



Treatment of landfill leachates with biological pretreatments and reverse osmosis

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Abstract

Landfill leachates from municipal landfills are usually heavily contaminated and thus require treatments before direct discharge into natural waters. Selecting the appropriate technology for leachate treatment is still a major challenge for operations in municipal landfills. Biodegradation is effective for treating young leachates, whereas old leachates require processes such as chemical oxidation, coagulation–flocculation, chemical precipitation, ozonation, activated carbon adsorption, and reverse osmosis. Recently, the combination of biological pretreatments followed by physico-chemical processes has been shown to be very efficient. Here we review the efficiency of biological treatment in combination with reverse osmosis to clean landfill leachates. We studied in particular processes including a membrane bioreactor, activated sludge, a rotating biological contactor, and up-flow anaerobic sludge blanket treatments, followed by reverse osmosis. We found a 99–99.5% removal of the chemical oxygen demand (COD), and a 99–99.8% removal of N-NH_4^+ using reverse osmosis and activated sludge. Using reverse osmosis with a rotating biological contactor, we observed 99% removal of COD, biochemical oxygen demand and N-NH_4^+ . The combination of reverse osmosis, activated sludge and rotating biological contactor removed 98–99.2% of Cl^- and 99–99.7% of Pb. Total suspended solids are best removed, up to 99%, by either a combination of reverse osmosis with membrane bioreactor, or reverse osmosis with activated sludge.

Keywords Biological pretreatment · Landfill · Leachate · Removal effect · Reverse osmosis

Introduction

A major issue arising from solid waste landfilling is the generation of landfill leachates. Leachates are high-strength wastewaters formed as a result of percolation of rainwater and moisture through waste in landfills (Hasar et al. 2009). Leachates contain a mixture of organic and inorganic contaminants including humic acids, ammonia nitrogen, heavy metals, xenobiotics, and inorganic salts, and its composition depends upon the landfill age, the quality and quantity of waste, biological and chemical processes that took place during disposal, rainfall density, and water percolation rate through the waste in landfill (Pasalari et al. 2018; Hasar et al. 2009; Wiszniowski et al. 2006).

With time leachate goes through the successive aerobic, acetogenic, methanogenic, and stabilization stages of organic waste degradation, in which its properties such as chemical oxygen demand, biological oxygen demand, BOD/COD ratio, ammonium nitrogen, and pH vary widely (Ahmed and Lan 2012; Kjeldsen et al. 2002). These parameters have their typical ranges depending on leachate/landfill age, which is commonly classified into three stages: young (lower than 5 years), medium/intermediate (5–10 years), and old/stabilized (more than 10 years) (Table 1) (Kurniawan et al. 2006; Alvarez-Vazquez et al. 2004; Ahmed and Lan 2012; Foo and Hameed 2009).

Leachate produced in young landfills is characterized by the high (more than 0.5) BOD/COD ratio, which is used as a measure of leachate biodegradability. Therefore, the BOD/COD ratio decreases with time because the non-biodegradable portion of COD will largely stay unchanged in this process (Ahmed and Lan 2012). Principal pollutant in leachate is also ammonia nitrogen. Ammonia nitrogen is present in leachate in young landfills owing to the deamination of amino acids during destruction of organic compounds

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Table 1 Characterization of landfill leachate with age

Parameter	Young	Intermediate	Stabilized
Age (years)	< 5 (< 1)*	5–10 (1–5)*	> 10 (> 5)*
pH	< 6.5	6.5–7.5	> 7.5
BOD/COD	0.5–1	0.1–0.5	< 0.1
Chemical oxygen demand (COD) (mg/L)	> 15,000	4–15,000	< 4000
NH ₃ -N (mg/L)	< 400	–	> 400
Total organic carbon (TOC)/COD	< 0.3	0.3–0.5	> 0.5
Total Kjeldahl nitrogen (TKN) (g/L)	0.1–2	–	–
Heavy metals (mg/L)	> 2	< 2	< 2
Biodegradability	High	Medium	Low

Quality of leachate from young landfills differs from stabilized leachate. For young leachate a high concentration of organics, low pH value, and higher BOD/COD ratio are observed in contrast to the low biodegradation of stabilized leachate, their higher pH value, and lower ratio of BOD/COD

TOC total organic carbon, TKN total Kjeldahl nitrogen

*Value according to Kurniawan et al. (2006)

(Kulikowska and Klimiuk 2008; Tatsi and Zouboulis 2002). Leachate from older landfill is rich in ammonia nitrogen due to hydrolysis and fermentation of the nitrogenous fraction of biodegradable substrates. The variation of organics and ammonia nitrogen with time may have important implications in leachate treatment. Regardless of landfill age, leachate contains many types of contaminants, which may be toxic to life or simply alter the ecology of receiving streams. It can accelerate algae growth due to its high nutrient content, deplete dissolved oxygen in the water, and cause toxic effect in the surrounding water life (Hasar et al. 2009).

Owing to the potential risk posed by the heavily polluted leachate, it should meet stricter quality standards regarding the direct discharge of leachate (or any wastewater) (Zolfaghari et al. 2017). To meet these stricter quality standards, on-site treatment of leachate becomes imperative and the selection of an appropriate technology more so (Ahmed and Lan 2012). Treatment technology for leachate, as well for wastewater, should be considered seriously after fully understanding its composition and concentration (Crini and Lichtfouse 2018). Biological treatments such as conventional activated sludge, aerated lagoons, sequencing batch reactors, up-flow anaerobic sludge blanket, membrane bioreactors, and rotating biological contactors are widely and effectively employed for treating young leachate with high BOD concentration (Kurniawan et al. 2006; Ahmed and Lan 2012).

It was found that the most studied aerobic processes for leachate treatment in the world are aerobic lagoons—21%, up-flow anaerobic sludge blanket—18%, activated sludge—17%,

and sequencing batch reactors—15%. The membrane bioreactor accounts for 8% (Hasar et al. 2009). These methods are probably the most efficient and cheapest process to eliminate nitrogen from leachate (Wiszniewski et al. 2006). However, biological treatment is hampered by the specific toxic substances and/or the presence of bio-refractory organics. That is why the COD removal from old leachate presents a problem for these conventional biological treatments. For such a leachate the physical and chemical processes including chemical oxidation, coagulation–flocculation, chemical precipitation, ozonation, activated carbon adsorption, and reverse osmosis should be considered. Among these processes reverse osmosis has been one of the most widely used methods for the last years. This development is due to the ability to retain inorganic and organic contaminations dissolved in leachate with high efficiency (Trebouet et al. 2001; Theepharaksapan et al. 2011). Chianese et al. (1999) reported, that the rejection coefficients for COD parameter and heavy metals concentration were higher than 0.98 and 0.99, respectively.

The disadvantage of treating leachate with reverse osmosis is membrane fouling, which decreases the treatment effectiveness and concentrate production, which is difficult to manage. Moreover, during reverse osmosis the separation of ammonium is often not sufficient. Therefore, a number of scientists around the world have intensively focused on the combination of biological and physico-chemical treatment systems for effective leachate treatment. A potential process in the treatment is biological pretreatment of leachate followed by reverse osmosis purification. Biological pretreatment is able to reduce the organic constituents that either contribute directly to organic fouling or provide carbon sources for the development of biofilms on the membrane surface (Wend et al. 2003). Integration of biological and reverse osmosis processes can yield a high reduction rate of COD, ammonium nitrogen, and heavy metals.

Numerous research studies on the treatment of leachate using biological (Geradi 2002; Alvarez-Vazquez et al. 2004; Sponza and Ağdağ 2004; Uygur and Kargi 2004; Kim et al. 2005; Parkes et al. 2007; Wiszniewski et al. 2006; Zhang et al. 2007; Kamaruddin et al. 2013) and reverse osmosis (Dydo et al. 2005; Robinson 2005; Liu et al. 2008; Li et al. 2009; Ushikoshi et al. 2002; Renou et al. 2008; Richards et al. 2010; Theepharaksapan et al. 2011) methods have been carried out worldwide in recent years. However, there are hardly any review papers that provide a comprehensive overview of efficiency of combination different biological pretreatment methods with reverse osmosis. To cover this gap this paper aims to evaluate the effectiveness of reverse osmosis system with different biological pretreatments.

Effectiveness of reverse osmosis with different biological leachate pretreatments

Membrane bioreactor and reverse osmosis

Membrane bioreactor is the combination of a membrane process like microfiltration or ultrafiltration with a suspended growth bioreactor (Judd 2006). So, it is essentially composed of two primary parts: the biological unit or bioreactor responsible for the biodegradation of waste compounds and the membrane module for the separation of treated water from biosolids or microorganisms (Cicek 2003; Ahmed and Lan 2012). It leads to increased microorganisms concentration in reactor and improvement in process efficiency with lower sludge production.

Membrane bioreactor allows for complete retention of biomass, enabling membrane bioreactor to operate with significantly higher mixed liquor suspended solids concentration (10–20 g/L) and produce higher-quality effluents (Patsios and Karabelas 2011). Moreover, it does not require space for sedimentation tanks; therefore, it is a good option in case of limited land area (Pearce 2008; Akgul et al. 2013). There are two types of membrane bioreactors according to the locations of membrane units, i.e. submerged (internal) and external (sidestream) reactors (Fig. 1) (Bohdziewicz et al. 2008).

In submerged membrane bioreactor the membrane module is installed inside the reactor. The membranes can be flat sheet or tubular or combination of both (Wang et al. 2008). In the sidestream configuration, the membrane is outside the reactor and the sludge is recirculated to the aeration tank. Sufficiently high cross-flow velocities need to be maintained in a sidestream membrane bioreactor to overcome flux decline due to fouling. The absence of a high-flow recirculation pump in a submerged membrane

bioreactor results in a more compact, low-cost, and energy-saving system (Ahmed and Lan 2012). In spite of the advantages offered by the submerged configuration, external systems are generally considered to be more suitable for wastewater with high temperature, pH, organic strength, toxicity, and fouling tendencies. Since membrane filtration in an external membrane bioreactor is usually operated in the cross-flow mode as opposed to the dead-end mode of submerged systems, membrane fouling is less of a problem in external systems. Given the high fouling potential and low filterability of leachate, the majority of the membrane bioreactor systems utilized for landfill leachate treatment are based on external systems system (Ahmed and Lan 2012).

The main advantage of the membrane bioreactor process is that it reduces the importance for biomass sedimentation, thus allowing a significantly smaller tank to be used for the bio-treatment process. The second main advantage of a membrane bioreactor is that the treated water quality is better than from a conventional process, since the membrane barrier removes essentially all particulates above the pore size rating of the membrane (Pearce 2008). The efficiency of membrane bioreactor according to different research studies is presented in Table 2.

The effluent from membrane bioreactors treating landfill leachate is characterized by low BOD/COD ratio (lower than 0.1) indicating the presence of refractory organic matter. The membrane bioreactor achieved more than 98% of BOD removal. However, high COD concentration was still found in effluents of membrane bioreactors due to a certain amount of refractory compounds present in landfill leachate. The removal rate of N-NH_4^+ was from 60 to 80%; the removal rate of total Kjeldahl nitrogen was slightly higher and ranged from 60 to 97%.

The membrane bioreactor filtration performance inevitably decreases with filtration time. This is due to the deposition of soluble and particulate materials onto and into the

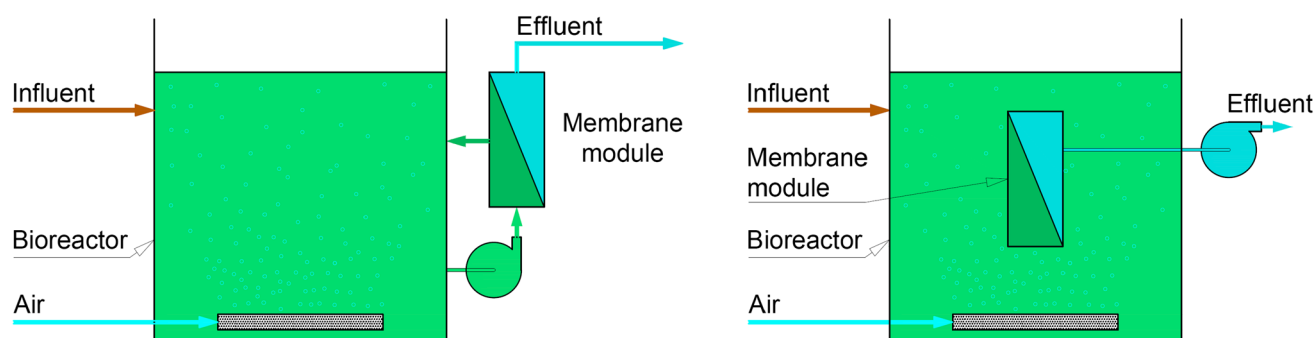


Fig. 1 Membrane bioreactor configurations. A membrane bioreactor is a combination of a biological leachate/wastewater treatment process with a membrane process such as microfiltration or ultrafiltration. Two configurations of membrane bioreactor exist: external (left),

where membranes are a separate unit requiring intermediate pumping step, and submerged (right), where the membranes are immersed in and integral to the biological reactor. *Source:* Adapted from Ng and Kim (2007)

Table 2 Performance of membrane bioreactors for treating landfill leachates

Parameter	Influent (mg/L)	BOD/COD	MBR effluent (mg/L)	Removal (%)	Type	References
COD	400–1500	≈ 0.3	211–856	–	Full scale	Ahn et al. (2001)
BOD	100–500		4.3–29	–		
N-NH ₄ ⁺	200–1400		100–408	–		
COD	1800	0.15	–	31.3	Laboratory scale	Setiadi and Fairus (2003)
BOD	267.5		–	98	HRT: 24 h	
N-NH ₄ ⁺	114.8		–	66		
BOD	–	n.a.	10–500	75–99	Laboratory scale	Akgul et al. (2013)
COD	442	0.65	–	82.4	Laboratory scale	Bodzek et al. (2006)
BOD	290		–	98.3		
TOC	127		–	74.7		
TKN	230–1960	n.a.	–	80–97	Full scale	Chiemchaisri et al. (2011)
COD	–	n.a.	–	60–80	Full scale	Visvanathan et al. (2007)
BOD	–		–	90–97	HRT: 24 h	
N-NH ₄ ⁺	–		–	60–80		
TKN	1300–1900		–	60–75		

Membrane bioreactor performance was characterized by higher efficiency of BOD removal than of COD removal. The removal rates for N-NH₄⁺ and total Kjeldahl nitrogen were similar and ranged from 60 to about 90%

MBR membrane bioreactor, TOC total organic carbon, TKN total Kjeldahl nitrogen, HRT hydraulic retention time, n.a. data not available

membrane, attributed to the interactions between activated sludge components and the membrane (Cui et al. 2003). Membrane fouling has been identified as the main disadvantage of operation of membrane bioreactors just as high membrane cost and high energy consumption.

Membrane bioreactor may provide excellent pretreatment for subsequent reverse osmosis stages. If dissolved substances need to be removed by reverse osmosis, membrane filtration is essentially mandatory as a pretreatment to reverse osmosis in order to achieve stable performance. Table 3 presents the effectiveness of reverse osmosis with membrane bioreactor pretreatment in purification of landfill leachate.

As can be seen from Tables 2 and 3, successful landfill leachate treatment using membrane bioreactor process requires the integration of additional physico-chemical stages such as reverse osmosis.

The treatment of leachate from landfill in Chung Nam Province (Korea) using a combination of membrane bioreactor and reverse osmosis unit was examined by Ahn et al. (2001). As presented in Table 3, the average removal rate of BOD in membrane bioreactor was 96% and then pretreatment water was transferred to reverse osmosis, with final removal rate of 97%. N-NH₄⁺ removal after membrane bioreactor stage was 50–70% and increased to 96% after reverse osmosis treatment. In case of N-NO₃⁻ the final removal effect was 93% and most of nitrate was removed during reverse osmosis process. This is due to the fact that generally negatively charged reverse osmosis membranes remove

negatively charged nitrate and nitrite better than positively charged ammonium ion or neutral ammonia (Ahn et al. 2001). Membrane bioreactor also performed an effective pretreatment for reverse osmosis membranes by removing total suspended solids by over 99%, which prevents clogging of reverse osmosis membrane. The overall COD removal rate was 97%. Only about 40% was removed by membrane bioreactor, and the rest about 60% was removed by reverse osmosis.

A combination of membrane bioreactor and reverse osmosis was studied for the treatment of stabilized leachate from Sobuczyna (Poland). The COD removal efficiency achieved a value of 99%. Effluent COD after membrane bioreactor process decreases from 5000 mg/L to the value of 417 mg/L, and after reverse osmosis process to the 12 mg/L. A slightly lower level of leachate purification was achieved in the case of N-NH₄⁺. A poor-quality effluent with 206 mg/L N-NH₄⁺ was directed to reverse osmosis module. The post-treatment reverse osmosis process allows to achieve the efficiency of 92% in N-NH₄⁺ removal.

A two-stage treatment of young/intermediate (BOD/COD: 0.4–0.7) leachate from Diyarbakir landfill (Turkey) consisting of membrane bioreactor and reverse osmosis was undertaken by Hasar et al. (2009). About 99% COD removal was achieved with the initial concentration of 7300 mg/L. This result is in agreement with those of previous studies carried out by Ahn et al. (2001) and Bohdziewicz et al. (2008). A combination of biological and physico-chemical treatments reduced the conductivity

Table 3 Effectiveness of reverse osmosis with membrane bioreactor pretreatment for purification of landfill leachate

Parameter	Influent	BOD/COD	MBR effluent	RO effluent	Removal	Type	Localization	References
BOD	100–500	0.25–0.33	4.3–29	1–7	97	MBR: submerged	Korea	Ahn et al. (2001)
COD	400–1500		211–856	6–72	97	RO: spiral wound	Chung Nam	
TSS	200–1000		1–5	1–1.6	99	module type,	Province	
N–NH ₄ ⁺	200–1400		100–408	10–47	96	polyamide mem-	Full scale	
N–NO ₃ [−]	28–251		34–378	7–23	93	brane 6.7 m ² , sodium rejection 99%		
COD	5000	Low ratio (stabi- lized leachate)	417	12	99	MBR: submerged	Poland	Bohdziewicz et al. (2008)
pH	8.03		8.18	8.9	n.a.	RO: pressure	Sobuczyna	
N–NH ₄ ⁺	381.5		206	29.8	92	4.0 MPa poly- amide membrane sodium rejection 98.9%	Laboratory scale	
COD	7300	0.4–0.7	450	3.4	99	MBR: submerged	Turkey	Hasar et al. (2009)
N–NO ₂ [−]	0.8		0.2	n.a.	n.a.	RO: pressure 2.758 kPa	Diyarbakir	
N–NO ₃ [−]	5–47		0.5–8.0	n.a.	n.a.	Thin-film mem-	Laboratory scale	
N–NH ₄ ⁺	200–600		15	n.a.	n.a.	brane 3.79 m ² sodium rejection 99.4%		
EC	7.4		n.a.	0.02	> 99			
COD	400–500	Low ratio (stabi- lized leachate)	n.a.	n.a.	97	n.a.	South Korea	Ahmed and Lan (2012)
N–NH ₄ ⁺	200–1400		n.a.	n.a.	96		Full scale	

A combination of membrane bioreactor with reverse osmosis was characterized by over 97% BOD and COD removal. The use of reverse osmosis as a second step of leachate treatment improves the efficiency of nitrogen compounds (N–NH₄⁺, N–NO₃[−]) removal

Values of influent and effluent in mg/L except for pH and EC (mS), removal effect in %

RO reverse osmosis, MBR membrane bioreactor, TSS total suspended solids, EC electroconductivity, n.a. data not available

of treated leachate from 7.4 to 0.02 mS giving over 99% removal effect. There is no clear value of removal effect for N–NH₄⁺ compound in Hasar et al. (2009) investigation. Nevertheless, they suggest that reverse osmosis is technically applicable and appealing for the treatment of stabilized leachate.

A comparative study of the treatment of leachate by using combination of membrane bioreactor and different physico-chemical processes was evaluated by Ahmed and Lan (2012). Authors point out a high removal of both COD (97%) and N–NH₄⁺ (96%) from old leachate with the use of a two-stage process that integrates a membrane bioreactor unit with a post-treatment reverse osmosis module. Membrane bioreactor in this case is responsible for removing the bulk of the influent N–NH₄⁺ and BOD and producing an effluent completely devoid of suspended solids, which aids in mitigating clogging and fouling problems commonly faced by downstream membrane processes (Ahmed and Lan 2012). The results suggest that a combination of membrane bioreactor and reverse osmosis treatment was able to optimize the removal of recalcitrant compounds and ammonia from landfill.

Activated sludge and reverse osmosis

The activated sludge is a process which involves air or oxygen being introduced into a mixture of screened and primary treated wastewater (leachate) combined with organisms to develop a biological floc which reduces the organic content of the sewage. The microorganisms consume the organic matter and transform it by means of aerobic metabolism, partly into new microbial biomass and partly into carbon dioxide, water, and minerals (Wisznio-wski et al. 2006). The combination of wastewater and biological mass is commonly known as mixed liquor. In all activated sludge plants, once the wastewater has received sufficient treatment, excess mixed liquor is discharged into settling tanks and the treated supernatant is run off to undergo further treatment before discharge. Part of the settled material, the sludge, is returned to the head of the aeration system to re-seed the new influent entering the tank. The surplus amount is discharged (Fig. 2).

The reactions occurring in the activated sludge process can be summarized as follows (Wisznio-wski et al. 2006):

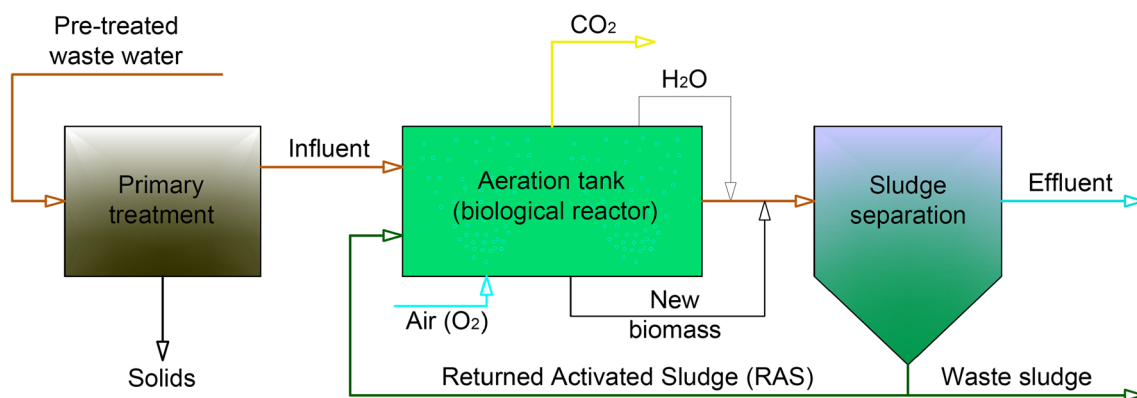
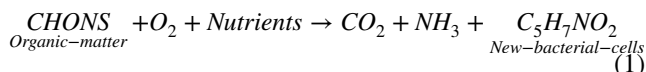


Fig. 2 Wastewater treatment by aeration and activated sludge. The settled leachate from primary treatment tank is directed to aeration tank where air (or oxygen) is injected in the mixed liquor. In aeration tank leachate is also mixed with required amount of activated sludge coming from sludge separation tank. The biological

process in aeration tank takes advantage of aerobic microorganisms that can digest organic matter in sewage and clump together creating flocs. Sludge separation tank allows the biological flocs to settle, thus separating the biological sludge from the clear treated water. *Source:* adapted from Kiely 1997

1. Sorption of soluble, colloidal, and suspended organics in and on the sludge flocs.
2. Biodegradation (oxidation) of the organics resulting in the end products (CO_2 , H_2O and minerals) and synthesis of new microbial biomass according to equation:



In aerobic treatment about half of the organic carbon is assimilated into the biomass, while the other half is respired to form CO_2 .

3. Ingestion of bacteria and possibly of other suspended matter by protozoa or other predators.
4. Oxidation of ammonium to nitrite and further to nitrate by the nitrifying bacteria.
5. In moments of insufficient supply of energy (leachate), oxidation of cell reserves (internal and also external) resulting in sludge mineralization takes place.

The important process in leachate treatment is nitrogen removal, whose concentration increases with landfill age. Old leachate has inhibition effect on activated sludge due to their high ammonium concentration. However, the phosphorus deficiency hampers the production of microorganisms and consequently the treatment performance (Chaundhari et al. 2008).

Three major biological processes directly involved in biological nitrogen removal in wastewater treatment are: ammonification, nitrification/denitrification, and anammox. Ammonification occurs when organic nitrogen is converted to ammonia. It is an important mechanism that allows organic nitrogen to be removed from wastewaters.

In nitrification process the oxidation of ammonium is performed by bacteria such as the *Nitrosomonas* species, which converts ammonia to nitrites (NO_2^-). Then, other bacterial species, such as the *Nitrobacter*, are responsible for the oxidation of the nitrites into nitrates (NO_3^-). These two groups of chemolithotrophic bacteria operate in sequence. Denitrification is the second step in the removal of nitrogen by nitrification/denitrification process. The reduction of nitrates back into the largely inert nitrogen gas (N_2) takes place during it. This process is performed by a great variety of bacterial species such as *Pseudomonas*, *Alcaligenes*, *Acinetobacter*, *Clostridium*, etc. They use the nitrate as an electron acceptor in the place of oxygen during respiration or—when oxygen is absent—they modify the cytochrome system and utilize nitrate.

The advantages of treatment leachate with activated sludge are possibility of its adaptation to any size of landfill and good elimination of some pollution parameters: total suspended solids, COD, and BOD, especially in case of young leachate. Disadvantages are relatively high capital costs and high energy consumption. The efficiency of activated sludge in leachate purification is presented in Table 4.

The denitrification consumes approximately 3.7 g COD/g $\text{NO}_3\text{-N}$ reduced (Chiu and Chung 2003) and produces 0.45 g new cell and 3.57 g of alkalinity per gram of $\text{NO}_3\text{-N}$ reduced (Eckenfelder and Musterman 1995). The removal efficiency of activated sludge for BOD ranged from 63 to 95% and for COD from 37 to 94.5%. The activated sludge process is able to achieve over 90% removal of N-NH_4^+ . The removal rate for total nitrogen was below 50%. The greatest differentiation was observed for P removal, which ranged from 17% according to Voronova et al. (2011) to over 80% according to Cicek et al. (1999). Activated sludge may be used together with reverse osmosis system giving a good pretreatment for

Table 4 Performance of activated sludge treating landfill leachate

Parameter	Influent (mg/L)	BOD/COD	AS effluent (mg/L)	Removal (%)	Type	References
COD	688	0.1	–	81	With ozonation before AS stage	Geenens et al. (2000)
COD	–	n.a.	–	69	n.a.	Bodzek et al. (2006)
BOD	–	n.a.	15	85–95	n.a.	Cicek et al. (1999)
COD	–	–	–	94.5		
TSS	10–15	–	–	60.9		
N–NH ₄ ⁺	–	–	–	98.8		
P _{total}	–	–	0.8–1	88.5		
BOD	150–1630	n.a.	45–525	63	n.a.	Voronova et al. (2011)
COD	988–8730	–	680–1960	37		
P _{total}	4.5–8.3	–	3.8–5.1	17		
TN	200–603	–	30–395	30		
N–NH ₄ ⁺	–	n.a.	60–150	< 60	HRT: 1.5d	Martienssen and Schops (1997)
TN	–	–	–	< 50	TOC: 1150 mg/L	
COD	–	n.a.	–	90	n.a.	Shou-liang et al. (2008)
N–NH ₄ ⁺	200–1400	–	–	90		
BOD	–	n.a.	10–500	75–99	Laboratory scale	Akgul et al. (2013)

The activated sludge process used for leachate treatment is able to achieve over 60% efficiency in BOD and total suspended solids removal. The removal rate for total nitrogen was below 50%. The high efficiency differentiation was observed in case of N–NH₄⁺ and COD removal, which ranged from 50 to 98.8% and from 37 to 94.5%, respectively

AS activated sludge, TSS total suspended solids, TN total nitrogen, HRT hydraulic retention time, TOC total organic carbon, n.a. data not available

landfill leachate. Activated sludge produces a secondary effluent which can be easily treated by a reverse osmosis system. Table 5 presents the effectiveness of reverse osmosis with activated sludge pretreatment in purification of landfill leachate.

A combination of activated sludge and reverse osmosis purification was studied for the treatment of stabilized leachate from Kolenfeld (Germany). The COD was reduced from the influent value of 3100 to 1160 mg/L in the effluent of the activated sludge step, meaning a 63% reduction rate of the total COD. More than 99% N–NH₄⁺ was nitrified. As for the metals, the following average treatment efficiencies by the activated sludge step were obtained: Al 25%, Fe 67%, Pb 59%, Zn 58%, and Cu 58%. After biological and reverse osmosis stages almost complete removal of suspended solids (more than 99.9%) was obtained. The reduction rate of COD was greater than 99.5%. Chloride was eliminated by more than 99%, while over 98% of N–NH₄⁺ was reduced. The overall reduction rates of Al, Fe, Pb, Zn, and Cu were above 98%. The biological pretreatment was effective to reduce the biological organics as BOD₅ and the main part of COD. However, the residual COD concentration after the biological processes was still high, confirming that biological treatment alone is insufficient for meeting the discharge standards (Li et al. 2009).

A two-stage treatment of young leachate (BOD/COD=0.7) from the Mechernich (Germany) consisting of

activated sludge and reverse osmosis module was undertaken by Baumgarten and Sayfried (1996). With initial concentration of 6440 mg/L for COD and 1153 mg/L for N–NH₄⁺ the removal rate of 99% was achieved for both of them. The results suggest that a combination of biological and physico-chemical treatment is able to optimize the removal of recalcitrant compounds and ammonia from landfill leachate.

Rotating biological contactors and reverse osmosis

The rotating biological contactor is an example of biological filter (attached growth) technology. It consists of a circular plastic disc mounted on a rotating shaft which is supported just above the surface of the wastewater (Wiszniewski et al. 2006). Commonly used plastics for the media are polyethylene, polyvinylchloride, and expanded polystyrene. The discs are submerged in wastewater to about 40% of their diameter and are slowly rotated by either mechanical or a compressed air drive (Wiszniewski et al. 2006) (Fig. 3).

The surface of the disc provides an attachment site for bacteria, and as the discs rotate, a film of biomass grows on their surface (The Attached Growth Process... 2004; Technology options... 2008). When the disc rotates out of the wastewater, the biofilm becomes exposed to air and so the oxygen necessary for the growth of microorganism is obtained (Crites and Tchobanoglous 1998; Wiszniewski et al. 2006). As the biofilm passes through the liquid

Table 5 Effectiveness of reverse osmosis with activated sludge pretreatment in purification of landfill leachate

Parameter	Influent	BOD/COD	AS effluent	RO effluent	Removal	Type	Localization	References
pH	7.9	Old leachate	7.0	6.6	n.a.	Activated sludge process operated at a volumetric load of 2.6 kg COD/m ³ day	Kolenfeld, Germany	Li et al. (2009)
EC	16.5		16.3	0.3	98.2			
TSS	315		33	Not detected	> 99.9			
COD	3100		1160	15	99.5			
N-NH ₄ ⁺	1000		6.5	11.3	99.8			
N-NO ₂ ⁻	5		6.8	0.15	97			
N-NO ₃ ⁻	15		115	2.6	82.7			
Cl ⁻	2850		2790	23.2	99.2			
Al	0.12		0.09	< 0.001	> 99.2			
Fe	7.6		2.5	< 0.001	> 99.9			
Pb	0.37		0.15	< 0.001	> 99.7			
Zn	0.65		0.27	< 0.001	> 99.8			
Cu	0.26		0.11	< 0.001	99.6			
COD	6440	0.70	n.a.	n.a.	99	n.a.	Mechernich, Germany	Baumgarten and Sayfried (1996)
N-NH ₄ ⁺	1153		n.a.	n.a.	99			

It was noted a high efficiency (over 99%) of activated sludge and reverse osmosis in COD, N-NH₄⁺ and total suspended solids removal. A combination of activated sludge and reverse osmosis had also a high removal rate for Cl⁻, Al, Fe, Pb, Zn, and Cu. The efficiency for nitrogen nitrate and nitrogen nitrite was slightly lower – 97% and 82.7%, respectively

Values of influent and effluent in mg/L except for pH and EC (mS), removal effect in %

AS activated sludge, RO reverse osmosis, EC electroconductivity, TSS total suspended solids, n.a. data not available

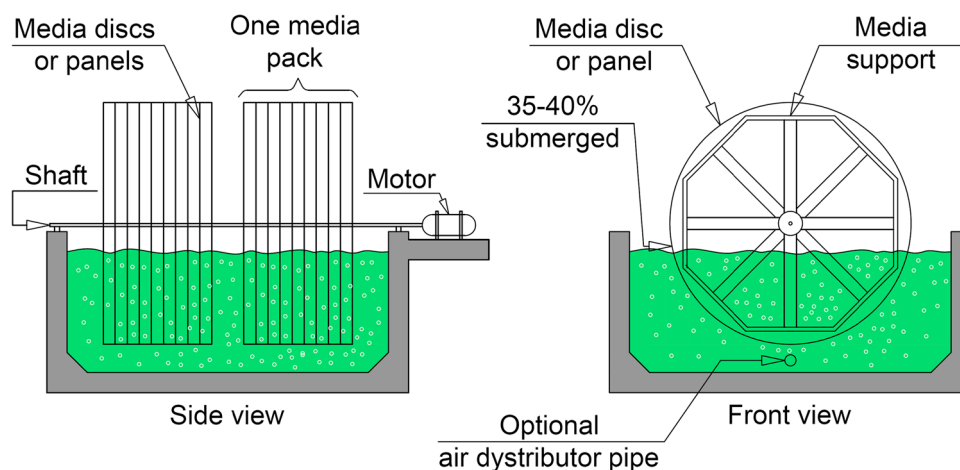


Fig. 3 Rotating biological contactors are fixed-bed reactors consisting of rotating discs mounted on a horizontal shaft. The surface of the discs provides an attachment site for bacteria. The microbial community is alternately exposed to the atmosphere and the leachate/wastewater. The oxygen necessary for the growth of these microorganisms

is obtained by adsorption from the air as the biofilm on the disc is rotated out of the liquid. This microbial population causes the biological degradation of organic pollutants. Source: Adapted from http://en.wikipedia.org/wiki/Rotating_biological_contactor

phase, nutrients and organic pollutants are taken up. All oxygen, nutrients, and organic pollutants are necessary for the growth of the microorganism and the conversion of the organic matter to CO₂. Nitrogen is removed by nitrification and subsequent denitrification transforming it to gaseous N₂, which is released to the air. The process is optimized

by adjusting the speed of rotation and the depth of submergence. In some designs, air is added to the bottom of the tank to provide additional oxygen in case of high-strength influents (Crites and Tchobanoglous 1998). As for all fixed-film processes, primary settling and/or screening is required for the removal of excessive oil or grease prior to rotating

biological contactor process (Technology options... 2008). Such primary treatments are typically septic tanks, Imhoff tanks, or anaerobic reactors.

The performance of rotating biological contactor systems depends on the design, the temperature, the concentration of the pollutants, the rotating velocity, and the hydraulic retention time. Rotating biological contactors can achieve biological oxygen demand reductions of 80–90% (Technology options... 2008). The removal of nitrogen (which is mostly present as ammonia) by nitrification and subsequent denitrification is also high, because both aerobic nitrifying bacteria and anaerobic denitrifying bacteria can simultaneously live in the attached biofilm, depending on whether they are situated on the bottom of the film, close to the disc support (and thus in anaerobic or anoxic conditions), or at the top of the film exposed to the air (Hochheimer and Wheton 1998).

The collected sludge in the clarifier requires further treatment for stabilization, such as anaerobic digestion, composting, constructed wetlands, ponds, or drying (Technology options... 2008). Effluents from rotating biological contactor, due to the reduced removal of microorganisms, require a further treatment. Treating high-organic polluted leachates may result in clogging by means of inorganic precipitates and/or produced biomass. On the other hand, in many cases nitrification processes are more effective in fixed-film reactors due to the high sludge age. For this reason these treatment methods are more appropriate for the treatment of leachate from old landfills (Stegmann et al. 2005).

The rotating biological contactor process appears to offer several advantages over the activated sludge process for use in landfill leachate treatment. The primary advantage of rotating biological contactors is the relative ease of operation and maintenance. This treatment method consumes relatively low amounts of energy, simple operation requires less maintenance and monitoring than the activated sludge, and lower sensitivity to load variations and toxins is observed (Wisniewski et al. 2006). Table 6 shows the results of rotating biological contactor process treating leachate on different landfills.

The rotating biological contactor process employed at El Carrasco landfill (Colombia) operated with an organic load of 24.7 g COD/m² per day with hydraulic retention time of 34 h, and angular speeds of 6 and 9 rpm gave a maximum COD removal of 58.5% (Castillo et al. 2007). A rotating biological contactor was also used to remove nitrogen from a high-ammonia landfill leachate collected from a municipal solid waste landfill in Kaohsiung (Taiwan). The research indicated that greater than 95% ammonia removal from high-ammonia-N (2142 mg/L) leachate can be achieved with rotating biological contactor ammonia-N loading rates up to 1.5 g/(m² day). At rotating biological contactor loading rates of 1.5–3.0 g/(m² day), ammonia removal ranged from 80 to 90%. Nitrogen removal averaged 54%. BOD and

COD removal averaged 92% and 49%, respectively. Overall removal of dissolved metals ranged from 19% for nickel to 59% for manganese (Henderson and Atwater 1995). The denitrification performance of a laboratory-scale rotating biological contactor using landfill leachate—from a municipal landfill in the North of Portugal—with high nitrate concentration was evaluated by Cortez et al. (2011). Under a carbon-to-nitrogen ratio (C/N) of 2, the reactor achieved N–NO₃—removal efficiencies above 95% for concentrations up to 100 mg N–NO₃—per 1 L. The effectiveness of COD removal was about 90%. In Vicevic et al.'s (2005) study the rotating biological contactor system averaged COD and BOD removal efficiency of 84% and 94%, respectively.

Biological reactor has also the capability to remove some metals. The mechanism by which this removal takes place is known as a bio-adsorption. Anaerobic system also removes metals by the reduction of sulphate to insoluble metal sulphides as the samples of sludge from rotating biological contactor reactor showed high concentration of these metals (Vicevic et al. 2005). Results of Torabian et al. (2004) showed that anaerobic reactor with detention time of 4.5 days had a 44% COD removal. The effluent COD of sequencing batch reactor was 21,309 mg/L. The removal of phosphorus was quite high—71%. The effectiveness for nitrate and nitrite removal was 32% and 33%, respectively.

Effluents from rotating biological contactor require a further treatment. One of the treatment possibilities can be the use of reverse osmosis. There are no too many data concerning leachate treatment by rotating biological contactor followed by reverse osmosis. In Table 7 the effectiveness of reverse osmosis with rotating biological contactor pretreatment in purification of landfill leachate from Mechernich landfill (Germany) is presented. The rotating biological contactor plant was designed for a nitrogen loading of 2 g N/m²·day. The contactor surface of 65,000 m² was divided into four lines with three biological contactors in series. The reverse osmosis was a two-stage plant. The first stage was equipped with tubular modules with cellulose acetate membranes. The second stage was equipped with composite membranes in spiral wound modules. Membrane plants were designed for leachate flow of 65–130 m³/day (Baumgarten and Sayfried 1996).

In the analysed treatment plant at Mechernich landfill the COD and BOD initial value was reduced by over 99%. The average COD value in permeate was 16.8 mg/L and BOD value—2.11 mg/L. The 97% of BOD removal was performed in rotating biological contactor. The rotating biological contactor pretreatment caused the big reduction of nitrogen compounds such as N–NH₄⁺, total organic nitrogen, and total inorganic nitrogen. The removal effects after rotating biological contactor were 99% for N–NH₄⁺, 86% for total inorganic nitrogen, and 67% for total organic nitrogen. The total removal effects for these compounds were over 97%.

Table 6 Performance of rotating biological contactor treating landfill leachate

Parameter	Influent (mg/L)	BOD/COD	RBC effluent (mg/L)	Removal (%)	Type	References
COD	3950	0.67	—	53.4	HRT = 34 rpm = 3	Castillo et al. (2007)
COD	3950		—	58.5	HRT = 34 rpm = 6	
COD	3950		—	58.5	HRT = 34 rpm = 9	
COD	5040	0.1	2660	49	rpm = 10–25	Henderson and Atwater (1995)
BOD	705		63	92		
N-NH ₄ ⁺	2142		222	≈ 90		
Ni	0.00113		0.00091	19.5		
Fe	7.3		4.59	37		
Mn	0.77		0.32	59		
N-NO ₃ ⁻	560	< 0.5	—	> 95	n.a.	Cortez et al. (2011)
COD	—	—	≈ 90			
BOD	5340	0.6	—	94	n.a.	Vicevic et al. (2005)
COD	9254		—	84		
Zn	3.6		—	92		
Mn	7.6		—	82		
Ca	700		—	92		
Mg	339		—	19		
Cr	0.14		—	70		
Ni	0.83		—	46		
COD	—	n.a.	21,309	44	n.a.	Torabian et al. (2004)
P _{total}	—		27	71		
N-NO ₃ ⁻	—		100	32		
N-NO ₂ ⁻	—		0.6	33		

The use of rotating biological contactor for landfill leachate treatment gave an efficiency of above 90% for BOD removal. The removal rates for COD and N-NO₃⁻ were characterized by a high variability and ranged from 44 to 90% for COD and from 32 to 95% for nitrogen nitrite. The lowest treatment efficiency was observed for metals (Ni, Fe, Cr, Ni) and Ca

HRT hydraulic retention time, rpm revolutions per minute (speed), n.a. data not available

The lower removal efficiency was noted for N-NO₃⁻ (68%) and N-NO₂⁻ (20%). The use of reverse osmosis as one of the stages of leachate treatment gave good purification results for Pb—99%, adsorbable organohalogen—more than 99%, and Cl⁻—98% (Baumgarten and Sayfried 1996).

Up-flow anaerobic sludge blanket and reverse osmosis

Up-flow anaerobic sludge blanket is found as one of the most studied biological processes for leachate treatment. It involves biological decomposition of organic and inorganic matter in the absence of molecular oxygen (Wiszniowski et al. 2006). The up-flow anaerobic sludge blanket plant design consists of a biological reaction zone and a sedimentation zone (Fig. 4).

Leachate is pumped from the bottom into reactor where influent suspended solids and bacterial activity and growth

lead to the formation of sludge. The sludge blanket is comprised of microbial granules of 1–3 mm in diameter. As the flow passes upwards through bed of activated sludge, bacteria living in the sludge break down organic matter by anaerobic digestion, transforming it into biogas (methane and carbon dioxide). The rising bubbles mix the sludge without the assistance of any mechanical parts. After several weeks of use, larger granules of sludge form, which act as a filter for smaller particles as the effluent rises through the cushion of sludge. In the up-flow anaerobic sludge blanket reactor, the substrate degradation occurs mainly in the lower part of the reactor due to the presence of a high concentration of active anaerobic sludge, effective mixing of the incoming wastewater flow with the partially purified water present in the upper part of reactor, and the occurrence of colloidal particles, precipitation, and sedimentation.

The clarified effluent is extracted from the top of the tank in an area above the sloped walls. A gas–liquid–solids

Table 7 Effectiveness of reverse osmosis with rotating biological contactor pretreatment in purification of landfill leachate

Parameter	Influent	BOD/COD	RBC effluent	RO effluent	Removal	Type	Localization	References
COD	3176	≈ 0.3	1301	16.8	99	Contactor surface:	Mechernich land-fill, Germany	Baumgarten and Sayfried (1996)
							Full scale	
BOD	1062		23.7	2.11	> 99	65,000 m ²		
TON	251		82.1	5.71	97	Two-stage RO		
N-NH ₄ ⁺	884		1.9	0.48	99	Leachate flow		
N-NO ₃ ⁻	32		129	10	68	of 65–130 m ² /day		
N-NO ₂ ⁻	0.1		2.4	0.12	20			
TIN	916		131.2	10.6	98			
Pb	0.593		0.142	< 0.001	99			
AOX	1261		775	< 0.01	> 99			
Cl ⁻	2172		2010	29	98			

A combination of rotating biological contactor with reverse osmosis gave a very good result in removal of organic parameters, such as BOD (> 99% removal), COD (99%), total organic nitrogen (97%), and adsorbable organohalogenes (> 99%). A high treatment efficiency was also observed for inorganics: N-NH₄⁺, total inorganic nitrogen, Pb, and Cl⁻. The lowest removal effect was noted for N-NO₂⁻ (20%)

Values of influent and effluent in mg/L except for pH and EC (mS), removal effect in %

RBC rotating biological contactor, RO reverse osmosis, TON total organic nitrogen, TIN total inorganic nitrogen, AOX adsorbable organohalogenes, n.a. data not available

separator separates the gas from the treated wastewater and the sludge. The pH value needs to be between 6.3 and 7.85 to allow the bacteria responsible for anaerobic digestion to grow. For an optimal growth of these bacteria and thus an optimal anaerobic digestion, the temperature should lie between 35 and 38 °C (Anaerobic Treatment...2001).

The optimal hydraulic retention time generally lies within 2–20 h because at lower hydraulic retention times, the possibility of washout of biomass is more prominent (Bal and Dhagat 2001). The up-flow anaerobic sludge blanket process has several advantages over other anaerobic processes. It is simple to construct and operate and is able to tolerate high organic and hydraulic loading rates. The key feature of the up-flow anaerobic sludge blanket process, that allows the use of high volumetric COD loadings compared to other anaerobic process, is the development of dense granulated sludge (Li et al. 1995).

Conventionally, an up-flow anaerobic sludge blanket has mostly been installed in leachate treatment process for treating high-loading organic compounds discharged from young landfills (Im et al. 2001). Table 8 presents the result of up-flow anaerobic sludge blanket process in treating leachate from different landfills. Singh and Mittal (2012) report the applicability of up-flow anaerobic sludge blanket process to treat the leachate from a municipal Okhla landfill located in Delhi (India). A laboratory-scale reactor was operated at an organic loading rate of 3 kg COD/L•day corresponding to a hydraulic retention time of 12 h for over 8 months. The removal efficiency of soluble COD ranged between 67 and 91% for fresh leachate and decreased drastically from 90 to 35% for old leachate. The use of up-flow

anaerobic sludge blanket reactor for leachate treatment at the Istanbul Kömürcüoda landfill (Turkey) provided over 80% of BOD and COD removal in young leachate samples. The organic loading rate ranged from 0.75 to 8 kg COD/L•day (Akgul et al. 2013). Data from landfills with up-flow anaerobic sludge blanket treatment process show that the BOD/COD ratio profoundly impacts upon effluent quality (Alvarez-Vazquez et al. 2004). Kettunen and Rintala (1998) reported a 63–75% COD removal from a young leachate matrix. In Keenan et al. (1991) up-flow anaerobic sludge blanket study, a 90% COD removal was achieved in a medium-aged leachate. Treating of leachate using up-flow anaerobic sludge blanket reactor at Ottawa-Carleton Landfill (Canada) was investigated by Kennedy and Lentz (2000). The up-flow anaerobic sludge blanket was operated at organic loading rates between 4.8 and 19.7 g COD l•day. The up-flow anaerobic sludge blanket reactor had soluble COD removal efficiencies ranging between 77 and 81% at hydraulic retention time of 24, 18, and 12 h. Removal effects for phosphorus, chlorides, and sulphides were below 50%; nevertheless, the concentrations of the effluents from reactor were below guideline concentration. The up-flow anaerobic sludge blanket had a sulphate removal efficiency of 81% and zinc removal efficiency of 75% (Kennedy and Lentz 2000). Research conducted by Calli et al. (2006) indicated that landfill leachate containing total ammonia concentration above 2000 mg/L can be treated successfully by using up-flow anaerobic sludge blanket. By reducing the influent pH to 4.5 to control the free ammonia levels in the reactors, COD removal

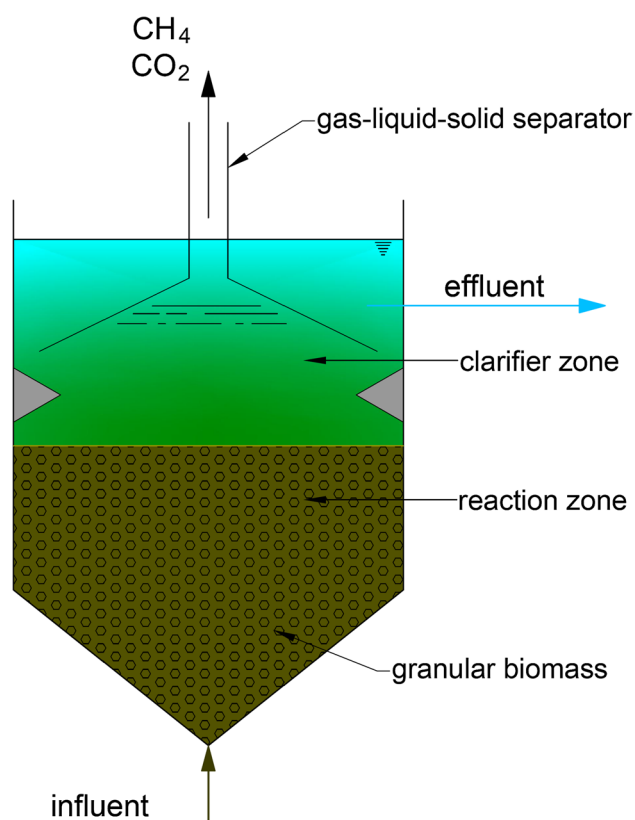


Fig. 4 Schematic diagram of an up-flow anaerobic sludge blanket. Leachate enters the reactor from the bottom and flows upwards. A suspended sludge blanket, which is comprised of microbial granules, filters and treats the leachate as the leachate flows through it. As a result of organic degradation, gases (methane and carbon dioxide) are released. The rising bubbles mix the sludge without the assistance of any mechanical parts. The clarified effluent is extracted from the top of the tank in an area above the sloped walls. *Source:* Adapted from <http://www.engineeringfundamentals.net/UASBs/fundamentals.htm>

efficiencies above 80% were achieved without any significant loss in methanogenic activity (Calli et al. 2006).

The up-flow anaerobic sludge blanket technology is widely and effectively accepted for treating young leachate with high BOD concentration (Kurniawan et al. 2006; Khan et al. 2013). However, COD removal from old landfill leachate presents a challenging problem for this conventional biological treatment due to the presence of bio-refractory and toxic contaminants, resulting in the requirement of multi-stage operations and large footprint systems to achieve moderate results (Ahmed and Lan 2012). Successful leachate treatment requires addition of non-biological stage such as among other membrane separation (Ahmed and Lan 2012). Bohdziewicz and Kwarciak (2008) showed an effective removal of leachate contaminants by using reverse osmosis following up-flow anaerobic sludge blanket (Table 9).

In their study an up-flow anaerobic sludge blanket reactor was operated at a hydraulic retention time of between 7 and 2 days and organic loading rate ranging between 0.6 and 2.0 kg COD/m³·day. The hydraulic retention time of 3 days and organic loading time of 1.3 kg COD/m³·day were taken as the optimum fermentation process parameters. Under such designed conditions COD removal after up-flow anaerobic sludge blanket achieved a value of 76%. The concentration of COD, BOD, ammonia nitrogen, chloride concentration in up-flow anaerobic sludge blanket effluent was kept on the level of 960 mg O₂/L, 245 mg O₂/L, 196 mg NH₄⁺/L, and 2350 mg Cl⁻/L, respectively. Due to poor quality of up-flow anaerobic sludge blanket effluent, leachate was put into the post-treatment process. In reverse osmosis process COD, BOD, chloride, ammonia nitrogen parameters were removed in 95.4, 90.2, 85.4, and 88.7%, respectively.

A combination of an up-flow anaerobic sludge blanket reactors and reverse osmosis was studied for the treatment of stabilized leachate from the Bavel landfill (Netherlands) (Kurniawan et al. 2006). The up-flow anaerobic sludge blanket reactor was employed for pretreatment of leachate (Table 9). Since recalcitrant compounds with initial COD and N-NH₄⁺ concentrations of 35,000 and 1600 mg/L, respectively, were able to be completely removed from the leachate, the effluent was discharged to surface water without further treatment (Jans et al. 1992; Kurniawan et al. 2006).

Comparison of biological pretreatments for leachate purification with reverse osmosis

To evaluate the reverse osmosis performance with different biological pretreatments a brief comparative study in terms of COD, BOD, N-NH₄⁺, Cl⁻, Pb, N-NO₂⁻, N-NO₃⁻, and total suspended solids was done (Table 10).

Although it has a relative meaning due to different testing conditions (pH, temperature, strength of leachate, seasonal climate changes, operation conditions), this comparison is useful to evaluate the overall treatment performance of each technique for helping the decision-making process.

It is found that the COD removal effect is similar in all analysed leachate treatments and ranged from 97 to 99% in combination reverse osmosis with membrane bioreactor pretreatment to 99–99.5% in reverse osmosis with activated sludge. Nevertheless, the more stable removal effect of 99% seems to be in up-flow anaerobic sludge blanket followed by reverse osmosis. The BOD removal achieved 91% in combination reverse osmosis and up-flow anaerobic sludge blanket, 97% in reverse osmosis with membrane bioreactor pretreatment, and over 99% in reverse osmosis and rotating biological contactor. With the passing of time concentrate (or leachate) recirculation affects the increase in ammonia

Table 8 Performance of up-flow anaerobic sludge blanket treating landfill leachate

Parameter	Influent (mg/L)	BOD/COD	UASB effluent (mg/L)	Removal (%)	Type	References
COD	88,000–66,420	n.a.	–	61–97* 35**	OLR = 3 kg COD/L•day HRT = 12 h Laboratory scale	Singh and Mittal (2012)
BOD	4640–27,465	0.75	–	> 80	OLR = 0.75–8 kg	Akgul et al. (2013)
COD	10,695–37,760		–	> 80	COD/L•day HRT = 24 h Laboratory scale	
COD	3100	0.6	–	63	On-site	Kettunen and Rintala (1998)
COD	1900	0.63	–	75		
COD	29,000	0.5	–	90	Pilot scale	Keenan et al. (1991)
COD	4800–9840	n.a.	600–1750	–	OLR = 4.8–19.7 g COD/L•day Laboratory scale	Kennedy and Lentz (2000)
				78	HRT = 24 h	
				81	HRT = 18 h	
				77	HRT = 12 h	
Cl [–]	3035		2352	22		
SO ₄ ^{2–}	165		31	81		
P _{total}	2		2	< 1		
Zn	0.4		0.1	75		
S [–]	35		18	48		
COD	–	n.a.	–	80	OLR = 1.3–23.5 Kg COD m ³ •day Laboratory scale	Calli et al. (2006)

The up-flow anaerobic sludge blanket process is able to achieve over 80% removal of BOD. But according to Ahmed and Lan (2012) the process is not enough efficient in COD reduction, especially from stabilized leachate, because of high concentration of refractory and toxic compounds UASB up-flow anaerobic sludge blanket, *OLR* organic loading rate, *HRT* hydraulic retention time, *rpm* revolutions per minute, *n.a.* data not available

*Young leachate, **Old leachate

Table 9 Effectiveness of reverse osmosis with up-flow anaerobic sludge blanket pretreatment in purification of landfill leachate

Parameter	Influent	BOD/COD	UASB effluent	RO effluent	Removal	Type	Localization	References
COD	4000	0.3	960	44	n.a.	HRT: 7–2 days	Sobuczyna	Bohdziewicz and Kwarciak (2008)
BOD	280		245	24	n.a.	OLR: 0.6–2.0 kg	landfill	
N–NH ₄ ⁺	890–994		196	22	n.a.	COD/m ³ •day	(Poland)	
Cl	2500		2350	215	n.a.		Laboratory scale	
COD	25,000–35,000	n.a.	3000–5000	5–8	99	HRT: 8–12 h	Bavel landfill	Jans et al. (1992)
TN	1600		1550	n.a.	99	OLR: 25 kg COD/	(Netherlands)	
TSS	0–50		150–200	n.a.	10	/m ³ •day	Full scale	

The use of reverse osmosis as a second step of leachate treatment significantly improved the efficiency of COD and nitrogen compounds removal to over 90%. However, combination of reverse osmosis and up-flow anaerobic sludge blanket may be inefficient in reduction of suspended solids due to the generation of additional quantities of suspended solids during biological decomposition in up-flow anaerobic process

Values of influent and effluent in mg/L except for pH and EC (mS), removal effect in %

UASB up-flow anaerobic sludge blanket, *RO* reverse osmosis, *TN* total nitrogen, *TSS* total suspended solids, *HRT* hydraulic retention time, *OLR* organic loading rate, *n.a.* data not available

Table 10 Comparison of reverse osmosis performance with different biological pretreatments during leachate purification

	Removal performance (%)							
	COD	BOD	N-NH ₄ ⁺	Cl ⁻	Pb	N-NO ₂ ⁻	N-NO ₃ ⁻	TSS
MBR and RO	97–99	97	92–96	n.a.	n.a.	n.a.	n.a.	99
AS and RO	99–99.5	n.a.	99–99.8	99.2	> 99.7	97	83	> 99.9
RBC and RO	99	> 99	99	98	99	20	68	n.a.
UASB and RO	99	91	97	91	n.a.	n.a.	n.a.	10

Comparing the combination of reverse osmosis with different biological pretreatment methods one can observe the high effectiveness (over 90%) in COD, BOD, N-NH₄⁺, Cl⁻ removal for all analysed methods. Rotating biological contactor followed by reverse osmosis had the lower reduction rate for nitrite and nitrate ammonia. Combination of up-flow anaerobic sludge blanket and reverse osmosis is insufficient in suspended solids removal

TSS total suspended solids, RO reverse osmosis, MBR membrane bioreactor, AS activated sludge, RBC rotating biological contactor, UASB up-flow anaerobic sludge blanket, n.a. data not available

concentration in landfill leachate. That is why a very important issue is the N-NH₄⁺ removal from leachate.

The almost complete N-NH₄⁺ removal (99–99.8%) was achieved in activated sludge followed by reverse osmosis. The high efficiency of 97 and 99% was also observed for up-flow anaerobic sludge blanket and rotating biological contactor, respectively. The chloride removal ranged from 91% in reverse osmosis and up-flow anaerobic sludge blanket to over 99% in reverse osmosis and activated sludge. There are also some data concerning N-NO₂⁻ and N-NO₃⁻ removal, which were highest (97 and 83%) in combination reverse osmosis and activated sludge. A very significant issue in leachate treatment with the use of reverse osmosis is total suspended solids removal before the process. It can contribute to prolongation of membrane's lifetime and to the decrease in exploitation cost. The almost complete total suspended solids removal was observed for reverse osmosis and activated sludge (over 99.9%) and reverse osmosis and membrane bioreactor (99%). The combination of reverse osmosis and up-flow anaerobic sludge blanket gave 10% effectiveness in total suspended solids reduction.

Biological pretreatment has many advantages for leachate treatment by reverse osmosis. It increases the final removal effect especially in terms of organic compounds. The conventional biological systems are usually easy in operation and simple in exploitation. They are suitable for pretreatment of leachate to complete the biological degradation process.

Conclusion

In order to meet the strict quality standards for leachate discharge, an integrated biological and physico-chemical method of treatment has been developed. The presented data have shown that all analysed combinations of biological pretreatment followed by reverse osmosis are effective

in removing COD, BOD, and N-NH₄⁺ from landfill leachate. Almost complete removal of both COD and N-NH₄⁺ has been accomplished by a combination of reverse osmosis and activated sludge. The highest removal of BOD has been achieved using reverse osmosis and rotating biological contactor.

Both activated sludge and rotating biological contactor in combination with reverse osmosis were effective in Cl⁻ and Pb removal (over 98%). Activated sludge followed by reverse osmosis gave a good result in reduction of N-NO₂⁻ and N-NO₃⁻ from leachate influent. A high total suspended solids removal effect (99 and 100%) provided by membrane bioreactor and activated sludge permits further treatment by reverse osmosis and suppresses fouling of membrane.

It is important to note that the selection of the most suitable treatment technology for landfill leachate depends on the quality and quantity of leachate, age of landfill, plant flexibility, and operating conditions. Economic parameters also play an important role in this decision-making process.

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