities: waste generation, waste collection, waste transportation, and waste disposal, often omitting the aspects of waste deposition and transfer. The generation of MSW is influenced by various factors such as seasonality, living standards, dietary habits, the nature and scale of commercial activities and studying these factors can aid in effective planning for waste collection and disposal (Talyan et.al (2011)).

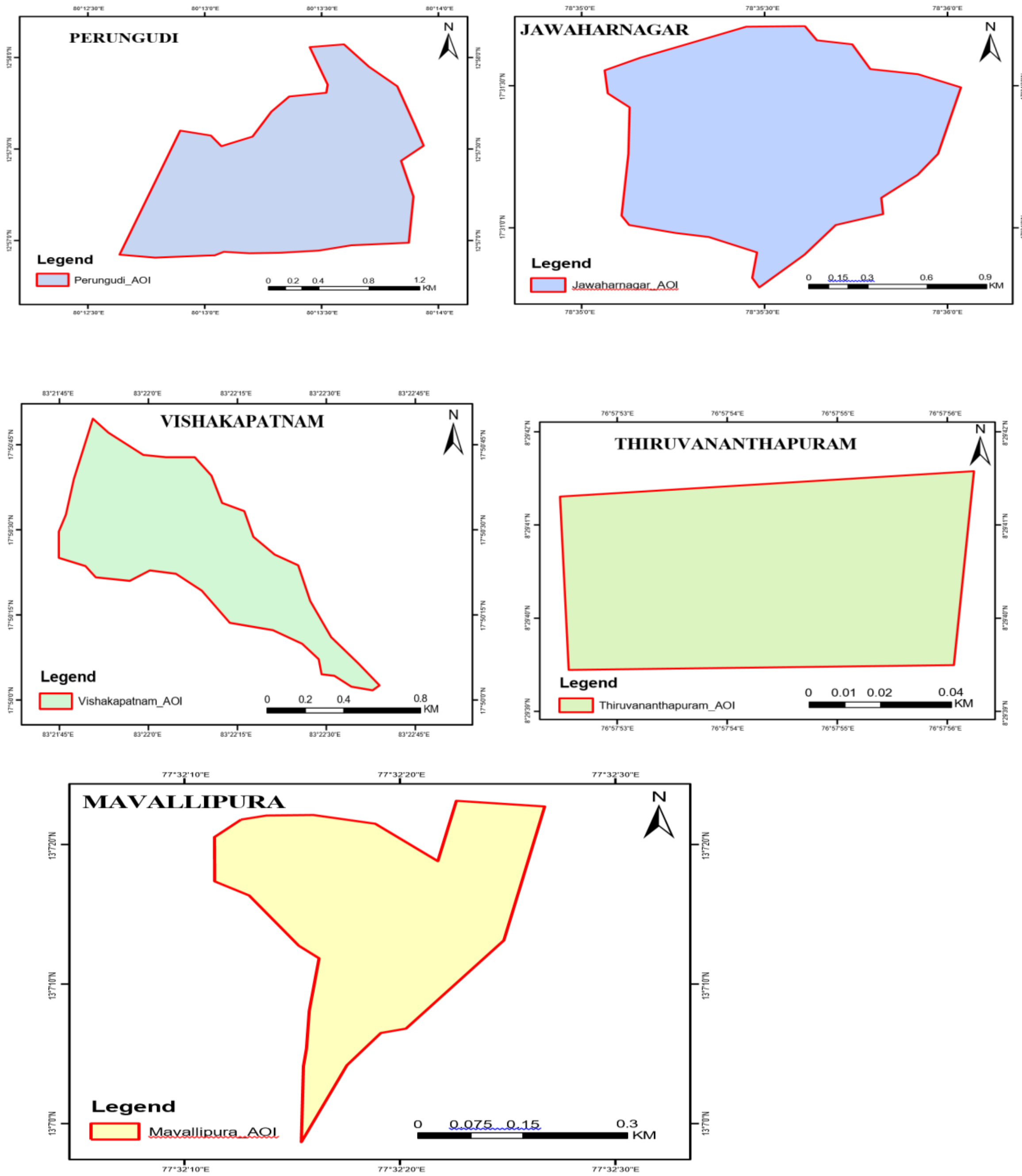

Fig 1:Geo-Mapping of Solid Waste and Leachate Challenges in Metropolitan South India

The current research review aims to examine landfill characteristics and analyse the impact of leachate flow by examining different landfill sites in South Indian states such as Karnataka, Telangana, Kerala, Tamil Nadu and Andhra Pradesh selected from various dumpsites in metropolitan cities with adopted innovative treatment and solid waste management methods. Fig 1 shows Geo-Mapping of Solid Waste and Leachate Challenges in Metropolitan South India. The involvement of generated waste characteristics depends on the type of leachate produced from the different landfill sites from various dumpsites of the cities.

TABLE 3: Characteristics of Leachate in South Indian States

PARAMETERS	**RANGE**				
	Naveen et.al (2019)	Kamble. (2016)	Kumar (2017)	Dantre et.al (2017)	Praveena et.al (2016)
BOD3(mg/L)	1500	2000	9877	15478	-
COD (mg/L)	10400	4000	28220	22148	680.65
TDS (mg/L)	9700	765	643	22961	5261.6
Nitrates (mg/L)	297	95	64.3	321	-
Sulphate (mg/L)	198.4	152	68	131	135.2
pH	11.5	7.3	7.57	6.9	7.29
Ca (mg/L)	510	115	92	112	103
Mg (mg/L)	770	55	36	153	118
Zn (mg/L)	3	4.22	1.45	1.29	1.04
Fe (mg/L)	1.7	1.2	0.68	58.91	12.1
Pb (mg/L)	0.3	0.46	1	1.2	-
EC	18700	15.2	12.22	2256	2360

The table 3 presents the characteristics of leachate specimens obtained from dumpsites in Chennai, Bangalore, Thiruvananthapuram, Vishakhapatnam, and Hyderabad, as evidenced by multiple studies and experiments. Various parameters including BOD5, COD, TDS, EC, nitrates, sulphates, pH, calcium, magnesium, etc., are included for comparison purposes.

5. Bangalore:

The Mavallipura landfill site (lat 13°50´ N, long 77°36´ E) is located about 20 km north of Bangalore city and serves as a processing site for municipal solid waste generated in the city. The site spans approximately 40 hectares, with around 14 hectares used for the landfill. Operated by M/s Ramky Environmental Engineers since 2007, the landfill was designed to handle about 600 tonnes of waste daily. However, the Bruhat Bengaluru Mahanagara Palike (BBMP) has been sending nearly 1000 tonnes of garbage from Bangalore city every day. Local residents have demanded the immediate closure of the landfill, citing its illegal and unscientific management. Consequently, the landfill is now closed for further land filling activities [Naveen et.al (2019)]. Currently, only 10% of solid waste is recycled in Bangalore. Most studies report a waste generation rate of approximately 0.5 kg per capita per day. Since 1990, the composition of Indian urban waste has changed significantly. The current waste generation is about 500 tonnes per day and is expected to increase in the coming years [BBMP TECH REPORT (2007)].

The characteristics of leachate generated from the municipal solid waste landfill near the Mavallipura area in Bangalore and its impact on surrounding water bodies have been studied. The physico-chemical analysis of the leachate revealed high concentrations of organic and inorganic constituents beyond permissible limits, while heavy metal concentrations were trace amounts, as the waste dumped is primarily domestic. The leachate's pH is slightly alkaline at 7.4. The results also indicated that iron had the highest metal concentration in the leachate, at approximately 11.16 ppm. The BOD5 and COD of the leachate were 1500 mg/L and 10400 mg/L, respectively. These characteristics suggest that the leachate could promote algae growth in natural water bodies contaminated with it, due to the alkaline conditions and the presence of magnesium as a nutrient, which has been confirmed in a nearby surface pond [Naveen et.al (2013)]. The following table below represents the characteristics of the leachate generated in the mavallipura landfill site [Naveen et.al (2019)]. Based on the current scenario and challenges of solid waste management in Bangalore, the following conclusions on treatment can be drawn [Naveen et.al (2017)]:

- Waste-to-Energy (WTE) plants require significant capital investment and are more complex compared to other waste disposal options.
- WTE plants are more suitable in developed countries due to the tipping fees/gate fees charged for waste disposal services, in addition to revenue from power sales.
- Given the high content of biodegradable waste in Bangalore, biological processes such as anaerobic digestion, composting, gasification, and Pyrolysis are necessary for effective treatment.
- Plasma gasification technology can reduce the need for landfills and generate more renewable energy than solar, wind, landfill gas, and geothermal energy combined.
- Refuse-Derived Fuel (RDF) plants are in the initial stages of development in India and are beneficial for preparing enriched fuel feed for thermal processes like incineration. RDF pellets can be used as a lower-cost coal substitute.
- The Pyrolysis process cannot handle a wide variety of waste types, and its end products, such as carbon black oil, can be sent to refiners, while hydrocarbon gases can be used for electricity generation.
- Sanitary landfills remain the cheapest, simplest, and most cost-effective method for waste disposal.

6. Hydrabad

The Hyderabad Integrated MSW Processing and Disposal Facility (HIMSW) manages around 5,000 to 6,000 tons of municipal solid waste (MSW) daily. The Jawaharnagar village municipal solid waste treatment plant, covering 350 acres, currently uses 182 acres for waste processing. This facility is located in the Medchal district of Telangana, with coordinates ranging between 17°26'N to 17°34'N latitude and 78°32.5'E to 78°40'E longitude. As of 2020, the Greater Hyderabad Municipal Corporation (GHMC), responsible for health and sanitation across an area of 625 square kilometers and serving a population of 8.7 million, is committed to maintaining better sanitation in Hyderabad city(Khoso et.al 2018). The GHMC employs a large workforce and utilizes an extensive fleet of vehicles to transport 5,000 to 6,000 metric tons of garbage daily. The GHMC is divided into five zones, 18 circles, five parliamentary constituencies, 24 assembly constituencies, and 1,150 election wards. The average daily waste generation within the GHMC is approximately 5,030 metric tons, with a per capita waste generation of about 599 grams. In Hyderabad, organic matter such as food waste, market waste, leaves, ash, stone, and fine earth mixed with soil make up the majority of the solid waste. The proportion of organic matter in the waste ranges from 39.17% to 64.57%, while ash and fine earth account for 7.13% to 17.07%. Stones, debris, and boulders contribute a notable 0.71% to 3.92% (Premsudha et.al 2022). Chemical properties of the municipal solid waste (MSW), including moisture, carbon content, nitrogen, calorific value, and heavy metals, were analyzed to determine the most suitable waste processing technology. The moisture content in the tested samples ranged from 31.75% to 59.24%, and the calorific values ranged from 1,250 to 2,550 kcal/kg (for dry waste). Carbon content is a key indicator for converting MSW into compost, while calorific value helps assess the suitability of waste for waste-to-energy technologies. Heavy metal concentrations were generally within desirable limits, with the exception of zinc(Krishna et.al 2015). An integrated municipal solid waste management (MSWM) system may prioritize waste management strategies in the following order: waste minimization, materials recovery/recycling, composting, incineration, and landfilling. The landfill is equipped with a leachate collection and treatment system with a capacity of 735 TPD, utilizing RCC drains to direct leachate from the landfill to storage ponds spread over 2 kilometers. These aerated ponds have a capacity of 10,000 cubic meters (Seetharam et.al 2023).

Bio-methanation is a pretreatment process that involves the anaerobic digestion of organic waste to produce biogas and electricity. This thermophilic process also generates biogas by dewatering the digested waste. Waste-to-energy technology at HIMSW Ltd. uses pusher grate technology in its waste-to-energy plant, which has a capacity of 19.8 MW. This plant reduces the waste volume by up to 90%, leaving only 10% as inert ashes that must be landfilled. The flue gases generated during combustion are treated by the air pollution control system. Plastic recycling involves mechanical recycling, an environmentally friendly process that recycles 60% of both industrial and urban plastic waste. On one side, pure-grade plastic scrap comes directly from the industry, while on the other side, post-consumer plastic waste included in MSW poses a challenge. This segment has a capacity of 600 TPD (Somani et.al 2019).

7. Thiruvananthapuram

A study on municipal solid waste (MSW) management in Kerala was conducted by the Socio-Economic Unit Foundation (SEUF) in 2006, an NGO working for the Government of Kerala (Nair et.al 2023). The location of Municipal Solid Waste (MSW) dumping site of Thiruvananthapuram is 8°28'48.19"N 76°57'8.86"E. The study revealed that the state generates approximately 8,300 tonnes of solid waste per day, with 70–80% being biodegradable. This biodegradable waste requires management within 24 hours (Kumar 2017). In Thiruvananthapuram Municipal Corporation, projections based on data from 100 wards estimate daily waste generation at around 450 tonnes. However, studies suggest that not all waste reaches the municipal system, as some is managed at the source or collected by rag pickers for recycling. Before 2011, waste entering the municipal system primarily came from markets and public spaces, distributed across 50 wards within the corporation boundary (Anilkumar et.al 2015). The fallowing solid waste management challenges in Thiruvananthapuram:

- Decentralized and Source-Level Treatment: Decentralized systems should be implemented to handle waste locally. Source-level treatment options such as pipe composting, bucket composting, bio-bin composting, pedestal composting, vermin composting, ring composting, and biogas plants should be promoted .
- Centralized Waste Management Plant: A small-scale centralized facility is required to handle biodegradable waste that cannot be managed through decentralized methods.
- Non-Biodegradable Waste Management: A dedicated system for the collection and management of non-biodegradable waste, including plastics, glass, and e-waste, should be established to complement source-level treatment efforts.

By integrating decentralized solutions with centralized systems and encouraging recycling initiatives, Thiruvananthapuram can achieve efficient and sustainable waste management (Menon et.al 2022).

8. Chennai

Chennai, located on the southeast coast of India, is the fourth-largest city in the country, with a population of 37.19 million as per the 2011 census. The city has two major open dump yards: Perungudi and Kodungaiyur (Dantre et.al 2017). The Perungudi dump yard, operational since 1987, serves as the primary disposal site for waste collected from southern Chennai. Spanning an area of 800 acres, 420 acres are exclusively used for dumping. The site is situated at 12°57'13.5"N, 80°14'05.8"E, with the Velachery marsh located immediately to its north (Gupta et.al (2007)). Within the Chennai Corporation limits, all collected waste is disposed of at either the Perungudi or Kodungaiyur dump yards. The city generates approximately 9,000 tonnes of solid waste daily, with an average per capita waste generation of 585 grams. Managing this significant volume of waste remains a critical challenge for the city (Dhanasekar (2017)). An effective waste management system for the Chennai Metropolitan

Area (CMA) is expected to take 15 to 20 years to fully develop. To transition from the current state to the proposed ideal system, it is essential to adopt a phased approach. This approach should draw on best practices from other regions, adapting them as needed to account for Chennai's unique climatic conditions, geographic location, cultural context, and local challenges (Chennai MSWM report). With the help of the leachate characteristic, physico-chemical treatment, the separation of suspended particles from the liquid phase is usually accomplished by coagulation, flocculation and sedimentation. Coagulation-flocculation processes have been widely used as alternative treatment to remove leachate pollutants such as BOD, COD, TSS, heavy metals, color, and nitrogen compounds prior to other treatment methods (Enayathali’s (2021)).Upgrade existing landfills at Perungudi and Kodungaiyur to controlled landfill status and to accept the co-disposal of Municipal Solid Waste with appropriate industrial and hospital wastes, to include, improved operational practices, improved site drainage and leachate control, improved access roads, relocation of weigh bridge at Kodungaiyur, development of screening bunds around sites, restoration and landscaping of completed areas (Municipal Solid Waste Management Master Plan for Chennai - Technical Action Programme).

9. Visakhapatnam

Visakhapatnam district covers a total area of 681.96 sq. km, with a population of 1,883,000 as per the 2011 Census, resulting in a population density of 3,533 persons per sq. km. The Greater Visakhapatnam Municipal Corporation (GVMC) is divided into six zones comprising 72 wards. The importance of proper Municipal Solid Waste (MSW) collection, transportation, processing, and disposal is widely acknowledged by residents, shopkeepers, service providers, and the hospitality industry (Chaitanya et.al 2017). Based on a field survey, the district generates approximately 920 metric tons (MT) of solid waste daily. About 70% of this waste is produced by domestic households, commercial establishments, hotels, restaurants, and institutional sources.(Aditya K (2021)). Vishakhapatnam is heterogeneous in nature. The major constituents of solid waste generated in Vishakhapatnam are organic waste (Dara (2017). The average per capita waste generation in Visakhapatnam ranges from 0.45 to 0.47 kg per day. Waste generation varies by income group, with high-income groups producing 0.40–0.45 kg/day and low-income groups generating 0.25–0.30 kg/day. Additionally, commercial activities and street sweepings contribute to the city's per capita waste generation. For planning the processing and disposal facilities, the MSW quantity has been estimated at 709,034 MT per day (Aditya (2021)).The waste generated from all the wards will be disposed at the dump site located near kapulappada, currently, GVMC disposes the entire waste generated at kapulappada disposal site. This site is operating for the last 7-9 years with about 800 acres. JCB’s and bulldozers are employed by GVMC for solid waste management, including the operation of the waste disposal site (Rao et.al 2019). There are three dumper bins provided in this compost plant to carry this inert material and disposes it in the kapulappada disposal site. Composting is done in the aerobic process which is in presence of oxygen. Refuse Derived Fuel (RDF) can be used for incineration to generate stream and subsequently RDF can be used as an alternate fuel to conventional fuels such as coal (Sainath et.al 2021). The heat content of RDF depends on the densification of the waste and its combustion characteristics. Hence RDF yield and calorific value as inversely proportional to each other; high calorific values requires higher densification which shall subsequently reduce the yield (Praveena et.al 2016).

10. Predominant Landfill Treatment Methods

Conventional landfill leachate treatment methods include recirculation and transfer to sewage treatment plants. To enhance the biodegradability of landfill leachate and improve BOD/COD ratios, researchers have explored mixing it with domestic wastewater before treatment (Mojiri et al., 2016). Discharging leachate into wastewater treatment plants (WWTPs) offers a cost-effective and practical disposal solution. However, leachate with high concentrations of dissolved organic matter (DOM) can adversely affect downstream treatment processes, reducing overall efficiency (Teng et al., 2021). The high COD levels and BOD/COD ratios make direct comparisons between landfill leachate treatment and domestic wastewater treatment difficult. Therefore, a combined treatment approach is recommended (Mojiri et al., 2017). Non-degraded organic compounds, especially persistent UV-absorbing DOM, can interfere with UV disinfection in WWTPs (Teng et al., 2021). Thus, effective pre-treatment is essential to remove UV-quenching Substances and minimize the negative impact of landfill leachate on UV disinfection. Fig 2 shows the predominant classification of the landfill leachate treatment methods.

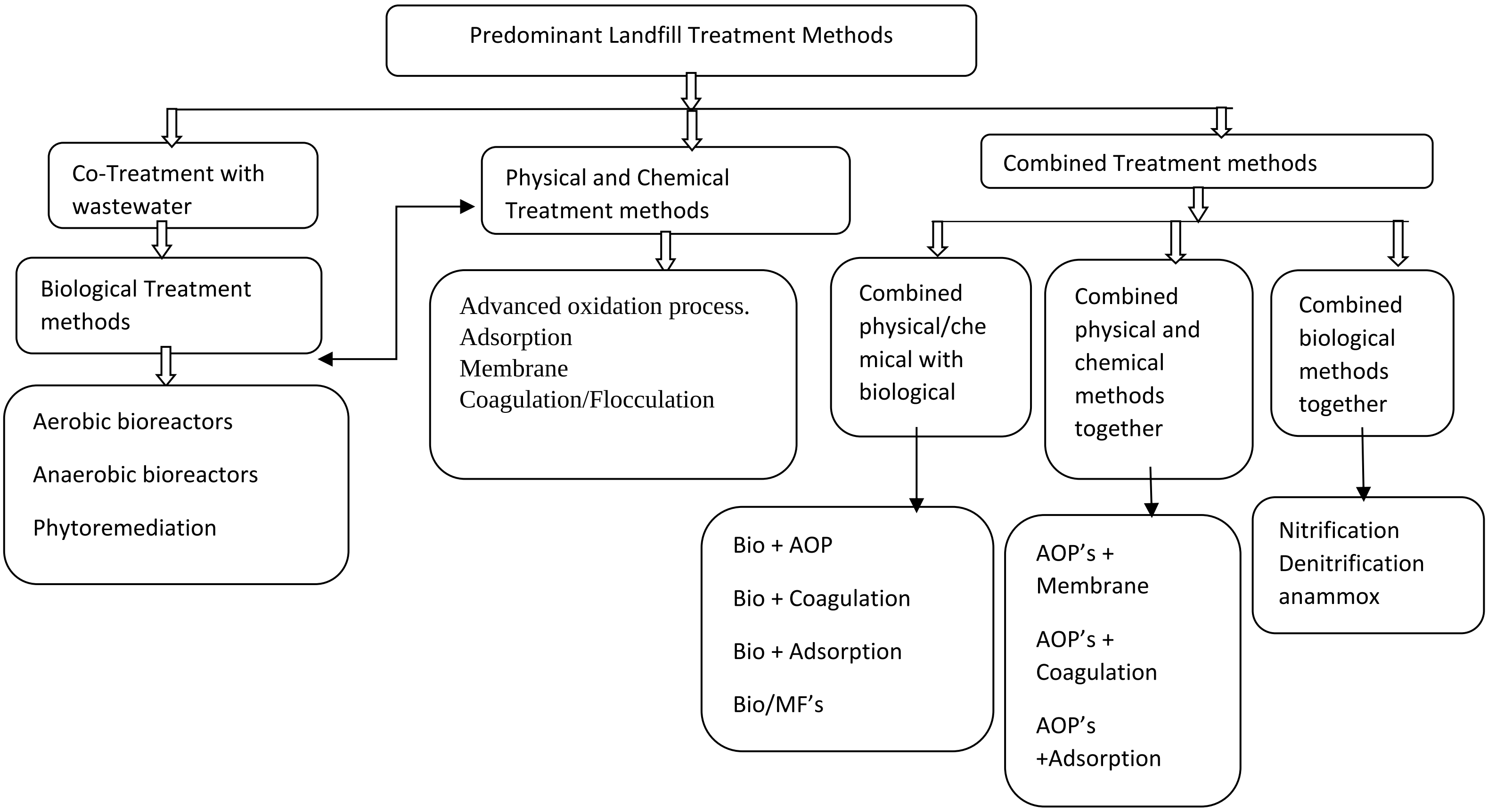

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Fig 2. Flowchart of landfill leachate treatment methods (Mojiri et.al 2021)

Bioreactors have been used for wastewater treatment for several years due to their simplicity, reliability, and cost-effectiveness. However, a significant number of refractory compounds often remain in the effluent (Mojiri et al., 2021). Biological treatment methods are typically chosen for young landfill leachate with high biodegradability. The activated sludge process efficiently removes biodegradable organic matter by converting it into carbon dioxide and water. Among the various biological treatment methods, the sequencing batch reactor (SBR) is the most commonly used for landfill leachate treatment. The SBR operates in time-oriented periodic stages, and its batch processing enhances treatment efficiency (Yong et al., 2018). The anaerobic activated sludge process may involve upflow anaerobic sludge blanket (UASB) and expanded granular sludge blanket (EGSB) reactors for landfill leachate purification. In a UASB reactor, wastewater passes through a sludge bed with high microbial activity, facilitating organic matter degradation (Gotvajn & Pavko, 2015). On the other hand, the EGSB, a third-generation anaerobic bioreactor, is distinguished by its high volumetric loading capacity, making it an effective treatment option (Wang et al., 2018).

The use of *Imperata cylindrica* for phytoremediation has shown potential in removing heavy metals such as lead, zinc, and cadmium in an environmentally friendly and sustainable manner. The presence of these plants in leachate systems contributes to the reduction of dissolved CO_2 through photosynthesis, creating conditions that support aerobic bacteria. This, in turn, helps lower BOD and COD levels while improving dissolved oxygen (DO) in the leachate treatment pond (Moktar & Tajuddin, 2019). Furthermore, the ability of plants to hyperaccumulate heavy metals is a key factor in the effectiveness of phytoremediation (Alaboudi et al., 2018). Bioremediation is the process of utilizing biological mechanisms to eliminate contaminants from the environment. This approach is recognized for being both cost-efficient and environmentally sustainable. Among the biological agents used, algae are particularly effective in removing inorganic substances and simple organic compounds, while more complex pollutants may undergo limited biotransformation. In the treatment of landfill leachate, a variety of microorganisms—including microalgae, algae, fungi, and bacteria—are employed. Notable examples include species from the genera Scenedesmus, Chlamydomonas, and Chlorella, as well as cyanobacteria and other related phylogenetic groups (Paskuliakova et al., 2018). Table 4 illustrates the removal efficiency of the organic pollutant compounds by the biological treatment methods

TABLE 4: Biological Landfill Leachate Treatment Methods

Treatment Process	Treatment Technologies	Removed Compounds	Removal efficiency	References
Bioreactor	Membrane bioreactor	Ammonia Total nitrogen (TN)	>98% >90%	Saleem et.al (2018)
	Air stripping, aerobic and anaerobic biological processes	COD Ammonia	80% 78%	Smaoui et.al (2020)
	SBR and Coagulation	Colour COD Ammonia TSS	85.8% 84.8% 94.2% 91.8%	Yong et.al (2018)
Phytoremediation	Colocasia esculenta Gynerium sagittatum Heliconia psittacorum	COD Cd Pb Hg	67% 80% 40% 50%	Madera-Parra (2016)
	Imperata cyclindrica	COD Cd Pb Zn	75% 16.2% 56.3% 6.5%	Moktar & Tajuddin (2019)
	Typha latifolia Canna indica	COD Ammonia COD Ammonia	81% 60% 84% 56%	Yalcuk & Ugurlu
Bioremediation	Aspergillus flavus	COD BOD Ammonia	48.5% 81.6% 98.8%	Zegzouti et.al (2020)
	Chlorella	Ammonia	90%	Ouaer et.al (2017)

		COD	60%	
	Chalmydomonas (SW15aRL)	Ammonia	83%	Paskuliakova et.al (2018)

Biological pre-treatment processes can be utilized to remove biodegradable organic matter, followed by advanced oxidation processes (AOPs) to eliminate refractory organic substances. AOPs, which employ a combination of oxidants and catalysts to generate hydroxyl radicals (OH-) in solution—such as ultraviolet (UV), Fenton, ozonation, and electrochemical oxidation (EO) methods—have gained attention for their effectiveness in degrading hazardous or biorefractory organic compounds in wastewater (Mojiri et al., 2021).The Fenton process initiates with Fe(II) catalyzing hydrogen peroxide (H_2O_2) to produce active oxidants, primarily hydroxyl radicals (OH-), that degrade organic compounds. Key factors influencing the removal of dissolved organic matter (DOM) in this process include pH levels and Fenton reagent dosages. The chemical oxygen demand (COD) removal efficiency in the Fenton process typically ranges from 35% to 90%. Both homogeneous and heterogeneous Fenton-like processes have been explored for landfill leachate treatment. Additionally, energy-enhanced variations, such as the electro-Fenton and photo-Fenton processes, have been introduced to enhance treatment efficiency. Ozone (O_3)-based processes are particularly effective due to their high oxidative power and lower sludge production when treating landfill leachate. Ozone can break down refractory macromolecular compounds into biodegradable forms, thereby increasing biodegradability. The removal of DOM via O_3-based processes occurs through two primary mechanisms: (1) a molecular ozone reaction, where ozone directly attacks recalcitrant pollutants through electrophilic interactions, and (2) an indirect reaction involving the generation of hydroxyl radicals (OH-) (Wang et al., 2015).UV irradiation is recognized as an environmentally friendly and efficient method for activating peroxides to produce reactive oxidative species. UV-based AOPs are increasingly used in landfill leachate treatment to degrade pollutants and improve water quality by generating highly reactive free radicals such as hydroxyl (OH-) and sulfate (SO_4-) radicals (Teng et al., 2021). Table 5 represents the photochemical and non-photochemical treatment methods for the removal of bio refractory organic compounds.

TABLE 5: AOP's Treatment Methods

NON – PHOTOCHEMICAL METHODS	PHOTOCHEMICAL METHODS
Ozonation (O3) at elevated pH (>8.5)	O_3/UV
Ozone + hydrogen peroxide (O_3/H_2O_2)	H_2O_2/UV
Ozone +catalyst (O_3/catalysts)	O_3/ H_2O_2/UV
Fenton process ($H_2O_2/Fe_{2+)}$	Photo –fenton and photocatalysis

The coagulation/flocculation process is a simple physico-chemical method that transfers pollutants from the liquid phase to the solid phase, resulting in sludge formation. It is commonly employed for landfill leachate pre-treatment or as a final polishing step. This process has been found to be more effective in removing high-molecular-weight organic compounds with strong hydrophobic characteristics than low-molecular-weight hydrophilic organics (He et al., 2006).Typical coagulants include trivalent-metal inorganic salts such as aluminum sulfate, polyaluminum chloride, and ferric chloride. Electrocoagulation has also been utilized for landfill leachate treatment by generating metal ions in situ through electrolytic oxidation. These metal ions produce polymeric hydroxides that function as coagulants, destabilizing colloidal particles and facilitating floc formation, which subsequently precipitate and settle (Xu et al., 2020).

Membrane technology encompasses microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), all of which utilize semi-permeable membranes for selective separation based on particle size. These membrane-based techniques offer several advantages, including compact system design, high processing capacity, excellent effluent quality, and strong disinfection capabilities (Teng et al., 2021).Membrane filtration is commonly used as a pre-treatment step in landfill leachate treatment to remove colloids and suspended solids, with pore sizes ranging from 0.1 to 1 µm. Ultrafiltration is particularly effective for eliminating macromolecules and particles within a size range of 2 nm to 0.1 µm, achieving chemical oxygen demand (COD) removal rates between 10% and 75%. Nano filtration efficiently removes organic, inorganic, and microbial contaminants with molecular weight cutoffs between 200 and 2000 Da (Renou et al., 2008).Reverse osmosis (RO) is considered the most promising membrane treatment method due to its high filtration efficiency. It selectively allows only water molecules to pass through while effectively removing heavy metals, suspended and dissolved solids, organic matter, and dissolved inorganic species from landfill leachate (Chen et al., 2020). In recent years, the integration of membrane technologies with other treatment methods has been extensively studied and applied to treat landfill leachate containing high concentrations of organic matter and heavy metals (Teng et al., 2021).

The adsorption process is regarded as one of the most effective methods for removing dissolved organic matter and ammonia from landfill leachate. Adsorbents with high surface area, microporous structures, surface reactivity, and thermal stability have been widely used for landfill leachate treatment. Activated carbon is the most commonly used adsorbent, capable of enhancing the biodegradability of aged landfill leachate. However, its overall chemical oxygen demand (COD) removal efficiency is relatively low, achieving only 40% organic matter removal with 10 g/L of activated carbon, while the BOD_5/COD ratio increased from 0.18 to 0.56 (Gotvajn et al., 2009). Activated carbon primarily targets chromophoric dissolved organic matter with hydrophobic properties, as well as microbial by products in fluorescent dissolved organic matter. The combination of coagulation and adsorption has also been applied to treat biologically processed landfill leachate, achieving up to 80% COD removal under optimal conditions (Deng et al., 2018). Table 6 represents the physiochemical treatment methods for the removal of DOM status of organic pollutants.

TABLE 6: Physical and Chemical Treatment Methods

Treatment Process	Treatment Techologies	Removed Compounds	Removal efficiency	References
Advanced Oxidation process	Electrocoagulation / Fiber filteration	COD As Fe P	94% 87% 96% 86%	Li et.al (2017)
	Electro catalytic ozonation	COD BOD	3381.9mg/L 1521mg/L	Ghahrchi et.al (2020)
	Supercritical oxidation (ScWO) /Zeolite	COD Ammonia Nitrate Nitrite Colour Turbidity	74% 90% 98% 100% 98% 98%	Scandelai et.al (2020)
	Activated carbon (oat hulls)	COD Colour	100% 100%	Ferraz &Yuan (2020)
	Zerovalent iron nanofibers/ reduced ultra large graphene	COD	93.6%	Soubh et.al (2018)

Adsorption method	oxide (ZVINF's/rULGO)	Ammonia	84.8%	
	Silica nanoparticle	COD Colour	77.3% 82.5%	Pavithra & Shanthakumar (2017)
Coagulation and flocculation	Polyaluminum chloride and Dimocarpus logan seeds as flocculants	COD Colour SS	61.9% 98.8% 99.5%	Aziz et.al (2018)
	Red earth as coagulant	COD Ammonia Turbidity	66.9% 43.3% 96.2%	Zainol et.al (2018)
	Ferric chloride as coagulant and cationic flocculant AN 934 SH ploy electrolyte as flocculant	COD	45%	Taoufik et.al (2018)
Membrane technology	Using membrane process of NF and RO	COD Ammonia	94.6% 88.9%	Kosutic et.al (2015)

To enhance removal efficiency and reduce energy consumption, various physical and chemical treatment methods have been combined for the treatment of landfill leachate. Following an advanced oxidation process (AOP) such as the Fenton process, the concentration of dissolved solids may remain high due to the incomplete oxidation of organic matter and the addition of salts, acids, or bases during treatment. This issue can be effectively addressed by incorporating membrane filtration (Santos et al., 2019).Integrated treatment approaches help lower the concentration of organic pollutants while improving the biodegradability of wastewater by modifying the molecular structure of residual organic compounds (Chen et al., 2019). Additionally, combining AOPs with adsorption has been recommended to enhance the removal of pollutants, particularly heavy metals, from landfill leachate. Although AOPs are effective in breaking down complex organic contaminants, complete mineralization is often impractical, and intermediate by-products are commonly generated during the process (Bello & Raman, 2019).Furthermore, the sequential application of coagulants and adsorbents prior to membrane filtration has been utilized to remove suspended solids and colloidal particles from wastewater. This approach helps reduce the organic load and minimize membrane fouling, thereby improving overall treatment performance (Alimoradi et al., 2018).

Biological methods are commonly used for landfill leachate treatment; however, biological processes alone are not sufficiently effective in removing most refractory contaminants (Wu et al., 2010). To enhance biodegradability and improve treatment efficiency, researchers have proposed integrating biological methods with physical and chemical techniques (Mojiri et al., 2016). Adsorption can be applied to reduce contaminant levels and leachate toxicity, creating favorable conditions for microbial growth (Er et al., 2018). Integrated adsorption and biological treatment have achieved over 70% ammonia removal from landfill leachate (Yi et al., 2018). Additionally, membrane bioreactors have demonstrated the ability to remove up to 90% of sulfonamides and tetracyclines. A combined semi-aerobic aged refuse biofilter and ozonation process has been shown to eliminate 92.1% of color and 61.4% of UV_{254} absorbance from landfill leachate (Chen et al., 2019).Other integrated approaches include coagulation combined with anaerobic bioreactors, which have achieved 72% chemical oxygen demand (COD) removal and 70% total organic carbon (TOC) reduction (Yadav et al., 2016). Constructed wetland systems have also been developed to improve water quality. These systems consist of permeable substrates such as gravel and are typically planted with emergent wetland species like Schoenoplectus, Typha, Phragmites, and Cyperus (Mojiri et al., 2016). Microbial removal of contaminants occurs through nitrification and denitrification. In this process, ammonia is converted into nitrate under aerobic conditions, which is then reduced to nitrogen gas (N_2) under anoxic conditions (Thakur & Medhi, 2019). Anammox bacteria, which are considered monophyletic, consist of six candidate genera, including Candidatus Jettenia, Candidatus Anammoxoglobus, and Candidatus Brocadia. However, the presence of high chemical oxygen demand (COD) and heavy metals can negatively impact anammox activity. As a result, anammox reactors are often integrated with other treatment methods to enhance efficiency (Kumar et al., 2016).

11. Conclusion

The choice of appropriate treatment technologies for landfill leachate depends on key parameters such as chemical oxygen demand (COD), the biological oxygen demand (BOD)/COD ratio, and landfill age. However, leachate composition can vary considerably, even among samples with identical COD values, leading to differences in treatment performance. The case studies of South Indian metropolitan cities highlight significant progress as well as persistent challenges in the areas of solid waste management and leachate management. Initiatives such as waste-to-energy plants, biomining of old dumpsites, and the promotion of source-level segregation reflect a shift toward more sustainable practices. Therefore, understanding the structural characteristics of dissolved organic matter in leachate and its transformations during treatment is essential for selecting the most efficient and cost-effective treatment method. Managing landfill leachate effectively to minimize environmental impact remains a significant challenge due to its complex and variable composition. The fluctuating nature of leachate, both over time and across landfill sites, makes it difficult to establish a universal treatment approach. An ideal treatment system should be straightforward, adaptable, and widely applicable. However, increasingly stringent landfill regulations and stricter environmental controls have made conventional treatment methods—such as aerobic and anaerobic biological processes or physico-chemical treatments—less effective or inadequate in meeting regulatory standards. Among the available treatment options, membrane technologies, particularly reverse osmosis (RO), have proven to be the most effective, versatile, and essential for landfill leachate treatment. Additionally, advancements in analytical methodologies and instrumentation are crucial for improving leachate characterization and monitoring. The development of sustainable treatment technologies should prioritize efficiency, cost-effectiveness, and reduced environmental impacts.

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