THE TREATMENT OF LEACHATE FROM LANDFILLS

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Abstract
Sanitary landfilling is the most common way to eliminate solid urban wastes. An important problem associated to landfills is the production of leachates. Because of its characteristics and because of its occurrence at remote locations, leachate needs to be treated separately from municipal or other wastewater. In this paper, the main technologies for the treatment of leachate from landfills are presented with special attention to hybrid processes, combining biological and physical treatment steps to fulfil the future demand on save, reliable and economic landfill leachate treatment. The technologies shall be grouped according to outlet requirements and inlet pollution load, pointing out the main advantages and disadvantages of each technology. This paper will summarize 25 years of experience in treating leachate in Europe, Asia and North Africa.

1. INTRODUCTION

For several decades it has been acknowledged that leachate from landfill sites imposes a severe and detrimental impact on the environment. Focal parameters are COD, BOD_5, NH_4-N, heavy metals and salts (especially chloride or sulphate). In the past, the adverse effect of leachate on waterbodies and wastewater treatment works very often was heavily underestimated due to its comparably low volumetric flows. In recent years it has become accepted that leachate even in small amounts is a very harmful liqueur, because its loadings on hazardous and toxic pollutants can exceed the loadings in municipal wastewater by approximately two to three orders of magnitude. It has now been widely recognized that leachate needs to be treated and needs to be treated separately. Yet for all the different types of wastewater, throughout one country the same effluent standards have to be met. This means that there is no such thing as the leachate treatment but from a range of technologies the most appropriate has to be chosen in accordance with leachate characteristics, effluent requirements and technical prerequisites at the site. This paper will concentrate on those forms of treatment that are most commonly used in Europe, Asia and North Africa, giving a brief overview on their advantages and disadvantages.

2. LEACHATE FROM LANDFILLS

The importance of good health requires the deposition of domestic and industrial solid waste in landfills, often located at remote areas. But the decomposing of the waste within these landfills creates major environmental problems: Emissions such as the landfill generated greenhouse gases methane and carbon dioxide as well as a liquid known as leachate are of major concern.

Landfill leachate originates from water contained in the discharged waste and from infiltration water that seeps through the body of the landfill. The so generated leachate is highly polluted due to a high content of ammonium ions and organic compounds. In most cases it is toxic, acidic and rich in halogenated hydrocarbons. It has a high buffer capacity, possesses a high amount of inorganics (salts) and usually shows an unbalanced COD to NH4-N ratio. Furthermore, the COD often consists of lots of non-biodegradable COD, the so called “hard COD”. The leachate can contain elevated values of chloride and sulphate ions as well as a high concentration of common metal ions especially iron or even heavy metals. In some European countries new pollutants like pharmaceuticals, pesticides or fluoro-surfactants and even nanoparticles have come into public focus recently and are discussed on expert levels and among authorities. It cannot be ruled out that these pollutants will be introduced to discharge limits in the future.

However, the composition of waste as well, as specific regulations on waste disposal have an impact on the leachate produced. Also the location of the landfill site has an influence: Different climates, different lifestyles, different waste collection systems etc. have an effect on the leachate amount and its composition. Moreover, the composition of leachate varies over the years: Leachate from an “aged” municipal landfill site in the methane phase has a very different composition than that from a “young” municipal landfill site in the acid phase or a landfill site containing industrial waste or mining waste. This can lead to distinct differences in the characteristics. As an example, the main pollutants (COD and NH4-N) of leachate from different origins are shown in Tab. 1.

When leachate moves downwards through the landfill-body it washes out all contaminants from the discharged waste and gets loaded with all components that are soluble in water. To avoid infiltration to the soil or even to the groundwater landfills are equipped with a bottom sealing, preventing the leachate from entering the environment.

The amount of leachate generated by a landfill can be quite different and it occurs discontinuously. The amount is mainly governed by the moisture content of the discharged waste, the climate (amount of rainfall) and the existence of a top cover of the landfill. For landfills it is significant that the occurrence of leachate can be observed for decades. Therefore, the landfills are commonly equipped with a piping systems installed above the liners as leachate collection and discharge system. From this system the leachate is pumped out and treated before discharging to the environment,

Tab. 1. Regional differences in the leachate characteristics

Region	COD range [mg/l]	NH_4-N range [mg/l]
Northern Europe	< 5.000	< 1.200
Southern Europe	< 15.000	< 2.000
Turkey	< 20.000	< 2.500
Northern Africa	< 70.000	< 2.500
Asia	< 25.000	< 3.000

Treating leachate can be difficult because of its complex and heterogeneous nature and because of its discontinuous occurrence. Additionally, regional differences in legislation for the leachate discharge are defining different demands on the treatment technology and the discharge limits as shown in Tab. 2.
When discharging leachate it is important to define to where it is to be discharged:

indirect discharge: → discharge to the sewer
direct discharge: → discharge to the watercourse

Tab. 2. Regional differences in the leachate discharge limits

	COD			NH_4-N		
	leachate	discharge		leachate	discharge	
		indirect	direct		indirect	direct
	[mg/l]	[mg/l]	[mg/l]	[mg/l]	removal	[mg/l]
Germany (northern Europe)	< 5.000	400	200	< 1.200		
Spain (southern Europe)	< 15.000	1.500	160	< 2.000	up to 95%	10
China (Asia)	< 25.000	1.000	100	< 3.000		

The table reflects the main and easy determinable pollutants. Generally, there are many other parameters to be met like NO_3-N, TN, AOX, heavy metals, which are part of different local discharge consents

There are also special forms of leachate such as the Asian bunker water (leachate from fresh municipal waste containing a very large proportion of organic matter that needs to be dewatered before being incinerated) or water from mechanical-biological waste treatment (MBT) plants which are not accounted for in this paper.

3. LEACHATE TREATMENT IN ACCORDANCE WITH INLET CONCENTRATIONS AND OUTLET REQUIREMENTS

In summary it can be stated that there is no typical process for landfill leachate treatment existing. In fact, there are very different leachate treatment processes available and applied to meet the different requirements and to handle the different types of leachate. The focus of this paper will be on aerobic technologies in combination with filtration techniques as principal means to treat landfill leachate successfully. Tab. 3 depicts the most appropriate concepts depending on influent contamination and effluent requirements.

There are also physico-chemical processes which can be used to treat leachate, for example chemical oxidation, flocculation/precipitation, evaporation, stripping, ion exchange. However, since none of them has proven successful as a sole treatment technology or has an elevated demand on chemicals and energy, they are not dealt with here; they may be used as additional pre- or post-treatment steps, though.

Anaerobic treatment is not used in Europe because COD concentrations are far too low and also because nitrogen removal is required and not achievable with an anaerobic treatment. In Asia, anaerobic treatment is often used as a first treatment step e.g. when bunker water with COD concentrations up to 70.000 mg/l needs to be treated but one has to consider the tendency to huge problems with precipitation of inorganics when this process is applied to treat leachate with its high salt content. Since bunker water is a special form of leachate and not focus of this paper, anaerobic processes will not be dealt with hereafter.

Tab. 3. Decision support matrix for leachate treatment processes

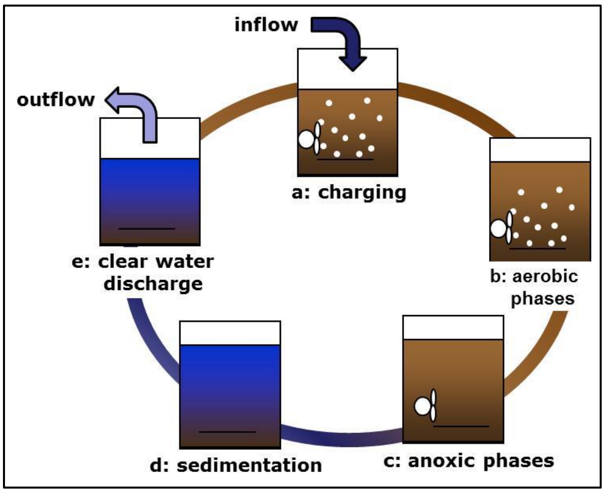
<table>
<tr><th></th><th>Discharge to sewer
COD < 500 mg/l</th><th>Discharge to watercourse
COD < 200 mg/l</th><th>Discharge to watercourse
COD < 200 mg/l
+ salt-reduction</th></tr>
<tr><td>Lowly loaded
COD < 1,500 mg/l
NH4-N < 500 mg/l</td><td>SBR
(option: + sandfilter + AC)</td><td>MBR + AC</td><td rowspan="2">Reverse Osmosis (RO)</td></tr>
<tr><td>Medium loaded
COD < 5,000 mg/l
NH4-N < 1,500 mg/l</td><td rowspan="2">MBR+ AC</td><td rowspan="2">MBR + NF
(option: concentrate treatment with AC)</td></tr>
<tr><td>Highly loaded
COD > 5,000 mg/l
NH4-N > 1,500 mg/l</td><td>MBR + RO</td></tr>
</table>

3.1. Low outlet requirements: BOD5 and NH4-N reduction in a Sequencing Batch Reactor (SBR)

If only reduction of BOD5 and NH4-N (no explicit COD and TN reduction) is desired, the most cost-effective form of treatment is the sequence batch reactor (SBR), a form of activated sludge treatment. Traditional activated sludge plants utilise an aerobic/biological tank followed by a settlement chamber. Solids/sludge separation is carried out by gravimetric settlement, where solids are settled to the bottom of the vessel. The supernatant liquid is removed as clean/treated leachate and the remaining solids are recycled to the aerobic/biological tank for reuse. The SBR combines several process steps in a single unit tank (Fig. 1). Raw leachate is fed to the reactor and the aerated biological stage is timed to operate for a specified period. After this, the aeration system is shut down and an anoxic phase with intensive mixing is following. Finally the mixing is shut down and the solids are allowed to settle to the bottom of the reactor. The supernatant (in equal volume to the initial raw leachate feed) is removed and discharged (to sewer or watercourse) and the cycle starts again with a new batch of raw leachate. When necessary a proportion of the suspended solids will be removed as excess sludge.

In case a SBR reactor is applied for the treatment of leachate with high NH4-N concentrations, one has to be aware of the complex control mechanisms which are required in order to maintain the pH value and with it to keep the biological process stable. This is necessary as the pH in a SBR is subject to great variations. Outlet requirements of NH4-N < 100 mg/l and BOD5 < 50 mg/l are easily fulfilled. However, depending on the local (cold!) climate and nitrogen removal requirements, large reaction volumes, i.e. large basins are required. Yet large basins imply large surfaces which enhances the cooling effect and, as a consequence, leads inevitably to a decrease of biological activity and thus to a loss of process stability. Only a sound insulation of tanks and perhaps heating of bioreactors can avert these problems.

Fig. 1. Principle of the SBR concept



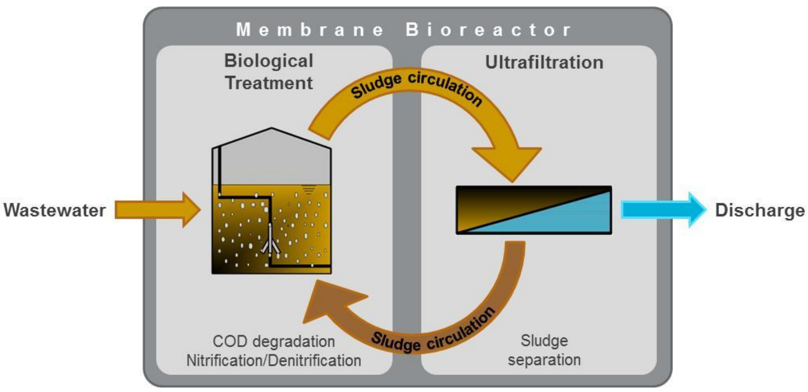
3.2. Medium outlet requirements: Nitrogen and COD reduction required

When requirements on the leachate treatment become somewhat tighter, the focus usually is on nitrogen (NH4-N < 10 mg/l and/or total nitrogen reduction of > 90 %) and COD removal. Then a SBR needs a more sophisticated process design and consequently the investment costs increase substantially - and still it often fails to meet outlet requirements. This again makes an additional treatment step obligatory. But since the effluent contains high concentrations of suspended solids, a subsequent treatment becomes difficult and expensive. In this case, a Membrane Bioreactor (MBR) is an excellent key-technology, which might be applied either exclusively or in combination with other treatment steps.

3.2.1 Membrane Bioreactor (MBR)

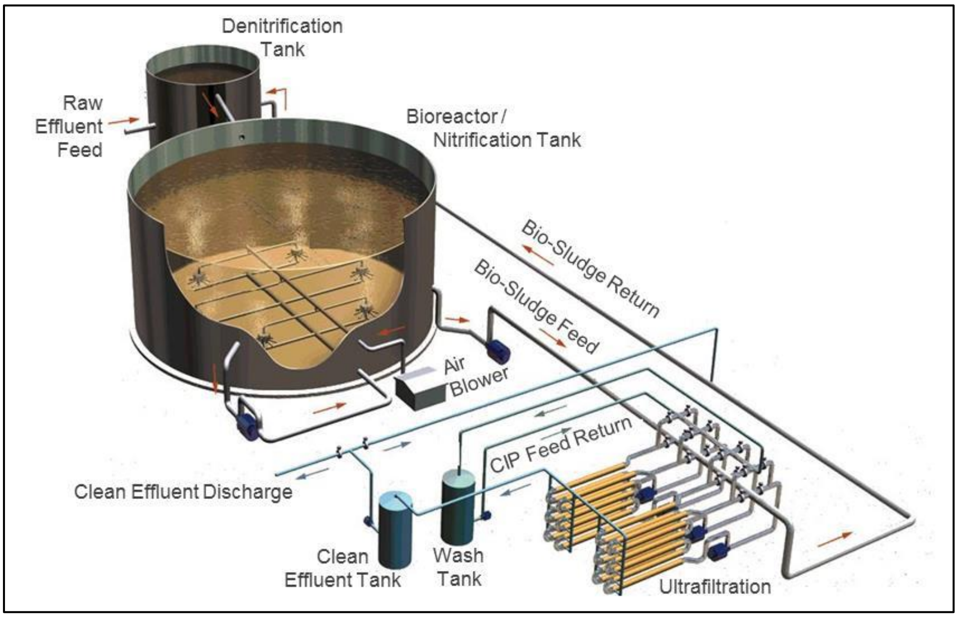
A MBR consists of two main units: A biological system and an ultrafiltration (UF) (see Fig. 2). The ultrafiltration separates the biomass from treated effluent and replaces the settling tank. The activated sludge is being pumped through external tubular membrane modules and during the passage of the modules, treated effluent is being separated from the biomass.

Fig. 2. Operation principle of a MBR



As the pore size of an ultrafiltration membrane lies around 0.02 - 0.05 µm, no activated sludge is lost, i.e. biomass and suspended matter are retained in the biological system. The complete retention of biomass is a distinctive feature compared to conventional treatment systems and SBRs which two main beneficial effects: - the concentration of adapted bacteria can be kept at a high level - the partical-associated contaminants remain in the system, which improves effluent quality.

Fig. 3. Schematic diagram of a MBR



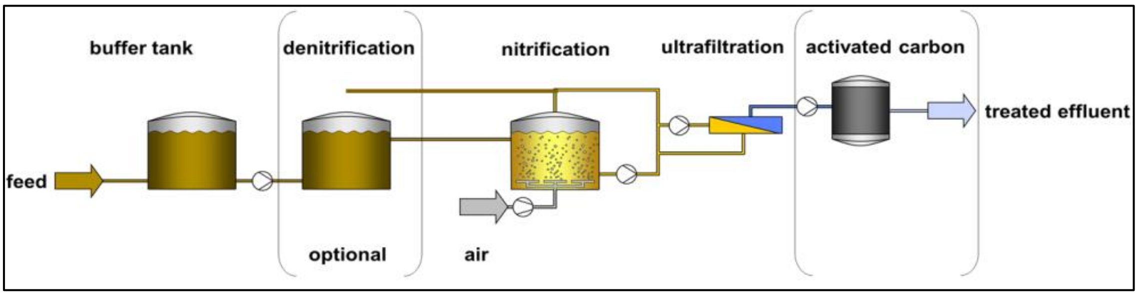
MBRs achieve more complete biodegradation compared to other aerobic systems because of high MLSS-concentrations in the reactors (10 – 25 g/l) and a very high sludge age (20 – 60 days). Some countries, such as Great Britain, set target values for TSS in the outlet. These requirements cannot be fulfilled by an SBR alone. Therefore, in most cases it is more cost efficient to build an MBR system than equipping an SBR with a subsequent solid retention step. They are very robust, reliable and fully automated systems. The easy CIP cleaning, the low membrane replacement costs and the modular and flexible operation (especially with varying leachate quantities and qualities) are the main arguments that make the MBR technology most suitable in landfill leachate treatment. In Fig. 3 a schematic diagram of a MBR-Process is shown.

3.2.2 MBR + Activated Carbon (AC)

Although in a MBR a substantial COD reduction is achieved, the outlet COD requirements often cannot be met because COD in leachate contains a lot of the so called “hard COD” which is difficult to digest - the readily digestible fraction has often already largely been removed during the passage through the landfill itself. In these cases, a physical-chemical treatment such as activated carbon (AC), chemical oxidation or flocculation / precipitation is included to complete the leachate treatment. The application of a subsequent AC step is an effective means to bring down COD effluent concentration, as COD is absorbed and retained. Fig. 4 depicts schematically the configuration of a MBR system with external membranes with a subsequent activated carbon absorber.

The significant advantage of this configuration over an SBR is apparent: The effluent is free of solids (< 5 mg/l) and the biodegradable COD is removed completely. Moreover, the footprint of the installation is significantly smaller. The discharge limits for the treated leachate require a biological treatment to meet the nitrogen limits, and an activated carbon system to ensure compliance with the limits for non-biodegradable COD and AOX in the effluent of the plant. Particular requirements for salinity are not provided. The activated carbon is loaded with COD and AOX until the effluent concentration reaches the discharge limits; after this, the activated carbon has to be replaced. The loaded activated carbon is regenerated in special furnaces of the supplier and can then be reused. With this concept, the only residual material to be disposed of is the excess sludge that is produced in the bioreactor.

Fig. 4. Scheme of MBR/AC configuration



3.2.3 MBR + Nanofiltration

Whereas the combination MBR/AC is appropriate for lower loads of contaminants, this set-up is not economically viable for larger volumes, as the frequent regeneration of activated carbon would result in elevated operational costs. In this case, a subsequent nanofiltration (NF) is the more adequate process. Due to its unique properties between ultra-filtration (UF) and reverse osmosis (RO) membranes, NF has found a place in the removal of recalcitrant organic compounds and heavy metals from landfill leachate. This treatment process has the ability to remove particles with a molecular weight of higher than 300Da as well as inorganic substances through electrostatic interactions between the ions and membranes. The significance of this membrane lies in its surface charges, which allow charged solutes smaller than the membrane pores to be rejected, along with bigger neutral solutes and salts.

As a pressure driven (3 - 20 bar) cross-flow filtration technology with membrane pore sizes of 1 to 10 nm, NF is able to hold back molecular substances, such as dissolved organic compounds and bivalent ions, which pass an UF membrane. Monovalent ions such as chloride or sodium, which would increase the osmotic pressure, pass through the membrane and leaving the system with the treated leachate. Due to these two characteristics of a NF membrane, the nanofiltration process is ideal as a secondary treatment after MBR.

When using membrane filtration units for the treatment of leachates, two outputs are produced: a concentrate and permeate. The permeate as the clean effluent is usually very low polluted. The average pollutant concentration is far below discharge limits and the permeate as the treated effluent can be discharged directly into the watercourse. The concentrate containing the dissolved organic fraction as well as the bivalent ions is considered as liquid waste. Therefore it requires further treatment before it is discharged or sent back to the landfill as waste. Thus concentrates from the NF need to be treated furtherly. Treatment options are activated carbon, oxidation or flocculation/precipitation. Costs for the operation of a NF and for the subsequent treatment of NF concentrates are still far lower than costs for the direct treatment of the MBR effluent with physical-chemical means. This is because of the high COD concentrations in the NF concentrate that makes secondary treatment much more effective. This concept of concentrate treatment is an economic alternative to either burning or evaporation.

3.2.4 MBR + Nanofiltration + Activated Carbon (BIOMEMBRAT® plus)

The MBR technology combined with a nanofiltration unit allows strict effluent conditions to be met. However, this concept has a handicap if it is not possible to return the concentrate to the landfill or if the disposal costs are too expensive. A low residues production process technology for the leachate treatment has been developed, combining not only MBR and nanofiltration technology, but also a sustainable solution for the concentrate treatment: the BIOMEMBRAT® plus Process (Fig. 5).

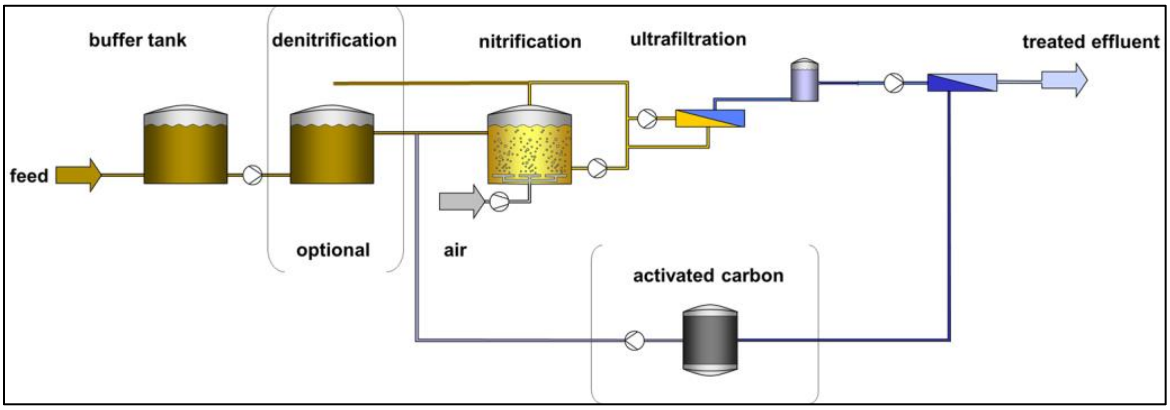
The process combines three of three different steps:

i. The biological treatment in the MBR, which reduces nitrogen concentration, BOD and biodegradable COD.

ii. A Nanofiltration Unit (NF) as post-treatment for the permeate coming from the MBR, where the slowly biodegradable COD, or the non-biodegradable COD are removed. In this step the wastewater is separated into two streams: A high loaded concentrate and a clean permeate. Depending on the type of membrane used for the NF, the COD of the permeate can reach values lower than 100 mg/l.
iii. An adsorption step with Activated Carbon (AC), where the concentrate coming from the NF will be treated. This concentrate can contain up to 8000 mg/l of non-biodegradable COD. This COD will then be adsorbed on the AC bed.

The costs of an AC-treatment are related to the maximal possible load before regeneration. Due to much higher pollution concentrations in the NF concentrate the achieved AC-loads are much higher as well. So, finally the operational costs caused by AC consumption are reduced by approx.. 50% compared to AC post treatment. Usually in a Reverse Osmosis plant (see chapter 3.3.1) both chlorides and sulphates are retained. This means that these salts will stay in the concentrate and since they are not adsorbed by the activated carbon, they will stay in the system. By using nanofiltration membranes the concentrate produced is more organic, because the monovalent ions mainly pass the NF membranes and therefore the NF permeates salts content is lower, and thus the efficiency that can be achieved at the AC reactor is much higher. The NF membranes are tough enough to cope with the discharge limit values.

Fig. 5. Schematic depiction of the BIOMEMBRAT® plus process



In the BIOMEMBRAT® plus process, only the excess sludge of the biological treatment has to be disposed of. The treated concentrate after the AC-treatment is sent back to the inlet of the plant and the permeate leaving the NF-unit can be directly discharged into the surface water bodies. The salts contained in the raw wastewater are discharged with the permeate. The AC can be regenerated by the supplier and can be reused again for the removal of organic matter from the wastewater. In Europe there are five plants working with this procedure. This process can not only be a solution for leachate treatment, but also for industrial wastewater treatment, where the production of lower residues is important.

3.3. High outlet requirements = Direct discharge to rivers

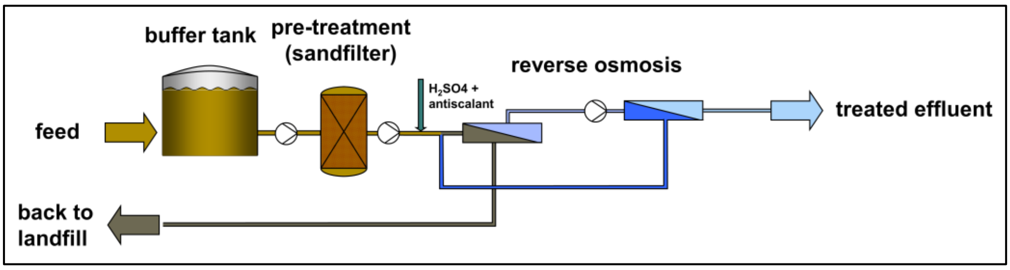
When a direct discharge of the effluent to a river is envisioned, high demands on the treatment regarding COD and nitrogen removal are made. In Europe, COD has to be lowered to 200 mg/l and in Asia even as low as 100 mg/l. NH4-N has to be lowering than 10 mg/l and denitrification as far as possible is demanded. Furthermore, some countries even ask for a distinct salt removal from the leachate before discharge to the watercourse. Environmental agencies survey inlets to rivers very closely; therefore the technique used for the leachate treatment has to fulfil high standards and has to be very reliable.

3.3.1 Reverse Osmosis

When stringent effluent quality parameters and especially low salinity/conductivity is demanded, the use of the reverse osmosis (RO) might be an adequate option for the treatment of landfill leachate. Fig. 6 shows a schematic flow diagram of the process. A pre-treatment, typically by filtration, is always needed to remove suspended solids. Moreover, if the NH4-N concentration in the leachate is high, a pre-treatment like a stripping unit is strongly recommended, to reduce the ammonium content before the leachate is pumped to the RO-unit, since strict NH4-N effluent limits cannot be met with high RO inflow ammonium levels when using single or two step RO systems. Some chemicals, such as sulphuric acid or antiscaling products, are added to prevent scaling on the RO membranes.

The reverse osmosis process is usually designed with at least two stages, where the permeate of the first stage is further treated in a second stage to fulfil the strict discharge limit requirements. The concentrate of this second stage is returned to the first stage, whereas the concentrate of the first stage has to be disposed of. This concentrate is usually a 20-40% of the total inlet volume and its disposal becomes a problem. As it will be described later, in many cases the concentrate is returned to the landfill, although this practice is nowadays forbidden in many countries. The only alternative is the external disposal by a waste management company, which leads to high operational costs. In this way, it has to be pointed out that the reverse osmosis is just a concentration process, which is not meant to degrade the pollutants but only to reduce volume of wastewater.

Fig. 6. Schematic depiction of a reverse osmosis plant for the leachate treatment



Although the RO permeate has a good quality (COD < 100 mg/L, no solids, low salt content), the RO process has a reduced reliability compared to other treatment techniques, mainly because of its troublesome operation, involving high operation costs (membrane replacement due to scaling/biofouling, chemicals consumption, etc.) and due to changes in the leachate composition which varies with the seasons of the year. In addition, the investment costs for large installations make this process a real alternative only in certain conditions: Low leachate volume (batch operation) and low pollutant concentration in the inlet.

3.3.2 MBR + Reverse Osmosis

As previously described, the treatment of landfill leachate by reverse osmosis implies a tough operation and high treatment costs, but a good quality effluent. The main problems of the RO process are related to the membrane performance. Landfill leachate contains many compounds, which are prone to affect the membrane, reducing the membrane flux by (bio)fouling, scaling or chemical damage. Most of these compounds may be removed or reduced in a MBR process, so the combination of MBR and reverse osmosis has achieved good performance in the treatment of landfill leachates, especially under direct discharge conditions, where high quality in the effluent is required.

The UF permeate from the MBR process is herein pumped into the RO unit, where the non-biodegradable COD and salts are removed. The reduced content in pollutants in the RO inlet leads to the installation of only one RO stage which is, moreover, operated at lower pressure. As a result, the concentrate volume and the amount of chemicals added are lower compared to the sole reverse osmosis process: The nitrogen compounds, as well as the biodegradable COD, are removed in the biological step by the combined nitrification/denitrification process, so there is no need of additional stages or treatments to remove NH4-N.

3.3.3 RO concentrate management: Back to the landfill?

As previously mentioned, the management of the RO concentrate has become a problem because of its high degree of pollution, especially in the case of a direct RO treatment, where all the pollutants contained in the leachate are concentrated in a lower volume. In some countries it is a common practice to return this concentrate back to the landfill. The aim is to try to deposit and fix in place some of the pollutants in the landfill bed once again, such as bivalent ions (carbonates, sulphates) or long-chained organic molecules.

However, the monovalent ions, such as ammonium or chloride, are barely or not at all retained in the landfill, leading to a re-concentration of these compounds in the leachate.

Fig. 7 and Fig. 8 show the evolution of concentration of COD and ammonium and the conductivity of the leachate, after the disposal of the concentrate back to the landfill. Obviously, there is a significant increase in these parameters once the client decided to return the concentrate back to the landfill, which has after a short time a notable effect on the leachate treatment in terms of treatment costs (increased demand on chemicals and energy, more concentrate production) and in terms of effluent quality, that is influenced negatively by increasing pollutant concentrations.

Fig. 7. Evolution of COD and NH4-N in leachate after the disposal of RO concentrate back to the landfill

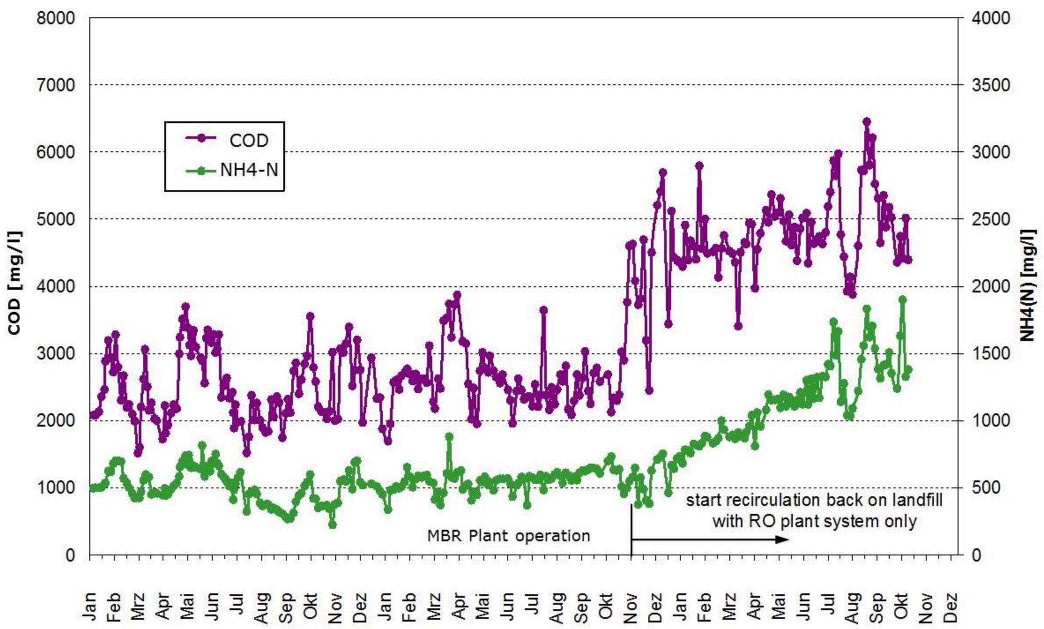
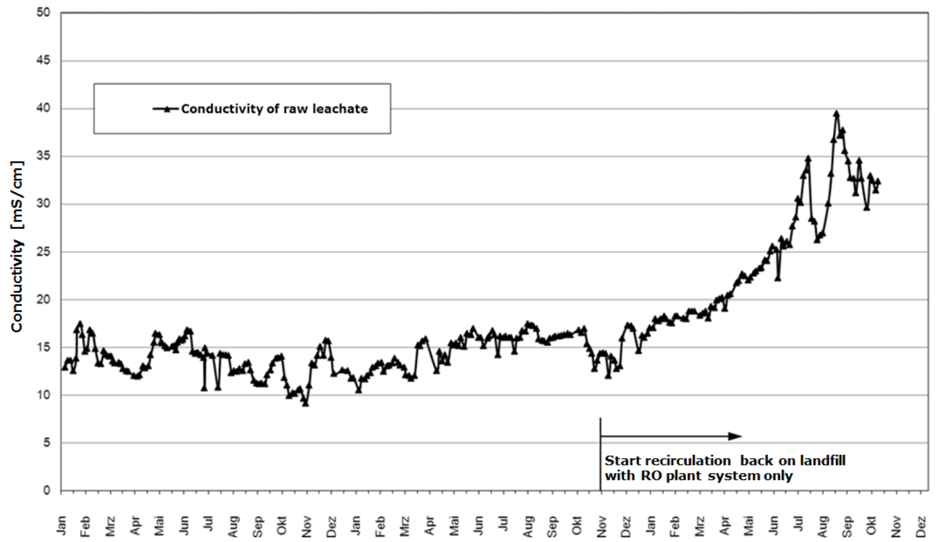


Fig. 8. Evolution of conductivity in the leachate after the disposal of RO concentrate back to the landfill



As the recirculation of RO concentrates results in a notable decrease of leachate quality and hence in plant performance, this is not at all a sustainable approach. As a consequence, several evaporation plants have been installed lately in landfills of Europe to reduce the waste volume of concentrates before they are disposed of externally. As a matter of fact, all these post-treatments increase the operation costs.

4. CONCLUSIONS

Aerobic processes for the treatment of leachate are very effective and more economical compared to the direct treatment of leachate with physico-chemical technologies. Throughout Europe and Asia, aerobic processes are the leading technology for leachate treatment. When effluent requirements exceed the pure reduction of BOD5, a Membrane Bioreactor (MBR) is an excellent means because it reaches maximal COD reduction and an effluent free of suspended solids. In combination with subsequent NF/RO, even very high outlet requirements can be met without the drawbacks that come along with a reverse osmosis as exclusive treatment process such as reduction of yield and deterioration of the overall treatment process performance due to constant salt enrichment.

To fully reduce the negative impact on the environment optimal leachate treatment is today's challenge. But, the complexity of the leachate composition makes it very difficult to formulate general recommendations on the proper treatment technology. Variations in leachates, in particular their variation in flow at a single landfill site as well as the variation in load and pollution at a single site and when different landfills are compared means that the most appropriate treatment should be universal and adaptable. In many cases the conventional biological or physical treatment alone is not suitable to reach the requested level of purification and thus more complex “hybrid” treatment processes are demanded.

The various methods presented in the previous sections offer individual advantages and disadvantages with respect to certain facets of the problem. Suitable treatment strategies depend on two major criteria:

1. The final requirements given by local discharge water standards

2. The leachate characteristics such as COD, BOD, NH4-N, heavy metals, salts which vary with the age of a landfill

The knowledge of these specific parameters may help to select the most suitable treatment processes, according to the decision support matrix presented as Tab. 3.