Emirates Journal for Engineering Research, 10 (1), 1-14 (2005)

(Review Paper)

BIOREACTOR LANDFILLS: STATE-OF-THE-ART REVIEW

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(Received September 2004 and accepted March 2005)

على الرغم من تزايد عمليات إعادة التدوير والتوليف والترميد (التحويل إلى رماد)، فلا تزال المدافن الصحية للنفايات هي البديل السائد للتخلص من الفضلات الصلبة، ويعد مدفن النفايات ذو الفاعل الحيوي أحد الأفكار التي لفتت الانتباه البالغ إليها. فمن النظام البيئي للمدفن ذو المفاعل الحيوي، يتم توخي الدرجات المثلى للظروف الملائمة للانحلال الحيوي للفضلات بإضافة غُسالة التربة أو القيام بأي تعديلات أخرى. ونتيجة لذلك، فإنه يتم تسريع ثبات الفضلات. وخلال الثلاثين عاماً الماضية، تم إجراء العديد من التجارب المختبرية وتجارب قياس تحلل المادة والدراسات الرائدة حو ل تحسين تحلل الفضلات العضوية، ومعدلات التحويل وعمليات الانحلال الحيوي وتأثير العمليات في مدافن النفايات. وتقدم ورقة البحث هذه استعراضاً لعمليات الانحلال الحيوي والآليات بالنظام البيئي للمدافن والتقنيات التي تطبق في مدافن النفايات ذات المفاعلات الحيوية وتطوير هذه النوعية من المدافن.

Despite increases in recycling, composting, and incineration, the sanitary landfill is still the predominant municipal solid waste disposal alternative. Today, “Bioreactor Landfill” is one idea that has gained significant attention. In the bioreactor landfill ecosystem, the conditions suitable for waste biodegradation are optimized by the addition of leachate or other amendments. As a result, the stabilization of wastes is accelerated. During the past 30 years, numerous laboratory experiments, lysimeter experiments, pilot-scale studies, and full-scale investigations have been done on enhancing organic waste decomposition, conversion rates and process effectiveness in landfills. This paper provides a review of the biodegradation processes and the mechanisms in landfill ecosystem, technologies applied in bioreactor landfills, and the development of the bioreactor landfill.

1. INTRODUCTION

Municipal Solid Waste (MSW) includes residential, commercial, and non-hazardous industrial waste but exclude combustion ash, hazardous waste, sludge, and industrial process wastes. However, many of these other wastes are often deposited in the same landfills that receive MSW[1]. Therefore, many researchers use “refuse” instead of MSW for solid wastes in landfills.

The generation of MSW has become an increasingly important worldwide issue over the last decade, because of the escalating growth in municipal populations, and the concomitant increase in waste production per capita. The increase in solid waste generation have promoted the development of the integrated management of MSW which is accomplished by recycling, composting, incineration, or landfilling of waste. Among these methods, to date, the sanitary landfill is the predominant municipal solid waste disposal alternative because it is less expensive comparing with combustion, and there is a limit to the types of waste that can be recycled or composted[1]. Despite increases in recycling, composting, and incineration, approximately 55% by weight of the MSW generated in the United States in 1997 was deposited in sanitary landfills[2].

Within the landfill ecosystems, biological, chemical and physical processes promote the biodegradation of organic wastes in the MSW. The conventional landfills usually include environmental barriers such as landfill liners and covers, which exclude moisture that is essential to waste biodegradation. Consequently, wastes are contained in a “dry tomb” and remain intact for long periods of time ranging from 30 to 200 years, possibly in excess of the life of the landfill barriers and covers. Liner failure could happen in conventional dry landfill sometime in future, which can cause serious groundwater and surface water contamination[3].

Today, the “bioreactor landfill” is one idea that has gained significant attention. A bioreactor landfill is a sanitary landfill that uses enhanced microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents within 5 to 10 years of bioreactor process implementation. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates and process effectiveness over what would otherwise occur within the landfill[4]. The “bioreactor landfill” provides control and process optimization, primarily through the addition of leachate or other liquid amendments, the addition of sewage sludge or other amendments, temperature control, and nutrient supplementation[5]. Beyond that, bioreactor landfill operation may involve the addition of air. Based on waste biodegradation mechanisms, different kinds of "bioreactor landfills" including anaerobic bioreactors, aerobic bioreactors, and aerobic-anaerobic (hybrid) bioreactors have been constructed and operated worldwide. According to the survey conducted by the Solid Waste Association of North America (SWANA) in 1997, there were over 130 leachate recirculating landfills in USA[6,5].

2. COMPOSITION OF MUNICIPAL SOLID WASTE

MSW composition can vary substantially with location and time depending on many factors, including socio-economic and climatic conditions, waste collection and disposal methods, sampling, and sorting procedures[7]. The composition of buried MSW influences the biodegradation processes in the landfill ecosystem, which then affect not only the landfill gas (LFG) production and composition but also leachate quality and quantity. Many studies have examined the chemical composition of MSW[8-13]. Table 1 presents typical organic composition of MSW.

Cellulose and hemicellulose represent the major degradable components of MSW. In contrast, lignin is essentially recalcitrant under methanogenic conditions; poly lignin is mineralized to CO_2 and CH_4 in anoxic sediments at slow but environmentally significant rates[14]. It was reported that cellulose plus hemicellulose fraction of MSW accounts for 91% of its methane potential[9]. Proteins and soluble sugars are other biodegradable organic materials that are present in smaller concentrations[1].

Table 1. Organic Composition of Residential Refuse[1]

Reference	% [dry wt]			
	Cellulose	Hemicellulose	Lignin	Volatile solids
Barlaz et al, 1989a* [8]	51.2	11.9	15.2	78.6
Eleazer et al, 1997 [15]	28.8	9.0	23.1	75.2
Rhew and Barlaz, 1995 [11]	38.5	8.7	28.0	Not measured
Ress et al, 1998 [13]	48.2	10.6	14.5	71.4
Barlaz, unpublished data	36.7	6.7	13.6	Not measured

* The following additional analyses were performed on this sample: protein, 4.2%; soluble sugars, 0.35%; starch, 0.6%; and pectin, <3%.

MSW recycle programs significantly contributed to change the composition of MSW, as well as the methane production from landfilled MSW. The actual methane yield of MSW decreased by 10% between the base case with no recycling (64.9 L wet kg-1) and a case in, which 31% of MSW is recycled (58.6 L wet kg-1)[12].

3. THE ANAEROBIC BIOREACTOR LANDFILL

3.1 The Anaerobic Decomposition Process in Bioreactor Landfill Ecosystem

The technologies of enhancing biodegradation of organic waste in bioreactor landfills can be possibly developed upon understanding the basic biochemical processes that occur in such ecosystem. Numerous studies have been carried out on the anaerobic biodegradation process in the landfills. Numerous researchers [17,17,8] have characterized the stabilization of waste in terms of an idealized sequence of phases between the burial of fresh MSW and well-decomposed waste. Some investigations have suggested that the stabilization of waste proceeds in five sequential and distinct phase[18,19]. The rate and characteristics of produced leachate and biogas vary from one phase to another, and reflect the microbially mediated processes taking place inside the landfill[16]. Major bacterial groups involved in this decomposition process include hydrolytic bacteria, fermentative bacteria, acetogenic bacteria, methanogenic bacteria and sulphate-reducing bacteria. The phases experienced by degrading wastes are described as following.

Phase I: Initial adjustment phase

In the aerobic phase, both oxygen and nitrate are consumed, with soluble sugars serving as the carbon source for microbial activity. The quantity of oxygen available is fairly low, depending on the degree to which the waste is compacted. All of the trophic bacteria groups required for MSW methanogenesis are present in fresh MSW (cellulolytics, acetogens, and methanogens), though there is little change in their populations[8]. In addition, this initial phase is associated with initial placement of solid waste and accumulation of moisture within landfills. An acclimation period (or initial lag time) is observed until sufficient moisture develops and supports an active microbial community[16].

Phase II: Transition phase

With the depletion of oxygen trapped within a landfill, a transformation from an aerobic to anaerobic environment occurs, and the facultative anaerobic microorganisms become active. The electron acceptors shift from oxygen to nitrates and sulfates[16.19]. The hydrolytic and fermentative microorganisms hydrolyze polymers such as carbohydrates, fats, and proteins. The initial products of polymer hydrolysis are soluble sugars, amino acids, long-chain carboxylic acids, and glycerol (9). By the end of this phase, measurable concentrations of COD and volatile organic acids can be detected in the leachate[19]. In addition, the ammonia can be detected due to the hydrolysis and fermentation of protein compounds.

Phase III: Acid formation phase

During the first stage of this phase, the intermediates produced from Phase II, such as sugars, amino acids, long-chain carboxylic acids, and glycerol, are further fermented into short-chain carboxylic acids, carbon dioxide, and hydrogen. Acetate and alcohols are also formed. During the second stage of this phase, the obligate proton-reducing acetogens become active. They oxidize the fermentation products of the first stage to acetate, carbon dioxide, and hydrogen. The conversion of short-chain carboxylic acids to acetate is only thermodynamically favorable at very low hydrogen concentration. The thermodynamic favorability of reactions recognized as potentially operative during landfill stabilization is presented in Table 2[20]. In nearly all cases, the role of hydrogen (H2) is apparent and has led not only to the suggestion that H2 will regulate reaction opportunity and pathway, but the relative predominance of process intermediates as well. However, there is a hydrogen-scavenging population, i.e., methanogens in an active anaerobic ecosystem. If fermentative and methanogenic activities are not balanced, intermediates will accumulate and may percolate from the landfill as leachate[9]. Therefore, intermediate VOAs at high concentrations and a decrease in pH accompanied by metal species mobilization are often observed before the onset of MSW methanogenesis. The viable biomass growth associated with the acid formers bacteria, and rapid consumption of substrate and nutrients are the predominant features of this phase[16].

Phase IV: Methane fermentation phase

During phase IV, both methanogens and sulphate-reducing bacteria are involved in the anaerobic degradation. The hydrophilic methanogenic bacteria transform hydrogen and carbon dioxide into methane, and the acetophilic methanogenic bacteria transform acetic acid into methane and carbon dioxide. The rate of methane production increases rapidly to some maximum value. Methane gas constitutes approximately 50-60% (by volume) of gas composition[9,21]. The pH value is increased, and consequently heavy metals are removed by precipitation. The organic matter present in the leachate declines, which causes the BOD and COD to fall.

In the mean time, sulphate-reducing bacteria convert hydrogen, acetic acid and higher volatile fatty acids (VFAs) into carbon dioxide and hydrogen sulphide. This group of bacteria competes with the methanogenic bacteria to transform the hydrogen and organic carbon. Based on their findings, Gurijala and Suflita[22] indicated that methanogenesis might be limited to an unknown degree by the availability of sulfate. Fairweather and Barlaz[23] reported that the presence of sulfate decreased methane yields, but sulfate reduction and methane production can occur concurrently during MSW decomposition and methanogenesis is the dominant electron sink process even in the presence of excess sulfate.

Phase V: Maturation phase

During phase V, the easily biodegradable organic matter is stabilized, and nutrients and available substrate become limiting. Gas production drops dramatically and leachate strength stays steady at much lower concentrations. Reappearance of oxygen and oxidized species may be observed slowly[16.19]. Concurrently, there is an increase in the rate of cellulose plus hemicellulose hydrolysis. The low level biodegradable matter gradually humifies (formation of complex molecules such as humic acid and fulvic acid).

MSW degradation time span ranges from 30 to 100 years in traditional landfill ecosystem. However, with leachate recirculation, the temporal domain of the acid formation and methane fermentation phases is compressed, and accelerated stabilization of the readily degradable waste fractions typically leads to either accumulation and retention of more aggressive leachate during acid formation phase, or higher gas production/recovery potential and more stable leachate during subsequent methane fermentation phase than is encountered at conventional landfills[24].

This idealized waste degradation sequence assumes that the waste is homogeneous and of constant age. A realistic landfill occupying waste cells with highly variable age and composition may yield a somewhat different picture[25]. In a large-scale landfill where waste is placed over a lengthy period of time, the waste stabilization phases tend to overlap and the leachate and gas characteristics reflect this phenomenon.

Table 2. Representative Redox Half-Reactions during Waste Stabilization in Landfill Bioreactor (Adapted from [20])

Oxidation (electron donating reactions)[1]		**Δ G^0 (KJ)**
Caproate → Propionate	$CH_3(CH_2)_4COO^-+2H_2O \longrightarrow 2CH_3CH_2COO^-+H^++2.5H_2$	+ 48.3
Caproate → Acetate	$CH_3(CH_2)_4COO^-+4H_2O \longrightarrow 3CH_3COO^-+H^++4H_2+2H$	+ 96.7
Caproate → Butyrate+ Acetate	$CH_3(CH_2)_4COO^-+2H_2O \longrightarrow CH_3(CH_2)_2COO^-+ CH_3COO^-+H^++2.5H_2$	+ 48.4
Propionate → Acetate	$CH_3CH_2COO^-+3H_2O \longrightarrow CH_3COO^-+HCO_3^-+H^++3H_2$	+ 76.1
Butyrate → Acetate	$CH_3(CH_2)_2COO^-+2H_2O \longrightarrow 2CH_3COO^-+H^++2H_2$	+ 48.1
Ethanol → Acetate	$CH_3CH_2OH+H_2O \longrightarrow CH_3COO^-+H^++2H_2$	+ 9.6
Lactate → Acetate	$CH_3CHOH\ COO^-+2H_2O \longrightarrow CH_3COO^-+ HCO_3^-+H^++2H_2$	-4.2
Acetate → Methane	$CH_3COO^-+H_2O \longrightarrow HCO_3^-+CH_4$	-31.0

[1] pH7, 1atm, 1 kg mol $^{-1}$ activity, 25ºC

3.2 Governing Abiotic Factors for Anaerobic Degradation

Moisture content

Moisture content is a critical factor affecting the rate and extent of organic waste decomposition. The benefits of increased water content in a landfill include limiting oxygen transport from the atmosphere, facilitating exchange of substrate, nutrients, buffer, and dilution of inhibitors and spreading of microorganisms within the landfill. The stimulatory effect of moisture content on anaerobic populations has been proved by numerous studies. Jones et al[26] characterized refuse samples from a sanitary landfill as a function of depth below the surface. The total anaerobic population as well as the populations of proteolytic, amylolytic, and cellulolytic bacteria increased near the water table, suggesting a stimulatory effect of moisture content. Protease and amylase activity increased sharply in the water table, which is consistent with the differences in enzyme activity between wet and dry refuse measured under laboratory conditions[9,27]. The strong effect of moisture content was also seen in the correlations of total mass loss and moisture content according to the research results performed in full-scale landfills[28].

Nutrients

In landfill ecosystem, the anaerobic degradation of wastes particularly need such nutrients as nitrogen and phosphorous besides organic matters. The anaerobic ecosystem requires much less nitrogen and phosphorous than the aerobic system which assimilates much substrate into new cells. The optimal ratio between organic matter (expressed as COD), nitrogen and phosphorous is 100:0.44:0.08 [17]. In general, the well-mixed waste landfill will not be limited by nitrogen and phosphorous. Sometimes, the heterogeneity of landfill may limit the nutrients' availability to microorganism. Other micronutrients, e.g. sulphur, calcium, magnesium, potassium, iron, zinc, copper, cobalt, molybdanate and selenium, are found to be present in most landfills.

pH

At neutral pH, the bacteria responsible for MSW decomposition are most active. The optimal pH for refuse methanogenesis is 6.8–7.4. As discussed in the former section, the role of hydrogen is crucial, and the methanogen is hydrogen-scavenger. In low pH conditions, the activity of methanogenic bacteria is low. As a result, their conversion of hydrogen and acetic acid decreases. This causes the hydrogen pressure to build up, and at elevated pressures, acetogenic bacteria cannot convert volatile fatty acids, particularly butyric and propionic acid. The accumulation of these acids further lowers the pH within the landfill, and eventually stops methane production. Therefore, the addition of buffering materials during bioreactor landfill operation is a critical strategy to maintain appropriate pH as well as balance relations between the various bacterial groups. The pH effect on the waste degradation is illustrated by the full-scale landfill studies in which a higher pH is correlated with more decomposed refuse reflected by the relationship between cellulose plus hemicellulose to lignin and pH[10,29].

Temperature

Many studies have proved microbiological degradation rate increases along with temperature increase. The van't Hoff-Arrhenius equation[30] is one of the most used equations that formulate the relationship between degradation rate and temperature as following:

$$k_t = k_{20} * \theta^{(T-20)}$$

where: k_t = degradation rate constant at a particular temperature; k_{20} = degradation rate constant at 20°C = 0.23; θ = constant of 1.056 for temperatures between 20 and 30°C; and T = temperature for which k is desired.

The investigation done by Baldwin et al[28] tested this relationship as well. Blakey et al[31] documented that the role of temperature may be an important factor offering the potential means of manipulating the methane content of LFG. Rees[32] observed that the optimum temperature for methane production from domestic refuse in a conventional anaerobic digester is about 40°C. Hartz et al[33] found that 41°C was the optimum for the generation of methane on a short-term basis, and methane generation would cease somewhere between 48 and 55°C. Mata-Alvares and Martina-Verdure[34] reported the optimum temperature is 34 °C to 38 °C. In addition, it was documented that the rate of methane generation increased significantly (up to 100 times) when the temperature was raised from 20 to 30 and 40°C in laboratory simulations[17].

Inhibitors

The anaerobic ecosystem is considered to be rather sensitive to inhibitors. Researchers have reported many inhibitors of anaerobic degradation, e.g. oxygen, carbon dioxide, hydrogen, proton activity, salt ions, sulphide, heavy metals, and specific organic compounds[17]. Cations such as sodium, potassium, calcium, magnesium and ammonium have been observed to stimulate anaerobic decomposition at low concentration while inhibit it at high concentrations. High sulphate concentration can inhibit methane generation.

It has been speculated that CO_2 acts as an inhibitor through the raising of the redox potential[35], or the impairment of the methanogen cell membrane function by increasing its fluidity through CO_2 dissolving in the cell membranes of methanogens[36]. Additionally, it is possible that CO_2 acts as an end-product inhibitor during acetate and propionate degradation.

3.3 Technologies of Enhancing Degradation in Anaerobic Bioreactor Landfill

As discussed above, the principal and governing factors in the anaerobic degradation are very clear. How to manipulate these factors to accelerate the waste stabilization rate and get benefits from landfill is what numerous researchers have been attempting during the past over 30 years. Many technologies have been examined and applied in full-scale practices.

The stabilization means that the environmental performance measurement parameters (LFG composition, generation rate and leachate constituent concentrations) remain at steady levels, and should not increase in the event of any partial containment system failures beyond 5 to 10 years of bioreactor process implementation[4]. Therefore, the stabilization of waste is quantified by leachate quality, gas composition and production, landfill settlement and waste temperature. The effects of the following technologies are evaluated according to these aspects.

Leachate Recirculation and Moisture Control

Previous experiences and researches have indicated that moisture content is a critical factor in enhancing waste decomposition in bioreactor landfills. Moreover, some studies indicated not only moisture content but also moisture movement could affect waste stabilization. Therefore, moisture control (including moisture content and movement) is the essential for landfill operation. Leachate recirculation has been demonstrated to be a superior management strategy for moisture control. The study of leachate recirculation in landfills has attracted numerous researchers since mid 1970s[9,16,,24,29,34,37,38,39,40,41]. Through leachate recirculation, liquid movement distributes the inocula, minimizes local shortages of nutrients, provides better contact between insoluble substrates, soluble nutrients, and the microorganisms, dilutes potential toxins, and transfers heat. As a result, microbial activities are increased. The advantages of leachate recirculation include: providing in-situ leachate treatment instead of off-site treatment, thus saving costs; enhancing waste settlement, thus decreasing the risk of damage to the final cover and permitting recovery of valuable landfill air space; increasing gas generation rate which make energy recovery more favorable; accelerating waste decomposition, thus shortening the post closure monitoring period and reducing the overall landfill operation cost. Laboratory, pilot scale and full-scale studies have tested all these advantages.

Poland[37,38] conducted studies on accelerating solid waste stabilization and leachate treatment by leachate recycle in simulated landfills. He concluded that the capture and recirculation of leachate through a simulated landfill can promote a more rapid development of an active anaerobic bacterial population of methane former, increase the rate and predictability of stabilization of readily available organic pollutants, dramatically decrease the time required for stabilization, and reduce the potential for environmental impairment.

Between 1993 and 1996 two pilot scale test cells were constructed at Yolo County, California, USA. Each cell has a surface area of about 930 m^2 and initial 12 m depth[42,29]. One cell was designated the "enhanced" cell in which supplemental liquid was added and leachate was recirculated. The "control" cell was constructed identically to the "enhanced" cell, however no liquid has been added. The two cells began operation in 1996. After about 3 years of operation, Mehta, et al[29] performed a comparison of the two test cells to evaluate the effects of leachate recirculation on refuse decomposition. After analyzing 44 samples from 33 distinct depth intervals and collecting the gas generation data and waste settlement data, Mehta, et al[29] arrived to the conclusion that the leachate recirculation has the potential to enhance settlement, methane production, and solids decomposition at field-scale. Refuse was excavated in three borings from the enhanced cell and two borings from the control cell. The moisture content analysis shows that the average moisture content in these samples range from 34 to 38 % in the enhanced cell, while the average moisture content in the control cell ranged from 14.6 to 19.2%. These data illustrate that leachate recirculation increase moisture content in enhanced cell. Leachate recirculation increased both methane production (63.1 versus 27.9 L CH4 wet/kg over 1231 days) and waste settlement (15.5% versus 3% of the waste thickness).

During record period, the total volume of leachate recycled in the enhanced cells is equivalent to 570 L/metric ton. This volume should increase the refuse moisture content in the enhanced cell to 46%. However, only 2 of 33 collected samples reached this value. This illustrates that the liquid likely flow through preferential flow paths in the waste. Therefore, the design of the system used for the distribution of recycled leachate is a critical factor for achieving good moisture management in bioreactor landfill.

Townsend et al[43] also presented the effects of leachate recycling on landfill stabilization at an existing lined landfill in North-Central Florida during the period from 1989 through July 1993. Leachate was recirculated to the landfill by means of an infiltration pond. The area of the landfill east of the ponds was left untreated to serve as the control area. The results indicated that leachate recycling significantly increased moisture content of the landfilled waste, and maintained conditions suitable for biological stabilization. The results of the settlement analysis illustrate the greatest subsidence occurred in the area close to the infiltration pond at 1.01 m (5.65% volume reduction), and the least subsidence was measured in the area farthest from the leachate recycle ponds at 0.69 m (3.82% volume reduction). The original average biochemical methane potential (BMP) from biodegradable organic fraction (BDOF) samples in the recycling area was 0.273 m^3 CH_4 kg^{-1} volatile solids (VS), and decreased to 0.196 m^3 CH_4 kg^{-1}VS. In contrast, the original average BMP from BDOF samples in control area is 0.297 m^3 CH_4 kg^{-1}VS, and only decreased to 0.281 m^3 CH_4 kg^{-1}VS.

In essence, the landfill itself can be used as a controlled anaerobic treatment system much analogous to an anaerobic trickling filter[37,44]. Leachate recirculation can also supply effective in-situ treatment for landfill leachate. Even where recycled leachate are more concentrated than single-pass leachate, they are treated primarily inside the landfill, utilizing its storage and biodegradation capacity as an effective bioreactor[16]. The in-situ treatment effect can be illustrated by comparing the leachate data of the Trail Road Landfill[45] with the leachate data of the Tre Monti site[46].

The Trail Road landfill Phase 3 in Ottawa, Canada started operation in 1991. The generated leachate was pumped into infiltration lagoons, which were constructed using on-site stockpiled clay for containment dykes. The infiltration lagoons were relocated periodically to ensure even distribution of the moisture and to accommodate the landfilling of the solid waste. The ratio of the BOD/COD decreased from about 0.9 to 0.4 over a period of eight years. Tre Monti is a 4.16-million-m^3 landfill located on a pliocenic clay declivity on the hills near Imola, in Northern Italy, and was built in 1989–1990. After a significant initial decrease, BOD remained relatively uniform from 1993 to 2001, ranging between 850 and 1700 mg l^{-1}, whereas COD, after a similar initial decrease, showed an overall tendency to increase in the 1994–2000 period. The BOD/COD ratio decreased from 0.50 to 0.18 from 1992 to 2001.

Klink and Ham[47] indicated that moisture content and movement are separate variables that affect landfill methane generation rates. They have observed that moisture movement through refuse bed enhanced the rates of methane production by 25 to 50%, compared to those rates during conditions of minimal moisture movement and at the same overall moisture content. Chugh et al[48] examined different leachate recirculation rates namely, 30%, 10%, 2% of the initial volume of waste in the reactors, and indicated that moisture movement significantly improve methane production rates.

Many studies agreed that leachate recirculation with pH control further enhanced landfill stabilization and treatment efficiency, and buffering the leachate prior to its recirculation is an important operation strategy for the maintenance of the desired pH values in the system[41]. When Pohland and Kim[24] examined the in-situ treatment of leachate and co-disposal of organic and inorganic hazardous wastes by using simulated landfill with leachate recirculation, they observed an early and rapid onset of acid formation with production of a strong and chemically aggressive leachate once field capacity was reached and excess moisture for leaching became available. However, the initial transformation pattern tended to persist until changes in leachate recirculation intervals occurred, neutralization and sludge seeding promoted the onset of active methane fermentation. The reason for this phenomena is that leachate recirculation, in some cases, can cause acid accumulation. In the acid formation phase, excess acids and hydrogen can make the thermodynamical favorable reactions (Table 2) reverse and shift the equilibrium to the left. Buffering the recirculated leachate can reverse this phenomenon.

The effect of variable rates of leachate recirculation was examined by Al-Yousfi and Pohland[12], where they employed a numerical model (PITTLEACH) to predict leachate quantity and quality, as well as biogas generation for both single-pass leaching and leachate recirculation. The results indicated that total volatile acids concentrations increased and the plateau section of concentration verses time relationship became more pronounced as the leachate recirculation rates increased. These profiles confirmed the effectiveness of landfills as in-situ bioreactors capable of treating and mineralizing high-strength leachate. The results indicated that higher leachate recirculation rates will cause higher methane gas generation and that there is a lag time needed for the methanogenic phase to prevail under leachate recycling operation. This confirmed that leachate recirculation can cause acidogenic conditions in landfills, and buffering with leachate recycling is very necessary to neutralize the acidic conditions.

Leachate recirculation reduces metal concentrations in leachate. The primary metal removal mechanisms appear to be sulphide and hydroxide precipitation and reaction with humic-like substance. Leachate recycling promotes neutral or above neutral leachate conditions as well as stimulates reducing conditions providing for the reduction of sulphate to sulphide[49]. Additionally, moderate to high molecular weight humic-like substances are formed from waste organic matter with time. These substances tend to form strong complexes with heavy metals. However, over time, oxygen and water may enter the landfill creating conditions that may mobilize metals and flush remaining inorganic contaminants out of the landfill[5].

Some researchers have carried out some studies on the co-disposal potential of bioreactor landfills for organic and inorganic hazardous wastes with leachate containment and in-situ recirculation. Reinhart et al[5] documented that bioreactors would tend to optimize removal of hazardous organic contaminants by (1) stripping volatile organics by increased gas production, (2) optimizing conditions for biodegradation, and (3) stimulating immobilization of contaminants through humification. Sanin and Barlaz (1998) also confirmed these mechanisms. Pohland and kim[24] reported that the effect of admixed loadings of inorganic and organic hazardous wastes on anaerobic degradation can be offset by managing their attenuation through leachate containment and regulated recirculation, the horizon of application of bioreactor landfills can be extended to co-disposal practices by implementing prospective design, construction and operational protocols consistent with simulated experiments' findings. The attenuation capacity of landfill bioreactors is equally effective for toxic organic compounds by employing leachate recirculation, and bioremediation with reductive dehalogenation is a prime example[50,51]. Pagano et al[52] carried out a study to determine the reduction potential of PCB-contaminated sediments in anaerobic bioreactor systems with leachate recirculation. After 13 weeks of operation, the average total chlorine/biphenyl of the original Aroclor was reduced by 11% and 23%, respectively.

At landfills whereas leachate recalculation is practiced to enhance decomposition of readily degradable organic constituents, leachate ammonia nitrogen concentrations may accumulate to higher levels than during conventional single pass leaching, thereby requiring treatment prior to ultimate discharge[50]. Leachate recirculation could create an environment that promotes the rapid development of desired microbial populations of denitrifiers, nitrifiers, and methanogens. Onay and Pohland[53,54] reported nitrogen and sulfate attenuation in simulated landfill bioreactors. The experimental results indicated that both nitrogenous and sulfur compounds can be attenuated through autotrophic denitrification, and leachate nitrate concentrations of 750 mg/l reduced to less than 1 mg/l by denitrification to nitrogen gas. Promoting this process in landfill environment can result in the reduction of leachate ammonia and sulfate concentrations without any need for external leachate treatment. Furthermore, autotrophic denitrification can utilize sulfur compounds, prevent their accumulation in landfills and decrease their potential for inhibition of methanogenic bacteria by sulfate-reducing bacteria in competition for substrate. Therefore, it is recommended to modify landfill design by involving an aerobic zone associated with the leachate under-drain system, and an anoxic zone associated with a surface leachate distribution system below the final cap.

Leachate over recirculation can lead into saturation, ponding, and high level of acid conditions, particularly during early degradation phases[19]. The principal operational challenge is to manage leachate recirculation in such a manner that the excessive accumulation and retention of more aggressive leachate during the acid formation phase does not inhibit the onset and development of an active methane fermentation phase[20]. In order to maximize waste stabilization, leachate recirculation frequency must be carefully selected. Leachate application, with pH control, four times per week was reported[41] to effectively increase waste stabilization in terms of high gas yield and lower organic content in the leachate. It is extremely crucial, in full-scale leachate recirculation, that leachate is applied at a slow rate before the onset of methanogenic phase of waste biodegradation, and can be increased once LFG production reaches a reasonable flow rate[19,50].

Inocula Addition

Many researchers suggested adding inocula as a bioreactor management alternative. Municipal sewage sludge, animal manure, septic tank sludge and old MSW have been recommended as potential inocula. The addition of sludge to MSW has been reported to have both positive and negative effects in waste biodegradation. Anaerobically digested sewage sludge can serve as a seed to microorganisms as well as source of nitrogen, phosphorous, and other nutrients. Early studies[37,38,55,56,57,58] indicated that leachate recirculaion with pH control and sludge seeding enhanced biological stabilization of organic pollutants in the leachate and substantially increased biogas generation rates in span of few months rather than years. More recent laboratory study[59] reported that in 10-liter laboratory-scale batch digesters filled with 2-year old MSW at ratios of 1:9, 1:6 and 1:4 (anaerobically digested sludge to waste on wet basis), pH of leachate ranged from 7.0 to 8.5 compared to sharp drop in pH levels to the acidic range in the control reactors (no sludge addition). This may be explained by the buffer capacity of sludge. Additional field practices of adding biosolids to waste[31],[60] indicated relative increase of biogas production and improvement of leachate quality.

On the other hand, Barlaz et al[61] observed carboxylic acid accumulations and decreases in pH associated with sludge addition to fresh MSW. The results of this study confirmed that sludge addition without buffer addition did not stimulate methane production. Moreover, it was suggested that sewage sludge addition to MSW might have a limiting effect on waste biodegradation if the anaerobic conditions are already established[62].

Another alternative source of inocula is composted solid waste. Stegmann and Spendlin[63] found that the addition of composted MSW to fresh MSW helps to initiate the methane phase relatively early. Furthermore, Suna Erses and Onay[64] suggested that the utilization of external leachate recycled from old landfills having desired acclimated anaerobic microorganisms, low organic content and higher buffer capacity into a young landfill could be a promising leachate management strategy for faster waste stabilization. In the above study, old landfill leachate containing large number of methanogens served as inocula, and helped the onset of methanogenic conditions.

Particle Size

The use of MSW with a reduced particle size relative to unprocessed MSW provides a more homogenous waste. The well mixed shredded waste permits greater contact between the key refuse constituents required for methane production: moisture, substrate, and microorganisms[9]. Waste shredding could lead to rapid oxygen utilization, increase rate of waste decomposition, and lead to early methane production[65,66]. Experimental results indicated that shredded MSW produces leachate with higher peak COD concentrations and slightly lower minimum pH levels than unprocessed MSW.

However, too small particle sizes could cause rapid waste hydrolysis, and lead to a build-up of acidic end products, that will have a negative impact on methane production. MSW shredding to particle size in the range of 250 to 350 mm particle sizes produced 32% more methane after 90 days than MSW with 100 to 150 mm particle sizes, and 100-150 mm shredded MSW produced 16 times as much methane as a finely shredded MSW of less than 25 mm particle size[56].

Temperature Control

As discussed above, the optimum higher temperatures will result in faster rates of gas production and refuse stabilization. The temperature attained by a landfill is determined by the balance between the rates of heat production and the rate of heat loss to the surrounding soil and atmosphere. The introduction of air and the consequential onset of aerobic activity contribute to rapidly increase temperature and have been found to stimulate methane production[19,32]. The phenomena was verified by full-scale tests[29]: temperatures in bioreactor cell with leachate recycle and cell without leachate recycle reached 50-55 °C in the top layer just after refuse burial According to Mehta et al[29] observations, leachate recirculation accelerated the anaerobic reactions in landfills, and increased the temperatures inside the bioreactor landfill. It was reported that temperatures in the control cell without leachate recirculation stabilized at 25-32 °C, and temperatures in the enhanced cell with leachate recirculation increased with the initiation of leachate recirculation and ultimately stabilized at 35 °C in the bottom layer and 40 °C in the middle and top layers.

According to a full–scale investigation, Rees[32] suggested that the method to maintaining temperatures of about 45 °C in an anaerobic landfill in a temperate climate is to allow water into the site from the bottom and maintain an insulating layer of about 4 m above the groundwater table in the landfill. Another potential method of temperature control is the heating of recirculated leachate such as used in Sweden's experimental "Energy Loaf", however the potential of this leachate heating needs further examination.

Lift Design

MSW is usually disposed of in 2 to 3 m lifts with or without daily cover. The depth of lifts, whether or not compacted, and with or without daily cover are important factors affecting the waste degradation. Early studies indicated that leachate COD concentration was a function of waste depth[65], whereas COD of deeper cells (2.4 m) exhibited more than double the typical COD of the comparable shallow ones (1.2 m). Stegmann[57] suggested that the first layer should be uncompacted, so readily degradable organics can decompose aerobically and are allowed to stabilize before addition of subsequent lifts. Reinhart et al[5] indicated that the increased MSW compaction not only reduces waste ability to move moisture through waste but also makes the waste achieve level of saturation with less moisture addition because both waste hydraulic conductivity is inversely related to waste density. Moreover, compaction contributes to anisotropic conditions within the landfill that magnify lateral movement of moisture. Several bioreactors in Iowa, Wisconsin, and the UK have operated with little or no compaction[31,60].

Field results confirmed that partially decomposed MSW has the ability to attenuate leachate[65,67]. The COD and BOD concentrations were reduced to 75% after leachate seeping through deeper lifts of MSW.

Applying of daily or intermediate cover of low permeability can lead to horizontal movement and the potential for leachate ponding or side seeps[19]. For example, Natale and Anderson[68] reported saturated conditions and ponding at the Lycoming County site during periods when high volumes of leachate were recirculated in areas using clay and silty soils for daily cover. Therefore, many researchers suggested lift design without daily cover, or a cover should not be used immediately. However, in the actual bioreactor landfill operations, daily cover is used to improve the access to the landfill; reduce the amount of waste that can blow away; reduce the risk of disease; reduce odors; reduce the potential of landfill fire.

In order to minimize ponding and horizontal movement, Reinhart and Townsend[19] suggested use of high permeability soils and/or alternative daily cover should be considered. Alternative daily cover materials include mulched or composted yard waste, foam, carpet, clay/cellulose additives, and geotextiles. The use of these alternative materials may result in landfill space and cost saving, increase of waste hydraulic conductivity within the landfill and extended life of the leachate drainage layers efficiency[69]. For example, the use of alternative daily cover in the form of green waste or tarps was successfully during the waste-filling phase of the Yolo County Central Landfill project[70].

Nutrients Addition

Nutrients required for waste degradation in landfills are generally met at least during early degradation phases. Sometimes, phosphorous may be limiting during later stages. Some studies found that the addition of nitrogen and phosphorous stimulated methane production or rapidly decreased BOD and COD concentrations in leachate[45,71]. Some researchers[57,72] observed that the addition of nutrients such as nitrogen and phosphorous to the recycled leachate significantly shortened the initial phase of biodegradation, and methane generation commenced earlier. However, other studies found nutrient control had no significant effect on stabilization of the waste[34,44]. Therefore, it is concluded that nutrient addition does not have sufficient advantages as other enhancement technologies.

4. OTHER BIOREACTOR LANDFILLS

4.1 The Aerobic Bioreactor Landfill

Recently, increased interest has been focused on the introduction of oxygen to the landfill to create an aerobic bioreactor[5]. In an aerobic environment, the indigenous, respiring microorganisms convert the biodegradable organic compounds of MSW to mostly carbon dioxide and water, instead of methane, with stabilized humus remaining. Anaerobic degradation of organic matters in landfills lead to the generation of biogas containing methane (CH_4) and CO_2. Methane generated in landfills is typically in excess of 45% of the total landfill gases[73]. Methane is a very active greenhouse gas. The most cost-effective alternative to reduce methane emissions from MSW is to compost it aerobically[74]. Optimum conditions for aerobic biodegradation are relatively easily manipulated in small-scale operations. Aerobic biodegradation processes have demonstrated that many of the organic compounds found in MSW can be degraded in significantly short time frames (as compared with anaerobic conditions) by the introduction of air and moisture in the proper proportions[75,76,77].

The ‘Fukuoka Method’ (a semi-aerobic landfill type) is one such attempt to enhance the aerobic biodegradation of organic substance in MSW. This semi-aerobic landfill type is extremely matched the rainy Japanese climate, and has become the standard Japanese landfill type[78]. In the semi-aerobic system, the ends of leachate collection system pipes are open to the atmosphere, the temperature differential between the interior landfill (high temperatures) and the outside air temperature (lower relative temperatures) produces a ‘chimney’ effect, and air is drawn into the pipes, moves through the headspace of pipes and circulates throughout the waste mass. In Germany, aerobic biological pre-treatment of MSW has been carried out since the late 1970s. The German system also employs the ‘chimney’ effect to passively supply air to waste mass[77].

A 1.0 ha portion of a solid waste landfill in Atlanta, Georgia, USA, was utilized as a test cell for demonstrating aerobic landfill. The cell measures 67×122 m, and was prepared according to standard operating procedures. The test area contained approximately 53,500 m^3 of MSW without yard waste or construction debris[79]. After 5 months of operation, organic content and metal concentrations were below EPA exceptional quality compost levels[80].

Two independent aerobic landfill demonstration projects in Columbia County landfill in Augusta, Georgia and Live Oak Landfill in North-Central Georgia, not only showed that aerobic decomposition of MSW in-situ could be accomplished, but also the data was very similar, with respect to LFG reduction and increased waste settlement, despite the fact that each landfill was constructed in a different style and with different waste inputs[76,77]. Leachate and additional make-up water were injected into the MSW mass for maintaining 40-70% moisture content. Compressed air was injected into the landfill mass through injection wells to ensure that the oxygen content remains above 0%. Additional nutrients were also added into the landfill by way of the injection wells to further promote the aerobic degradation. It has been found that a preferred concentration ratio of carbon to nitrogen in the range of about 20:1–50:1 is desired. Based on the data from the above aerobic landfills, it was concluded that: (a) significant increase in the biodegradation rate of the MSW over anaerobic processes; (b) a reduction in the volume of leachate as well as organic concentrations within the leachate, and (c) significantly reduced methane generation and “anaerobic” odors.

4.2 Anaerobic-Aerobic (Hybrid) Bioreactor Landfill

Some studies have been done using combined anaerobic and aerobic systems. Ziehmann and Meier[81] investigated the efficiency of a frequent change between both processes in large-scale simulated bioreactors. It was concluded that the degradation of waste by alternating aerobic /anaerobic conditions was not significantly higher than that in aerobic service, however, the operating expenditure was much higher during the alternating process.

5. LEACHATE OR MOISTURE DISTRIBUTION

As discussed above, the critical aspect of a bioreactor landfill is the moisture control through leachate recirculation, which includes leachate addition and/or make-up water addition if necessary. Whether via aerobic or anaerobic processes, leachate recirculation in landfills can potentially lead to more rapid waste decomposition, stabilization and settlement. Therefore moisture distribution effects on leachate collection systems, and optimum design and operating strategy are of particular concern to the users of bioreactor landfill technology. The moisture content and movement, as well as mathematical models of the hydrodynamics of leachate flow are discussed in this section.

5.1 Waste Field Capacity

The internal storage of a landfill is quantified using the concept of waste field capacity, or the moisture content at which the maximum amount of water is held (through capillary forces) against gravity. The addition of more moisture will result in continuous leachate drainage[19]. On weight basis, moisture content is described as the weight of the water divided either by dry or wet waste weight. On a volumetric basis, moisture content is expressed as the volume of water divided by the volume of wet waste. Tables 3 and 4 list some field capacity values reported in various studies. The range is wide as expected since field capacity is a function of the waste composition, density and porosity, particle sizes, waste overburden, waste age[19,82]. In addition, in full-scale cases, there are inevitably dead zones in the waste mass where the added moisture cannot reach due to channeling. Hence the effective moisture retention capacity is expected to be lower[82].

5.2 Predicting Leachate Quantity

Many researchers have tried to develop models for predicting leachate quantity from the landfills. The model most frequently used is the Hydrologic Evaluation of Landfill Performance (HELP). The HELP model is useful for long-term prediction of leachate quantity and comparison of various design alternatives[19]. Moreover, Hatfield and Miller (1994) developed two models to better simulate leachate generation at active landfills: the Deterministic Multiple Linear Reservoir Model (DMLRM) and the Stochastic Multiple Linear Reservoir Model (SMLRM).

Table 3. Range of MSW Field Capacity (Adapted from [19])

Field Capacity % wet weight	Density, kg m $^{-3}$ (lb yd $^{-3}$)	Reference
53	213[a] (359)	Kmet,1982
54	500-800 (843-1350)	Quasim and Buchinal, 1970
43-50[b]	500-800 (843-1350)	Reinhart and Ham, 1974
53[b]	690-950 (1160-1600)	Reinhart and Ham, 1974
47	710(1200)	Reinhart and Ham, 1974
20-30	616[a] (1038)	Holmes, 1983
20-35	688 (1160)	Korfiatis et al, 1984
36.8	310 (520)	Oweis et al, 1990
28.6	287 (485)	Walsh and Kinman, 1979
31-48	503 (850)	Remson et al, 1968
48	440 (735)	Canziani and Cossu, 1989
35	474 (800)	Fungaroli and Steiner, 1979

[a] dry ; [b] shredded

Table 4. Range of MSW Field Capacity (Adapted from [82])

Reported Field apacity (v/v)	Reference
29	Remson et al, 1968
29-42	Holmes, 1980
30-40	Straub and Lynch, 1982
20-30	Korfiatis et al, 1984
20-30	Owesis et al, 1990
14	Zeiss and Major, 1993
29	Schroeder et al, 1994
44	Bengtsson et al, 1994

5.3 Modeling Leachate Recirculation

Horizontal trenches or vertical wells are the most common method for distributing leachate. Al-Yousfi[83] developed an equation that can be used to estimate the required distance between trenches. U.S. Geological Survey (USGS) model for Saturated and Unsaturated Flow and TRAnsport (SUTRA)[84] is developed to simulate the behavior of horizontal leachate recirculation trenches and vertical leachate recirculation wells.

6. WASTE SETTLEMENT

After the MSW is disposed of in landfills, the thickness of waste layers will decrease with time. The Waste settlement analysis is very important because it can influence: (1) making projections of the remaining site life or remaining time before operations need to move to a new lined area; (2) the design of landfills' components, such as cover and liner systems; (3) post-closure development of landfills. The rate of landfill settlement depends primarily on the waste composition, operational practices and factors affecting biodegradation of the landfill waste, particularly moisture content[85]. Five mechanisms governing the settlement of MSW have long been defined as mechanical, raveling, physicochemical change, biochemical decay, and interaction among these mechanisms briefly described in Table 5.

Landfill settlement generally follows a non-uniform pattern because of the great special variations in waste composition and biodegradation processes. The differential settlements can devastate the integrity of any structure erected on the landfill as well as cause problems such as surface ponding, development of cracks, and failure of the cover system, including tearing of geomembrane and damage of gas collection and drainage pipes. Warith and Salem[86] indicated that one of the most important aspects of MSW settlement is the strain induced in the cover's geomembrane by differential settlement across the landfill. Based on the settlement data got from the Mountain View Bioreactor Landfill, El-Fadel et al[87] concluded that differential settlement is to be expected irrespective of how uniform the refuse is initially placed because the formation of pockets with different biodegradation characteristics appears inevitable.

The ability to predict settlement becomes a key issue in the design and construction of landfills. Currently, the settlement analysis models developed for analyzing conventional landfills are being applied to analyze bioreactor landfills as well. Most models developed to date can be categorized into four types: (a) Soil Mechanics-Based Models, (b) Rheological Models, (c) Empirical Models and (d) Biodegradation-Induced Settlement Models.

Table 5. Mechanisms of Solid Waste Settlement (Adapted from [88])

Mechanism	Description
Mechanical	Distortion, bending, crushing and reorientation of the materials; it is similar to the compression of non-organic soils
Raveling	Shifting of fine materials into the voids between larger soils
Physicochemical processes	Corrosion, oxidation, and/or combustion of the waste material
Biological Processes	Aerobic/anaerobic decay of the waste material
Interaction	Above mechanisms could interact to cause additional settlement

The emphasis of these models is generally have been on estimating the rate and magnitude of these settlements relying on soil consolidation theory typically employed in conventional geotechnical engineering. However, biodegradation processes are critical factors affecting landfill settlements. Theoretically, waste decomposition can cause settlement in the order of 30 to 40% of the original landfill depth, and on average, settlement of about 15 to 20% of the original landfill thickness is expected due to waste decomposition.

7. SUMMARY AND CONCLUSIONS

The bioreactor landfill is an innovative MSW disposal alternative to achieve accelerated stabilization of MSW, primarily through the addition of leachate or other liquid amendments, if necessary; the addition of sewage sludge or other inocula amendments, temperature control, nutrient supplementation, as well as the addition of air in aerobic and hybrid bioreactor landfills.

Among the technologies applied in bioreactor landfill for enhancing waste biodegradation, moisture control through leachate recirculation has been proven to be the most effective and practical strategy. Numerous practices have showed that whether via aerobic or anaerobic processes, leachate recirculation in landfills can potentially lead to more rapid waste decomposition, stabilization and settlement. Some studies have indicated that moisture content and movement are separate variables, affecting landfill methane generation rates in anaerobic bioreactor landfills. Optimum moisture content and movement rate can be obtained through leachate recirculation.

Frequent leachate recirculation at the beginning of the landfilling, small particle size or the addition of inocula amendments can cause acid build-up and delay the onset of methane production in anaerobic bioreactor landfills. Therefore, buffering with leachate recirculation is necessary in the anaerobic biodegradation process because it can reduce the acid formation phase and supply desired pH for MSW methanogensis.

The advanced technologies applied in bioreactor landfills can enhance the waste settlements. Waste settlement analysis is very critical not only for post-closure development of landfills but also for the design and operation of bioreactor landfills. Most models currently developed estimate the rate and magnitude of settlements relying on soil consolidation theory typically employed in conventional geotechnical engineering. It is necessary to develop a comprehensive model integrating gas generation, leachate movement, and waste settlement. Moreover, accurate field data of bioreactor landfills are needed for the calibration of the models

Generally, there are four advantages for employing bioreactor landfill technology comparing to conventional landfills: (1) contain and treat leachate, (2) rapidly recover air space, (3) accelerate waste stabilization and avoid long-term monitoring and maintenance and delay siting of a new landfill, and (4) make more potential benefits from increased methane generation in anaerobic bioreactor landfill. For aerobic bioreactor landfill, there are three other advantages: a) significant increase in the biodegradation rate of the MSW over anaerobic processes, (b) a reduction in the volume of leachate, and (c) significantly reduced methane generation and “anaerobic” odors. Furthermore, bioreactor landfills can co-dispose sewage sludge, organic and inorganic hazardous wastes, and high concentration ammonia in the leachate if operation models are reasonably adjusted.

Although many benefits can be obtained from bioreactor landfills, there are some limitations to this technology, including (a) recirculation increases the water head on the bottom liner which may enhance the possibility of leachate leaking through the lining, (b) addition of air to aerobic bioreactor increases the fire possibility, and (c) bioreactor landfills require more construction and operation costs comparing with the conventional landfills.

ACKNOWLEDGEMENTS

Ryerson University and the National Research Council of Canada provided support for this research.

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