Municipal Landfill Leachate Treatment Processes

Stacy Souders

ABSTRACT

Domestic wastes from urban areas are collected and are usually disposed of by either combustion or landfilling. Landfilling consists of burying and compacting wastes into components called cells which are then covered by an impermeable soil top cover. Drainage design is very important in the design of landfills because it gives less of a chance for water to percolate into the landfill. Some of the water is able to percolate into the landfill and mix with the existing trash forming an aqueous substance called leachate. Pre-treated leachate is very hazardous and can cause contamination of groundwater, environmental pollution, and chronic human diseases. For these reasons, the leachate needs to be collected and treated before discharged into the environment. There are several ways to treat the leachate such as: aerobic/anaerobic biological process, land or physical-chemical treatments, and recycling back into the landfill or treatment with the domestic sewage at existing waste water plants. Although, aerobic/anaerobic process are fairly efficient they are more costly and may not be economically feasible. Chemical process can be used for odor control but are also expensive when used on a full-scale operation. Land treatment and recycling of the leachate is some of the cheaper alternatives but their effectiveness is unpredictable due to the heterogeneous environment where the leachate travels through. Overall, treatment with the domestic sewage has been the most popular process due to the use of existing operations but the capacity to handle both sewage and leachate needs to be analyzed before the treatment can begin. All of these processes, when chosen, need to be engineered appropriately and maintained for successful treatment of landfill leachate with the main goal being little or no environmental impact and human health.

KEYWORDS

Leachate, Landfill, domestic waste, hazardous/toxic material, aerobic, anaerobic, biological oxygen demand (BOD), ammonia, methane, nitrification/denitrification, inorganic, organic

INTRODUCTION

Currently 200 million tons of solid waste is generated every year which comes out to greater than 41 pounds per day per person (Pokhrel and Viraraghavan, 2004). Most of the domestic solid wastes are transported to a landfill where it can be dumped, compacted, and covered to prevent large amounts of surface water infiltration and gaseous movement within the structure. Some of the water is able to percolate throughout the landfill and mix with the wastes to produce a liquid by-product known as leachate (Pokhrel and Viraraghavan, 2004).

Pre-treated leachate is classified as industrial waste under federal guidelines so appropriate collection and treatment facilities need to be implemented either on or off site to prevent contamination of groundwater, pollution of nearby environments, and human health problems. There are many ways to treat the leachate such as: anaerobic/anaerobic biological processes (Cartmell et al., 2004), land treatment (McBride and Preston, 2004), physical-chemical treatments, recycling (Park, 2004), and treatment with domestic sewage (Pokhrel and Viraraghavan, 2004). The process, results, advantages, and disadvantages are all explained in further detail in the treatment solutions section of the paper. Each treatment will be unique to the environment at where the process occurs and money willing to be spent. Overall, each treatment process should be operated and maintained with care to ensure little or no harm to the surrounding environment and animal/human health.

DESCRIPTIONS

A landfill is a carefully designed structure built into or on top of the ground which is isolated from the surrounding environment such as: groundwater, air, and rain and urban settings. The landfill is built in lots of layers to accomplish this isolation and prevent contamination. There are two types of landfills, sanitary landfill which uses a clay liner and a municipal solid waste (MSW) landfill which uses a synthetic or plastic liner (Daniel, 1993). The landfill should be kept as dry as possible and not be in contact with air in order to keep the trash from decomposing too much. Most importantly, a landfill is not like a compost pile, it is not there to decompose trash but to simply bury it and it must be monitored and maintained for up to 30 years.

A landfill consists of many parts. A bottom liner is used to separate trash and leachate from groundwater and the cells are where the trash is being stored within the landfill (Daniel, 1993). There are several collection systems to eliminate landfill residues from contaminating the surrounding environments such as: a leachate collection system to collect the water which has percolated through the landfill, a methane collection system to collect methane gas formed by the breakdown of trash, and a storm water drainage system to collect all of the surface water runoff which has not percolated through the landfill. Finally, there is a low permeable soil cover which is compacted at 6 inches initially and then a final 2 foot cover is compacted onto the cells in order to eliminate surface water infiltration and gas movement (Daniel, 1993).

The leachate collection system will be looked at in more depth as it is a component of the study. Since it is not possible to exclude all of the water from getting into the landfill, a small amount percolate through the cells and soil and on the way it picks up contaminants (organic and inorganic chemicals, metals, biological waste products) from the trash itself (Daniel, 1993). This water along with the dissolved contaminants is called leachate and it is typically acidic. The leachate is collected by first flowing through perforated pipes which run throughout the landfill and then those pipes drain into the leachate pipe which carries the leachate to the collection site. The leachate is then tested for acceptable levels of various chemicals (biological and chemical oxygen demands, organic chemicals, pH, calcium, magnesium, iron, sulfate, and chloride) (Daniel, 1993). After testing, the leachate must be treated either on-site or off-site. There are many popular options such as: release into the wastewater treatment plant, leachate recirculation and later treatment which reduces the volume of leachate taken away from the landfill but increases the concentrations of contaminants. The purpose of this paper is to study other types of treatment options which could be beneficial to nationwide municipalities and will be discussed in detail later on.

Finally, the factors affecting leachate components and generation will be described. The amount of leachate generated is directly related to the amount of rainfall on the landfill during a given time and its characteristics such as: pH, temperature, and quantity (Crawford and Smith, 1985). Also, the higher the moisture content of the trash being brought into the landfill the more amount of leachate will be generated. If the material inside of the landfill is highly biodegradable and toxic there is more of a chance for highly contaminated leachate; leachate contains higher pollutant loads than raw sewage or many industrial wastes. The conditions inside of the landfill also need to be considered such as: pH, temperature/climate, degree of decomposition, moisture content, and landfill age and depth (Crawford and Smith, 1985). There must also be a good drainage system and low impermeable soils present in and around the landfill to prevent large amounts of leachate generation.

	Age of Refuse	
	<2 yrs. Old	>10 yrs. Old
pH	5.0-6.5	6.5-7.5
BOD	4000-30000	<100
COD	10000-60000	50-500
TOC	1000-20000	<100
Total Solids	8000-50000	1000-3000
TSS	200-2000	100-500
Total N	100-1000	<100
Phosphate	5-100	<5
Chloride	500-2000	100-500
Sulfate	50-1000	<10
Iron	100-1500	10-400
Sodium	500-3000	<200
Potassium	200-1000	50-400
Calcium	500-2500	100-400

Table 22.1 Typical analyses of leachate from domestic landfill prior to dilution by surface runoff (Crawford and Smith, 1985)
*All units are expressed in mg/L

This table shows that the composition concentrations tend to peak around an age of 2 years old and then the landfill begins to stabilize and concentrations begin to greatly decrease (Crawford and Smith, 1985). The large ranges account for the many variables which come with the landfill location.

PROBLEMS

Landfill leachate consists of harmful inorganic, organic, and toxic chemicals which can be harmful to the environment. Some of the inorganics such as: arsenic, iron, lead, cadmium, ammonia, and nitrogen can be harmful in even small concentrations (Baterman et al., 2004). This can cause fish kills, an alteration of biodiversity, and slimy deposits in the discharge area. Most of the organic toxins can be broken down by micro-organisms present in the discharge area, but some of the leachate may contain hazardous organic compounds such as phenolic wastes and tar bases. These wastes can cause sterilization of the stream or river and again fish kills. Also toxic chemicals coming from pesticides and volatile organic compounds can evaporate and harm the atmosphere if they are at high enough concentrations (Dezotti et al., 2004).

There are also physical aspects of leachate which can affect the discharge river or stream such as: increased total suspended solids (TSS), color, turbidity, and temperature. TSS, color, and turbidity reduce the light intensity in the river or stream which limits or stops the ability for plant growth (Pokhrel and Viraraghavan, 2004). This not only effects the food chain in the river or stream it also greatly reduces the photosynthetic activity in the water environment which reduces the amount of oxygen being put into the water. Suspended solids can settle out in a river bed and smother organisms which are important to the food chain and carbon cycle, although this would take very high concentrations for lots of harm to be done (Rowe et al., 2004). Finally, the leachate could increase the temperature of the river by only a few degrees which would affect the life cycles and population densities within the river.

Leachate not only harms its discharge area directly from effluent or surface runoff it can also pollute the groundwater aquifers. If the leachate reaches the water table it mixes and moves with the groundwater (Pfeffer, 1992). If there is a shallow water table and slow moving groundwater flow there is more of a chance of contamination to the nearby drinking water. The leachate causes less pollution to the groundwater since it is usually fairly acidic so the true pollution comes from the mineralization of the water itself due to the present leachate. If the rock or soil in the underground aquifer is sand then the capacity for absorption may be limited leading to an increased travel of pollutants (Pfeffer, 1992). The increase of the pollutants may eventually eliminate this groundwater source for possible drinking water.

These problems stem from the fact that some facilities lack engineering controls, past controls are being used which do not meet recent standards, or the facility continues to accept hazardous and industrial wastes which enhance toxic substance release inside the landfill. The result of high concentrations of these toxic substances can be a threat to humans if they reach their drinking water source and my cause cancer, disease, sterility, abortions, heart disease, or a variety of other chronic effects (Chiang and Qasim, 1994).

LEACHATE TREATMENT SOLUTIONS

Once the leachate has been collected it requires treatment in order to meet effluent standards. Each treatment is greatly affected by the age of the landfill leachate and the stabilization lifetime, because the values for biological oxygen demand (BOD) are lowered the older the landfill as explained before (Crawford and Smith, 1985). This section will explain the following treatment options: biological processes (aerobic biological treatment, anaerobic biological treatment), physical-chemical processes (land treatment, physical-chemical treatments) and leachate channeling (recycling throughout the landfill, treatment with sewage).

Aerobic Biological Treatment

Most of the organic material in leachate from young landfills (<2yrs.) is easily biodegradable by aerobic biological oxidation, although some adjustments will need to be made to the pH and nutrient additions to optimize the process. The most common aerobic biological treatment methods are activated sludge process, aerated lagoons, trickling filters, and rotating biological contactors. Another process has been researched called biological nitrification by using biological aerated filters (BAFs) (Cartmell et al., 2004). This study was done to see the effectiveness of treating methanogenic landfill leachates.

BAFs are submerged media wastewater treatment reactors combining aerobic biological treatment and biomass separation by depth filtration (Cartmell et al., 2004). Combining the two processes allows for a smaller system to be utilized instead of the conventional model and they can also operate at BOD loadings much higher than trickling filters and activated sludge plants. Carbonaceous BOD removal, solids filtration and nitrification are all happening in a single unit operation however; further process modifications are needed for denitrification and phosphate removal (Cartmell et al., 2004). This process ultimately focuses on eliminating ammonia concentrations from reaching the discharge area.

Aerobic treatment is usually required for ammonia removal through two step nitrification. Ammonia is first converted to nitrite by nitrosomonas and then into nitrate by nitrobacter, with the supply of oxygen. The temperature would have to be maintained around 20-25C for the nitrifying bacteria to work efficiently. The pH should also be maintained at 7.5-8.5 for optimum nitrifying results. The addition of calcium carbonate and a phosphate compound may also be added to produce efficient alkalinity and nutrient balance respectively (Cartmell et al., 2004). The leachate may also have to initially be stabilized to assure the process will work.

The results showed that there was enough dissolved oxygen concentrations in the effluent indicating that the oxygen was not limiting. There were also enough alkalinity and phosphate concentrations to efficiently undergo nitrification. The nitrification actually improved until there was a steady-state of 99% ammonia removal (Cartmell et al., 2004). However, high effluent concentrations of nitrite showed that the first stage of nitrification was happening but the second stage was not leaving high concentrations of nitrite which would be unacceptable to discharge.

Overall, this process enhances ammonia removal but is unable to go through the second process of nitrification efficiently. The major problems are keeping the temperature steady throughout the seasons and although nitrification happens at moderate pH levels optimum ammonia transfer happens at higher pHs. The effect of a wide range of toxic substances on the nitrifying bacteria and the cost of the treatment system may also make the process less satisfying (Cartmell et al., 2004). For a leachate with low BOD5 and high ammonia, a more cost effective approach may be land treatment and will be discussed later.

Anaerobic Biological Treatment

Anaerobic biological treatment uses micro-organisms which grow in the absence of dissolved oxygen and convert organic material to carbon-dioxide, methane and other metabolic products (Hollopeter, 1993). Usually, the process occupies two stages, the first being acid fermentation in which facultative and anaerobic bacteria break down the complex substances into simpler ones (Pfeffer, 1992). In the second stage methanogenic bacteria form methane and carbon dioxide from the organic acids.

The acid fermentation tends to reduce the pH of the leachate but methane formers prefer a pH above 6.5, so the pH should be kept above 7.0 (Kaczorek and Ledakowicz, 2004). The temperature should be maintained at about 35C inside the reactor vessels. The conventional anaerobic plant uses two stages. The first, primary stage, the tanks are closed and mixed by recirculating the liquor containing the leachate or gas or both. The tank is heated and the gas is collected then used for fuel in the heat exchanger to heat the primary tanks. The second stage (sludge settlement) open, unheated tanks are used to separate the treated effluent from the sludge, and then can be discharged (Kaczorek and Ledakowicz, 2004).

The results show that there is a long retention time (approx. 20 days) or more to complete the anaerobic treatment of the leachate, which can be very costly. There is also no possibility of oxidation of ammonia. Nitrogen is removed from the leachate only by the low production of new biological solids. Also, soluble ferrous iron remains in solution, and unlike the aerobic process, the iron doesn't just precipitate out (Kaczorek and Ledakowicz, 2004). Although the ammonia removal is low, BOD removal can be significant with the methane collected and used to maintain the temperature in the primary tank. Overall, this process can be very expensive when applied to a full-scale operation so anaerobic oxygen of landfill leachates is probably even less useful economically than aerobic oxidation.

Land Treatment

The treatment of wastewaters, including leachate, dates far back into history and is very cheap if large area of lands are available. The design objective in land treatment is that the wastewater should not be applied to soil system in such quantities where that the land becomes unusable for agriculture or forestation. The capacity of the soil for each relevant component must be considered by the equation (Crawford and Smith, 1985):

$$area(ha) = \frac{leachateflow(m^3/yr) * chemicalconc.(kg/m^3)}{assimilativecapacity(kg/ha.yr)}$$

This calculation is repeated for each important component and then the largest area is chosen. Land treatment can be implemented in one of three ways, slow rate, rapid infiltration, or overland flow.

An overland flow system is probably the most practical option, with a collection site of the runoff and a discharge system to a nearby water body. The treatment occurs on the upper levels of the soil or vegetation. The vegetation gives a source of aerobical oxidation as well as filtering the leachate (Pokhrel and Viraraghavan, 2004). The soil components give a high potential for adsorption and ion exchange. The appropriate application rate and surface loading should also be chosen to eliminate saturation down into the water table but allowing enough absorption to eliminate toxins. If the appropriate application rate and loading is chosen there should be no harmful affects on the vegetation or soil should occur.

The results show that a loading rate of 50-500 m3 leachate/hectare.day should yield greater than 50% BOD5 removal and ammonia along with the removal of suspended solids. However, the removal efficiencies for ammonia can be highly variable because the ammonia can get trapped and immobilized in the structure of clay materials, adsorbed onto negatively charged sites of the organic components in the soil, or volatilize into the atmosphere although plant uptake can be very effective (Baun and Christensen, 2004). The oxidation of ammonia into nitrate will occur and then the nitrate may then undergo denitrification to yield nitrogen gas. Young plants may also take up too much nitrogen could lead to excessive vegetation growth, delay crop maturation, and weaken the plant structure (Baun and Christensen, 2004). If heavy metals are present in significant amounts in the leachate then it may be easier for it to absorb into the soil structure and will eventually make the soil infertile or the crops may become useless for consumption (Baun and Christensen, 2004). If the leachate contains toxic organics even more special care will need to be used and the application would need to be fully monitored.

In general, land treatment is very cheap and could be a possible treatment of leachate if enough land and monitoring systems are available. It may be difficult to predict the performance of the land-treatment system due to the heterogeneous soil/vegetation environment. The application rates and loading amounts would need to be obtained regularly by practical fieldwork due to the unpredictable rainfall on the system.

Physical-Chemical Treatment

Many physical and chemical processes have been studied in the treatment of landfill leachates, where as you have seen previously ammonia desorption has been the most applicable. The most popular treatment is the addition of chemicals such as: lime, ferric chloride, or alum (Crawford and Smith, 1985). These chemicals produce a precipitate which can be settled in a sedimentation tank or lagoon; this may need a retention time of several hours. The BOD reduction is due to the removal of high molecular weight organics such as hummic acid. This type of organic material is more likely to be found in middle to older aged leachates, and a lime treatment may be helpful. Younger leachates have a higher BOD and may need the addition of oxidizing agents such as: chlorine, calcium, hypochlorite, potassium permanganate, or ozone in order to oxidize the organic material, activate the carbon for absorption, or to allow ion exchange and reverse osmosis to occur (Crawford and Smith, 1985).

The results show that after initial settlement there will be a low amount suspended solids in the in the effluent but a majority of the soluble organic compounds or dissolved salts will remain in the discharge. BOD5 removal may be 20% or less, although some of the metals may precipitate out of the solution particularly at a high pH. Younger leachates become a problem because it is harder for the chemicals to precipitate out of the solution (Crawford and Smith, 1985). Most of these techniques have restricted practical application in landfill technology due to the cost and or efficiency in the landfill leachate treatment. However, hydrogen peroxide has been used during full scale treatment to limit sulfide odor emissions from leachate lagoons which have low aeration.

Recycling

The recycling of the leachate is an on site treatment process where the leachate is collected and then returned directly back into the landfill (Park, 2004). This should increase the stability of the landfill because the recirculation may promote the development of an anaerobic bacterial population within the landfill. Therefore, the landfill is acting as an uncontrolled anaerobic filter. This will allow the methanogenic bacteria to flourish and the organic acid content of the leachate may remain stable or decrease.

The results show that excessive acid fermentation within the landfill may drop the pH and methanogenic bacteria may be less likely to work effectively. This results in a higher concentration of organic acid in the leachate and lower gas production. Thus the leachate BOD tends to increase due to the recycling if the methane production is inhibited (Park, 2004). Although the recycling may lead to an increase in methane and BOD the increased microbial activity allows the landfill to stabilize more quickly. The highly polluting leachate or methane production tends to occur for a shorter period of time than without leachate recycling.

Data from full-scale leachate recycling operations are few and the overall result of the treatment seems hard to predict. This is the result of the many complex interactions which occur in the landfill such as: climatic variations, nature of cells, and hydrogeology of the site and landfill management practices.

Treatment with Domestic Sewage

Landfill sites could be planned so that the leachate can be discharged into the local sewage plants, this would probably be one of the less costly operations but would need to be monitored closely. Some problems can occur such as: high sulfate levels may lead to concrete erosion and a precipitate may occur on surfaces due to iron precipitation (Chiang and Qasim, 1994). Low acidity and high organic matter from younger leachates may cause problems in the aerobic biological oxidation stage and organic overloading of the activated sludge may lead to poor settling in the sedimentation tanks. If trickling filters are involved, the filters may suffer from clogging and the leachate may also become nutrient deficient (Chiang and Qasim, 1994).

However, the acidity of the leachate-sewage liquor could be corrected by the addition of lime at the plant which would also convert the primary sedimentation into a chemical precipitation process. This should help the removal of suspended matter and iron in the primary sedimentation tanks, although the mass of sludge would increase. The nutrient deficiency could be solved by the addition of appropriate chemicals but this may be costly. Further testing would need to be done in order to limit the toxicity of the sludge.

The best approach would be to make sure the ratio between sewage to leachate is 20:1 and then nutrient deficiency and toxicity should not be a problem unless other nutrient deficient waste waters are present (Chiang and Qasim, 1994). The advantage of treating leachate at an existing waste water treatment plant is it would be less expensive to use an existing facility and its operators. Overall, this could be a good alternative to on-site treatment but it would have to be made certain that there is enough capacity at the treatment plant to handle the increased solids, oxygen demand and hydraulic loading.

CONCLUSION

Leachate is an inevitable bi-product of landfilling caused by the percolation of water into the landfill and mixing with the trash inside of the landfill cells. It contains many hazardous compounds and could be very destructive to its surrounding environments, discharge areas (rivers/streams), and human health if it is left untreated.
The landfill consists of many liners and layers to prevent the additional percolation into the water table itself. The landfill is also designed so there is sufficient surface water runoff and a collection system is built for removal of the hazardous leachate.

Once the leachate has been removed the most effective and economical treatment option is selected for the area. Many processes can be chosen such as: biological aerobic or anaerobic treatment, land and other physical-chemical treatments, or recycling and treatment at the local waste water treatment plant. The aerobic treatment (BAF) is good for young leachate and is very efficient for ammonia removal but may not be cost effective (Baterman et al., 2004). The anaerobic treatment does not show very good ammonia removal but BOD removal can be significant and the methane gas produced may be used for heating during the process. This process may be even less cost effective than the aerobic process.

Land treatment allows a natural oxidation and filtration process to occur but enough area must be available to eliminate any harmful effects on the environment. The efficiency of the treatment is also hard to predict due to the climate and heterogeneous environment (Rowe et al., 2004). Physical-chemical applications are good for eliminating suspended solids but there is low BOD removal. However, hydrogen peroxide is used for odor control in leachate lagoons.

Recycling the leachate back into the landfill allows for faster stabilization although there may be an increase of pollutants and BOD levels for a short amount of time (Hollopeter, 1993). It can be done easily but there are many complex situations that are happening within the landfill which would need to be analyzed. Finally, treating the leachate with the local domestic waste but may become a problem with younger leachates because of the increased BOD and organic levels (Chiang and Qasim, 1994). This is the most cost effective option because it involves the use of existing operations but there must be enough capacity for the combination of the sewage and leachate mixture.

REFERENCES

Baterman, S.; de Krester, D.; McRae, D. (2004) Treatment of municipal landfill leachate by SBR. *Water(Australia)*, **Vol. 31**, no.1, pp.47.

Baun, D.L., Christensen, T.H. (2004) Speciation of heavy metals in landfill leachate. *Waste Management and Research*, **Vol. 22**, no.1, pp. 3.

Cartmell, E.; Pollard, S.J.T.; Stephensen, T. (2004) Feasibility of biological aerated filters (BAFs) for treating landfill leachate. *Environmental Technology*, **Vol. 25**, no.3, pp.349.

Castrillon, L.; Fernandez, E.; Maranon, E.; Rodriguez, J.; Sastre, H. (2004) Removal of non-biodegradable organic matter from landfill leachates by adsorption. *Water Research*, **Vol. 38**, no. 14-15, pp.3297.

Chiang, W., Qasim SR. (1994) *Sanitary Landfill Leachate: generation control, and treatment*. Technomic Publishing Co., Lancaster, PA.

Crawford, J.F., Smith, P.G. (1985) *Landfill Technology*. British Publishing. UK.

Daniel, David E. (1993) *Geotechnical Practice for Waste Disposal*. New York: Chapman & Hall, 1st ed. London.

Dezotti, M.; Sant'Anna, G.L., Jr.; Silva, A.C. (2004) Treatment and detoxification of a sanitary landfill leachate. *Chemosphere*, **Vol. 55**, no. 2, pp. 207.

Gulsen, H.; Turan, M. (2004) Startup of an anaerobic fluidized bed reactor for landfill leachate treatment. *Environmental Technology*, **Vol. 25**, no. 10, pp.1107.

Hollopeter, Jake Allen. (1993) Anaerobic sequencing batch reactor treatment of municipal landfill leachate at 350 C. *ISU thesis*.

Kaczorek, K., Ledakowicz, S. (2004) Laboratory simulation of anaerobic digestion of municipal solid waste. *Environ. Sci. Health Part A: Toxic Hazard. Subst. Environ. Eng.*, **Vol. A39**, no. 4, pp.859.

Kargl, F., Pamukogul, M.Y.; (2004) Absorbent supplemented biological treatment of pre-treated landfill leachate by fed-batch operation. *Bioresource Technolog,*. **Vol. 94**, no. 3, pp.285.

McBride, R.A., Preston, G.M. (2004) Assessing the use of poplar tree systems as landfill evapotranspiration barrier with the SHAW model. *Waste Management and Research*, **Vol. 22**, no. 4, pp.291.

Park, Jaeyoung. (2004) Evaluation of leachate treatment and recycle options using the static granular bed reactor. *ISU thesis*.

Pfeffer, Fred M. (1992) *Landfill leachate effects on transport of organic substances in aquifer materials*. U.S. Environmental Protection Agency, p.194-204. Washington, D.C.

Pokhrel, D., Viraraghavan, T. (2004) Leachate generation and treatment. *Fresenius Environmental Bulletin*, **Vol. 13**, no. 3b, pp.223.

Rowe, R.K.; Uenlue, K.; Yildiz, E.D. (2004) Modeling leachate quality and quantity in municipal solid waste landfills. *Waste Management & Research*, **Vol. 22**, no. 2, pp.78.