International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2022): 7.942

A Comprehensive Review on Landfill Leachate Characteristics and Biogas Generation Potential from Anaerobic Digestion of Landfill Leachate

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Abstract: ***Landfill leachate is the percolated liquid from the discarded waste; it is defined by a high COD, BOD, in addition to the presence of unwanted organic and inorganic pollutants. This review compiles findings from numerous studies on landfill leachate treatment methods focusing on anaerobic digestion and biogas generation potential of landfill leachate. The studies in this paper investigate the characteristics of landfill leachate in major landfill sites in India. In this study chemical oxygen demand was found to be as high as 25110mg/l in an Indian landfill site. Different leachate treatment methods were investigated in this study. Biological treatment is an advantageous method as it can achieve removal efficiency up to 90% of COD from the leachate with biogas yield of 6 to 8 liter/day. Furthermore, due to its high chemical oxygen demand and biodegradability, anaerobic digestion treatment approaches for treating landfill leachate have been shown effective.***

Keywords: Landfill leachate, Leachate treatment, MSW, AD (Anaerobic digestion), Biogas

1. Introduction

As per the CPCB, 152076.7 TDP of MSW was generated every day in 2018–2019 in India (CPBC, 2019), averaging 0.11 kilogrammes waste per capita per day. Among which only 50161.33 TDP was land filled, which has an organic fraction of 60-70% (*SWACHH BHARAT MISSION MUNICIPAL SOLID WASTE MANAGEMENT MANUAL Part I: An OvervIew*, n.d.). Because of the economic benefits, sanitary landfill is still the often utilised technique for disposing of municipal solid waste in the world. For urban India, solid waste management (SWM) has become considerably significant developmental concerns. Global MSW production is expected to hit 3.4 billion tonnes in year 2050 (Nawaz et al., 2020). Urban local body (ULB) is liable under the 12th Schedules of the 74th Constitutional Amendment of 1992 for maintaining city's immaculate. The majority of urban local bodies, on the other hand, lack proper infrastructure and suffer from a variety of strategic and institutional flaws, including a lack of institutional capability, financial constraints, and political will (S. Singh, 2020). When a landfill is chosen for disposal, the main pollution problems are the generation of leachate and landfill gas. Despite the fact that today's landfills are more efficient, they nonetheless pose a built structure meant to avoid or reduce the negative influence of wastes, production as for leachates remains a serious issue for municipal solid waste landfills since generated leachates can stance a considerable hazard to the surface water, groundwater, and soil (Luo et al., 2020). Existing waste will continue to create leachate for several years even after a landfill is closed owing to decomposition and other biological processes (Naveen et al., 2017) (Somani et al., 2019). Because of heterogeneous mixture in solid waste, non-biodegradable organics, pesticides, and xenobiotics are also released through leachate. Anaerobic digestions can effectively remove up to 90% of pollution from leachate in terms of COD, BOD, TKN, pH, etc (de Castro et al., 2020). Owing to their simple, dependable, and cost-effective nature, biological treatments (aerobic or anaerobic) are often employed to remove the leachates accomodating large amounts of organic compounds (i.e., BOD, COD)(Luo et al., 2020). Lower sludge generation, lower organics stabilisation; and energy production due to methane recovery makes the anaerobic biological process advantageous compared to the aerobic one (Luo et al., 2020). Anaerobic treatment, on the other hand, has considerable drawbacks, particularly in terms of reactor stability (Yarimtepe & Oz, 2015). The authors suggested pretreatment method before anaerobic treatment, for improvement of the breakdown of complex organic matter and generate a high amount of biogas with higher methane concentration (He et al., 2007). To lower the Total ammonium nitrogen content in leachate, air striping is widely utilized as a pretreatment option (Ren et al., 2017). Many methods have been used to circumvent the problem of fast acidification or other inhibitors in AD, including co-digestion with different substrates.(Salehiyoun et al., 2019). The trade of 2nd generation bio fuel i.e; non-food crops and waste; and 3rd generation bio fuel i.e; algae was valued at \$3.574 billion in 2015 and is expected to grow to \$57.124 billion by 2022, with the CAGR of 48.9% from 2016 to 2022, biodiesel accounted for the largest percentage of the industry in 2015. (Nawaz et al., 2020). This paper highlights the various methods available for leachate treatment, Indian landfill leachate characteristics, anaerobic digestion types and biogas generation potential of landfill leachate.

2. Landfill Leachate Characteristics

2.1 Formation of landfill leachate:

Leachate is a soluble organic and mineral compound formed when water infiltrates into waste layers, brings out various pollutants, then initiates a rate of diffusion as a result of a complicated interaction between hydrological plus biogeochemical mechanism for generating moisture content elevated enough to start seeping of liquid, caused due to gravity, rainfall, and irrigational surface runoff, snowfall, recirculation, co-disposal of liquid waste, waste digestion, underground water infiltration, along with initial moisture content of landfills (Sanjay et al., n.d.). Formation of leachate occurs through degradation of the waste matrix in landfills primarily through chemical and biological mechanisms that follow four stages: (1) the aerobic stage; (2) the anaerobic acidogenic stage (3) the methanogenic stage; (4) the stabilising stage (Luo et al., 2020)(Mandal et al., 2017). On the time of the first aerobic stage, oxygen available in the freshly buried waste empty spaces are quickly depleted, the outcome is the formation of CO_2. Many literatures suggested the waste's temperature rises in this condition (Mandal et al., 2017). The amount of leachate created during this phase is due to moisture loss in the time of compacting process in addition to precipitation short-circuiting via deposited waste (Mandal et al., 2017)(Kjeldsen et al., 2002). Waste becomes anaerobic when oxygen sources are reduced, allowing fermentation processes to take place and the anaerobic phase or the second step begins. The hydrolytic, fermentative, and acetogenic bacteria predominate in this phase, resulting in the carboxylic acid build-up and a pH drop. In the acid phase, the BOD: COD ratio has been reported to be over 0.4 or 0.7 (Mandal et al., 2017)(Kjeldsen et al., 2002). Acid stage leachate is highly chemically reactive which improves the dissolution of numerous chemicals since the pH is acidic. The first stage of methanogenesis or the third phase begins as a quantifiable amount of methane is generated. The beginning with this stage is mostly linked to when pH of the waste reaches a satisfactory neutralised level to allow for the methanogenic bacterial germination, at least in a limited capacity. Acids which are formed during acidic stage get transformed into CH_4 and CO_2 by methane forming bacteria during this phase, and rate of methane generation rises. The methane production rate will peak in the stable methanogenic phase, then decline as carboxylic acids diminish. CH_4 generation rate during acid phase is measured by the hydrolysis rate of cellulose and hemicellulose. As pH continues to rise, reaching steady-state pool values of a few milligrams per litre. As carboxylic acid is digested as quickly as generated, the BOD: COD ratio often go as low as 0.1 during stabilizing phase (Kjeldsen et al., 2002).

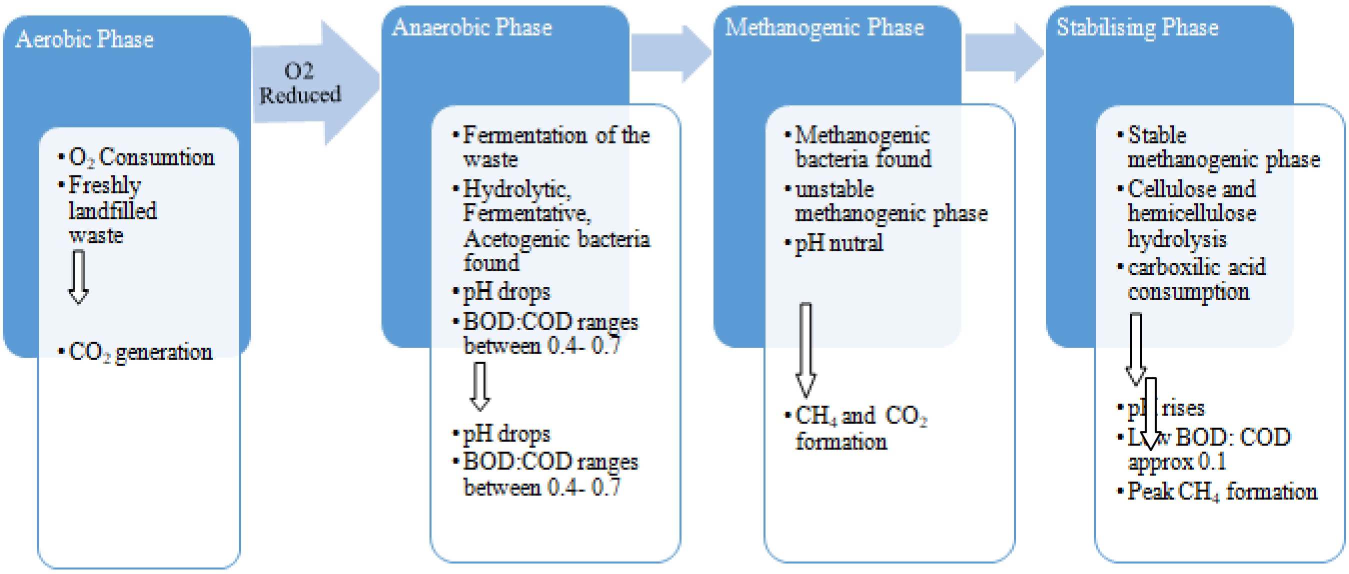


Figure 1: Leachate formation process in Landfills

2.2 leachate quantity

World Bank research from 2016 reported MSW generation on a worldwide scale was 2.01 billion tonnes per year; per person per day, and municipal solid waste production was 740 gram, with a broad range of 110–454 gram in 2016. Worldwide municipal solid waste production is anticipated to reach 3.4 billion tonnes by 2050. In worldwide basis, the majority of household waste is currently deposited or discarded in landfills of various types (Landfills account for 37%, sanitary landfills for 8%, and open dumping for 31%.(Nawaz et al., 2020).

Precipitation, rainwater, evapotranspiration, surface runoff, underground water infiltrate, and the degree of compaction within the landfill all influence the quantity of leachates generated (Miao et al., 2019)(Luo et al., 2020). The amount of infiltrating water has a big impact on how much leachate is produced in a landfill. This, in turn, is influenced by the weather and operational procedures. The quantity of rain that falls on a landfill has a big influence on the leachate characteristics and amount. The amount of precipitation is dependent upon geographical location (Chu, 2008). In modern engineered landfill a number of strategies are employed to restrict water entrance into the landfill to reduce the amount of leachates, which includes top linings, waterproof layers, top soil cover layers etc (Luo et al., 2020)(A. M. Costa et al., 2019).

As per the rules of Solid Waste Management and Handling, 2016 Sanitary landfills should be prohibited on marshy territory and when the ground water table is not more than 2 meters below the liner's base(Chu, 2008). In CPHEEO, 2000 a rough estimate for leachate generation quantity is prescribed, for landfills that do not receive run-on from outside regions, assume 25 to 50% of precipitation from the active landfill area and 10 to 15% of precipitation from covered areas. This rule of thumb is given by CPHEEO and should only be applied as a rough rule during the design phase of a landfill.

Leachate generation Rate in 'Active Area': During the operating period of landfill leachate quantity could be calculated out as mentioned way advised by Solid Waste Management and Handling Rules, 2000:

Leachate quantity= (precipitation amount) + (volume of liquid generated by compression of waste) – (evaporation volume) – (volume of rain water absorbed by the waste)

. …..equation 1 (Chu, 2008)

Leachate generation Rate after Closure of landfill: Only the water that can penetrate through the final cover percolates through deposited waste then creates leachate after the closure of the landfill, once the final cover is constructed.

Leachate quantity = (precipitation amount) – (ammount of surface runoff) – (evapotranspiration volume lost) – (volume of absorbed water by the solid waste and intermediate soil liner)

. …..equation 2 [12]

General theoritical hydrological balance equations are frequently used to calculate leachate quantities. Another empirical formula mentioned by Torretta et al, 2016(Torretta et al., 2017) to calculate the amount of leachate generated in the landfill. In this method, the quantity of leachate is linked to the mass balance related with water influx and outfluxes in a landfill that has previously been closed with top liner after the fill up and closure of the landfill, example a drainage basin, where waste layers, final cover bothare previously installed:

Volume of leachate= Rainfall- Surface runoff + Runoff from outside landfill- Evapotranspiration + Recirculation of leachate and/or irrigation water + Infiltration of water from surface+ Ground water infiltration+ (ΔUS - ΔUW) +b

…..equation 3

Where,
ΔUS = Top cover water content variable ;
ΔUW = Deposited waste water content variable;
b = generation or utilization of water related to, organic material biochemical breakdown processes, for both aerobic and anaerobic.

Aspects of water balances of landfill leachate formation were mentioned by Torretta et al, 2017 (Renou et al., 2008), (Torretta et al., 2017). According to them, leachate is formed primarily in wet and rainy areas; leachate quantity is a functional result of the effectiveness of the capping cover and it continues to occur prolong period of time; following the precipitation trends leachate generation varies extremely. To use the hydrological equilibrium technique during operational times is extremely challenging owing to not being able for account of every variables which affect the equilibrium. Management factors, like waste disposal techniques or land elevation, have the greatest impact on leachate generation, whereas the post-closing period permits physical and geometrical characteristics remains fix and well defined. Therefore, the content and movement of leachate may differ significantly from instance to case (Torretta et al., 2017)(Bove et al., 2015)

2.3 Leachate properties

The content of the waste, the method used to treat waste, the waste age are all key elements that influence the quality of the leachate. MSW leachate pollutants generally classified into four main category, organic pollutants and substrates, inorganic chemicals, heavy metals, xenobiotic compounds (Mojiri et al., 2021). Based on the age landfill leachate is categorised in to three types (Table 1) based on its age: young, intermediate, and old. According to Vaccari et al., leachate from young landfill (still in acid stage) is categorised by lower pH, higher volatile acid amount, and decomposed organic material (Mojiri et al., 2021). In mature landfills (methanogenesis stage), methane output and pH are both high, also mostly humic and fulvic portions of biodegradable compounds are found. Although, due to waste characteristics dependent on nations, there is a variation in certain other research (Wang et al. 2018a, 2018b) (Mojiri et al., 2021)(Wang et al., 2018).

Table 1: Leachate properties and analysis related to landfill age

Age(years)	Young (0-5years)	Intermediate (5-10 years)	Old (>10 years)
pH	<6.5	6.5–7.5	>7.5
COD(mg/L)	>10,000	5,000–10,000	<5,000
BOD_5/COD	0.5–1.0	0.1–0.5	>0.1
NH_3-N (mg/L)	<400	–	>400
Heavy metals	Medium to low	Low	Low
VFA/HFA	VFA (80%)	VFA (5–30%)+HFA	HFA (80%)
Biodegradability	High	Medium	Low

VFH= volatile fatty acids; HFA= humic and fluvic acids. Table adopted from Mojri et al, 2021 (Mojiri et al., 2021)(Tejera et al., 2019).

India's solid waste has a moisture level of 50 to 60%, which is significantly greater than that of North America or Europe (Mishra et al., 2016). Another important consideration is the biological contamination generated by leachates. The microorganism load caused by excessive levels of organic waste can contaminate both surface water and groundwater, wreaking havoc on fresh water resources in particular (Frikha et al., 2017).

Various authors have done experiments to determine the landfill leachate characteristics in Indian landfill sites. 9 landfill sites in India are selected from the literature in this review and characteristics are put together in Table No 2 to compare the characteristics of leachate and to get an idea of biogas generation potential. Table 2 below comparers the parameters of leachate collected from the literature of municipal Landfill sites in India, i.e; Turbhe landfill Navi Mumbai, Mavallipura landfill Bengaluru Karnataka, Dhapa Landfill Kolkata West Bengal, Chandigarh landfill Haryana and Punjab, Okhla Landfill Delhi, Kodungaiyur dumping yard Chennai Tamilnadu, Gurgaon Landfill Haryana, Hyderabad landfill Telengana, Kadapa landfill Andhra

Pradesh. From Table 2 it is seen all the physicochemical characteristics of landfill leachates in India exceed the guideline provided in IS 10500: 2012. COD, BOD, and TDS levels were found to be excessive in Indian landfills leachates, according to published research (Somani et al., 2019). Keeping a view in mind of biogas generation high COD and BOD content is an attribution of high organic content which is a source of biogas(., 2013). When the physicochemical characteristics were compared with Indian MSW guidelines (2016), it was observed that total dissolved solids, alkalinity, biochemical oxygen demand, chemical oxygen demand, chloride are over the regulatory thresholds in Indian Landfills.

2.3.1 Colour, TDS, and Conductivity

In landfill leachate, colour is a frequent contaminant. Water can become yellow to dark brown due to the breakdown of some organic molecules, such as humic acid (Naveen et al., 2017). Color and turbidity are produced by chemicals and particles present in the leachate, according to Gotvajn & Pavko, 2015. TDS show the integrative effect of specific cations and anions on water/wastewater, example ca^{2+}, cl^{-}, mg^{2+}, Na^{+}, K^{+}, and bicarbonates. Additionally, total dissolved solids may be created from little quantities of dissolved organic matter, additionally it has been suggested that higher EC (electrical conductivity) along with TDS (total dissolved solid) can be used to identify dissolved organic and inorganic compounds in leachate (Mojiri et al., 2021).

In table 2 the electrical conductivity (EC, μS/cm) of the landfills in Gurgaon and Hyderabad was mentioned to be 14,400 μS/cm and 15, 200 μS/cm, respectively by Somani et al, 2019 (Somani et al., 2019). It was reported lower than 20,000 μS/cm for Okhla and Ghazipur landfills, (Somani et al., 2019) but it was substantially higher at 38,840 μS/cm for Chandigarh landfill as stated by Mor et al, 2018 (Mor et al., 2018). A high EC value implies a greater concentration of the cations and anions. TDS levels were reported to be excessive in all landfills.

2.3.2 pH and Alkalinity

The variation of the amount of H^{+} ions in landfill leachate depends on the number of years the landfill is active and the amount of volatile acid accumulated when methanogenic bacteria are present. The pH of leachate from new landfill sites ranges from 5.0 to 6.5, whereas the pH of old dump leachate ranges from 7.8 to 8.64 (Mor et al., 2018). From Table 2 value of pH Turbhe landfill Navi Mumbai, Mavallipura landfill Bengaluru Karnataka, Dhapa Landfill Kolkata West Bengal, Chandigarh landfill Haryana and Punjab, Okhla Landfill, Delhi, Kodungaiyur dumping yard Chennai Tamilnadu, Gurgaon Landfill Haryana, Hyderabad Telangana, Kadapa Andhra Pradesh, leachate samples had pH values of 7.77, 7.5, 8.18, 7.8, 8.2, 6.98, 6.62, 7.42, 7.29 respectively. It has been found that the leachate from the Gurgaon landfill was acidic, while the leachate from Kolkata and Delhi landfill was alkaline in nature (Somani et al., 2019)(Polley, 2013). Landfill leachate may raise the pH of drinking water, resulting in the formation of trihalomethane, a poisonous chemical to humans (Mor et al., 2018).

Alkalinity determines the concentration of bicarbonate, carbonate, and hydroxyl ions in leachate (Naveen et al., 2017). All of the landfills studied in this study had alkalinity levels between 10,000 and 15,000 mg/L, except for Kadapa, which is presented in Table 2. Earlier investigations have found alkalinity values of 10,000 to 15,000 mg/L in MSW leachate from Indian landfills (V. Singh & Mittal, 2009)(Somani et al., 2019)(Mandal et al., 2017).

2.3.3 COD and BOD

Dissolved organic matter constitutes about 80percent of TOC (total organic compound) in landfill leachate in addition with mostly made up of refractory humic chemicals and VFA (volatile fatty acid) (Mojiri et al., 2021)(Jiang et al., 2019). BOD_5 and COD are two measurements of dissolved organics (Mojiri et al., 2021)(Samadder et al., 2017). Both COD and BOD are associated with organic and inorganic pollution in landfill leachate, as well as the BOD/COD ratio has been utilized to assess the age and presence of organic contaminants in a landfill (Mor et al., 2018). The BOD/COD ratio of stabilised or old leachate is usually less than 0.1. Young landfills or when leachate is in the acid phase, have a BOD/COD ratio approx 0.7(Brennan et al., 2017). The landfill would be at the intermediate stage whereas if ratio ranges within 0.1 and 0.5. (Azlina et al., 2009).

COD is a tested to determine organic content of liquid, in this study liquid is landfill leachate. In Gurgaon, Hyderabad, Okhla, and Kolkata landfill, the chemical oxygen demand (mg/L) were mentioned to be 22,000, 18,000, 13,000, and 12,604 correspondingly in Table 2. The lower chemical oxygen demand in Kadapa landfill was because of landfill waste's age (> 40 years) and the fact that the leachate had been diluted by rain. Higher COD value gives more biogas production.

2.3.4 Inorganic macro compounds

Anions and cations are found in in landfill leachate such as SO_4^{2-}, cl^{-}, Fe, NH_3, Al, and Zn (Mojiri et al., 2021) .The trace components in leachate are nitrogen and Cl-. Nitrogen is a major contaminant in leachate because it may stays over an extended duration in the atmosphere and remains stable even in anaerobic conditions. Haarstad et al., (2007), on the other hand, claimed that biological and geological processes had little effect on Cl^{-} concentration. As a result, it's utilized to investigate hydro-geological routes. Nitrogen concentration in leachate changes mostly owing to protein breakdown also hydrolysis addition with biodecomposition of organic compounds by microorganisms, leading to nitrogen (NH_4-N) build-up.

The chloride content was consistently elevated in every one of the leachates. Higher cl^{-} value reported by the authors validates a high range of TDS values. As night soil too is disposites into the Indian landfill sites and presence of animal excrement, attributes to the high amount of chloride in leachate(Somani et al., 2019). Leachate from landfills might be having greater ammount of chlorides because of the dissolving of alloy and salts found inside industrial waste that too are disposed into MSW landfill as reported by Mor et al, 2018. Sulfate concentrations in leachate samples were found to be high as denoted in Table 1, which perhaps attributed by the existence of various inorganic wastes products.

2.3.5 Heavy Metals

Heavy metal is among the most harmful elements found in landfill leachate (Mojiri et al., 2021). Because separation of non-hazardous and hazardous wastes prior disposal is rare in most underdeveloped nations , larger quantities various heavy metals are found within landfill leachates (Chuangcham et al., 2008) heavy metal elemination is a tough process (Mojiri et al., 2021). Heavy metal pollution may leach from various sources in the landfill leachate. Heavy metals can be found in MSW in rejected battery, light bulb, old motor lubricants, plastic, paint chips, among many other things. Tannery industries waste, electroplating, and used rechargeable and home battery are the primary sources of Cd, Cr, Mn, and Ni in the landfill(Somani et al., 2019).

Amounts of heavy metals from this 9 various landfills (Table 2) reported in the literature showed a significant variation. Metal concentrations, on the other hand, were reported to be rather low on average. In comparison with the criterion for regulation set by Indian standards, it is apparently indicating heavy metal concentrations were significantly lower than physicochemical characteristics. It is clear see that Cr was high in the Chandigarh landfill reported by Mor et al, 2018. Fe content is reported very high in Mumbai landfill by Mishra et al, 2016. Mumbai Chandigarh and Gurgaon landfills reported higher Zn concentrations of leachate (Somani et al., 2019)(Mor et al., 2018)(Mishra et al., 2016). Comparing, the drinking water specification in India (IS- 10500- 2012) Table 2 represents the majority of content of heavy metals within landfill leachate the same if not exceeds the IS- 10500-2012 standard.

Table 2: Comparison of various parameters of landfill leachate from various landfill sites in India

Parameters	pH	EC	TA	Cl^-	$SO_4^=$	TDS	SS	COD	BOD_5	TKN	P	Ca^{2+}	Mg^{2+}	Fe	Ni	Na^+	K^+	Cr	Cu	Co	Mn	Al	Zn	Source
Turbhe landfill, Navi Mumbai, Maharastra	7.77	22.99	10922	3584	854	18367	1356	6444	3391	-	82.36	176	272	166	0.38	1524	191.86	0.84	3.62	0.43	1.60	12.92	7.59	(Mishra et al., 2016)
Mavallipura landfill, Bengaluru, Karnataka	7.5	4120	11000	760	40	2097	-	1080	1500	2170	-	440		11.25	1.004	3302	1675	0.032	0.008	-	-	-	2.4	(Naveen et al., 2017)
Dhapa Landfill, Kolkata, West Bengal	8.18	-	-	2668	-	9159	-	12604	8980	1030	-	-	-	9.5	2.0	-	-	0.82	1.43	-	-	-	3.53	(Polley, 2013)
Chandigarh landfill, Haryana and Punjab	7.70-7.8	31120-38840	900-6900	4898-6997	1461-2126	19916-24857		14560-17920	2150-3340	1899-3750	16.64-126,	2580-4889	2055-2230	-	-	1540-2006	630-917	-	2.05-4.01	-	-	-	7.72-10.21	(Mor et al., 2018)
Okhla Landfill, Delhi	7.6-8.2	-	12000-3000	16000-23000	-	2000-19000	20000-35000	6000-20000	-	-	-	-	-	4.0-9.5	1.0-5.0	-	-	0.8-2.2	0.2-1.5	0.3-1.0	0.2-0.5	-	0.8-1.5	(V. Singh & Mittal, 2009)
Kodungaiyur dumping yard, Chennai, Tamilnadu	6.6-6.98	2256-2360	-	-	-	2247-25920	-	23748-25110	16385-18439	-	-	-	-	61-78	-	539-674	1126-1267	0.33-0.38	0.63-0.78	-	-	-	1.67-2	(Eshanthini & Padmini, 2015)
Gurgaon Landfill, Haryana	6.62± 0.08	14.37 •± 0.50	14,366.67 ± 450.25	7166.67 ± 351.26	1353.34 ± 83.27	10,666.67 ± 472.25	-	21,533.34 ± 750.25	-	-	-	-	-	26.38 ± 5.29	0± 0	-	-	4.56 ± 1.48	0± 0	-	1.51 ± 0.26	-	7.28 ± 1.04	(Somani et al., 2019)
Hyderabad landfill, Telengana	7.42 ±0.12	15.2 ± 0.32	11,652.45 ± 739.81	9169.34 ± 377.52	1353.34 ± 83.27	16,808.67 ± 307.10	-	18,184.32 ± 593.04	-	-	-	-	-	13.24 ± 2.75	1.02 •± 0.31	-	-	0.32 •± 0.03	0.35 •± 0.09	-	0.59 ± 0.38	-	4.22 •± 0.96	(Somani et al., 2019)
Kadapa Landfill, Andhra Pradesh	7.29 •± 0.04	8.63 •± 0.61	912.34 •± 63.22	1644.55 ± 78.45	135.25 •± 7.05	5261.67 ± 120.20	-	680.65 ± 40.25	-	-	-	-	-	12.18 ± 2.42	0±0	-	-	0.35 •± 0.29	0.19 •± 0.01	-	0.41 ± 0.23	-	1.04 •± 0.07	(Somani et al., 2019)

All are in mg/l except EC (µS/cm) and pH

3. Leachate Treatment Methods

Treatments for landfill leachates in the past have been divided into three categories: (1) biological (aerobic or anaerobic) processes; (2) physical and chemical processes; (3) biological with physical-chemical processes in combination. (Luo et al., 2020)(Renou et al., 2008).

3.1 Biological treatment:

It is widely employed owing to its accessibility dependability, as well as cost efficiency, to treat leachates containing significant quantities of organic compounds. Microorganisms decompose organic molecules into carbon dioxide and sludge in aerobic circumstances then into biogas in anaerobic ones. In landfill leachates having higher BOD/COD ratio, biodegradation is quite effective in extracting organic plus nitrogenous compounds (Luo et al., 2020)(Miao et al., 2019). Biological treatment based in terms of quantity of oxygen present, is classed as aerobic or anaerobic.

3.1.1 Aerobic treatment:

Aerobic treatments results NH_3-N nitrification with the elimination of some biodegradable organic contaminants (Luo et al., 2020). Various Aerobic biological treatments shown to be able to successful to treat landfill leachate, such as: (1) aerated lagoon, 40% COD removal rate (Frascari & Nocentini, 2004) (2) aerobic activated sludge procedure, 50% COD removal rate (Hoilijoki et al., 2000); (3) sequencing batch reactors (SBR), 76% COD removal rate (Neczaj et al., 2005); (4) rotating biological contactor (RBC) 38% COD removal rate (Torretta et al., 2017) ; (5) trickling filter 49% COD removal rate (Luo et al., 2020)(Torretta et al., 2017); (6) moving- bed biofilm reactor (MBBR), 62-70% removal rate (Hajipour et al., 2011); (7) fluidized-bed biofilm reactor (FBBR) 85% COD removal rate (Luo et al., 2020); (8) membrane biological reactor (MBR) 79% COD removal rate (Luo et al., 2020)(Torretta et al., 2017); (9) constructed wetlands 50% COD removal rate (Bulc & Academic, 2007); (10) fungal treatment and phytoremediation has 60% removal rate (Luo et al., 2020)(Kamaruddin et al., 2015).

3.1.2 Anaerobic Treatment:

Anaerobic tratment, unlike aerobic treatment, preserves energy and generates less sludge; nevertheless it has slow response rates. The end product produced in anaerobic digestion is biogas i.e, CH_4 and CO_2(Abbas et al., 2009). Examples of anaerobic treatment of landfill leachate are (1) Anaerobic digestion (AD), 387 m^3/ton of COD biogas can be generated by treatment of leachate, methane content 65percent and chemical oxygen demand removal of 70percent with organic loading rate of 17 kg m-3 day-1 (Nayono et al., 2010), (2) anaerobic filter (AF) has approx 90% COD removal rate (Abbas et al., 2009), (3) up-flow anaerobic sludge blanket (UASB) 90% COD removal rate (A. M. Costa et al., 2019)(Saddoud et al., 2007) , and (4) anaerobic ammonium oxidation or Anammox (AAO) 62% COD removal rate (Torretta et al., 2017)(Luo et al., 2020).

Table 3: Biogas yield by Anaerobic digestion

Source of leachate	% COD removal	Biogas yield	Remarks	Reference
Press leachate from MSW composting plant	60	270 m^3 CH_4/t COD added	Leachate liquid pressed from municipal solid waste generates higher biogas also in high rate of loading	(Nayono et al., 2010) (Bong et al., 2018)
Landfill leachate	sCOD removal 60%	453 ml biogas 101 ml CH_4/gr VS/day	Leachate was pretreated with 45 min sonication process	(Yarimtepe & Oz, 2015)
MBT-treated MSW fresh leachate	88-97	6.0 L/L.d	COD removal efficiency of 90% achieved by keeping OLR below 30 kg COD/m^3d. Efficient COD removal is achieved by proper hydraulic mixing to guarantee consistent optimum contact.	(Liu et al., 2012) (Bong et al., 2018)
Municipal incineration plant leachate	~ 80 - 90	8.9 - 11.5 L/d	Usage of carbon cloth increased 34.2% in the Organic loading rate	(Lei et al., 2016) (Bong et al., 2018)
Biowaste leachate	NA	0.79 - 0.90m^3 biogas/kg VS, 66 - 68% CH_4	Thermophilic temperatures resulted in increased methane generation, thermophilic zone contained fewer pathogens than the mesophilic zone.	(Micolucci et al., 2018) (Bong et al., 2018)
Municipal solid waste landfill leachate	NA	4,257 mL/ g DOC, 56 % CH_4	Leachate having a large proportion of transphilic chemicals is more appropriate for mechanization than leachate containing hydrophilic compounds.	(Baccot et al., 2017)(Bong et al., 2018)
MSW leachate from Seropedica and Gramacho landfill sites, Brazil	82 and 78.2 respectively	NA	Fenton process (especially solar photo-Fenton), efficiently works for bio digestion and toxicity removal of leachate	(F. M. da Costa et al., 2018)
Canteen food waste leachate	-	0.191 m^3/kg VS of CH_4 Potential	Theoretical methane potential was found to be higher than the experimental methane potential	(Suhartini et al., 2019)
Co-digestion of Industrial leachate class II-A (non-hazardous and non-inert) with crude residual glycerin	92	accumulated CH_4 production 74ml	High CH_4 generation and high removal efficiency achieved as materials were potential to balance organic compounds, nutrients, and other factors which influence the biological process.	(de Castro et al., 2020)
Co-digestion of landfill leachate and acid mine drainage (AMD).	83	1589 mL/day	UASB reactor gave higher metal and sulfate removal efficiency	(Zhou et al., 2021)

3.2 Physical/ Chemical Treatment:

As described by Luo, et al 2020 (Luo et al., 2020) Physical/ chemical treatment includes (1) coagulation-flocculation: The use of coagulants ($Fecl_3$, $Al_2(SO4)_3$, and PAC) resulted in extremely high turbidity 98% and colour91% removals, COD removal 26% (Marañón et al., 2008). Whereas polyferric sulphate and $Fe_2(SO_4)_3 \cdot 7H_2O$ removes 56.38%, 63.38%, 89.79%, and 55.87%, 74.65%, 94.13%, of COD, Color, Turbidity respectively (Liu et al., 2012). ; (2) chemical precipitations: Hydroxide and sulphide precipitation having heavy metal elimination effectiveness of 92-100% (Luo et al., 2020). ; (3) adsorption: 80% Total organic carbon extraction within leachate acquired by Activated carbon (V. Singh & Mittal, 2009). GAC or PAC, carbon nanotube, magnetic particles, zeolite, and fly ash are also used for adsorption (Luo et al., 2020). ; (4) membrane filtration: Microfiltration (MF), ultrafiltration (UF), nano filtration (NF), reverse osmosis (RO) are the most utilised for landfill leachate remediation (Gao et al., 2015) ; (5) ion-exchange: it's a reversal ion exchange process that removes metal ions and dissolved organic matter from wastewater. 94.2 % of $NH_4{}^{+}$-N removed, by using synthetic cation ion exchange resin, the conditions were 24.6 cm^3 resin dose, 6 minute contact duration, 147.0 rpm shaking speed (Bashir et al., 2010). (6) air stripping: At 20 °C and 6 °C, air stripping with respect to pH = 11 with a 24 hour detention period removed 89percent and 64percent NH_3-N, respectively, according to studies.(Luo et al., 2020) ; (7) advanced oxidation processes (AOP): cl^-, O_3, $KMnO_4$, and $Ca_2(OCl)_2$ are used (Luo et al., 2020)(Asaithambi et al., 2017). Studies utilising pre-treatment method given by Fenton revealed by adding 10,000 mg L^{-1} H_2O_2 with 830 mg L^{-1} Fe^{2+} to a mature leachate, up to 60percent of the Chemical oxygen demand at the beginning (i.e., 10,540 mg L^{-1}) conceivably eliminated (Luo et al., 2020). (8) electrochemical treatment: electro-coagulation, electro-Fenton, along with electrochemical oxidation are the most researched electrochemical methods of landfill leachates tratment, and which is able to efficiently eliminate two primary contaminants found in landfill leachates organic material, ammonium nitrogen. COD, TN, colour, and turbidity removal efficiency with Al electrodes were 70 %, 24%, 56% , and 60 %, respectively, whereas removal efficiencies with Fe electrodes were 68%, 15%, 28%, and 16%.

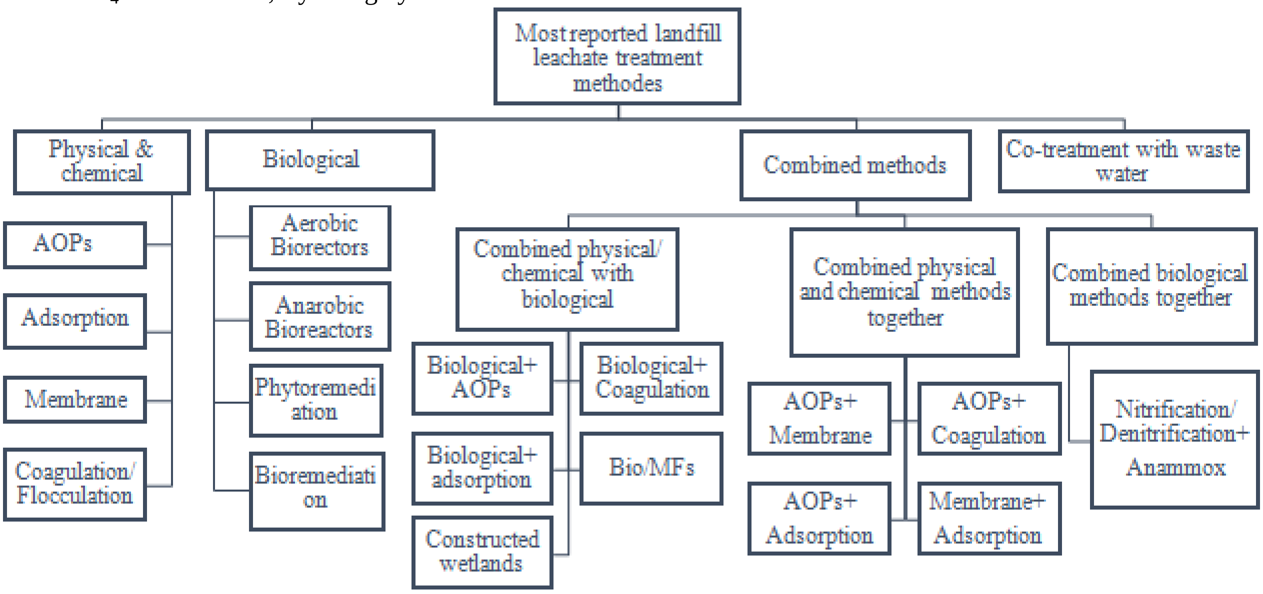


Figure 2: Treatments for landfill leachate that are often used. Adopted from Mojiri et al, 2021 (Mojiri et al., 2021)

4. Anaerobic Treatment

Anaerobic digestion (AD) is a biochemical function which produces biogas and a semi-solid digestate that may be used as fertiliser to treat high moisture MSW (Abdeshahian et al., 2016)(*Markphan 2020.Pdf*, n.d.). However, the anaerobic digestion method, reveals several limits when it comes to the municipal solid waste's organic portion, including lower stability, rapid acidification because of higher carbohydrate amount, less CH_4 generation rate, with less volatile solid degrading affectivity (*Markphan 2020.Pdf*, n.d.)(Pavi et al., 2017).

Table 4: Anaerobic treatment pollutant removal rates from Leachate

Technology	Pollutant Removal Rates (%)				
	COD	BOD	NH_4-N	SS	References
Up flow-Anaerobic Sludge Blanket Reactor (UASB)	42, 55–75	72–95	48	45, 45	(Lin et al., 2000)(Hoilijoki et al., 2000)
Submerged anaerobic membrane bioreactor (SAMBR)	90	88	-	100	(Saddoud et al., 2007)
Anaerobic filter (AF)	90	-	-	-	(Abbas et al., 2009)

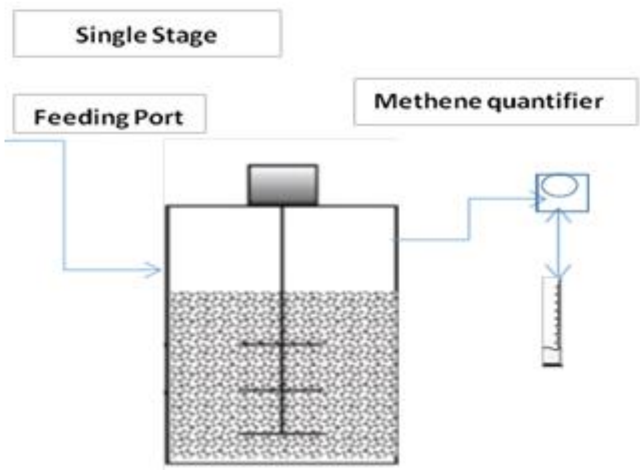
Table adopted from Torretta et al, 2017.(Torretta et al., 2017)

4.1 Types of AD, with regards to tank configuration:

Single stage anaerobic digester is the most commonly used digester. Anaerobic digestion treatment takes place in a single-stage stirred tank reactor (CSTR), every stage of anaerobic digestion (starting with hydrolysis upto methanogenesis) takes place inside one reactor and SRT is around 20–30 days (Malav et al., 2015)(Jo et al., 2018). Single-stage anaerobic digestion method is often used considering biogas generation from higher water content municipal solid waste, although it is prone to buildup and inhibition of volatile fatty acids (*Markphan 2020.Pdf*, n.d.). Being in the same tank improves environmental conditions for various microorganism groups, allowing for better process control and increased methane production. This arrangement is useful for quickly or readily acidifiable components having higher solid with heterogeneous components, example food waste, since it allows for quicker digestion additionally more stabilized process with a larger organic loading rate function (Parra-Orobio et al., 2021) (Jo et al., 2018). These circumstances, on the other hand, are not optimal for bacterial groupings like acidogenic microorganisms, which have physiological and growth properties that differ from methanogenic Archaea (Parra-Orobio et al., 2021)(Aslanzadeh et al., 2014). According to a investigation reported by Michele et al. (2015) (Michele et al., 2015), biogas generation out of biodegradable portion of municipal solid waste leads the reactors to be unstable, as evidenced with hydrogen ammount of 8percent within biogas having low pH (6.5) (*Markphan 2020.Pdf*, n.d.). The buildup of VFAs, which hinders methanogenic activity, is a major factor in not been able to stable of anaerobic digestion systems fed biodegradable part of municipal solid waste(Pavi et al., 2017). When biodegradable waste is mixed with ash prior feeding into anaerobic digestion process, it becomes more stable and lowers VFA buildup (*Markphan 2020.Pdf*, n.d.).

The stages of the two-stage anaerobic digester design are divided, with hydrolytic acidogenic being generally put together as acidogenic reactor and acetogenic-methanogenic being commonly grouped in a methanogenic reactor. arrangement improves surroundings for various types of microbes, allowing for finer management of the method and increased methane generation (Parra-Orobio et al., 2021). While comparing with single-stage anaerobic digestion process, the two-stage anaerobic digestion method enhances CH_4 generation from olive mill waste by 10percent (*Markphan 2020.Pdf*, n.d.). At high organic loading rates, the two-stage anaerobic digestion process provides high reactor operating stability than the single-stage anaerobic digestion method. A two-stage anaerobic digester, on the other hand, has limited commercial uses (*Markphan 2020.Pdf*, n.d.). Aslanzadeh et al, 2014 (Aslanzadeh et al., 2014) reported for FPW and organic portion of municipal solid waste, the two-stage process require 26percent and 65percent smaller reactor capacity than single-stage process, respectively.

Furthermore, anaerobic digestion by two-stage process is preferred than conventional single-stage configuration with regard to CH_4 generation with process stability, as well as the production of elevated valued by-products like H_2 and C_2H_5OH (ethanol), as well as a distinct pattern of long chain fatty acid (LCFA) generation (Jo et al., 2018)(Parra-Orobio et al., 2021). Because it creates less sludge for later treatment, the two-stage anaerobic digestion have a greater removal efficiency compared to single-stage anaerobic digestion (Parra-Orobio et al., 2021).



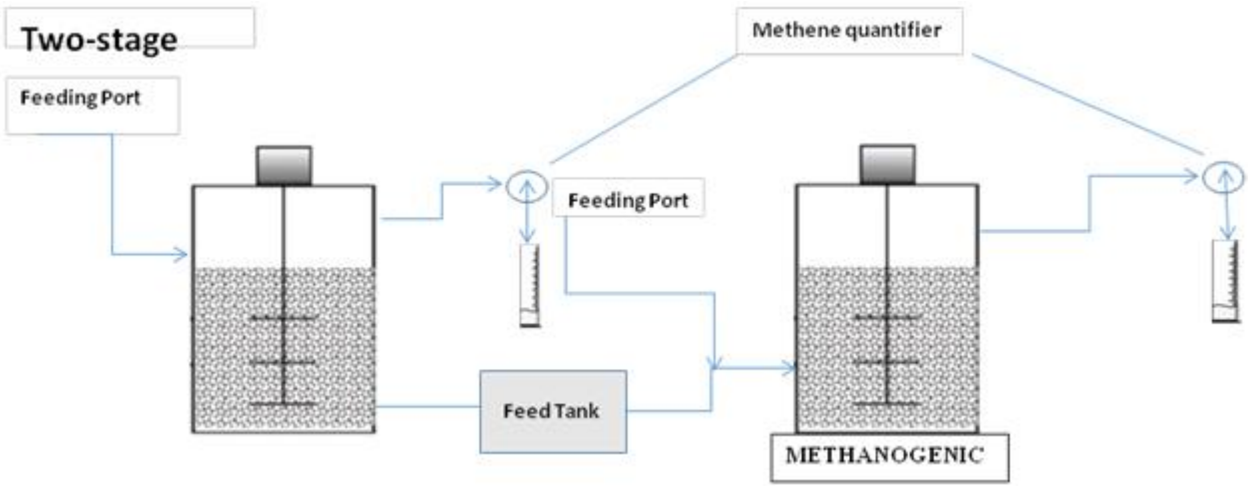


Figure 3: Single and two stage AD

4.2 Microorganism dynamics and metabolite dispersion concerning bioreactor design:

Anaerobic biodegradation is done in four stages. The hydrolytic as well as fermentative bacteria undergoes hydrolysis polymers as well as ferment it into carboxylic acid and alcohol; the acetogenic bacteria transform the above acid & alcohol into acetate, hydrogen, as well as carbon dioxide; and the methanogenic bacteria transform the acetogenisis's final products into methane and carbon dioxide.(Kjeldsen et al., 2002).

Volatile fatty acids, amino acids, alcohol, CO_2 (gas phase), H_2 (gas and liquid phase) are all produced during the hydrolysis/acidogenesis of complex organic substrates. Acetic acid out number formic, propionic, valeric, and butyric acids among other acids generated. The digester's pH and ORP value are generally 4.50±5 and 50 mV (Eh), respectively, due to the buildup of these organic acids(Karthikeyan & Visvanathan, 2013).

In the second stage, known as acidogenesis/acetogenesis under a pH range of 3.5–6.0 and ORP -170 50 mV (Eh), products such as acetate, hydrogen, with small quantity of CH_4 are generated. The Wood-Ljungdahl route manufactures acetate by homoacetogen, a unique bacterial family engaged in the use of hydrogen and carbon dioxide at this step. Additionally, during the third step (acetogenesis) of anaerobic conversion, acetogensis of propionic with butyric acid occurs at very lower hydrogen partial pressures/ concentration.(Karthikeyan & Visvanathan, 2013).

Following acetogenesis, acetoclastic methanogens use acetate for carbon sources (Eq. 3), hydrogenotrophic methanogens which use H_2 and CO_2 (Eq. 4), and methylotrophic methanogens (Eq. 5) create CH_4. During the active methanogenesis period, the pH range is in neutral to the alkaline span, ranging from 6.7 to 8.0, due to the constant use of stored VFAs inside the system(Karthikeyan & Visvanathan, 2013) (Gerardi, 2003).

$4CH3COOH \rightarrow 4CH_4 + 4CO_2$ …equation 3.

$CO_2 + 4H_2 \rightarrow CH_4 + 2CO_2$ …equation 4

$3CH_3OH + 3H_2 \rightarrow 3CH_4 + 3H_2O$ …equation 5

Acetocalstic methanogens are more common in bioreactors than other species. This group is responsible for more than 70% of the CH_4 generated. The population of hydrogentrophic methanogens fluctuates greatly depending on the availability of H_2 and CO_2. Studies show (Jha et al., 2011) the population creates 29% of the methane. As hydrogenotrophic methanogenic bacteria contend homoacetogens in order to use the hydrogen and carbon dioxide, investigations on interdependent relation have been sparse. Through the single-stage AD procedure, however, hydrogen is thought to be the key regulatory element inside the acidogenesis/acetogeneis and methanogenesis bioconversion processes.(Karthikeyan & Visvanathan, 2013)

Regardless matter regardless the bioreactors are run in batch or continuous mode, the hydrolysis, acidogenesis, acetogenesis, and methanogenesis stages are consecutive. All the stages may be met at any time throughout a continuous operation. As a result, the overall process is dependent on the preservation of comparatively delicate equilibrium in such various microorganism families as well as the bioconversion potential of those respective products. Within the bioreactors, an inconsistency between the overall population and the redistribution of metabolites, affects the actual effectiveness of the procedure which can result in full microbial activity stoppage.(Karthikeyan & Visvanathan, 2013)

4.3 Characterisation of substrate for anaerobic digestion treatment:

Anaerobic treatment is contingent on, nevertheless restricted to, subsequent elements: (1) leachate mass and flow flux; (2) leachate physico chemical properties; (3) economical considerations impacting process controling variabled; (4) fulfilling the designated aim. The properties of leachate play important role in the end products of anaerobic bioconversion processes, selecting optimal pretreatment conditions and optimizing process parameters for leachate treatment is critical. The total organic carbon (C) and TKN content of organic substrates are frequently used to design process variables(Karthikeyan & Visvanathan, 2013).

The C/N ratio, along with the total solids contents, is taken into account while choosing an organic solid for anaerobic treatment. Protein acts as a primary origin of nitrogen in organic solid (OS), that could be solubilise into NH_3-N and cumulate in anaerobic environments. Even though nitrogen is one of the most important nutrients for microbial development, the ammonia-N build-up has been shown to impair the performance of an anaerobic bioreactor. The substrate transformation rate is decreased including a reduced biogas output when the TS concentration is high (Karthikeyan & Visvanathan, 2013) It's plausible that all this is caused by a C/N imbalance in the system. To regulate total CH_4 yield, the anaerobic bio degradation process primarily considers the total solids of the organic substrates as well as the physicochemical characteristics of the substrates. The total solid of organic substrates have been shown to have an impact on the mentioned characteristics: rheological characteristics with viscosity within the reactor content, fluid dynamics, clogging, lastly solid sedimentation, all of which could have a direct impact on total mass transfer rates inside bioreactors(Karthikeyan & Visvanathan, 2013) (Jaroenpoj & Eng, 2014). Besides carbon and nitrogen, the characterization of leachate for proteins, fats, carbohydrates, sugar, volatile fatty acid, and alcohol are also important for biogas generation.

Laboratory incubation experiments are used to determine the substrate's methane emission potential, which is used to choose the best substrate anaerobic digestion in the early stage. For screening organic substrate and estimating CH_4 production, two alternative techniques are available: the fermentation test (GB21) and the biochemical methane potential (BMP). Owens and Chynoweth (1993) were the first to suggest the BMP test. The fermentation test (GB21) is the updated form of the biochemical methane potential test which is developed specially targeting dry anaerobic digestion application for the selection of organic substrate (Karthikeyan & Visvanathan, 2013). Other approaches, like the incubation test-GS90 and BM100, have been devised by various researchers to aid in the knowledge of the OS's biodegradability (Karthikeyan & Visvanathan, 2013).

The amount and quality of the organic substrate (OS) to be treated are the two most important cost factors when planning a treatment system. Other cost issues in the centralized design, in addition to OS quality, including collection, transport, segregate, pretreatment, with operating and maintaining expenses, as well as manpower costs. In several cases, it was stated that the proposed centralised facility were unable to secure adequate feed stocks to function in optimum capacity annually, resulting in a net loss. Decentralized systems, on the other hand, are studied as a means of substituting key expenses associated with collecting, transportation, and segregation in order to optimize total economic gain (Karthikeyan & Visvanathan, 2013)(Zeshan et al., 2012). As a result, the understanding organic content flow of leachate and its properties is critical in the design of an anaerobic digester in order to achieve the goal of safe disposal methods while also mitigating associated environmental hazards.

4.4 Factors affecting Anaerobic digester design:

The anaerobic digestion has been used to construct a variety of commercial facilities, pilot plants, and prototype bio-reactors for treating landfill leachate. There are four important factors to consider when designing a bioreactor. (Karthikeyan & Visvanathan, 2013)

(1) Organic Loading Rate (OLR): It is a measurement of the anaerobic system's bioconversion potential (Karthikeyan & Visvanathan, 2013). The OLR assesses a digester's efficiency, the needed food-to-microbes (F/M) ratio, and whole production efficiency. It can be calculated by equations 4 and 5 below.

$$OLR = \frac{Q \times S}{V} = \frac{S}{RT} \qquad \text{equation 4}$$

(Karthikeyan & Visvanathan, 2013)

$$RT = \frac{V}{Q} \qquad \text{....equation 5}$$

(Karthikeyan & Visvanathan, 2013)

Where, OLR = organic loading rate (kg substrate/m^3 digester/day), RT = Retention time (days), S = concentration of the substrate (kg substrate based on Total volatile solids), V = volume of digester (m^3), Q = flow rate (m^3/day).

Studies suggest total COD, soluble COD, total solids, volatile solids, total phosphorus, and ammonia nitrogen removal efficiencies of 42.2 %, 58.1 %, 45.3%, 68.2 %, 44.3 %, 47.8 %, respectively, can be achieved by treating landfill leachate inflow with an HRT of 1.5 days, an organic loading rate of 6.73 kg COD/m^3-day, and an operating temperature of 35^0 C (Torretta et al., 2017).

(2) Solid retention time (SRT): It is the ratio of volume intake and output of Organic substrate relating to time. It's the mean time that solid remain in the digester(Karthikeyan & Visvanathan, 2013)(Appels et al., 2008). Solid retention time is primarily concerned regarding reactor's functional stadiness (Karthikeyan & Visvanathan, 2013). With maximum biogas output at a given organic loading rate and thermophilic system operations, systems having higher efficiency needs lower solid retention time giving optimum biogas yield to a certain organic loading rate (Zeshan et al., 2012). For first-generation reactors, other names of SRT are mean cell residence time and the hydraulic retention time (Hilkiah Igoni & Sepiribo Kingnana Harry, 2017).

$$\theta_c = \frac{X}{\Delta X} \qquad \text{...equation 6}$$

(Hilkiah Igoni & Sepiribo Kingnana Harry, 2017)
θc - mean cell residence time, days
X - Vol of dry solids in the digester, kg
ΔX -Vol of dry solids produced per day in the digested sludge, kg

(3) Hydraulic retention time (HRT): The average duration the cells and substrates stay within the reactor is represented by HRT, which has the definition of, the ratio of reactor's volume to the feed flow rate (David et al., 2019). In continuous mode hydrogen and methane generation, HRT is a crucial variable. Low HRT encouraged methanogen washout, ensuring the survival of hydrogen producers. Low HRT and a slightly acid pH (6.0–6.5) are thus the ideal conditions for hydrogen synthesis; on the other hand when HRT rises, the hydrogen fermentation pattern would shift to a methanogenic one (David et al., 2019). A study shows at an hydraulic retention time of 20 days, 10 days, and 5 days, average methane purity generated by the methanogenic AFBR was 50.6 %, 57.9%, and 60.1 %, respectively of landfill leachate sample. These results varied somewhat, but they indicate that the methanogenic bacteria emitted more methane at lower HRT (Prasetyo et al., 2017). In another study regarding anaerobic baffled reactor (ABR) to treat landfill leachate, HRT of 52 days was evaluated, result shows removal in COD, TKN, nitrate, TDS contents from 55 to 86%, 42 to 92.4%, 41 to 96.6%, and from 20 to 64%, respectively (Arvin et al., 2016).

(4) Methane yield: Maximizing methane yield is most important in bioreactor design, and it also serves the main role in controlling operating conditions. The yield may be maximized by providing proper external circumstances, depending on the OS features and pre-treatment degrees (Karthikeyan & Visvanathan, 2013). Methane yield of mono digestion of leachate under standard experimental conditions gives up to 350 to 480ml/g VS (Jaroenpoj & Eng, 2014). Another study shows inflow chemical oxygen demand load of the UASB reactor of 1.08 kg m^{-3} day^{-1} at 10 day HRT, chemical oxygen demand eliminaltion is 30% and sulfate eliminaltion of 40%. The total quantity of biogas generated was 875 mL/day, whereas the quantity of CH_4 produced was approx 578 mL/day (Zhou et al., 2021).

The OLR, SRT, HRT, and CH_4 yield are all interconnected characteristics that must be taken into account while developing the anaerobic digester system. Other variables like leachate properties, leachate flow, temperature, digestates recirculation rate, and inhibitory substrate have a significant impact on these fundamental components (Karthikeyan & Visvanathan, 2013).

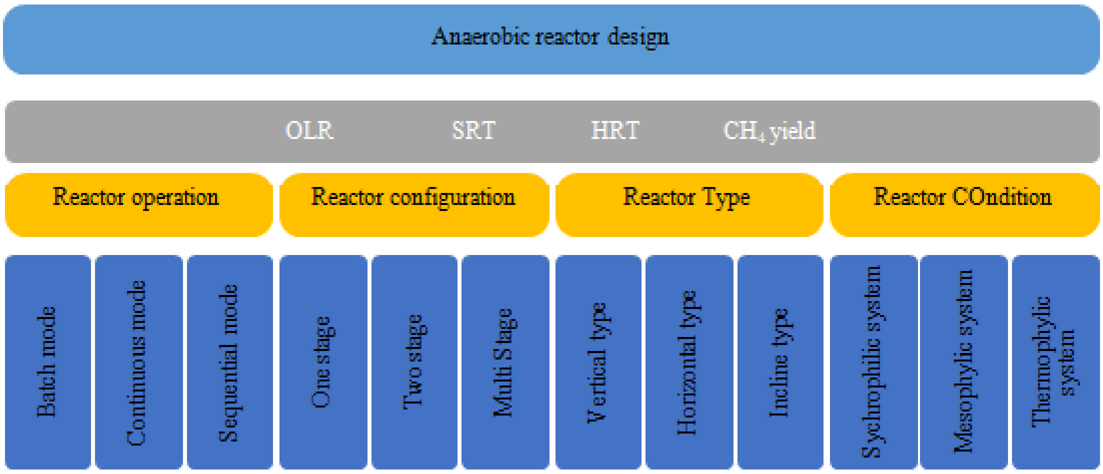


Figure 4: Important aspects to consider while choosing anaerobic bioreactors along with system classification

4.5 Techniques for improving bio energy recovery by anaerobic digestion:

A number of approaches for improving bio-energy recovery from leachate in AD procedure are proposed by various authors. In general, all of these strategies were utilized alone or in combination to improve the bioreactor's performance. The specifics are explained further down.

4.5.1 Temperature

Temperature control is one method for increasing system efficiency and lowering total SRT in anaerobic digestion treatment. Thermophilic temperatures convert organic acids more quickly, producing more CH_4 (25–35%) than the mesophilic system (Karthikeyan & Visvanathan, 2013). Most methanogenic bacteria are mesophilic, surviving in temperatures ranging from 28^0 to 42^0c, and thermophilic, surviving at temperatures ranging from 55 to 72 ^{0}c (ZiemjDski & Fs c, 2012)(Kahar et al., 2017). At 35 °C, 40 °C, 45 °C, lastly 50 °C, biogas output of 178 mL, 157 mL, 208.6 mL, and 134 mL, respectively was found by authors (Sibiya et al., 2014) on grass silage anaerobic digestion. Within thermophilic range, highest temperature regarding methane formation was found at 47.5-57.5 °C, with reduced methane, found up to 67.5 °C (Schupp et al., 2020). The authors also found methanogenic activity resumed as the waste pile cooled, despite the fact that microbial populations did not acclimatize above 67.5 °C (Schupp et al., 2020). Another author found anaerobic digestion of leachate with a 1.0days temperature range of 35 to 45^0c gives a biogas yield of 0.057-2.372 mol CH_4/g COD. The study also found decrease and increase in COD is regulated by temperature and pH. At Temp 35°C, Temp 45°C; COD reduces by 79.64 %, 79.00 %, respectively, at pH 7.2, and Temp 45°C; pH 8.0, COD reduces by 80.00 %. VFA concentration is affected by temperature and pH. As the temperature rises, the concentration of VFA obtained increases up to temperature 45^oc.(Kahar et al., 2017)

4.5.2 Co-digestion

In comparison to mono-digestion, co-digestion is capable to provide macro, micro nutrients, to maintain equilibrium of the C/N ratio, improvement of buffering ability with stabilized process, dilute inhibitors, addition of feed water into the procedure, and boost biogas generation (Salehiyoun et al., 2019)(Karthikeyan & Visvanathan, 2013). Literature has already looked at the co-digestion potential of organic portion of MSW mixing with materials like sludge, slaughterhouse waste, and manures (Salehiyoun et al., 2019). Due to nutrient restrictions, the use of landfill leachate for anaerobic treatment might occasionally impair total process conversion. Treatment would be required to provide nutrition externally during operations. Co-digestion provides a number of advantages, including (1) fugitive gas emissions reduction; (2) manipulating the C/N ratio for increased procedure stability; (3) creating buffering equilibrium condition (4) enhancing the system's rheological characteristics; (5) decreasing the need for external nutrient supplyment; (6) minimising the impact of harmful or prohibitting chemicals on the microbial group; (7) enhancing digested residue's nutritional quality considering land application; and (8) increasing biogas yield (Karthikeyan & Visvanathan, 2013). However, because the sluggish development of microorganisms was a frequent stumbling block to using anaerobic digestion for leachate treatment, the use of a standard anaerobic digester requires a large digester capacity (Sudibyo et al., 2018). Methane yield for mono digestion of landfill leachate under standard experimental conditions gives up to 350 to 480ml/g VS (Jaroenpoj & Eng, 2014). The study found co-digestion of the leachate with two kgVS of pineapple peel m^{-3} gives methane yield of 269 L kg $consumed^{-1}$, as well as an 80 percent VS and 89 percent COD removal efficiency in the reactor with good stability (Jaroenpoj & Eng, 2014). Another author tested natural zeolite and sugarcane bagasse fly ash as immobilisation media to improve digestion efficiency of landfill leachate in an anaerobic packed bed reactor. In comparison to sugarcane bagasse fly ash, zeolite demonstrated higher favorable impacts for increase efficiency of AD of landfill leachate as an immobilisation media(Sudibyo et al., 2018). Another co-digestion study done on leachate with acid mine drainage utilizing up-flow anaerobic sludge blanket the chemical oxygen demand and sulphate removing efficiency was 83 percent and 78 percent, respectively found by the authors (Zhou et al., 2021). Jaroenpoj (2014) reported the behavior of anaerobic co-digestion of landfill leachate and pineapple peels, with an emphasis on biogas generation, results showed methane yield of 269 L $kgVS_{consumed-1}$ and removal efficiency of 89%COD 88%TS and 80%VS on a batch type digester (Jaroenpoj & Eng, 2014).

4.5.3 Mixing techniques in the digester and leachate exchange:

The mixing method and frequency of mixing of anaerobic digestion are quite important (Wang et al., 2018)(Bergamo et al., 2020). Mixing, according to Paul et al 2004 (Shea, 2005), is the elimination of inhomogeneity non-order to obtain the designed outcome. Concentration, phase, or temperature inhomogeneity are all possibilities. The key objectives are mainly secondary consequences such as mass transfer, reaction, and product qualities. By decreasing temperature, concentration, with various field parameters within the reactor, mixing facilitates the creation of a homogenous environment for anaerobic digestion (Sindall et al., 2013)(Meegoda et al., 2018)compiled thorough chart of concerns around digester mixing.

The importance of mixing within digester: (1) creates a homogeneous environment; (2) restricts stratification also the formation of a surface crust; (3) increases exposure between microganisms with biodegradable fractions; (4) aids in the releasing of trapped gas bubble; (5) increases the diffusivity co-efficient of moisture and other nutrients; (6) helps in the development of active microorganism; and (7) re-suspend heavy particles. (Karthikeyan & Visvanathan, 2013)

Solids sinking at bottom, short-circuiting, dead-zone development, in addition with scum generation due to inadequate mixing are key issues that result in sub-optimal biogas output(Bergamo et al., 2020). There are contributions in the literature in which biogas generation is restrained under not properly mixed or not at all mixed environment (Wang et al., 2018)(Bergamo et al., 2020). Intermittent mixing is also occasionally advised (Lindmark et al., 2014)(Leite et al., 2017) (Bergamo et al., 2020). Compared to continuous mixing, resting durations could result in larger methane yields while preventing the creation of floating layers. Achieving an equilibrium condition within organisms engaged within anaerobic bioconversion of biomass to CH_4 is the cause for increased gas production. Furthermore, as compared to continuous mixing methods, intermittent mixing is recommended for energy savings.(S. Singh, 2020) . Three mixing methods are often used in large-scale anaerobic digestion applications Mechanical mixing, gas mixing, and pumped liquid recirculation using designed mounted pumps or submerged jets (Bergamo et al., 2020).

Mechanical mixing has 3 main mixing techniques: (1) low-speed, vertical mixer having one tiny impeller with draught tube, mounted within digester's top; (2) high-speed, inclined mixer having one tiny impeller alongside digester's wall; (3) high-speed, inclined mixer having one tiny impeller within digester's wall (Manea & Robescu, 2012)(Bergamo et al., 2020).

Recirculating biogas within the anaerobic tank works like a mixer in gas mixing systems. Unconfined digesters accumulate biogas on top of the tank, compact it, after that, it's discharged via a succession either bottom nozzles or diagonally arranged upper-mounted lances. Confined digesters accumulate biogas within bottom of the tank, compact it, after that, it's discharged via a succession either bottom nozzles or diagonally arranged upper-mounted lances. In confined type an airlift effect can be achieved by collecting biogas at the roof inside the tank, compressing it, and then evacuating it down restricted tubes. (Lindmark et al., 2014)(Bergamo et al., 2020)(Serna-Maza et al., 2017).

In the third type of mixing pumping system remove a part of the biomass and tangentially re-inject it via injectors at tank's base. However, this method of mixing considered having lowest success, generally not employed alone for mixing (Tang). Despite having a significant impact on flow patterns, pumped recirculation does not promote mixing.(Bergamo et al., 2020)(Meister et al., 2018)

4.5.4 Inoculum and enzyme addition:

Inoculum typically comprises bacterium with archaea in a diverse collection acquired from earlier anaerobic digestion. Adapted culture refers to the preceding batch's microbial populations. However, sewage sludge by wastewater treatment facilities that has been anaerobically decomposed is claimed to be the most often employed inoculums for landfill leachate treatment. (Karthikeyan & Visvanathan, 2013)(Forster-Carneiro et al., 2007). In addition to sewage sludge, anaerobically treated slurry out of a working digester, ruminant culture, manures are frequently utilised as feed inoculum. The inoculum's contents changes with period and reactor's operation parameters throughout successive reactor runs.(Karthikeyan & Visvanathan, 2013). Utilizing biochemical methane potential, the effect of lyophilizing inoculum on CH_4 generation using food waste as the substrate was investigated by Yarberry et al, 2019 (Yarberry et al., 2019). Jaronpog, 2014 (Jaroenpoj & Eng, 2014) in anaerobic digestion of leachate with pineapple peel used pineapple peel sludge as inoculum to increase the initial CH_4 generation.

Cellulose and hemicelluloses, which are commercial enzymes, are also employed to boost biogas generation (Karthikeyan & Visvanathan, 2013). Saffira et al, 2018 researched the anaerobic bio-reaction of landfill leachate. The experiment had two setups: recirculation of leachate with and without the inclusion of cellulose. The study showed cellulose was shown to have a substantial effect on lowering organic content as measured by volatile solid parameters. The average volatile solid content differential between with and without enzyme addition is 7.19% of total solid (Saffira & Kristanto, 2018).

4.5.5 Neutralization techniques:

To facilitate the establishment of methanogenic bacteria with minimising the duration during the start-up stage, the single-stage anaerobic digestion procedure requires initial neutralization. For successful CH_4 conversion, literature observed that mixing 0.2 g NaOH/g VS maintains alkalinity around 2,500 mg $CaCO_3$/L having a pH of over 7(Chen et al., 2010). Once CH_4 generation has been stabilised, alkali should be used to keep the pH between 7.2 and 8.0. The presence of numerous process metabolites in the system, such as carbon dioxide, dissolved hydrogen, hydrogen sulphide , volatile fatty acids, and ammoniacal-N, alters the reactors pH, inhibiting the methanogenesis process (Karthikeyan & Visvanathan, 2013). At the same time, the methanogenesis process is not suited to higher alkaline pH

(8.3) (Jaroenpoj & Eng, 2014). Providing a neutralized environment for bacterial growth is necessary for optimum biogas generation.

4.5.6 Nutrient supplement:

Micro parameters such as Fe, Co, Ni, W, Mo, Se have been identified as key co-factor of enzymes takes part in the production of methane with anaerobic bacterial development (Zielinski et al., 2019). Micronutrients were added to the system while it was running, especially when the ammonia-N concentration was high. This helped to keep the process stable (Karthikeyan & Visvanathan, 2013). The lower methane production, decreased acidification with respect to time, additionally general instable process (has higher prevalent in mono-digestion system) were all difficulties caused by organic substrates with low nutritional content. Furthermore, it has an impact on the output characteristics of digested slurry for soil usage. As a result, a nutritional supplement is advised (Karthikeyan & Visvanathan, 2013).

5. Cost and energy parameters based on the anaerobic digestion

The altogether methane yield and overall power usage for different operations, like bioreactor operations leachate pre-treatment, co-digestion material, lastly digested residues post-management, are used to determine the energy balance. Typically, expenditures for waste collection and transportation are not included (Karthikeyan & Visvanathan, 2013). Auditing economies of scale, expenses of producing biogas out of wastewater sludge lowers as scale increases (Bhatt & Tao, 2020). Latest literatures estimates with plant sizes less than 10 MGD, the cost figures are optimistic (Mishra et al., 2016)(Bhatt & Tao, 2020). However, the cost figures for a handful of the literature studies at sizes more than 10 MGD are relatively low (Bhatt & Tao, 2020). This is mostly due to differences in sludge composition among waste water treatment plants, optional use of pretreatment methods of making sludge appealing to the anaerobic digestion. The modeling aspects, on the other hand, simply evaluating a set sewage sludge component without taking into account some kind of preprocessing, resulting in the cost inequality (Bhatt & Tao, 2020). Furthermore, the economic benefits of higher vast capacity facility yield enable lower the cost of biomass to roughly 1USD/GJ (Misra, 2021).

Another way to earn profit by selling digested waste after it has been treated. However, the sum is widely seen as insignificant. Per tonne treated food waste may, for example, restore 9.5 kg of mineral nitrogen fertiliser, ecominizing 105 kWh of energy and 77 kg of carbon dioxide emissions (Karthikeyan & Visvanathan, 2013). The economic worth of such fertiliser products is now governed by the supply demand ratios, product quality, and nation wise regulations. To figure out how to get more income from anaerobic digester fertilisers, an additionally It is necessary to have a good grasp of the characteristics of digested residues as well as regional data on the supply-demand cycle.(Karthikeyan & Visvanathan, 2013)

6. Summary and Conclusion

Bio-energy production from landfill leachate is intended to be a clean bio-fuel production method that could eventually replace fossil fuels, coal, and oil. In addition, resource conservation, recycling, and reuse initiatives help to reduce overall GHG emissions from landfills. This review summarizes the recent municipal landfill leachate treatment methodology, focusing on its properties, treatments, and pollutant removal efficiency. The properties from landfill leachate from Indian landfill sites are summarised in this study using existing information. COD and total solids levels in landfills are greater than average. Its seen in this review most of the leachate pollutant levels are exceeding the potable water standard IS 10500:2012. The data imply that geographical factors, consumption patterns, and individual waste management behaviors all have a role in pollutant concentrations at locations. Though numerous waste-to-biogas plants are currently up and running, more study into factors like optimising COD levels for higher biogas output or enhancing yield will aid future anaerobic digestion advances. This study summarized the available treatment methods for landfill leachate treatment. Anaerobic digestion shows good results for bio energy recovery from landfill leachate. Major limiting constraints in anaerobic bio digestion processes were found to be bioreactor configuration and operational variables example organic loading rate, SRT/HRT, temperature, with internal mixing/recirculation method. Because of its high organic content, anaerobic digestion is excellent for both landfill leachate treatment and biogas generation. To enhance the efficiency of pollutant removal and biogas production from landfill leachate, anaerobic digestion can be employed in combination with other methods. The constancy of biogas production is critical for the design of biogas for energy projects, as equipment selection is based on the amount of biogas generated. Mono digestion of leachate yields 350 to 480 ml/g VS under conventional experimental conditions. Per m^3 biogas generates 2.14 kWh of power. Landfill leachate biogas has high potential for power generation.

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