Chapter

Effectiveness of Anaerobic Technologies in the Treatment of Landfill Leachate

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Abstract

Improper Solid Waste Management leads to the generation of landfill leachate at the landfills. To reduce the negative impacts of highly toxic and recalcitrant leachate on the environment, several techniques have been used. A lot of research is conducted to find suitable methods for the treatment of landfill leachate such as biological processes, chemical oxidation processes, coagulation, flocculation, chemical precipitation, and membrane procedures. The biological process is still being used widely for the treatment of leachate. The current system of leachate treatment consists of various unit processes which require larger area, energy and cost. In addition, the current aerobic treatment is not able to treat entirely the pollutants which require further treatment of the leachate. Anaerobic wastewater treatment has gained considerable attention among researchers and sanitary engineers primarily due to its economic advantages over conventional aerobic methods. The major advantages of anaerobic wastewater treatment in comparison to aerobic methods are: (a) the lack of aeration, which decreases costs and energy requirements; and (b) simple maintenance and control, which eliminates the need for skilled operators and manufacturers. Several anaerobic processes have used for leachate treatment such as up-flow anaerobic sludge blanket (UASB) reactor, anaerobic filter, hybrid bed reactor, anaerobic sequencing batch reactor and Anaerobic baffled reactor. The following chapter provides an insight to the solid waste management at the landfills, generation of leachate and details of some of the highly efficient anaerobic treatment systems that are used for the overall treatment of landfill leachate.

Keywords: landfills, leachate, anaerobic reactors, biological, removal

1. Introduction

Currently, Municipal Solid Waste (MSW) generation is increasing day by day with the rapid growth of population, industrial developments to match the changing life standards of the people followed by uncontrolled urbanization are triggering the generation of municipal solid waste. It is estimated that currently about 2 billion tonnes per year of MSW is generated globally, which accounts to an average of about 0.74 kg/cap/day. It is predicted to reach a value of 3.4 billion tonnes in the year 2050.

The tragic situation even worsens when from the waste which is collected by municipalities (~67% of the total waste) about 70% is disposed in landfills and dumpsites, 19% gets recycled, about 11% goes for energy recovery [1]. Since most of the underdeveloped and developing countries are still far behind the efficient solid waste management system, therefore the study reveals that about 46% of the world population is unable to avail basic waste management facilities [2]. Researchers are suggesting the concept of circular economy where the preference of solid waste management is modified to the order of reduce, reuse, recycle, recovery (4R) and disposal of waste [3]. When the waste is disposed and carried forward to anaerobic digestion then biogas and the digestate is produced, this digestate is very rich in nutrients therefore it can be used as fertilizers creating the possibility of a fifth R that is rejuvenate.

The practice of landfilling is the organized disposal of MSW at a designated site called as landfill. But in terms of by-products landfill is extremely threatening to environment. Sanitary landfill is the most common MSW disposal method due to the simple disposal procedure, low cost, and landscape-restoring effect on holes from mineral workings. The primary objective of the landfill site design is to provide effective control measures to prevent negative effects on surface water, groundwater, soil and air [4]. Nevertheless, inappropriate management of the landfills and especially landfill leachate as it is declared as a hazardous substance leads to ecological and social problems, such as air, soil, surface water and groundwater pollution, flooding, noise from the garbage collection vehicles, and scavenging activities next to the landfills [5, 6]. Landfills can broadly be classified as open dumping landfills, semi-controlled landfills and sanitary landfills [7]. The details are clearly shown in **Figure 1** [8]. Open dump landfilling is mostly practiced in almost all the developing countries where the solid waste is dumped arbitrarily in open and low-lying areas causing serious environmental and health hazards. Semi controlled landfills are having basic facilities like sorting, segregation, shredding and compaction of solid waste followed by soil covering. While sanitary landfills are engineered and technologically advanced landfills. In addition to all the facilities of semi controlled landfills they have proper leachate collection and recirculation system, appropriate lining system and gas collection system [9].

When rainwater and the moisture is mixed and gets percolated with the waste it forms highly polluted, toxic, colored, and odorous liquid called as landfill leachate (LFL). LFL is highly concentrated liquid containing organic and inorganic chemicals, heavy metals, nitrogen, ammonia, humic acids, fulvic acids and xenobiotics [10, 11]. The characteristics and composition of landfill leachate is varying, depending upon its age (young, intermediate, and old) and this governs primarily the selection of the treatment technology (**Table 1**). Till date, most of the research on the treatment of landfill leachate is focused on using physical, chemical, and biological processes. Young landfill leachate contains significant amount of biodegradable organic fraction and therefore conventional biological techniques can be employed while intermediate and old landfill leachate contains high amount of recalcitrant compounds and low BOD/COD ratio thereby requiring combined or integrated technologies [12]. Leachate treatment include anaerobic biological treatment technologies i.e. anaerobic bioreactors; aerobic biological treatment methods i.e. aerobic ponds/lagoons, activated sludge; physico-chemical treatment including coagulation, flocculation, air stripping, chemical precipitation, filtration and adsorption [13].

The selection of the optimum treatment technology depends upon the characteristics of landfill leachate and its composition [14]. Landfill leachate treatment generally involves multistage or integrated technologies for better removal efficiency, as any single technology cannot obtain desired results for the effluent of LFL to be discharged into water bodies [15]. The previous studies suggest that biological

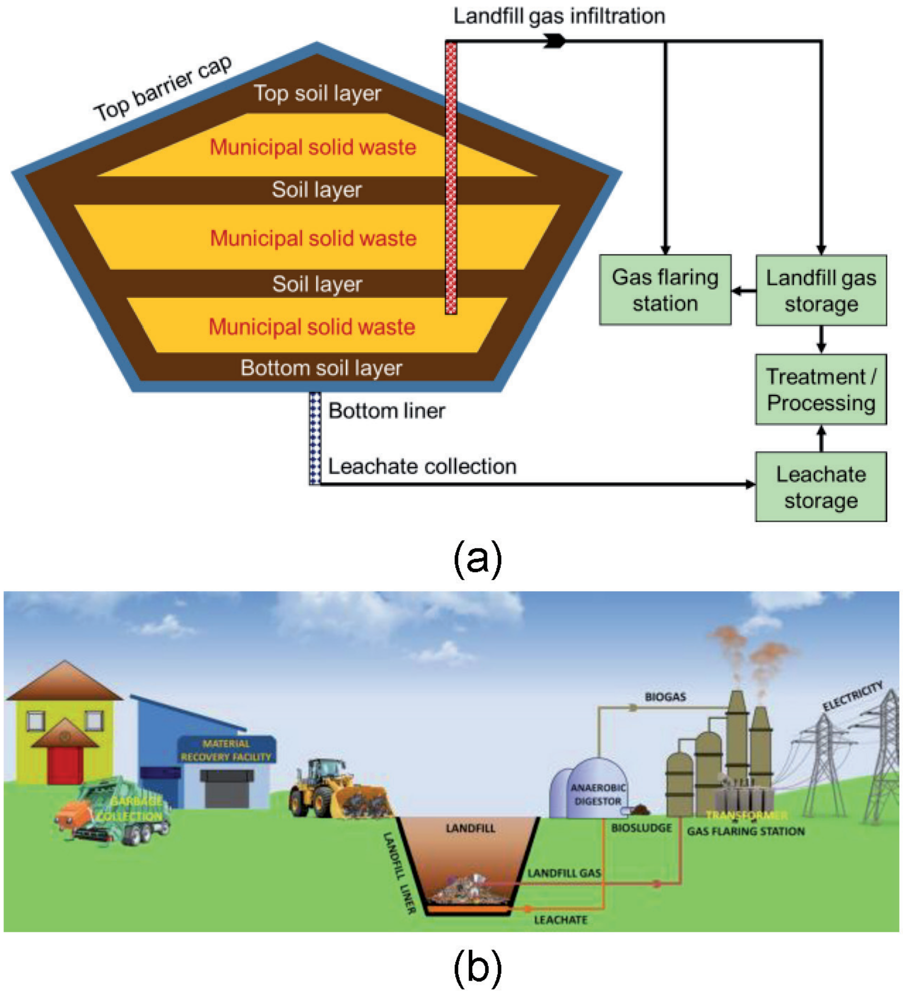

Figure 1.
Details of a sanitary landfill (a) processes (b) structural {adapted from [8]}.

Parameters	Young	Intermediate	Old
Age(years)	<5	5–10	>10
pH	<6.5	6.5–7.5	>7.5
COD (mg/l)	>10,000	4000–10,000	<4000
BOD_5/COD	>0.3	0.1–0.3	<0.1
Biodegradability	High	medium	low
NH_3-N (mg/l)	<400	—	>400
Organic composition	VFA (80%)	VFA (5–30%), humic and fulvic acid	Humic and fulvic acid
Heavy metals	Low-medium	low	low

Table 1.
The composition of leachate based on age [15, 19].

treatment can be utilized to treat the biodegradable matter present in waste, ammonia is removed by ion exchange, coagulation/flocculation is used for colloids, adsorption is adopted for the metals and organics while advanced oxidation process for the organic compounds [16, 17]. Anaerobic digestion of municipal solid waste is very advantageous because we can obtain biogas which contributes to about 35% of the bioenergy obtained from different biomass sources [18].

2. Anaerobic treatment

Anaerobic treatment technology is an attractive and demanding pathway because it serves the purposes of pollutant removal and energy recovery. Anaerobic treatment can be achieved efficiently for the complex industrial wastewater which may contain toxic substances [20]. Anaerobic treatment of landfill leachate can become a viable option as it has following advantages: (i) less space is required (ii) low energy requirement (no aeration is required)(iii) no or little sludge production (iv) Methane production and recovery thus helping to reduce the emission of green-house gas (CH4 potential is 25 times more than that of CO_2, [21]. Anaerobic digestion of waste includes biological action of different types of microorganisms acting together to breakdown the biomass typically in the absence of oxygen [22]. Anaerobic digestion is a process carried out by microorganisms that can live in an oxygen-deprived environment. The disintegration of organic substance happens in four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis are shown in detail in **Figure 2** [23, 24].

The first stage of anaerobic digestion is called as hydrolysis in which the anaerobic microorganisms convert the organic matter into basic organic substances like monomers, while, the proteins, carbohydrates and fats are converted to amino acids, monosaccharide and fatty acids, respectively.

Eq. (1) explains how a hydrolysis reaction converts organic waste into a simple sugar (glucose) [25].

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \quad (1)$$

During the second stage of anaerobic digestion the acidogenic bacteria convert the products of the hydrolytic reaction into alcohols, short chain VA, ketones, hydrogen, and carbon dioxide. The products obtained in the acidogenesis stage are propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), acetic acid (CH_3COOH), formic acid ($HCOOH$), lactic acid ($C_3H_6O_3$), ethanol (C_2H_5OH) and methanol (CH_3OH). From these products, the hydrogen, carbon dioxide and acetic acid will omit the acetogenesis stage and be utilized by the methanogenic bacteria in the methanogenesis stage (**Figure 2**). Eqs. (2)-(4) [25] represent three typical acidogenesis reactions where glucose is converted to ethanol, propionate and acetic acid, respectively.

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \quad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (4)$$

Acetogenesis is the stage in which all the acidogenesis products (butyric acid propionic acid and alcohols) are converted into carbon dioxide, hydrogen and acetic acid with the help of acetogenic bacteria (**Figure 2**). Eq. (5) shows the conversion of propionate to acetate. Glucose and ethanol are also converted to acetate during the third stage of anaerobic fermentation (Eqs. (6) and (7)) [25].

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2. \quad (5)$$

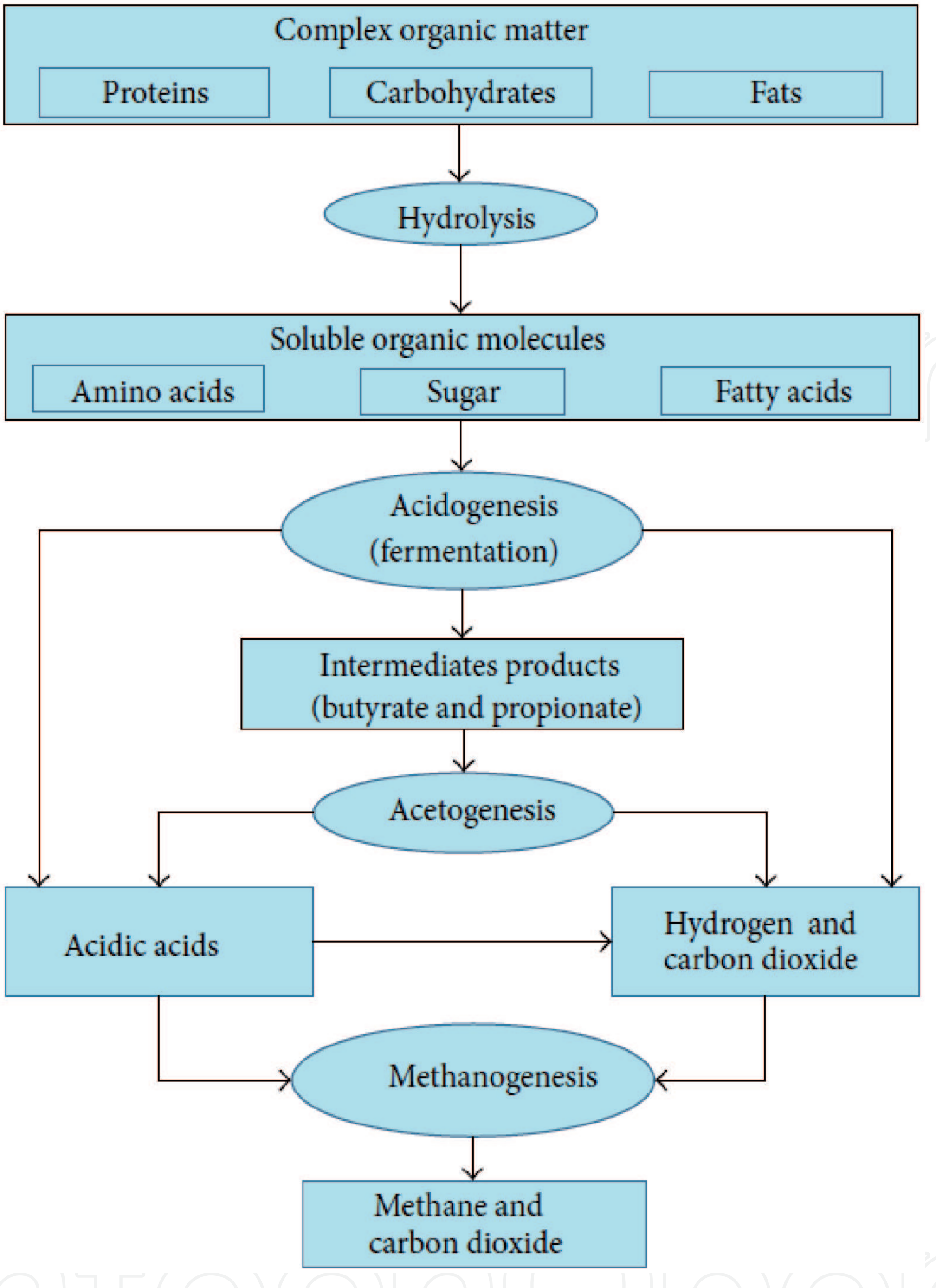

Figure 2.
Degradation steps of anaerobic digestion process [23, 24].

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \tag{6}$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+ \tag{7}$$

The last accomplishing stage of the anaerobic digestion is termed as methanogenesis. During methanogenesis the microbes convert the acetic acid and hydrogen to methane gas and carbon dioxide [25]. The anaerobic microorganisms that help to perform this conversion are called as methanogens. Waste is considered completely reduced in anaerobic treatment when methane gas and carbon dioxide are produced.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{8}$$

$$2C_2H_5OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \tag{9}$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{10}$$

2.1 Factors Affecting the Anaerobic treatment of landfill leachate

Anaerobic digestion of the pollutants present in landfill leachate depends on several factors such as temperature, pH, OLR and HRT, they are discussed below:

i. Temperature: Bacteria need an optimum temperature to grow, generally for anaerobic reactors, it is 25 to 35°C. The removal efficiencies dropped if the temperatures are below the optimum range [26]. The temperature was found to influence the SS removal, and high VFA concentration prevailed at low temp, showing that the reaction rates were influenced by the decrease in temperature in an ABR [27]. In another case, the reaction rate decreased when the temperature was reduced to below 15°C in an ABR system [28].

ii. pH: pH is an important controlling factor for operation of the ABR. The pH in the ABR is determined by the alkalinity and the VFA concentration. As mentioned above, there is compartmentalization in the ABR, and the favorable pH of each compartment differs. Due to fermentative bacteria, the VFAs accumulate in the initial chambers, but the pH increases down the reactor due to a decrease in VFA concentration and an increase in alkalinity [26]. The souring caused by excessive accumulation of the VFAs can lead to the process failure. Therefore, to prevent these fluctuations, pH can be adjusted using different substances like NaOH and $NaHCO_3$ [29].

iii. Organic Loading Rate (OLR): The OLR refers to the amount of organic material per unit reactor volume, which is subjected to the anaerobic digestion process in the reactor per unit time. OLR can be expressed as $OLR = \frac{Q \times COD}{V}$, upon simplifying $OLR = \frac{COD}{HRT}$ where OLR is organic loading rate (kg COD/m^3·d), Q is flow rate (m^3/d), COD is chemical oxygen demand (kg COD/m^3), and V is reactor volume (m^3). OLR does not directly influence the performance of an ABR but has an impact on the removal efficiencies. ABR treating a complex wastewater was operated at different OLRs ranging from 0.6 to 2 kg COD/m^3/day, for about 600 days without wasting sludge at temperatures of 20 to 38°C.The average COD removal decreased with a decrease in OLR. At max OLR i.e. at minimum HRT, the COD removal exceeded 88% [30]. It can be concluded that the OLR is an indicator of the nutritional condition of microorganisms.

Therefore, when low-concentration wastewater is being treated, lower HRT and higher OLR are preferred to ensure the availability of nutrients to the microorganisms. When high-concentration wastewater is being treated, lower OLR is suggested to enable complete biodegradation of the substrate and prevent sludge floating caused by higher yields of biogas [26].

iv. Hydraulic Retention Time (HRT): Hydraulic retention time is the volume of the aeration tank divided by the influent flow rate can be shown by the expression $\text{HRT [d]} = \frac{\text{Volume of reactor}[\text{m3}]}{\text{Influent flow rate}[\text{m3/d}]} = \frac{V}{Q}$ where HRT is in days or hours, V is volume of reactor in m^3 and Q is influent discharge in m^3/d [31]. HRT is the macro-conceptual time of the stay of organic material in the reactor the inverse of which is called as dilution rate and if the dilution rate is greater than the growth rate of microorganisms the microbes will be washed out. Otherwise the accumulation of microbes will take place [24]. The decrease in efficiencies at very lower HRTs could be because the bacteria did not get enough time to consume the substrate. Hydraulic shock loads can also result in process souring and failure due to the accumulation of VFAs, as they could not be degraded effectively by the heterotrophic bacteria and methanogens. HRTs also can influence the dead space volume, at lower HRTs, hydraulic dead space increases, and at higher HRT, biological dead space increases [26].

3. Anaerobic technologies treating landfill leachate

Anaerobic technologies are widely utilized for the treatment of wastewater, more precisely for the treatment of landfill leachate as they have following merits over aerobic technologies; Remarkably less sludge production, energy production in the form of methane, and efficient removal of pollutants [32]. Some of the treatment technologies/reactors are mentioned in **Table 2**.

Anaerobic reactor	Process parameters	Leachate type	COD removal (%)	References
Anaerobic contact reactor	COD = 16,250 mg/l	Young	37.5%	[33]
Anaerobic membrane bioreactor	COD = 7000 mg/l	Young	90%	[34]
UASB reactor	COD = 6000 mg/l	Intermediate	77%	[35]
Anaerobic filters	COD = 15,200 mg/l HRT = 4.5 days	Young	40%	[36]
Fluidised bed reactor	COD = 2000 mg/l HRT = 0.6 days	Young	80%	[37]

Table 2.
Some of the anaerobic treatments of leachate.

3.1 Anaerobic contact reactor

Anaerobic contact reactors are widely used for anaerobic treatment process. ACR consists of a main reactor and a sedimentation tank from where the settled sludge is brought back into the parent reactor. The ACR reaches steady state due to proper mixing and can even work for short HRTs getting higher removal efficiencies. The drawback usually encountered is the gas formation in the settling tank which causes reactor upset [38]. The drawback of this reactor is the development of gas in the settling tank, which upsets the solid settlement process. Şentürk et al. [39] studied an anaerobic contact reactor treating potato-chips wastewaters (COD = 5500 mg/l, OLR = 0.6 to 8 kg $COD/m^3/d$). The performance of ACR was evaluated based on COD removal, VFA production and the composition of biogas. The removal of COD was 86–97% and the methane content of the biogas production was about 68–89% accounting an yield of 0.42 m^3 CH_4/kg COD removed. El-Gohary and Kamel [33] recently found that an anaerobic contact reactor was able to remove 37.5 and 40.5% COD and BOD, respectively, from young leachate.

3.2 Anaerobic membrane bioreactor

The membrane bioreactor works on the application external membrane filter before/after the anaerobic reactor. This helps to capture the solids preventing the solids washout and getting them returned to the reactor sludge. Membrane bioreactor (MBR) technology became viable and popular as compared to activated sludge systems because of the following additional merits; MLSS concentration is high, low cost of treatment, less sludge production and quality of effluent is high [12]. The limitation of the system is the high probability of organic fouling in the membrane. Bohdziewicz and Kwarciak [40] found that using an anaerobic membrane bioreactor as much as 90% COD removal was possible for landfill leachate treatment. In another study by Zayen et al. [41], 90% COD removal was obtained using this type of reactor. In a separate study, an anaerobic membrane bioreactor achieved 26% COD removal at a low HRT of 0.4 days during the anaerobic treatment of leachate [34]. However, Trzcinski and Stuckey [42] demonstrated that the same reactor achieved 60% COD removal during the treatment of young leachate. Nuansawan et al. [43] found that treatment of young leachate using an anaerobic membrane bioreactor attained 81 and 92.1% removal of COD and BOD, respectively.

3.3 Up-flow anaerobic sludge blanket (UASB)

In an UASB reactor the sludge blanket provided at the bottom of the reactor serves the purpose of a filter and medium helping the anaerobic microbes to grow and utilize the organic matter. Influent wastewater is introduced by an inlet at the bottom and goes in an up-flow manner with the help of a pump. When the wastewater passes the anaerobic sludge blanket it is being treated by the microorganisms. This is the principle which governs the mechanism of UASB globally. Singh and Mittal [44] found that treatment of old leachate by UASB was only able to remove 35% of COD. Abood et al. [45] studied leachate treatment by UASB and found that the treatment could achieve COD, NH_3-N, and BOD_5 removal percentages of 69.27%, 92.18% and 23.81%, respectively. In a separate study by Tauseef et al. [46] found that leachate treatment by UASB was able to remove 80% COD and produce 70% methane. Montalvo et al. [47] found that treatment of leachate via UASB was capable of removing 92.4% nitrate, whereas a study conducted by Liu et al. [48] reported that leachate treatment by UASB could achieve removal of NH_3-N, TN and COD as high as 99.3%, 85.4% and 90.3%, respectively. In support of this, Moharram et al. [49] also found out that UASB could achieve 50 to 75% of COD removal. Lu et al. [50] stated that UASB could achieve COD removal rates between 77% and 91%. Alvarino et al. [51] stated that they could achieve 96.7% COD removal via UASB. Intanoo et al. [52] discovered that by using UASB, up to 60% COD removal could be attained, while according to Wu et al. [16] leachate treatment via UASB could achieve COD removal of 95%. Lu et al. [53] found that leachate treatment by UASB could attain COD removal rates of 93%.

3.4 Anaerobic filters

An anaerobic filter consists of a filter media usually made up of packed material (non-degradable polymer) having high surface area to volume ratio. These filters facilitate microorganisms to get developed as a biofilm and forming an anaerobic channel mat. The problem in such type of reactors arises when the wastewater is rich in solids causing clogging. Wang et al. [54] revealed that by applying an anaerobic filter in leachate treatment more than 90% COD removal could be accomplished. A recent study by Zayen et al. [17] reported 40% COD removal from young leachate.

Nanayakkara et al. [55] studied the treatment of 10% diluted landfill leachate using downflow anaerobic filters. One of the columns was filled with a mixture of Washed Sea Sand (WSS), Dewatered Alum Sludge (DAS) and Firewood Charcoal (FWC) while in the other the same materials were used but in layers. The parameters studied and their removal efficiencies using both columns are given below.

Parameters	COD	BOD_5	TN	NH_3-N	TP	PO_4^{3-}-P	Pb	Cd	Cu	Mn
Mixed column	59%	87%	49%	26%	71%	78%	40%	48%	41%	52%
Layered column	73%	84%	61%	55%	76%	79%	54%	37%	54%	57%

3.5 Fluidised bed reactor

In a fluidised bed reactor, the biomass grows as a biolayer around particles made up of plastic, polymer or sand which are suspended and remain fluidized because of upward movement of water. Some of the advantages are higher treatment capacity, no clogging as in the case of anaerobic filters but the limitation is that sometimes particles aggregate too much with biomass and settles after becoming dense [38]. Tisa et al. [56] found that fluidised bed reactor could remove 80% COD from landfill leachate. The role of the fluidised bed reactor in removing metal ions was explored by Sahinkaya et al. [37] who found that it was able to remove 80 to 99.9% of metals. According to Eldyasti et al. [57], their fluidised bed reactor was capable of achieving COD, nitrogen, and phosphorus removal efficiencies of 85%, 80%, and 70%, respectively at a low carbon-to-nitrogen ratio of 3: 1 and nutrients loading rates of 2.15 kg COD/m^3/d, 0.70 kg N/m^3/d, and 0.014 kg P/m^3/d).

In another study by Sahinkaya et al. [37], treatment of young leachate using a fluidised bed reactor resulted in 80% of COD removal and 60% of sulphate removal.

3.6 Leach bed reactor

This reactor works on an opposite principle to a UASB reactor in that the flow of wastewater is in the opposite direction: downflow direction. However, it shares some similarities with the UASB in terms of the sludge blanket. The difference is that effluent will leach out of the sludge bed and will be re-circulated as influent back into the reactor until maximum treatment is achieved [38]. According to Xu et al. [58] a leach bed reactor is capable of removing up to more than 80% COD. In a recent study by Degueurce et al. [59], a leach bed reactor was able to remove 27% COD from a young leachate; whereas, according to Ko et al. [60], treatment of young leachate via leach bed reactor was able to remove 80% COD.

3.7 Hybrid bed filter

A hybrid bed filter with a filter volume of 2.75 L and HRT of 2.4 d consisted of the combination of an anaerobic filter at the top and an up-flow sludge blanket situated at the bottom resulted in the removal efficiency of 37.5 to 76% COD from landfill leachate [61]. Karabelnik et al. [62] showed that at steady state a hybrid bed filter achieved COD removal efficiencies of 83 to 88% under an OLR of 2.50 kgCOD/m^3/d. Deng et al. [63] found that under the similar operational condition the hybrid bed filter was capable of achieving COD removal of more than 90% from leachate. In another study by Dastyar et al. [64] a hybrid bed filter was able to remove 45% COD from young leachate.

3.8 Anaerobic baffled reactor (ABR)

This reactor comprises of a progression of UASB reactors in series. The wastewater will stream over and under every baffle, which acts to isolate every chamber or compartment, thus counteracting solids washout and thus helping to retain the solids in the reactor. The successful compartmentalisation of the reactor guarantees phase division inside the compartments of acidogenic and methanogenic stages [38]. According to Rongrong et al. [65], an ABR demonstrated COD and Polyvinyl alcohol (in leachate) removal efficiencies around 42.0% and 18.0%, respectively. In a recent study by Yu et al. [66], leachate treatment by an ABR resulted in 80% of total nitrogen removal. Overview of landfill leachate treatment using different configurations of ABR is shown in **Table 3**.

Performance of an ABR treating landfill leachate was evaluated by Amin et al. [67], The influent COD of landfill leachate was 2700 mg/l and the pH during the treatment varied from 6.1 to 8.2 the maximum COD and nitrate removal obtained were 86 and 96.6%, respectively at an HRT of 48 h. Burbano-Figueroa et al. [68] studied the effect of OLR and sulphate loading rate (SLR) on landfill leachate treatment by a lab-scale ABR. The COD of landfill leachate was 3966–5090 mg/L with no traces of sulphate. Iron-sulphate was fed at a SLR of 0.05 g SO_4^{2-}/L/d during the reactor start-up. The range of organic loading rate was 0.30 up to 6.84 g COD/L/d, while SLR of 0.06–0.13 g SO_4^{2-} /L/d was adopted for SO_4^{2-} in the influent. The maximum value of COD removal obtained at an OLR of 3.58 g COD/L/d and SLR of 0.09 g SO_4^{2-}/L/d with a (COD/SO_4^{2-} = 40) was 66%. Sulphate is added for the consumption of molecular hydrogen and the organic content is degraded during methanogenesis.

ABR system of four compartments (volume = 64 L and HRT = 4 days) was used by Mohtashami et al. [69] to treat the landfill leachate and obtained the COD removal efficiencies of 82.38, 85.19, 82.53, 82.22, and 80.12% for OLR of 1.2, 2, 3, 5, and 7.75 kgCOD/m^3/d, respectively. The performance of an ABR was evaluated by Wang and Shen [70] as a hydrolysis-acidogenesis unit in treating the wastewater (landfill leachate mixed with municipal sewage) in different volumetric ratios. The study revealed that ABR substantially improved the biological treatability of the mixed wastewater by increasing its BOD_5/COD ratio to 0.4–0.6 from 0.15–0.3. The effects of the ratios of NH_4^+-N/COD and COD/TP in mixed

Anaerobic process/reactor	Studied pollutants	Performance	Reference
ABR (5compartments)	COD, TKN, Nitrate and Total dissolved salts	86%, 92.4%, 96.6% and 64%, respectively	[67]
ABR (5compartments)	COD	66%	[68]
ABR (4compartments)	COD	80% COD	[69]
ABR (4compartments)	BOD_5/COD ratio	BOD_5/COD ratio improved to 0.4–0.6 from the initial values of 0.15–0.3	[70]
MABR (4 Compartments)	COD, color and Heavy metals (As, Cr, Fe)	COD Removal-82% Color Removal-78% As Removal-88% Cr Removal-89% Fe Removal-88%	[71]

Table 3.
Different configuration of ABR in the treatment of landfill leachate.

wastewater on the operational performance were also studied, from which it was found that a reasonable NH_4^+-N/COD ratio should be lower than 0.02, and the phosphorus supplement was needed when the volumetric ratio was higher than 4: 6 for stable operation of ABR.

3.9 Anaerobic ammonium oxidation (Anammox)

It is an auto trophic nitrogen removal method which uses ammonium and nitrite as electron donor and acceptor respectively to attain nitrogen removal. Anammox is specially recommended for mature type of leachate, which has non-biodegradable COD and high concentration of nitrogen [72]. Anammox process overcomes the requirement of organic carbon for nitrification in activated sludge process, reduces the amount of energy required for aeration and there is less production of excess sludge and CO_2 emission [73]. A continuous flow process having nitrification and anammox has been studied to treat mature type of landfill leachate. The efficiency for removal of TN and COD were found to be 94 and 62% respectively [74].

3.10 Comparison of anaerobic reactors

Anaerobic reactors are comparable by the common features they share, such as HRT, COD removal and OLR (**Table 4**). Supposedly, the best reactor should be able to obtain high OLR, have short HRT and should have high COD removal. Of all the reactors discussed above OLR range from 1 to 30 kg COD/m^3/d. The reactors have an HRT ranging from 1 to 360 hours and COD removal of all anaerobic reactors ranges from 60 to 90%. From **Table 4** the fluidised bed reactor is the best reactor having an OLR of 2 to 50 kg COD m^{-3} d^{-1}, an HRT of 1 to 4 hours and a COD removal of 80 to 90%. Batch scale anaerobic digestion treating landfill leachate in Nepal (Sisdole landfill) obtained removal of COD as 50% at a retention time of 10 days while it was increased to about 85% using anaerobic sequential batch reactor (SBR) [75]. Due to obstacles in the operation of the fluidised bed reactor, UASB steals the spot of being the best type of reactor with OLR of 2 to 30 kg COD/m^3/d, an HRT of 2 to 72 hours and COD removal of 80 to 95%. This is also after considering issues of convenience in operating these types of reactors. That does not mean other types of reactors are not as good as each situation depends on the type of wastewater and the motivation to treat that specific type of wastewater.

Reactor type	OLR (kgCOD/m^3/d)	HRT (hr)	COD removal (%)
Conventional anaerobic reactor	1–5	240–360	60–80
Anaerobic contact reactor	1–6	24–120	70–95
Anaerobic sequencing batch reactor	1–10	6–24	75–90
Anaerobic filter	2–15	10–85	80–95
Fluidised bed	2–50	1–4	80–90
UASB	2–30	2–72	80–95
Anaerobic baffled reactor	3–35	9–32	75–95
Two phases anaerobic digestion	5–30	20–150	70–85

Table 4.
Comparison of various anaerobic reactors [53].

4. Combined technologies for landfill leachate treatment

Since the characteristics of landfill leachate is varying and the nature is recalcitrant, therefore no single technology is said to be sufficient for the overall treatment. To overcome this issue the technologies are applied as an integrated system in which various physicochemical and biological techniques with their different combinations are implemented for the removal of pollutants from landfill leachate. **Table 5** consists of some of the combined technologies used in the treatment of landfill leachate.

Claudia et al. [76] coupled the processes of photo electrooxidation (PEO) and activated carbon (AC) to treat highly concentrated stabilized leachate from a landfill and obtained the removal of 67.2%, 58.3% and 48.4% for COD, ammoniacal nitrogen and total Kjeldahl nitrogen respectively.

Mojiri et al. [77] performed the treatment of landfill leachate using the application of dual techniques by using electro-ozonation followed by sequencing batch reactor (SBR) process augmented with a composite adsorbent (P-BAZLSC) and obtained high efficiency in the removal of COD, color and nickel. In the electro-ozonation treatment the optimum ozone dosage and reaction time were kept as 120 mg/l and 96.9 min, respectively. The removal obtained was 64.8%, 90.4%, and 52.9% for COD, color and nickel, respectively. Sequentially the leachate was transferred to PB-SBR system. PB-SBR improvised the removal efficiencies from 64.8% to 88.2%, from 90.4% to 96.1%, and from 52.9% to 73.4% for COD, color, and nickel respectively.

The anaerobic treatment of landfill leachate having high concentration of (341.6 ± 21.3 mg/L) was combined by coagulation flocculation (CF) process in which the coagulant and flocculant used are ferric chloride and cationic polymer respectively. The removal efficiencies obtained at an optimum dose of 4.4 g/L of coagulant and 9.9 ml/L of flocculants: 80 ± 8.7, 69 ± 4.8, 94 ± 1.3 and 89 ± 6% for COD, turbidity, color and phenolic compounds respectively [78].

The treatment of landfill leachate was investigated using electrocoagulation process, the anode and cathode in the electrocoagulation system was both of iron. The conditions which were optimized to get the desired results were pH: 7.73, inter-electrode distance: 1.16 cm, and electrolyte concentration (NaCl): 2.00 g/l (key factors playing significant role). The process obtained the removal efficiency for

Type of treatment	COD/Pollutants	Performance	Reference
Photo-electro oxidation with activated carbon	1113 mg/L	69%	[76]
Electro-ozonation and a composite adsorbent augmented SBR	COD 3018 mg/L Color	88.2% 96.1%	[77]
Anaerobic combined with coagulation and flocculation (ferric chloride and cationic Polymer)	COD 11520 mg/L Color	80% 94%	[78]
Electro coagulation (iron as electrodes)	COD 7230 mg/L Color	45.1% 82.7%	[79]
Two stage anoxic/oxic combined membrane bioreactor	4000–20,000 mg/L	80.6%	[80]
Up-flow anaerobic sludge and semi fixed filter (UASB + AF)	68,500 mg/L	81%	[81]

Table 5.
Combined technologies for landfill leachate treatment.

COD and color as 45.1% and 82.7% respectively [79]. A two-stage anoxic/oxic (A/O) combined membrane bioreactor (MBR) developed by Liu et al. [80], was operated for 113 days to treat landfill leachate. The removal for different parameters obtained were COD = 80.6%, ammonia (NH_4^+ -N) = 99.04% and total nitrogen (TN) = 74.87%.

Hua et al. [81] developed an up flow anaerobic sludge semi-fixed filter for the treatment of landfill leachate by using soft polyurethane belt packing as the supporting carrier. The removal of COD increased with the gradual increase of OLR while the removal of sulphate decreased. However, the study showed that when the reactor was operated at the designed value of 9 kgCOD/m^3/d the removal of sulphate and COD were found to be 90 and 81% respectively. The results indicate that the semi fixed carrier can form an effective biofilm and the UASSF system can work efficiently in the treatment of landfill leachate.

5. Conclusion

Municipal solid waste disposal is a critical global issue which needs to be addressed to check the environmental hazards associated with improper disposal. Sanitary landfilling is the widely adopted method of disposal throughout the globe, but it is linked with the severe consequences of the generation of landfill leachate, which should be treated before disposal because of its toxic and recalcitrant nature. The chapter provides the brief overview of the landfills, landfill leachate and different treatment technologies suggested by the previous studies. Extensive details are incorporated about the anaerobic technologies treating landfill leachate followed by the hybrid or combined technologies. Hopefully, the chapter will give an understanding about different anaerobic bioreactors efficiently treating the landfill leachate.

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Conflict of interest

The authors find no conflict of interest.

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