Leachate management: leachate generation, collection, treatment and costs

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ABSTRACT

The control of leachate quantity and quality is the basis for long-term landfill operation with minimized emissions and also for leachate treatment. Biological processes as aerated lagoons or activated sludge plants are the most common practice for leachate treatment. But the remaining values of COD and AOX are still high. This was the reason to develop physical-chemical treatment steps as alternative or additional treatment methods. Many experiences with these treatment methods have been made in the past. Although a lot of treatment plants for leachate are under operation nowadays, the development is not yet finished. Some results of operation and effluents and the corresponding costs are presented.

INTRODUCTION

Sanitary landfill leachate is a high and complex polluted wastewater. Leachate pollution is the result of biological, chemical and physical processes in landfills combined with waste composition and landfill water regime. A characteristic of this wastewater is the change of some components with the change of biological conditions in landfills.

To secure long term dewatering of landfills and reduce increasing of treatment costs it is necessary to control leachate quantity and quality.

With increasing water quality standards the requirements on leachate treatment also increases. Treatment procedures must consider the small flow rates and the complex composition which often results in special operation problems. The following chapters

should give an overview on leachate generation, its development and standards of leachate control and treatment.

LEACHATE GENERATION: QUALITY AND QUANTITY
Leachate quality: aerobic and anaerobic biochemical processes

Aerobic degradation phase: The first phase of aerobic degradation of organic substances is generally of limited duration due to the high oxygen demand of waste relative to the limited quantity of oxygen present inside a landfill (Phase I, Fig. 1). The only layer of a landfill involved in aerobic metabolism is the upper layer where oxygen is trapped in fresh waste and is supplied by diffusion and rainwater. In this phase it was observed that proteins are degraded into amino acids, thus into carbon dioxide, water, nitrates and sulphates, typical catabolites of all aerobic processes (BARBER, 1979). Carbohydrates are converted to carbon dioxide and water and fats are hydrolysed to fatty acids and glycerol and are then further degraded into simple catabolites through intermediate formation of volatile acids and alkalis. Cellulose, which constitutes the majority of organic fraction of wastes, is degraded by means of extracellular enzymes into glucose which is used subsequently by bacteria and converted to carbon dioxide and water. This stage, due to the exothermal reactions of biological oxidation, may reach elevated temperatures if the waste is not compacted. Usually the aerobic phase is quite short and no substantial leachate generation will take place.

In very old landfills, when only the more refractory organic carbon remains in the landfilled wastes, a second aerobic phase may appear in the upper layer of the landfill. In this phase the methane production rate is so low that air will start diffusing from the atmosphere, giving rise to aerobic zones and zones with redox potentials too high for methane formation (CHRISTENSEN & KJELDSEN, 1989).
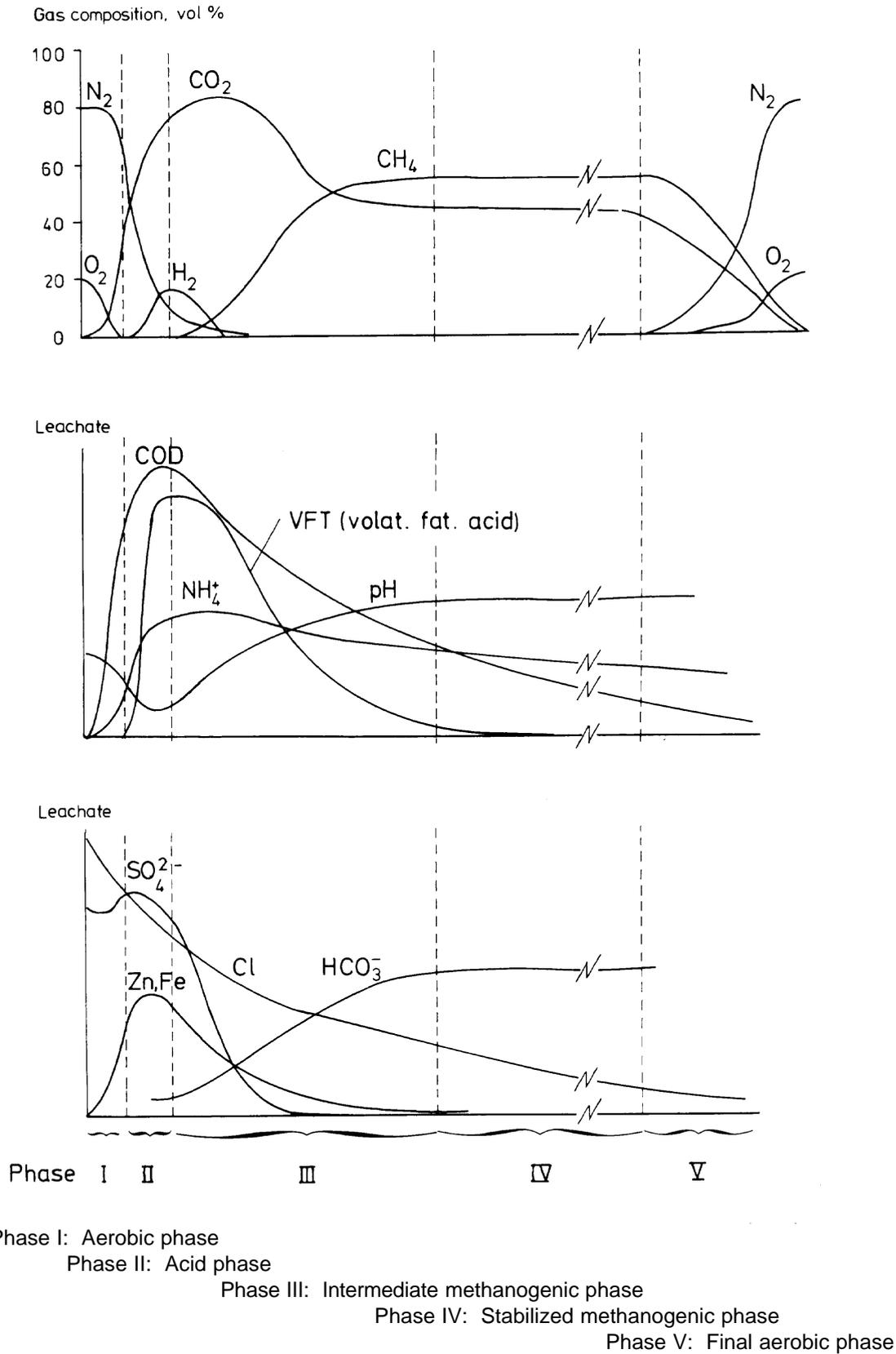
Phase I: Aerobic phase
    Phase II: Acid phase
        Phase III: Intermediate methanogenic phase
            Phase IV: Stabilized methanogenic phase
                Phase V: Final aerobic phase

Figure 1. Illustration of developments in leachate and gas in a landfill cell
(CHRISTENSEN & KJELDSEN, 1989)

Anaerobic degradation phases: Three different phases can be identified in the anaerobic decomposition of waste. The first phase of anaerobic degradation is acid-fermentation, which causes a decrease in leachate pH, high concentrations of volatile acids and considerable concentrations of inorganic ions (for example, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+). The initial high content of sulphates may slowly be reduced as the redox potential drops and metal sulphides are gradually generated that are of low solubility and precipitate iron, manganese and other heavy metals that were dissolved by the acid-fermentation (CHRISTENSEN & KJELDSEN, 1989). The decrease in pH is caused by the high production of volatile fatty acids and the high partial pressure of CO_2. The increased concentration of anions and cations is due to lixiviation of easily soluble material consisting of original waste components and degradation products of organic substances. Initial anaerobic processes are elicited by a population of mixed anaerobic microbes, composed of strictly anaerobic bacteria and facultative anaerobic bacteria. The facultative anaerobic bacteria reduce the redox potential so that methanogenic bacteria can grow. In fact, the latter are sensitive to the presence of oxygen and require a redox potential below -330 mV. Leachate from this phase is characterized by high BOD_5 values (commonly > 10.000 mg/l), high BOD_5/COD ratios (commonly > 0,7) and acidic pH values (typically 5 - 6) and ammonia (often 500-1.000 mg/l) (ROBINSON, 1989), the latter due to hydrolysis and fermentation of proteinous compounds in particular.

The second intermedial anaerobic phase (Phase III, Fig. 1) starts with slow growth of methanogenic bacteria. This growth may be inhibited by an excess of organic volatile acids which are toxic to methanogenic bacteria at concentrations of 6.000-16.000 mg/litre (STEGMANN & SPENDLIN, 1989). The methane concentration in the gas increases, whilst hydrogen, carbon dioxide and volatile fatty acids decrease. Moreover, the concentration of sulphate decreases owing to biological reduction. Conversion of fatty acids causes an increase in pH values and alkalinity with a consequent decrease in solubility of calcium, iron, manganese and heavy metals. The latter are probably precipitated as sulphides. Ammonia is released and is not converted in the anaerobic environment.

The third phase (Phase IV, Fig. 1) of anaerobic degradation is characterized by methanogenic fermentation elicited by methanogenic bacteria. The pH range tolerated by methanogenic bacteria is extremely limited and ranges from 6 to 8. At this stage, the composition of leachate is characterized by almost neutral pH values, low concentrations of volatile acids and total dissolved solids whilst biogas presents a methane content which is generally higher than 50 %. This confirms that solubilization of

the majority of organic components has decreased at this stage of landfill operation, although the process of waste stabilization will continue for several years and decades. Leachates produced during this phase are characterized by relatively low BOD values and low ratios of BOD/COD. Ammonia continues to be released by the first stage acetogenic process.

In Table 1 the ranges of leachate concentrations depending on the degradation phase for some relevant parameters are presented. EHRIG (1990) compiled leachate concentrations from German landfills from the seventies and eighties. According to his evaluation the organics (COD, BOD_5, TOC) as well as AOX, SO_4, Ca, Mg, Fe, Mn, Zn and Cr are determined by the biochemical processes in the landfill, there are striking differences between the acid phase and the methanogenic phase.

KRUSE (1994) investigated 33 landfills in Northern Germany, the leachate concentrations mainly derive from the late eighties and early nineties. He defined three characteristic periods according to the BOD_5/COD-ratio:

Acid phase: $BOD_5/COD = 0,4$

Intermediate phase: $0,4 > BOD_5/COD > 0,2$

Methanogenic phase: $BOD_5/COD = 0,2$

Between the two investigations there are significant differences concerning the organic parameters. In the younger landfills (KRUSE, 1994) leachate concentrations of COD, BOD_5 and TOC are lower than those determined by EHRIG (1990) some ten years before. This can be explained by developments in the technology of waste landfilling. In many younger landfills waste deposition and compaction in thin layers in combination with an aerobic pretreated bottom layer was carried out. This led to a reduction of the period for the acid phase and to an accelerated conversion of organic leachate components to the gaseous phase, the degradation of organics to methane and carbon dioxide.

Table 1. Constituents in leachates from MSW landfills (after EHRIG, 1990 and KRUSE, 1994)

Parameter	Unit	Leachate from MSW landfills (EHRIG, 1990)				Leachate from MSW landfills (KRUSE, 1994)					
		Acid phase		Methanogenic phase		Acid phase		Intermediate phase		Methanogenic phase	
		Range	Medium	Range	Medium	Range	Medium	Range	Medium	Range	Medium
pH-value	-	4,5 - 7	6	7,5 - 9	8	6,2 - 7,8	7,4	6,7 - 8,3	7,5	7,0 - 8,3	7,6
COD	mg/l	6.000 - 60.000	22.000	500 - 4.500	3.000	950 - 40.000	9.500	700 - 28.000	3.400	460 - 8.300	2.500
BOD_5	mg/l	4.000 - 40.000	13.000	20 - 550	180	600 - 27.000	6.300	200 - 10.000	1.200	20 - 700	230
TOC	mg/l	1.500 - 25.000	7.000	200 - 5.000	1.300	350 - 12.000[2]	2.600[2]	300 - 1.500[2]	880[2]	150 - 1.600[2]	660[2]
AOX	µg/l	540 - 3.450	1.674	524 - 2.010	1.040	260 - 6.200	2.400	260 - 3.900	1.545	195 - 3.500	1.725
org. N[1]	mg/l	10 - 4.250	600	10 - 4.250	600						
NH_4-N[1]	mg/l	30 - 3.000	750	30 - 3.000	750	17- 1.650	740	17- 1.650	740	17- 1.650	740
TKN[1]	mg/l	40 - 3.425	1.350	40 - 3.425	1.350	250 - 2.000	920	250 - 2.000	920	250 - 2.000	920
NO_2-N[1]	mg/l	0 - 25	0,5	0 - 25 0	0,5						
NO_3-N[1]	mg/l	0,1 - 50	3	0,1 - 50	3						
SO_4	mg/l	70 - 1.750	500	10 - 420	80	35 - 925	200	20 - 230	90	25 - 2.500	240
Cl	mg/l	100 - 5.000	2.100	100 - 5.000	2.100	315 - 12.400	2.150	315 - 12.400	2.150	315 - 12.400	2.150
Na[1]	mg/l	50 - 4.000	1.350	50 - 4.000	1.350	1 - 6.800	1.150	1 - 6.800	1.150	1 - 6.800	1.150
K[1]	mg/l	10 - 2.500	1.100	10 - 2.500	1.100	170 - 1.750	880	170 - 1.750	880	170 - 1.750	880
Mg	mg/l	50 - 1.150	470	40 - 350	180	30 - 600	285	90 - 350	200	25 - 300	150
Ca	mg/l	10 - 2.500	1.200	20 - 600	60	80 - 2.300	650	40 - 310	150	50 - 1.100	200
tot. P[1]	mg/l	0,1 - 30	6	0,1 - 30	6	0,3 - 54	6,8	0,3 - 54	6,8	0,3 - 54	6,8
Cr[1]	mg/l	0,03 - 1,6	0,3	0,3 - 1,6	0,3	0,002 - 0,52	0,155	0,002 - 0,52	0,155	0,002 - 0,52	0,155
Fe	mg/l	20 - 2.100	780	3 - 280	15	3 - 500	135	2 - 120	36	4 - 125	25
Ni[1]	mg/l	0,02 - 2,05	0,2	0,02 - 2,05	0,2	0,01 - 1	0,19	0,01 - 1	0,19	0,01 - 1	0,19
Cu[1]	mg/l	0,004 - 1,4	0,08	0,004 - 1,4	0,08	0,005 - 0,56	0,09	0,005 - 0,56	0,09	0,005 - 0,56	0,09
Zn	mg/l	0,1 - 120	5	0,03 - 4	0,6	0,05 - 16	2,2	0,06 - 1,7	0,6	0,09 - 3,5	0,6
As[1]	mg/l	0,005 - 1,6	0,16	0,005 - 1,6	0,16	0,0053 - 0,11	0,0255	0,0053 - 0,11	0,0255	0,0053 - 0,11	0,0255
Cd[1]	mg/l	0,0005 - 0,14	0,006	0,0005 - 0,14	0,006	0,0007 - 0,525	0,0375	0,0007 - 0,525	0,0375	0,0007 - 0,525	0,0375
Hg[1]	mg/l	0,0002 - 0,01	0,01	0,0002 - 0,01	0,01	0,000002 - 0,025	0,0015	0,000002 - 0,025	0,0015	0,000002 - 0,025	0,0015
Pb[1]	mg/l	0,008 - 1,02	0,09	0,008 - 1,02	0,09	0,008 - 0,4	0,16	0,008 - 0,4	0,16	0,008 - 0,4	0,16

[1] parameter more or less independent from the biochemical degradation phase
[2] DOC

Leachate quantity - the water table of landfills

Leachate production is the result of precipitation, evaporation, surface runoff, infiltration, storage capacity etc.. Under humic climatic conditions the average difference between precipitation and evaporation also with different vegetation covers is positive (in Germany and many other parts of Europe). Beside evaporation the infiltration could be reduced by surface runoff. But preventing of erosion problems needs a limitation of surface runoff.

In many Northern German Landfills the measured leachate flow rates are often between 12 and 22 % with 18 % as mean value of precipitation. Values lower than 10% are from very young landfills. Values above 25% of precipitation are from landfills where the end of storage capacity can be observed. Beside storage fill up another process of water consumption is the anaerobic biological degradation with water consumption of the biological process and water transport by gas. Over long time both processes - storage fill up and biological water consumption - must decrease. The result must be an increase of leachate flow up to a value of precipitation minus evaporation.

Reduction and collection of leachate

To control long-term leachate flow and reducing treatment costs the reduction of infiltration could be helpful and sometimes necessary (especially for old landfills without bottom sealing).

The strategy for water input control is strictly related to the quality of the waste to be landfilled. In the case of non-biodegradable waste and according to its hazardous potential for the environment, prevention of water infiltration can be adopted as the main option (normally by means of top sealing). On the contrary, in the case of biodegradable waste, a water input must be assured until a high degree of biostabilization is achieved. In this case the water input should be limited to the strictly necessary amount and minimization techniques should be applied.

The two final surface sealing systems that must be applied according to the regulations of the German „TA Siedlungsabfall" (TASI, 1993), *Technical Instructions on Waste from Human Settlements,* are shown in Figure 2.
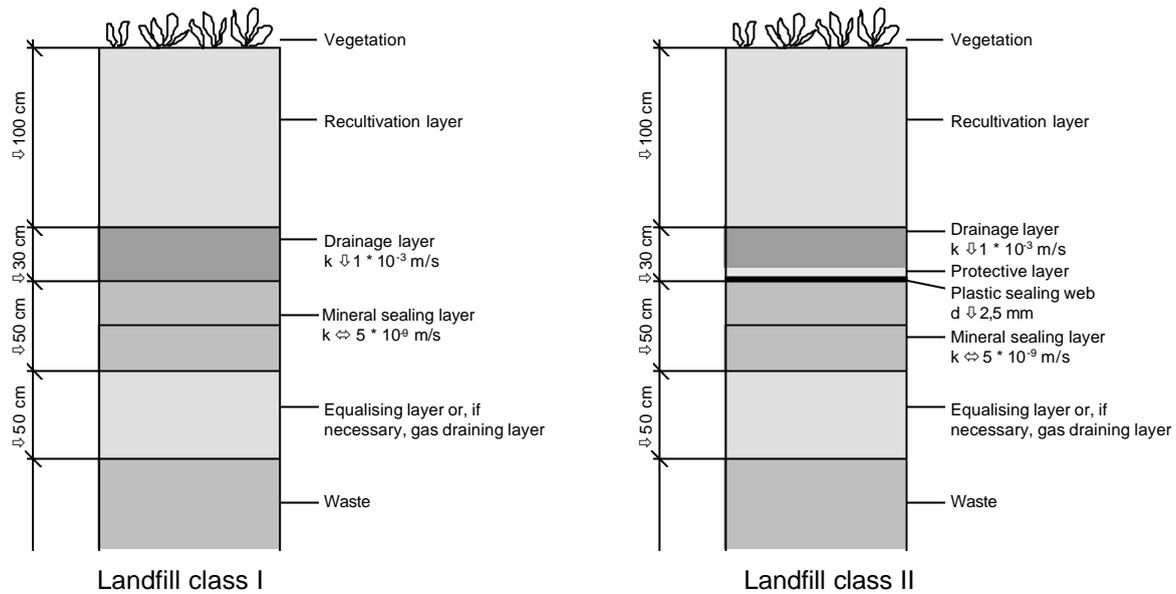
Figure 2.   Landfill surface sealing systems (TASI, 1993)

If water infiltrates into the landfill it is necessary to take care that the drainage system also operates well. With high polluted leachate clogging of the whole drainage system (drainage layer and drainage pipe) could occur. One suitable action is to prevent the penetration of oxygen into the drainage system. The drainage pipes could be controlled by camera and cleaned with high-pressure scouring. But no cleaning procedure for drainage layer is suitable. In Figure 3 the base sealing systems of landfill class I and II according to the requirements of the German TA Siedlungsabfall (TASI) are presented. They must be arranged on the landfill base and on the sloping areas.
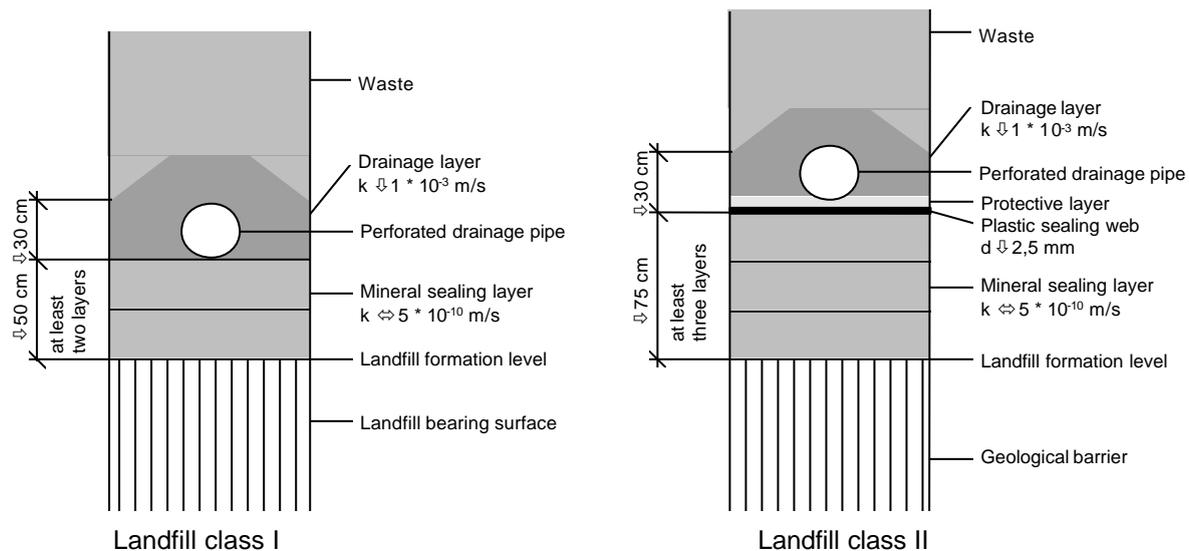

Figure 3.   Landfill base sealing systems (TASI, 1993)

LEACHATE TREATMENT

In Table 2 the current German requirements for the leachate quality before discharge are presented. There are a few parameters which are of great importance for the treatment technology that has to be applied, mainly COD and AOX, furthermore Nitrogen and BOD_5. The first two parameters require a more comprehensive treatment technology respectively a combination of different treatment methods that are described in the following.

Table 2. Limiting concentrations for the discharge of treated leachate according to German standards (51. Anhang AbwasserVO)

Parameter	limiting concentration mg/l	Parameter	limiting concentration mg/l
COD	200	Chromium	0,5
BOD_5	20	Chromium (VI)	0,1
Nitrogen, total ($NH_4 + NO_2 + NO_3$)	70	Nickel	1
Phosphorus, total	3	Lead	0,5
Hydrocarbons	10	Copper	0,5
Nitrite-Nitrogen	2	Zinc	2
AOX	0,5	Cyanide[#]	0,2
Mercury	0,05	Sulfide	1
Cadmium	0,1		

[#]: Cyanide, easy liberatable

Biological co-treatment of sewage and sanitary landfill leachate

The published data of co-treatment experiments show that this could be a possible leachate treatment step (KAYSER, 1986; DAHM, 1994). But this result could be also concluded from the worldwide usage of biological sewage treatment plants and a lot of results from different biological leachate treatment experiments (HEYER ET AL., 1998). If both wastewaters could be treated separate with specific biological systems also any combination of these wastewaters could be treated with the same systems. But it is necessary to attend some simple consequences of leachate addition to a biological sewage treatment plant. If the leachate is added without any other changes of the treatment process the loading increases and thereafter in most cases the effluents and sludge production also increases. The increase could reduce the nitrification rate dramatically with the result of ammonia toxicity. That means that also with leachate addition the same loading conditions must be kept as without leachate addition. If this is considered no increase of nitrogen- or BOD_5-effluents and no operation issues could

be estimated. A restriction could be necessary if sewage should be used as carbon source for denitrification of nitrogen of both wastewaters - sewage and leachate from old landfills with low organics.

Also for many other wastewaters the nutrient requirement of the biomass must be considered. The increase of nondegradable leachate components (residual COD, halogens, metals) is a function of dilution reduced by additional precipitation and/or adsorption effects. The concentrations of heavy metals are also in non-treated leachate relatively low. Only in leachates from acetic phase landfills with high organic loading zinc could have also high concentrations (see also Table 1). During biological treatment most of the zinc precipitated and still remains in the sludge.

Overall biological co-treatment of sewage and sanitary landfill leachate is a proven technology and operates well, if the treatment plant is carefully designed and operated. Experiences have shown that the operation of co-treatment plants are much more stable with less failures as separate leachate treatment systems. But the todays demand to more extensive leachate treatment in some countries show the way to more sophisticated treatment systems with less polluted effluents, but also less stable operation conditions and increasing costs and probability of failures.

Biological treatment

Biological treatment processes are the most common practice for leachate treatment. Biological systems could be divided in anaerobic and aerobic treatment processes. Both could be realized by different systems. In the following chapters some of them are presented:

anaerobic biological treatment
- parts of the landfill body used as a reactor
- anaerobic filter
- anaerobic sludge bed reactor (UASB)
aerobic biological treatment
- aerated lagoons
- activated sludge
- rotating biological contactors (RBC)
- trickling filter

Anaerobic treatment

During the period of high organic concentrations in leachates a anaerobic treatment step might be an effective way of reducing main parts of the organics (MENNERICH, 1988). The main advantage of the anaerobic treatment process is the low energy requirement, because no oxygen has to be supplied. Technical anaerobic processes need adequate temperatures and have to be designed right. The process is also very sensible in regard to changing milieu conditions; for this reason the plant has to be operated adequately.

In investigations and under operation anaerobic filters were sometimes hindered by iron and calcium clogging. The free volume of the reactors was filled up to 60 % after a COD-reduction of 2.000-3.000 kg/m^3 by precipitation. At UASB reactors the anorganic content of sludge increases dramatically with time and reduces elimination rates.

Anaerobic leachate treatment is an effective process but the remaining BOD_5- und COD-effluents are still high with COD-values of 1.000-4.000 mg/l and a BOD_5-COD-ratio > 0.3. After the anaerobic treatment step the leachate has to be treated to final effluent standards by means of aerobic processes.

Aerated lagoons

Aerated lagoons are a relatively simple leachate treatment system. The basic idea is that the retention time of the leachate is long enough so that as many bacteria can develop per time as the number of species that are transported out of the lagoon with the effluent. Long retention times are necessary in order to degradate also the medium degradable organic fraction and because of low temperatures. The maintenance and operation costs are relatively low.

Activated sludge

The detention time in activated sludge plants can be considerably shorter than in aerated lagoons. The reason is that the sludge content (amount of bacteria) can be controlled to a certain degree and is several times higher than in aerated lagoons. This is achieved by installing a settling tank behind the aeration tank and recirculating the sludge back into the activated sludge tank. A certain amount of sludge has to be removed out of the system.

Beside BOD_5-reduction the nitrification of ammonium is a very important process in many activated sludge plants. Nitrogen elimination becomes more and more important

with aging of landfill and the increasing reduction of BOD in the landfill body. The treatment of such leachates are more complicated than with high organic values. The pH of these leachates can be in the area of 8,0 - 8,3. But during aeration the pH increases in some cases up to pH 9 and higher. Under these circumstances the equilibrium shifts from ammonium to free ammonia. Even concentrations of free ammonia have inhibiting effects on nitrifying bacteria. If on the other side the ammonium is converted to nitrate the pH decreases as a result of alcalinity destruction. Overall a very careful operation and pH-control is necessary to get low ammonium effluent values.

To prevent low temperatures it is necessary to cover the aeration tank, to use fine bubble aerators (with elastic plastic tubes) and to use a part of the heat from air blowers. To reduce the high nitrate content in leachate effluent and to stabilize pH-conditions in activated sludge plants a denitrification step could be helpful. The pre-denitrification would be more effective if also small amounts of leachate organics have to be used. This is very important for old landfills. But the denitrification rate depends on the recirculation water and sludge rates and BOD_5 to N-ratio. To reach nitrogen effluent values lower than 5 to 10 % of influent extremely high recirculation rates are necessary. In opposite with a post-denitrification process very low nitrate effluent values are possible. But the leachate organics cannot be used as carbon source and a separate pH-stabilization for the nitrification tank could be necessary. Leachate from the methanogenic phase could only be denitrified with addition of carbon sources as acetic acid, methanol etc..

Rotating biological contactors (RBC) and trickling filters

These processes differ from the activated sludge process in so far that the bacterica are attracted to material of rotating contactors or trickling filters. The air supply takes place naturally, i.e. the rotation contractor is partly in the air and partly in the water and rotates, while the air vents through a trickling filter. These methods consume low amounts of energy. Treating high organic polluted leachates clogging by anorganic precipitates and/or produced biomass could exclude these processes. But in many cases nitrification processes are more effective in fixed film reactors. The influence of temperature on nitrification is relatively strong. Temperature effects are lower at RBC's, because they are normally covered.

Summary of biological treatment

Biological treatment processes are very effective methods to reduce biodegradable organics as BOD_5 and the main part of COD. Also from leachates with low organics

and BOD_5-COD-ratio < 0.2 the COD could be removed by biological treatment up to 50 %. It is also an effective method to oxidize ammonium to nitrate and if necessary to reduce ammonium by nitrification and additional denitrification to gaseous nitrogen. The decreasing elimination rates during period with low water temperatures especially for ammonium reduction are a disadvantage.

Figure 4 shows a processing sequence for biological treatment in combination with a reverse osmosis of a treatment plant in Northern Germany. Concentrations for COD, ammonium and AOX of the influent, the effluent of the biological and of the reverse osmosis are compiled below.
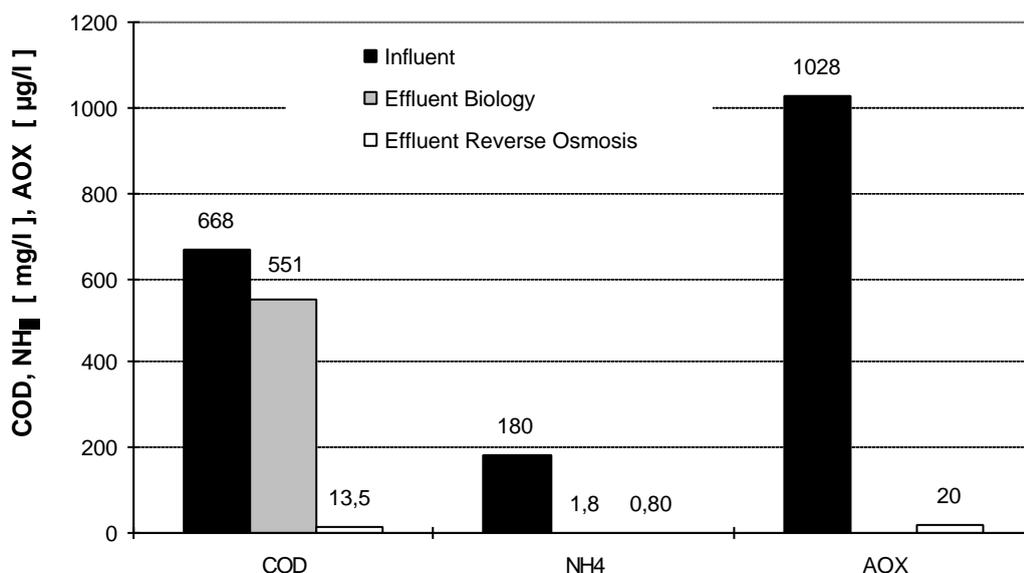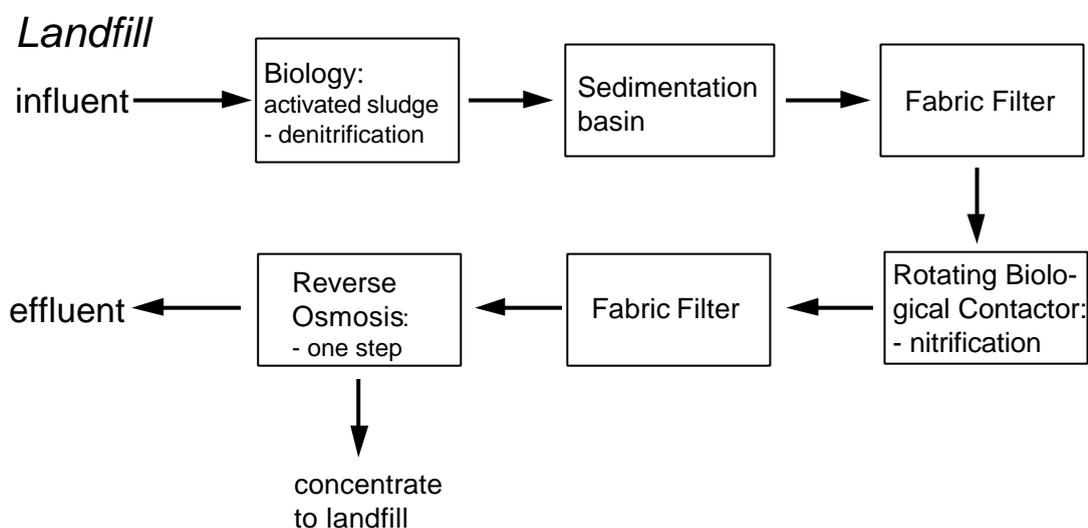

Figure 4.   Processing sequence for a combination *biology* + *reverse osmosis*; characteristic leachate concentrations of a treatment plant (adopted from ATV 7.2.26, 1996)

Chemical oxidation and adsorption (active carbon)

During the last years chemical oxidation processes were developed at different locations. In opposite to earlier experiments a combination of oxidation agents as ozone or hydrogen peroxide and ultraviolet light (UV) is used. This combination shows high oxidation rates for leachate COD and AOX. The process consists of a mixing chamber to mix influent leachate and the oxidation agent and thereafter a chamber with UV-lamps. To increase elimation rates manifold of leachate flow are recirculated. In opposite to mixing hydrogen peroxide and water the mixing of gaseous ozone and water is more difficult.
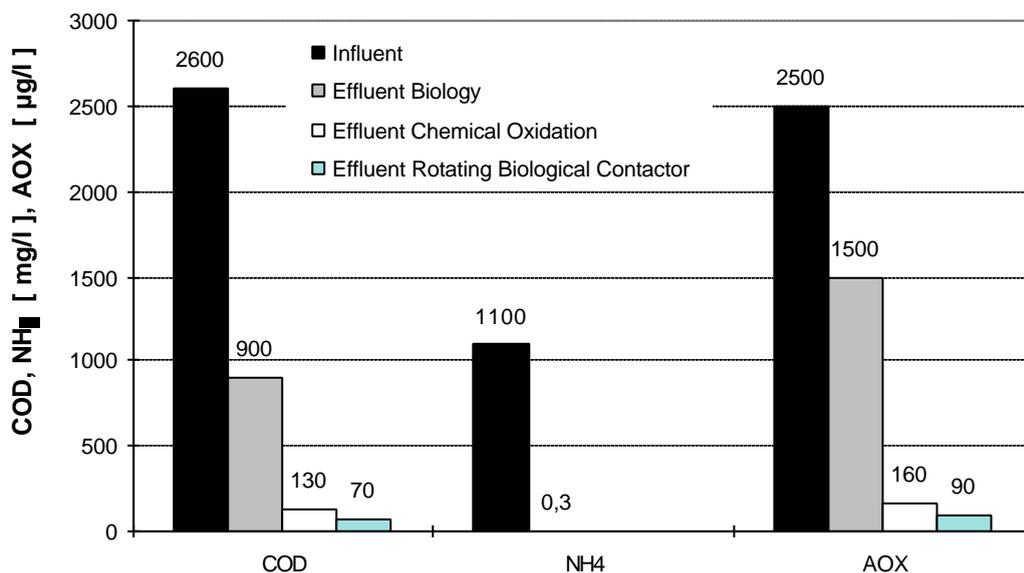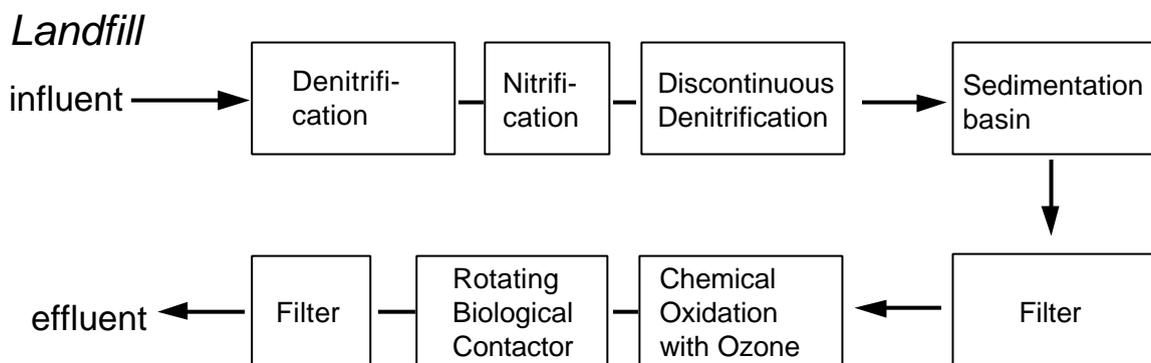

Figure 5. Processing sequence for a combination *biology + chemical oxidation + biology*; characteristic leachate concentrations of a treatment plant (adopted from ATV 7.2.26, 1996)

Figure 5 shows a processing sequence for biological treatment in combination with a chemical oxidation (ozone) of a treatment plant in Northern Germany. Concentrations for

COD, ammonium and AOX of the influent, the effluent of the biological and of the chemical oxidation and of the second biological treatment step in the rotating biological contactor are compiled below.

The oxidation agents are expensive and the oxidation of all organics is sometimes not convenient. In addition leachate contains so many components (e.g. manganese) that also large parts of ammonium oxidize. To prevent the expensive oxidation of good biodegradable components a biological pre-treatment including nitrification is necessary.

During chemical oxidation not all organics are oxidized to carbon dioxide and water. Some organics are only partly oxidized often to biological degradable components. These new biodegradable organics must be reduced by biological treatment. To reduce these relatively low concentrations a fixed film reactor is an effective solution.

Chemical oxidation is a very expensive step. In many cases a combination of chemical oxidation and activated carbon filters (partly as biological filters) could reduce the costs. Additional carbon filters don`t react so direct on variation of influent concentrations than the chemical oxidation with very short detention times. Carbon filters are also used in combination with biological degradation.

Physical-chemical processes
Reverse Osmosis

One of the developments in the last decade for leachate treatment is the reverse osmosis (RO). But in contrast to the biological treatment it is a separation process with two streams - one low polluted permeate stream and one high polluted concentrate stream. With new developments for membrane material it is possible to get very low polluted permeats with exception of the acetic phase leachate. These very small organic molecules are not kept back. In such cases a biological pretreatment is strictly necessary - e.g. leachate recirculation. In many cases also the separation of ammonium is poor. This could be improved by chemical addition to adjust pH or by a two step reverse osmosis. In some cases ammonium is removed by a pre-stripping process. But also a biological nitrification and denitrification could be useful.

A very important disadvantage of RO is the liquid concentrate. The technique of back passing the nonbiodegradeable concentrate stream to landfill is not a solution, it is only an adjournment for a real treatment solution. At present in Germany vaporation of concentrats are developed and tested on landfills. Several full scale combination plants are operated (see also Figure 4).

Flocculation/ Precipitation

Flocculation/Precipitation within leachate treatment, e.g. with $FeCl_3$, is mainly done to reduce the organic load (humic acids and halogenated organic constituents characterized by the parameters COD and AOX) of the leachate after the biological treatment. Although this technology is rather cheap it is not used frequently because of the addition of chloride and sulfate into the leachate effluent.
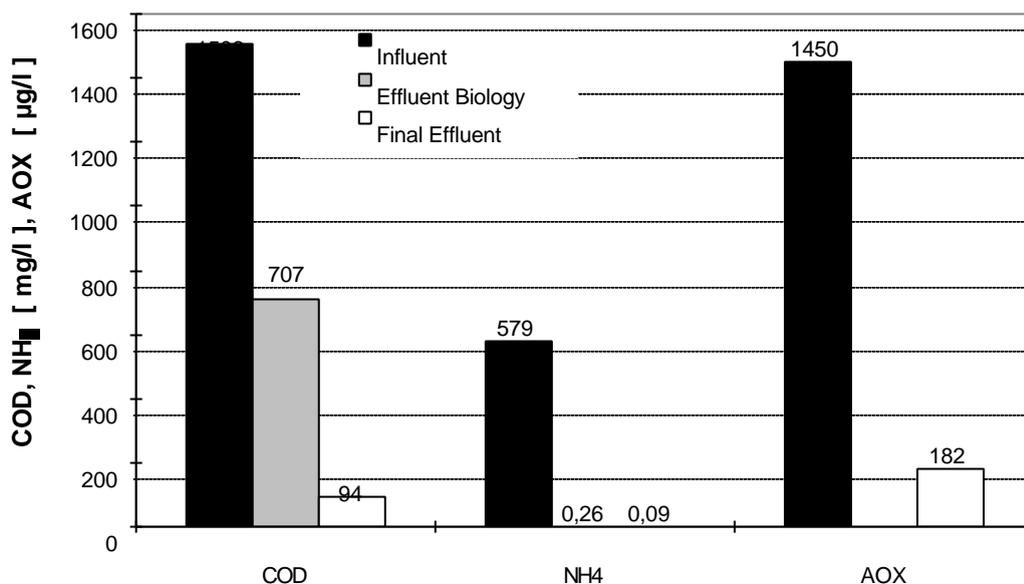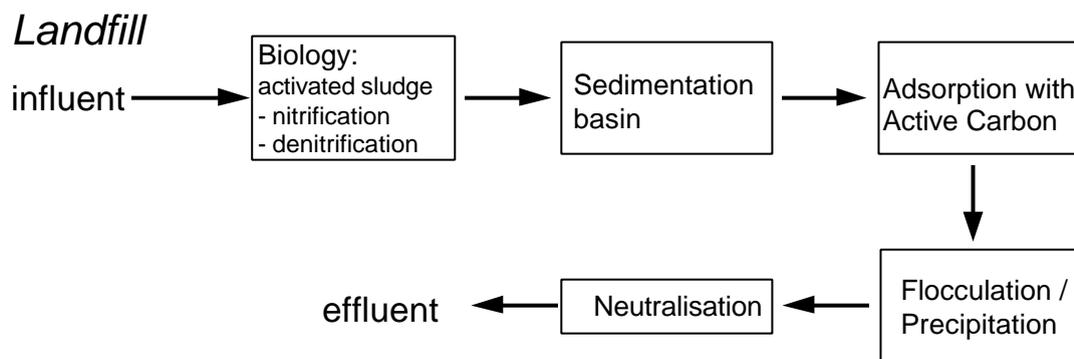

Figure 6. Processing sequence for a combination *biology + adsorption (activated carbon) + flocculation/precipitation*; characteristic leachate concentrations of a treatment plant (adopted from ATV 7.2.26, 1996)

In Figure 6 a processing sequence for biological treatment in combination with adsorption (activated carbon) and a flocculation/precipitation is presented. Concentrations for COD, ammonium and AOX of the influent, the effluent of the biological and of the final effluent are compiled below.

Vaporation and Drying

For some years vaporation of the leachate has been discussed in Germany as a last resource, meaning that these technique are a separation in a clean water stream and a solid phase which includes all pollution material. In reality the separation is not so strong and accurate. Normally the solids are pulpy and the condensated vapours contain volatile components. The predominant components in effluent of vaporation plants are volatile, sometimes chlorinated organics and ammonium with the necessity of additional treatment steps.

To reduce vaporated liquids a reduction of leachate by reverse osmosis could be helpful.

COMBINATIONS OF TREATMENT METHODS

Current treatment facilities for the treatment of leachate mainly consist of several of the above mentioned treatment methods to meet the limiting concentrations for the effluent. Typical combinations are shown in Figure 7.
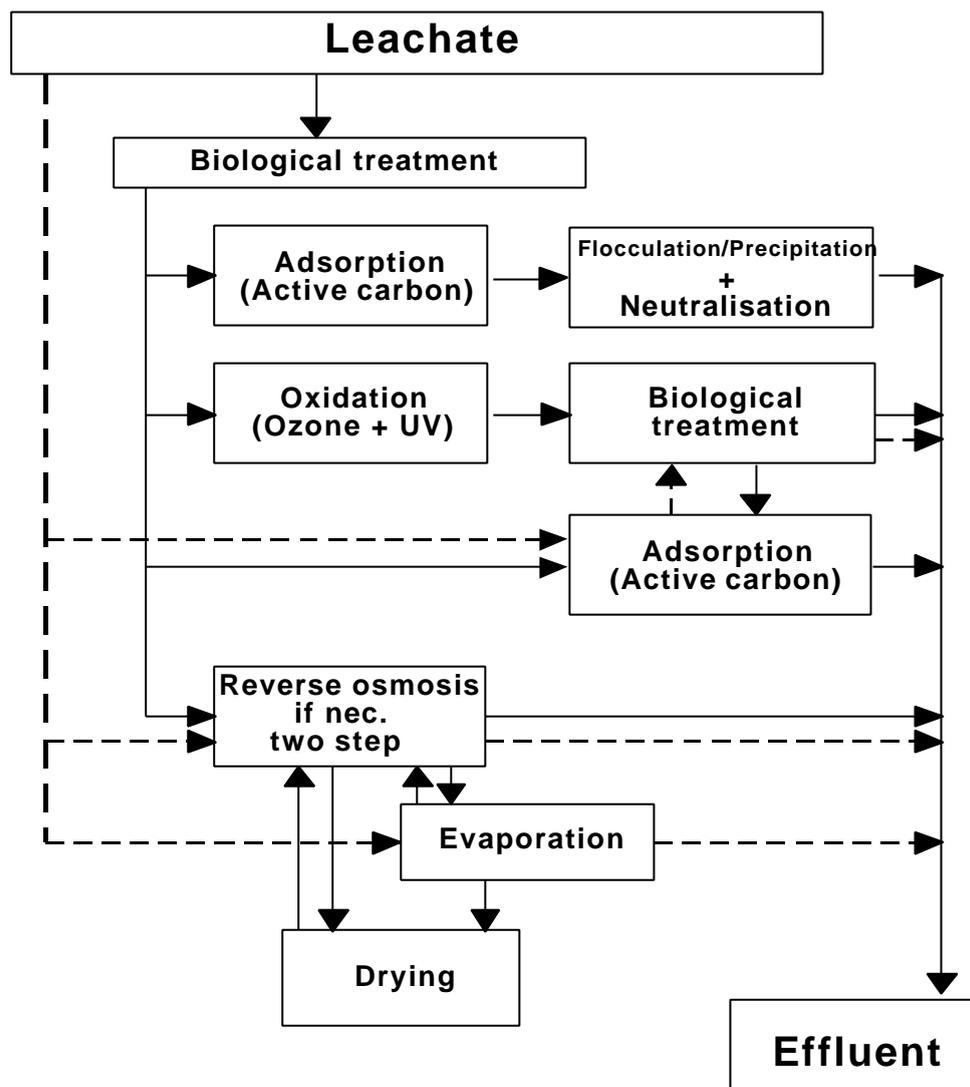

Figure 7. Scheme of often used methods and combinations for leachate treatment (according to EHRIG ET AL., 1998)

For some combinations the influent and effluent concentrations of characteristic leachate components are compiled in Table 3. All the mentioned combinations meet the limiting criteria. They have been operated for several years and can be regarded as state of the art treatment facilities.

Table 3. Examples of influent and effluent concentrations of different combinations for leachate treatment (ATV Group 7.2.26, 1993)

COD [mg/l]		NH$_4$-N [mg/l]		AOX [mg/l]	
Influent	Effluent	Influent	Effluent	Influent	Effluent
A: biology - active carbon - flocculation/precipitation - neutralisation					
1571	76	579	0,09	1,45	0,18
686	51	528	0,7	1,65	0,23
B: biology - ultrafiltration - active carbon					
1000 - 12000	< 200	400 - 800	< 10	1 - 2,5	0,1 - 0,7
C: biology - chemical oxidation (ozone + UV)					
320 - 5796	30 - 137	125 - 1350	0,4 - 36,2	-	-
D: biology - chemical oxidation (ozone + UV) - biology					
1200 - 4000	18 - 150	600 - 1900	0,1 - 9	1 - 3,8	0,04 - 0,18
E: biology - chemical oxidation (ozone + UV) - biology - active carbon					
758 - 1332	1 - 85	375 - 885	0,1 - 0,6	0,85 - 2,1	0,17 - 0,43
F: one step reverse osmosis					
4124	20	577	8	-	-
1550	68	750	7	1,4	< 0,01
G: two step reverse osmosis					
1590 - 2980	4 - 25	900 - 1800	4,4 - 8,8	1,5 - 1,9	0,002 - 0,02
H: biology - reverse osmosis					
446 - 872	5,3 - 27	80 - 396	0,03 - 10,1	0,4 - 1,4	< 0,01 - 0,05
I: biology - two step reverse osmosis					
1366 - 3010	< 2	130 - 854	6,3	1,09 - 2,24	0,045

For the concept of a leachate treatment plant several aspects have to be taken into account:

- limiting concentrations
- low demand of resources
- low demand of energy
- low generation of residues, especially hazardous wastes
- low environmental impact
- economical efficient operation

In Table 4 the specific energy demand and the kind as well as the quantity of residues of the treament methods are compiled. The same is done for some typical combinations in Table 5.

Table 4. Specific energy demand, quality and quantity of residues of treament methods (Dahm et al., 1994)

Treatment method	Residue	Amount	Specific energy demand [kWh/m^3 leachate]
Biology	Sewage sludge	0 - 0,6 kg/kg ($COD_{eliminated}$)	15 - 25
Adsorption (active carbon)	no residues	1 - 6 kg/m^3 leachate	0,5 - 3
Chemical Oxidation	Ca-Oxalate		50 - 100
Reverse Osmosis	liquid concentrate	15 - 30 %/m^3 leachate	8 - 10
High Pressure Reverse Osmosis	liquid concentrate	5 - 10 %/m^3 leachate	13 - 15
Evaporation	liquid concentrate	2 - 4 %/m^3 leachate	8 - 10
Drying	dry matter (<5 % H_2O)	0,5-1,0 %/m^3 leachate	20 - 25

Table 5. Total specific energy demand, and total quantity of residues of treatment combinations with and without added chemicals (Dahm et al., 1994)

Combinations of treatment methods	Amount of residues [kg/m^3 leachate]		Specific energy demand [kWh/m^3 leachate]	
	without chemicals	with chemicals	without chemicals	with chemicals
Biology + Adsorption	0,1 - 2,6	1,7 - 7,4	16 - 28	26 - 78
Biology + Chemical Oxidation	0 - 1,8	4,5 - 11,8	65 - 125	73 - 160
Biology + Nanofil-tration + Adsorption	0,6 - 2,4	2,3 - 7,2	20 - 32	29 - 77
Biology + Nanofiltration + Chemical Oxidation	0,5 - 2,4	3,7 - 10,5	45 - 100	52 - 130
Reverse Osmosis (+ Nanofiltration) + High Pressure Reverse Osmosis	0,5 - 1,0	2,4 - 3,8	25 - 30	29 - 45

COSTS OF LEACHATE TREATMENT

The costs of leachate treatment in Germany can be only roughly estimated and compiled because they vary between 12 and 75 €/m^3 leachate (EHRIG ET AL., 1998). This has several reasons:

- the same treatment procedures were totally different put into practice; treatment facilities were installed in cheap containers or in expensive buildings
- the technical equipment can be very simple or very sophisticated, e.g. for on-line measurements of the leachate components
- the total capacity and the utilization coefficient of the treatment plant; a small capacity and a low utilization coefficient means high costs per m^3 of treated leachate
- a growing competition between companies who are producing treatment plants leads to dropping prices
- dropping prices for energy and chemicals like oxygen or active carbon
- cut backs in the budgets of landfill operators for landfill operation in general (reduced waste quantities for disposal, dropping prices for waste, growing competition between landfill operators etc.)

In 1994 seven treatment plants with capacities from 11.000 up to 64.000 m^3/a were examined. The total costs for investment and operation varied between 9 and 30 €/m^3 leachte. For a few combinations very rough estimations of total costs can be given (Table 6):

Table 6. Estimations for costs of combinations for leachate treatment in relation to the capacity

Treatment (combination)	costs for small capacity (< 10m^3/h) [€/m^3]	costs for high capacity (> 10m^3/h) [€/m^3]
Biology + Membrane Sep.	9 - 30	7 - 15
Biology + Chemical Oxid.	12 - 50	9 - 30
Biology + Active Carbon	2 - 25	1 - 10
Biology + Flocc./Precip.	2 - 30	2 - 15
Biology + Reverse Osmos.	5 - 25	2 - 7
Evaporation	6 - 24	

Because of some of the above mentioned reasons the costs for leachate treatment dropped in the last two to three years in Germany. There is a trend to cheaper treatment facilities with lower costs for investment as well as operation. As Table 7 shows mainly biological treatment facilities in combination with activated carbon filters as the second step were installed in the last years.

Table 7. Installation of leachate treatment plants from 1993 to July 1997 in Germany

Year	Biology + Reverse Osmosis	Biology + Chemical Oxidation (Ozone)	Biology + Active Carbon	Biology + Nano-filtration	Total
1993	5	4	4	1	14
1994	4	2	11	1	18
1995	2	8	14	2	26
1996	1	5	15	1	22
1997	0	0	6	0	6
Total	12	19	50	5	86

CONCLUSIONS

The presented paper has shown different methods for leachate control, collection and treatment. Leachate control is a very important step to receive the long-term functionality of the drainage system, to reduce treatment costs and to render possible high-tech treatment systems. The development of treatment methods differs between lab., pilot and full scale operation. Nowadays many treatment plants are under operation in Germany, so there are many experiences concerning the technology and the effluent quality. In some cases the treatment of leachate resulted in increasing operation problems in opposite to the treatment of other wastewaters. It is necessary to test the whole area of wastewater treatment processes to select the most effective and econo-mic systems depending on the specific discharge limits and the specific conditions of a landfill. The judgement of treatment processes should not only include possible effluent values and maintenance but also the production of residuals with new pollution potential and the demand of energy.

The decrease of discharge limits in many countries in the past and in future requires high-tech treatment technologies and often a combination of different processes. But the results of presented treatment processes have finally shown that the existing pollution potential of leachates could be reduced to a high percentage.

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