



Bioreactor landfills: experimental and field results

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Abstract

Bioreactor landfills allow a more active landfill management that recognizes the biological, chemical and physical processes involved in a landfill environment. This paper presents the results of an experimental study carried out to determine the effect of solid waste size, leachate recirculation and nutrient balance on the rate of municipal solid waste (MSW) biodegradation. Higher rates of MSW biodegradation eventually cause a reduction of the contaminant life span of the landfill and decrease in the cost of long term monitoring. The study indicated that the smaller the size of the MSW the faster the biodegradation rate of the waste. In addition, the paper presents the results of leachate recirculation on solid waste biodegradation in a full-scale landfill site, which is located in Nepean, Ontario, Canada. The leachate was recirculated into the landfilled solid waste for 8 years through infiltration lagoons. Similar results to those obtained in the laboratory scale experiments were noted. The average pH of the leachate in the early stages of recirculation was on the acidic range of the pH scale, however, the pH value was in the range of 7–8 after 2 years of leachate recirculation. The concentration of chloride remained fairly constant at about 1000 mg/l during the leachate recirculation period. A decreasing trend of the organic load, measured as biological oxygen demand and chemical oxygen demand, was observed. Recovery of landfill air space was also noted because of the enhanced subsidence and decomposition of the solid waste. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In recent years, due to the advance in knowledge of landfill behaviour and decomposition processes of municipal solid waste (MSW), there has been a strong thrust to upgrade existing landfill technology from a storage/containment concept to a process-based approach, in other words, as a bioreactor landfill. Engineered bioreactor landfills are usually designed to maximize the infiltration of rainwater and snowmelt into the waste under controlled conditions. The design objectives of these landfills are to minimize leachate migration into the subsurface environment and maximize landfill gas (LFG) generation rates under controlled conditions. Over the past 10 years, experimental testing and field pilot studies have been conducted to develop and improve landfill techniques and designs, the

goal being to control the negative effects of landfill sites on the environment [1].

There are many advantages to enhancing solid waste degradation such as reducing the time period of leachate treatment, increasing methane production under controlled conditions, accelerating subsidence and decomposition of solid waste, thus permitting landfill air space recovery and the reduction of the contaminating on life span of the landfill [2]. Techniques used to enhance biological degradation of the waste are shredding, leachate recirculation and the addition of nutrients and sludge. Other techniques such as controlling temperature and moisture content [3] also proved to be pertinent in accelerating MSW biodegradation.

Engineered bioreactor landfill sites can provide a more controlled means by which society can reduce the emission of global warming greenhouse gases, and additionally they can provide immediate improvements to the surrounding local environment in terms of controlling odor and methane gas migration [4–6]. This landfill technology is gaining popularity and has been

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tried in pilot and full scale in various landfills in North America, particularly in areas where landfill closure is costly and/or where landfill space is crucial.

1.1. Advantages of bioreactor landfills

Engineered bioreactor landfills have the following advantages, if properly implemented and managed:

1. *Enhance the LFG generation rates* — the generation and recovery of LFG under controlled conditions improves the quality of the LFG and this in turn improves the economics for LFG recovery and utilization [7].
2. *Reduce environmental impacts* — by containing the leachate and controlling the LFG emissions, engineered bioreactor landfills will have minimum impact on groundwater, surface water, and the neighboring environment. Another major benefit of bioreactor landfills is the reduction of greenhouse gas emissions to the environment.
3. *Production of end product that does not need landfilling* — by encouraging microbial degradation of solid waste and removal of inert end products through periodical engineered mining, the bioreactor landfill cells could be re-used, and the end product could be spread on land as compost like material. The opportunity of re-using the bioreactor landfill cells highly improves the economics of the bioreactor cell technology.
4. *Overall reduction of landfilling cost* — by successive re-uses of the same bioreactor landfill cell, there are overall savings arising from not requiring the siting of new landfills every 15–20 years. Bioreactor landfills could be built in modules, where additional cells can be added in the future as the need for additional capacity as the need arises.
5. *Reduction of leachate treatment capital and operating cost* — a bioreactor landfill enhances the biological and chemical transformation of both organic and inorganic constituents within the landfill airspace, which will have an effect on the final leachate treatment requirements [3,5].
6. *Reduction in post-closure care, maintenance and risk* — a bioreactor landfill minimizes long-term environmental risk and liability because of the controlled settlement of the solid waste during landfill operation, the low potential for leachate migration into the subsurface environment and the recovery of LFG during landfill operation. Proper operation of a bioreactor landfill will reduce landfill-monitoring activities and post-closure care cost.
7. *Overall reduction of contaminating life span of the landfill* — this occurs as a result of a decrease in contaminant concentrations during the operating period of the bioreactor landfills.

1.2. How a bioreactor landfill differs from a conventional landfill?

A bioreactor landfill is a sanitary landfill site that uses enhanced microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents within 5–8 years of bioreactor process implementation. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates of complex organic compounds and process effectiveness over those which would otherwise occur within the traditional landfill sites. Stabilization means that the environmental performance measurement parameters (LFG composition and generation rate, and leachate constituent concentrations) remain at steady levels, and should not increase in the event of any partial containment system failures beyond the life time of the bioreactor process.

The bioreactor landfill requires specific management activities and operational modifications to enhance microbial decomposition processes. The single most important aspect for effective operation is liquid addition and management. Other strategies, including waste shredding, pH adjustment, nutrient addition and balance, waste pre-disposal and post-disposal conditioning, and temperature management, may also serve to optimize the bioreactor process. The successful operation of a bioreactor landfill also requires the development and implementation of focused operational and development plans to ensure that optimal conditions for bioprocesses exist and to allow the system to function effectively.

The bioreactor landfill is an extension of leachate recirculation in landfilling, however, the bioreactor process requires significant liquid addition to reach and maintain optimal conditions. Leachate alone is usually not available in sufficient quantity to sustain the bioreactor needs. Water or other non-toxic or non-hazardous liquids and semi-liquids are suitable amendments to supplement the leachate (depending on regulatory approvals).

At the closure stage of bioreactor landfills:

1. leachate quantity will be a finite amount, amenable to on-site treatment with limited need for off-site transfer, treatment and/or disposal;
2. LFG generation will be at its declining stage; and
3. long-term environmental risk will be minimized.

This paper summarizes the methodology and results of pilot scale solid waste bioreactor landfill cells to quantify the effect of moisture increase, nutrient addition, and sewage sludge addition on the rate of biological degradation of the solid waste. In addition, the paper briefly presents the results of a full-scale leachate recirculation at the Trail Road landfill site (an engineered landfill), which is located in Nepean, Ontario, Canada.

2. Materials and methods

2.1. Experimental set-up

The solid waste used in this experiment was collected from the curbsides of the City of Toronto, in order to achieve a representative sample of solid waste that normally goes to a landfill. Visual inspection of the refuse showed presence of a variety of food wastes, paper, cardboard, packaging materials, yard wastes and inorganic materials including glass containers and tin cans. The wet-weight moisture content of the waste was calculated to be 12.8%, and the average specific weight of the waste compacted in the waste cells was 252 kg/m^3 which is comparable to what is been achieved in low volume landfill sites. The solid waste bioreactor cells were equipped with outlet ports to allow leachate withdrawal from the cells, and influent ports to allow even spreading of the recirculated leachate. Leachate was

collected and stored in containers, attached to each bioreactor cell.

Larger particles of the collected waste were broken down in size, and the material was thoroughly mixed prior to loading of the bioreactor solid waste cells. The MSW utilized in this experimental study was 60% organic matter and was shredded to a maximum of 150–250 mm in size.

Complete bioreactor experimental cell configuration is shown in Fig. 1. A 200-mm thick layer of gravel was placed at the bottom of each bioreactor solid waste cell to simulate a leachate collection system, and to prevent clogging of the leachate withdrawal outlets. Solid waste was loaded in 150–200 mm layers and compacted using a shovel and a sledgehammer. A gas collection well was then inserted into the waste matrix of each waste cell, made of perforated 50 mm diameter PVC pipe wrapped in a plastic mesh. A second gravel layer was placed on top of the waste to simulate intermediate cover and upper drainage layer, and further to provide even

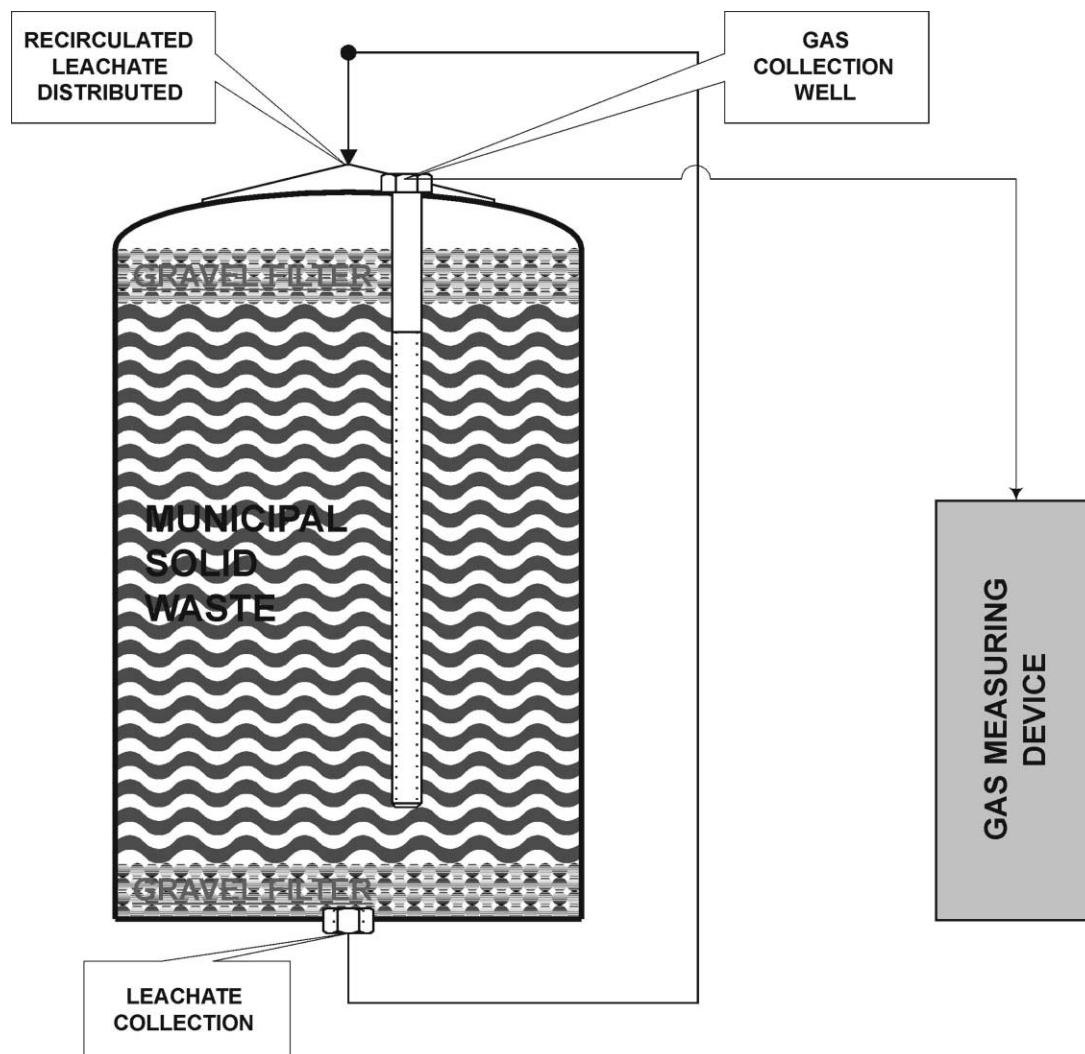


Fig. 1. Schematic of experimental landfill bioreactor.

distribution of the recirculated leachate. The nominal size of the gravel used for both filter layers range from 19 to 38 mm. Finally, the bioreactor cell covers were placed on top of each cell, and the whole unit was sealed using construction type sealant. The protruding ends of the gas collection wells were connected to the gas measuring devices, consisting of flexible tubes inserted in inverted graduated cylinders submerged in water.

The moisture content of the solid waste was quickly brought to field capacity (45% by volume) by adding tap water to the bioreactor cells daily, until the amount of leachate collected from the cell equaled the amount of water added the previous day. Leachate was recirculated three times a week for the first 6-month period, which corresponds to a volume of approximately 12 liters, or 15% of the total volume of solid waste in each waste cell. Following the initiation period, the leachate was recycled on a daily basis using a pumping system operated and controlled by a computerized operation system. The leachate recirculation pump inlet was attached to the tubing exiting the leachate collection tank. The outlet was connected to approximately 800 mm of tubing that extended vertically and was attached to a plastic hub that divided the flow into four 100-mm pieces of aquarium airline tubing. The four equal streams were then inserted into the cover of the bioreactor. The pump was attached to a 120-V power supply that was switched via relays connected to a personal computer. The system was operated by a computer built in clock to monitor the time and the status of the pump (on or off) at the specified intervals. The continuous recirculation of the leachate was carried out to ensure that the solid waste was always fully saturated. Continuous monitoring of the rate of leachate recycled also ensured that the leachate was flowing through the solid waste, and there was no short-circuiting within the waste.

Three sets of bioreactor cells were used during this study. The first was a control bioreactor cell, where only leachate was recirculated. In the second bioreactor cell, pH buffer and nutrients were added to the leachate prior to its recirculation and in the third cell wastewater treatment sludge was added to the leachate. Enhancement materials were added to the leachate prior to recirculation once a week. Sodium hydroxide (NaOH) was used for the adjustment of pH of the leachate, and the nutrients were added in the form of plant food with nitrogen content of 20%, and phosphorus content of 20%. The amount of municipal sewage sludge added to the recirculated effluent equaled 5% of the total leachate volume. The sludge was collected from a wastewater treatment plant in Toronto and provided a source of biomass, nitrogen and phosphorous and other nutrients and micronutrients to the solid waste during leachate recirculation.

Leachate samples were collected weekly from leachate outlet ports and pH values were measured. Leachate

samples were then preserved and stored at 4°C prior to being tested for pH, biological oxygen demand (BOD) and chemical oxygen demand (COD). All chemical analyses were carried out in duplicate to ensure the validity of the results.

The ratio between COD and BOD provided an indication of the variation in the biodegradable organic fraction (BDOF) of the waste. Heavy metals were determined using the ICAP technique. Solid waste volume reduction and settlement were monitored at the beginning and during the leachate recirculation investigation.

2.2. Full scale leachate recirculation

The Trail Road landfill site is located in the Regional Municipality of Ottawa-Carleton (RMOC) in Nepean, Ontario, Canada. The site exists on a 200-ha area of which 135 ha is a buffer zone surrounding the footprint of the fill area. Approximately one third of the solid waste collected in the RMOC is disposed of at the Trail Road site. There are currently four stages of development at the landfill site, two of which are capped with engineered landfill covers. Stage III of the landfill is currently an active filling area, which is lined with a composite liner. The liner consists of one meter of compacted clay and a layer of 80 mm high density polyethylene geo-membrane. This stage covers an area of 13.5 ha.

Leachate recirculation was carried out at the Trail Road Landfill site-Stage III to enhance organic waste biodegradation and to reduce the contaminant life span of the landfill site. In addition, leachate was recirculated to defer leachate treatment and handling for a period of time, until better characterization of the leachate was determined.

The leachate was withdrawn from the landfill cell via a layer of granular material, a series of leachate collection pipes, and a main header collection pipe. The header pipe is connected to a pump station to withdraw the leachate from the landfill cell and to maintain the head on the liner to lower than 0.3 m. The leachate was pumped back into infiltration lagoons on the top of the landfilled waste. The infiltration lagoons were constructed using on-site stockpiled clay for containment dykes. The locations of these infiltration lagoons were constantly changed to ensure uniform distribution of the leachate into the landfilled waste, as well as to accommodate the landfill operation and solid waste filling. The organic strength of the leachate, measured as BOD and COD, as well as pH and chloride concentration were monitored for a period of eight years to determine the effect of leachate recirculation on the change in MSW properties, in particular the decrease of the organic load of the waste. Landfilled solid waste subsidence was determined on an annual basis.

3. Results and discussion

3.1. Laboratory results

The variation of pH profile over time is provided in Fig. 2. The first two weeks of the testing represents the initial adjustment and transition of MSW degradation from aerobic to anaerobic phases. During these two weeks pH levels were approximately 6.0, or on the acidic side of the pH scale. The observed pH levels ranged from 5.3 to 6.0. The primary sludge bioreactor cell had the highest pH levels because of the sludge buffering capability as indicated by [1]. During the intermediate anaerobic degradation stage, methanogenic bacteria slowly start to appear. As the methane gas production rate increases, hydrogen, carbon dioxide and volatile fatty acid concentrations decrease [8]. The conversion of fatty acids causes the pH within the waste cells to increase.

The methane fermentation phase occurs when the pH levels for all three bioreactor cells rise to the neutral ranges of 6.8–8.0. This methane fermentation phase started between week four and five (Fig. 2). The peak

pH level for all bioreactors occurred on week six. The peak pH results of the control, nutrient and primary sludge bioreactor cells were 7.8, 7.5 and 7.7, respectively. After the initial pH increase, the pH levels slowly declined to a pH of about 7. During this time, the methanogenic bacteria activity is low and the maturation phase is starting [9,10]. The average pH levels of the control, nutrient and primary sludge bioreactors were 7.2, 7.0 and 7.3, respectively. From week 4 to 18, the leachate samples from the control cell were less acidic than the nutrient and primary sludge cells. In most weeks, the control cell had the highest pH readings. After week 18, the primary sludge had the highest pH level (Fig. 2). This pattern occurred in the 1997–1998 experiment with un-shredded municipal solid waste as well [11]. Comparing the pH results produced from the unshredded and shredded MSW indicates that the time duration for the biodegradation stages was reduced with shredded MSW.

The results of the BOD concentrations over time are shown in Fig. 3. After week 3, the pH values started to increase, which in turn resulted in a decline in the BOD

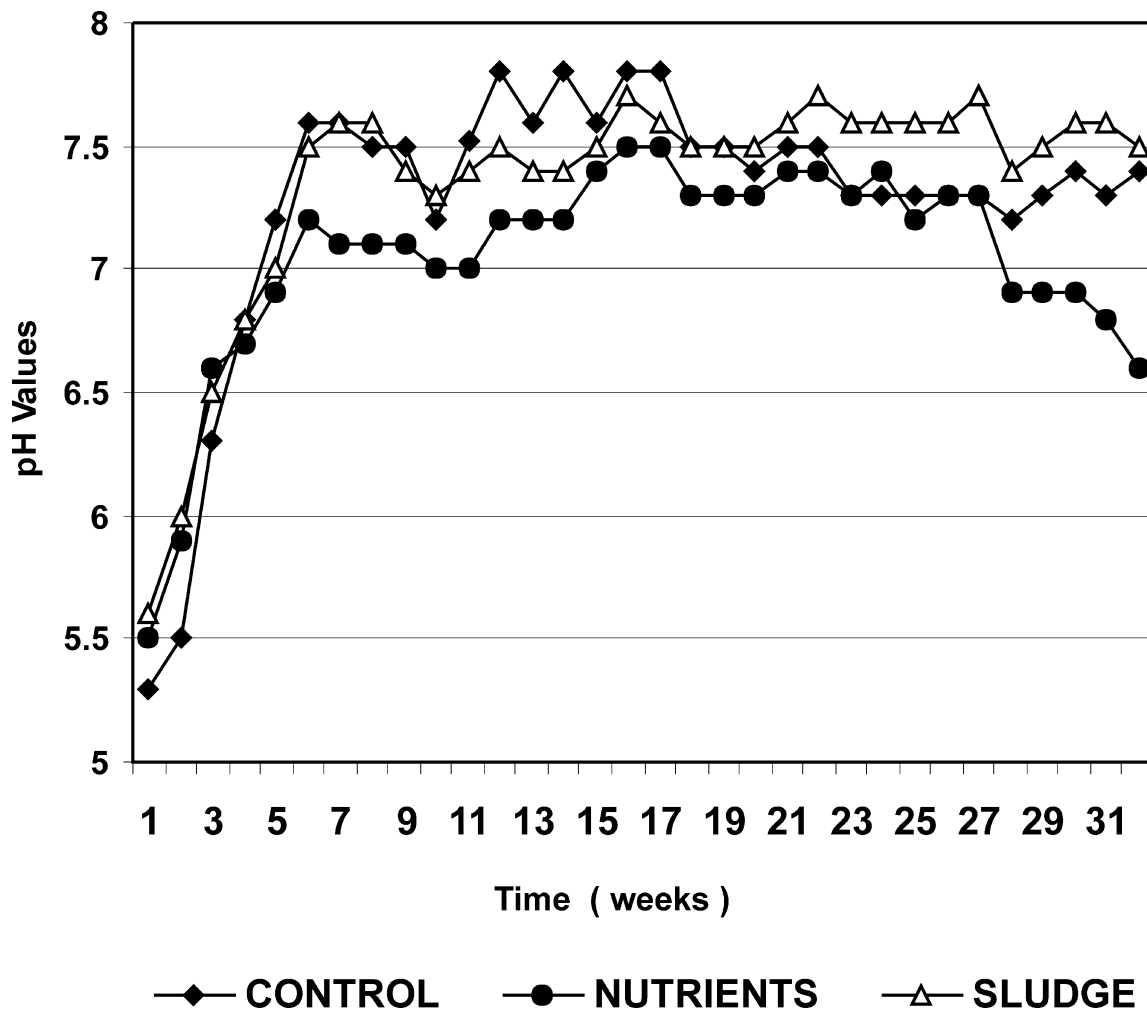


Fig. 2. Changes of leachate pH values over time.

concentrations in all three bioreactor cells at the beginning of the experimental testing. The BOD values were ranging initially from 1440 to 2055 mg/l. This represents the initial aerobic phase of biodegradation. After the completion of this phase of biodegradation, the BOD decreased substantially by about 48, 71 and 43% in the control, nutrient and the primary sludge bioreactor cells, respectively.

The high BOD concentrations in the leachate only lasted for five weeks followed by a quick BOD decline. This occurred since leachate was recirculated through the cells and moisture content was reasonably high to allow MSW biodegradation. Al-Youssifi and Pohland [2] achieved similar results from their experimental research. From week 8 to 16, BOD values from the nutrient and primary sludge test cells experienced slightly more constant range of BOD concentration in the leachate. The same also occurred within the control cell after week eight. The average BOD concentration after the initial phase declined in the control, nutrient and primary sludge bioreactor cells to 650, 440 and 685 mg/l, respectively. After week 16, BOD concentration decreased in all three cells to lower than 200 mg/l, as indicated in Fig. 3.

The experimental results indicated that the MSW stabilization was achieved in the nutrient-added bioreactor cell at a higher rate than that of the sludge-added and

controls bioreactor cells. The experimental results also indicate that, assuming the total BDOF in all three bioreactor cells is the same, the concentration of BOD in the nutrient added cell would reach a minimum value within a reasonable time frame (20–30 weeks).

The COD results are displayed in Fig. 4. The COD results follow a similar trend as the BOD results. The COD concentrations ranged from 5040 to 9910 mg/l for the first few weeks followed by a steep decline. The initial high COD range for the nutrient cell lasted for the shortest time, 4 weeks, as shown in Fig. 4. In comparison, the COD and BOD initial high peak occurred over a longer duration for the primary sludge cell than the control and the nutrient cells. The initial high COD phase lasted for approximately 6 weeks. For most of the experiments, the primary sludge's COD results were the highest amongst the tested cells, while the nutrient-add bioreactor cell experienced the lowest COD results. This pattern was also observed in previous leachate recirculation experiments that were conducted using the unshredded MSW [11]. Unlike, the unshredded MSW, COD concentrations dropped to less than 200 mg/l during the duration of the experiment, in all three bioreactor cells as indicated in Fig. 4.

The BOD/COD ratio indicates the changes in the amount of biodegradable compounds in the leachate.

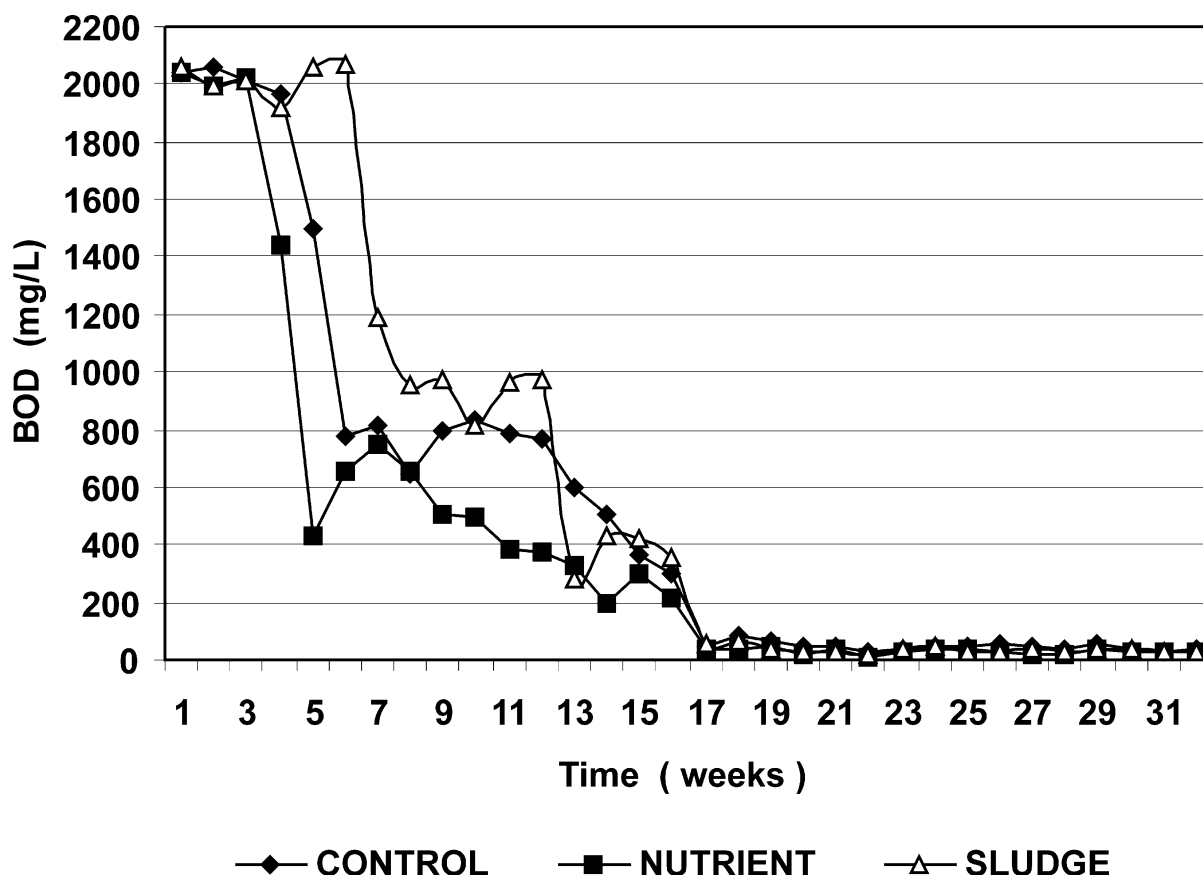


Fig. 3. Changes of leachate biological oxygen demand concentration over time.

As the organic content biodegradation of MSW occurs, the BOD/COD ratio would decrease. In general, the BOD/COD ratios observed were very low ranging from below 0.15 to 0.40 (Table 1). The BOD/COD ratio in the control bioreactor cell remained stable at about 0.2 from week 16 to the termination of the experiment at week 32. The highest BOD/COD ratio was observed during weeks 11–15. A ratio of 0.4–0.8 implies a highly biodegradable leachate.

Settlement of the compacted solid waste in each of the experimental cells was measured. The distance from the top gravel layer to the top of the cell was measured

prior to sealing the cell and after 32 weeks of leachate recirculation. Table 2 summarises the waste settlement results. The highest degree of settlement was achieved through addition of sludge, where settlements were about 50%. Other waste bioreactor cells exhibited settlement in the range of 37–40% after 32 weeks of leachate recirculation.

The analysis of the heavy metals indicated that the concentrations of various metals varied within a narrow range (Table 3), with no trend of heavy metal increase in concentration within the leachate samples after 30 weeks of continuous leachate recycling. The results are very similar to the results reported in Ref. [11]. It is worthwhile to indicate that the heavy metal concentrations were elevated in the solid waste cell with sludge addition compared to that of the control and nutrient and buffer solid waste bioreactor cells.

Table 1
Summary of biological/chemical oxygen demand ratios

Week No.	Control	Nutrient	Sludge
1	0.15	0.16	0.16
5	0.2	0.13	0.18
10	0.36	0.32	0.3
15	0.24	0.35	0.34
20	0.17	0.1	0.1
25	0.17	0.17	0.14
30	0.23	0.22	0.13

3.2. Field experience

Fig. 5 illustrates the relation between the average monthly precipitation, the volume of leachate generated and the volume of leachate pumped from Stage III of the Trail Road landfill site. As noted, the leachate generation

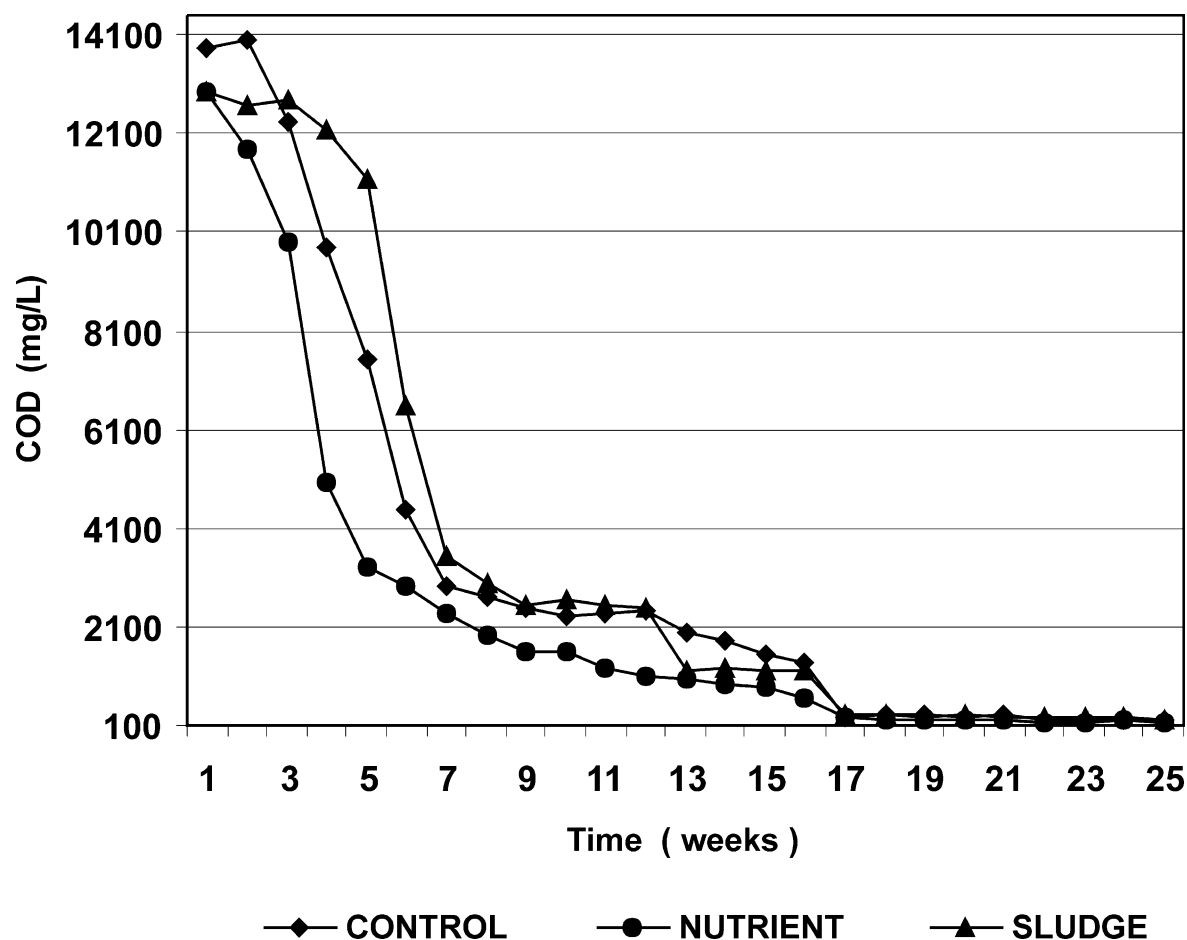


Fig. 4. Changes of leachate chemical oxygen demand concentrations over time.

rate was approximately 25–30% of the total precipitation. 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. In addition Fig. 5 illustrates the effect of short-circuiting within the waste which restricts the landfilled waste from reaching 100% of its field capacity.

The variation of pH over time in the leachate is provided in Fig. 6. During the first two years of leachate recirculation at the Trail Road Landfill, which represents the initial adjustment and transition of MSW

Table 2
Summary of solid waste settlement in the bioreactor cells

Cell identification	Original waste height (mm)	Final waste height (mm)	Settlement (mm)	Settlement (%)
Control	600	380	220	37
Nutrient	600	355	245	40
Sludge	600	300	300	50

Table 3
Concentration of heavy metals in recirculated leachate in all three solid waste cells^a

Time (weeks)	B	Cr	Cu	Fe	Mn	Ni	Zn
<i>Control</i>							
2	1.30	1.45	0.110	2.80	0.021	0.39	0.42
4	1.20	0.93	0.100	1.20	0.007	0.54	0.31
6	0.80	0.21	0.060	1.82	0.184	0.36	0.25
8	0.90	0.91	0.061	1.22	0.173	0.40	0.29
10	0.75	0.30	0.061	1.23	0.057	0.66	0.40
15	0.74	0.89	0.063	0.34	0.055	0.65	0.11
20	0.45	0.85	0.033	0.66	0.099	0.56	0.10
30	0.75	0.62	0.122	0.60	0.039	0.52	0.21
<i>Nutrient</i>							
2	1.00	0.09	0.038	2.84	0.239	0.11	0.27
4	0.70	0.67	0.041	3.55	0.045	0.27	0.29
6	0.60	0.15	0.023	2.23	0.403	0.38	0.82
8	0.56	0.53	0.029	1.98	0.136	0.21	0.71
10	0.70	0.22	0.038	1.87	0.079	0.06	0.80
15	0.64	0.31	0.024	5.66	0.079	0.11	0.77
20	0.65	0.97	0.027	2.83	0.195	0.23	0.62
c > 30	0.59	0.82	0.062	3.75	0.217	0.34	0.44
<i>Sludge</i>							
2	1.95	1.20	0.021	8.59	0.136	0.44	0.33
4	1.64	0.88	0.082	8.79	0.606	0.36	0.52
6	1.75	0.87	0.088	8.15	0.318	0.31	0.53
8	1.43	0.83	0.061	9.04	0.283	0.19	0.31
10	1.05	0.90	0.048	7.37	0.236	0.20	0.13
15	0.98	0.55	0.031	4.80	0.333	0.24	0.33
20	0.98	0.28	0.006	7.46	0.190	0.20	0.39
30	0.97	0.28	0.005	7.39	0.111	0.13	0.56

^a All concentrations are in mg/l.

degradation from aerobic to anaerobic phases, pH levels were in the range from 6.0 to 6.5, or on the acidic side of the pH scale. During the intermediate anaerobic degradation stage, methanogenic bacteria slowly start to appear. As the methane gas production rate increases, hydrogen, carbon dioxide and volatile fatty acid concentrations decrease [8]. The conversion of fatty acids causes the pH within the waste cells to increase. The methane fermentation phase occurs when the pH levels rise to the neutral ranges of 6.8–8.0. During this time, the methanogenic bacteria activity is relatively low and the maturation phase begins [9].

Fig. 7 illustrates the changes in leachate chloride concentration during the leachate recirculation period. The concentration of chloride in the leachate remained fairly constant at an average concentration of about 1000 mg/l.

A decreasing trend of BOD and COD was noted over a period of eight years of leachate recirculation. Fig. 8 displays the relationship of BOD, COD and the ratio between BOD/COD over time. The ratio of the BOD/COD decreased from about 0.9 to 0.4 over a period of eight years, which illustrates the reduction in the biodegradable organic compounds and the increase of the microbial activities because of the increase in the solid waste moisture.

Leachate management at the Trail road Landfill site through lagooned recirculation has not been without its challenges. What it has successfully accomplished, was the effective management, on an interim basis, of the leachate and the deferral of the leachate treatment until such time, the quantity and quality of the leachate is determined. Leachate recirculation reduces the contaminant life span of the landfill and effectively utilizes the engineering components of the containment system during the landfill operation.

Leachate recirculation at the Trail Road Landfill site enhanced the settlement of the solid waste in Stage III and resulted in the recovery of 25% of landfill air space which was utilized for land-filling more solid waste. Table 4 provides the ratio between the total waste tonnage to air space utilized on a yearly basis. The initial ratio of air space utilization was in the range from 0.5 to 0.7, i.e. 500–700 g of MSW will occupy about 1 m³ of air space, which is a reasonable ratio to expect taking

Table 4
Air space utilization ratio

Year	Ratio
1991	0.63
1992	0.54
1993	0.72
1994	0.58
1995	0.63
1996	0.59
1997	1.03
1998	1.09

into account the limitation of the compacting equipment used on site. However, the air space ratio in 1997 and 1998 increased to above 1.0 (Table 3). In other words, more waste is fitting in the same air space. This

observation reveals the advantages of the leachate recirculation and its effect on accelerating waste biodegradation, as well as increasing the rate of landfill gas generation.

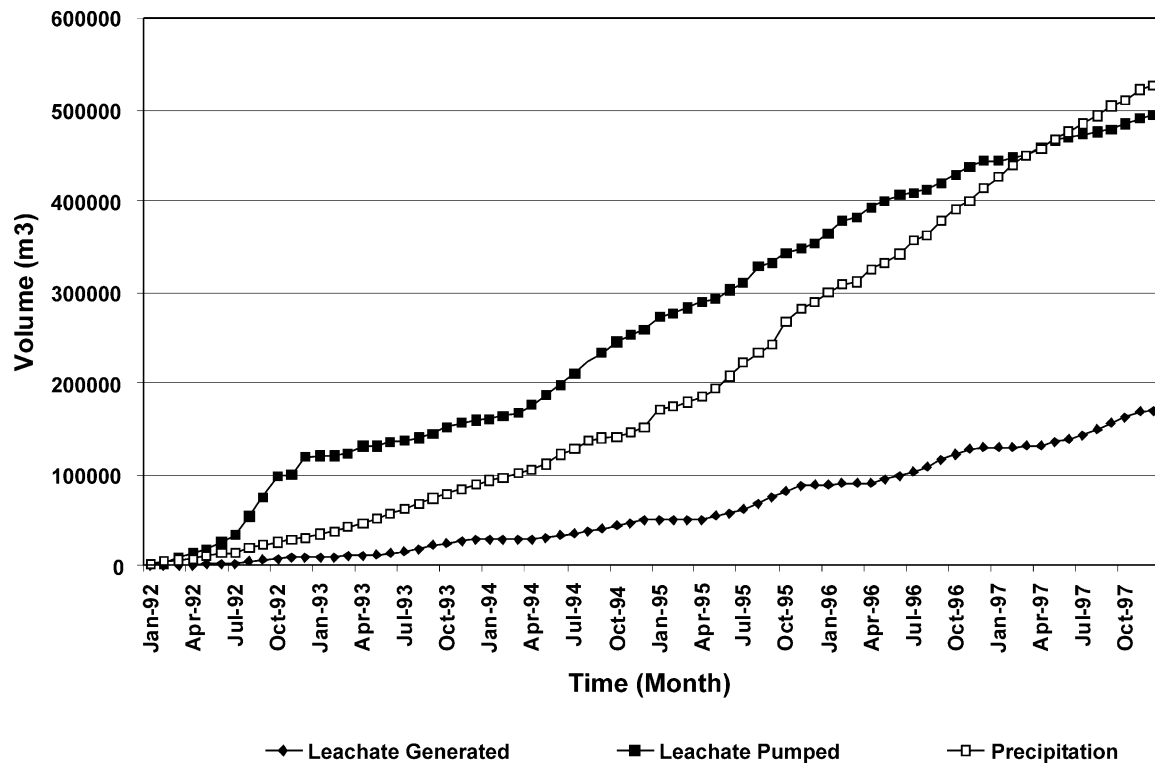


Fig. 5. Comparison between average monthly precipitation and actual leachate generation rates.

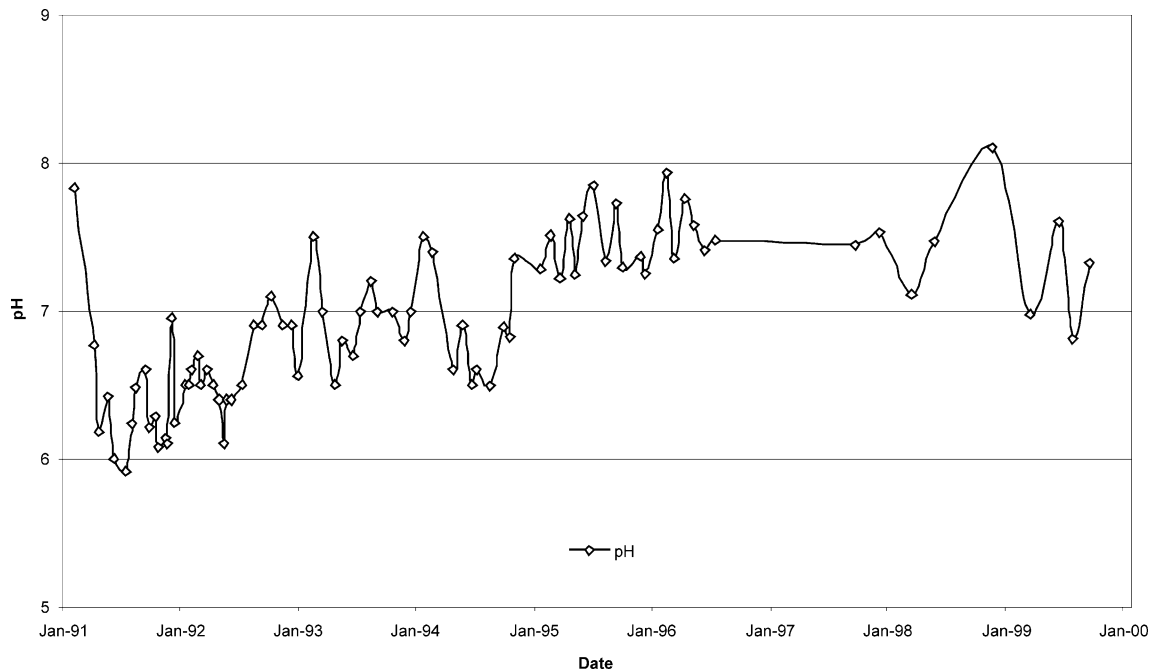


Fig. 6. Changes in pH during leachate recirculation.

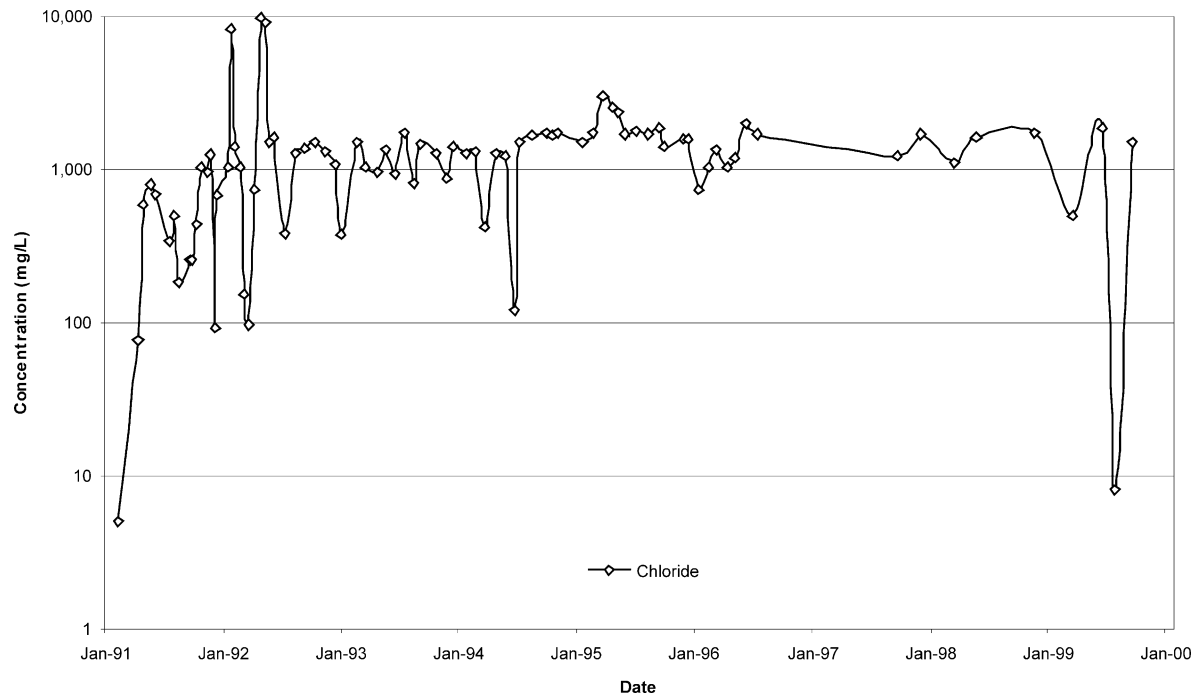


Fig. 7. Changes in chloride concentration during leachate recirculation.

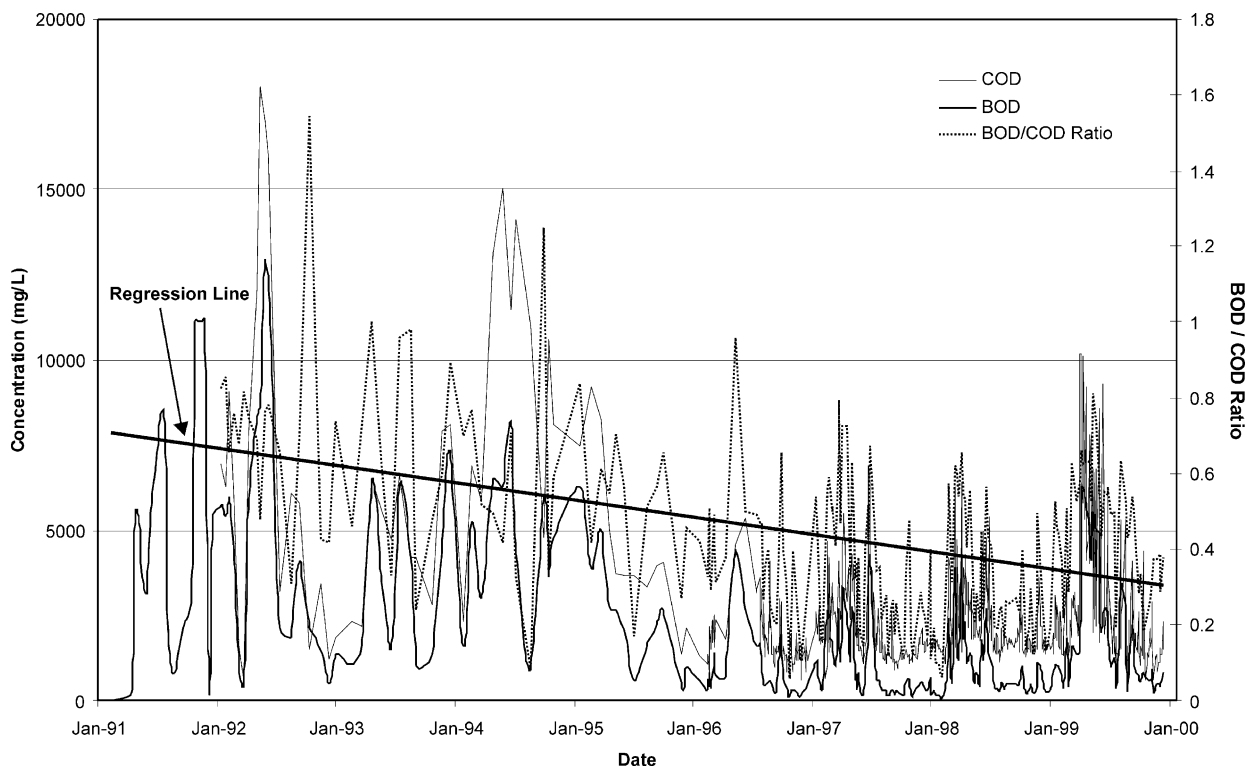


Fig. 8. Changes of leachate biological oxygen demand and chemical oxygen demand concentrations at Trail Road Landfill Site.

4. Conclusion

Addition of supplemental materials to the leachate during recirculation was found to have positive effect on the rate of biological degradation of MSW. The addition of primary sludge and supplemental nutrients

enhanced conditions such that there was a rapid decrease in BOD and COD concentrations in the effluent samples.

In addition, the experimental results indicate that, shredding the MSW is an effective method of improving waste biodegradation compared to the trends established

with un-shredded solid waste. The pH levels from the shredded MSW experiments were higher than the un-shredded MSW cell results noted in the Ref. [11] experimental program. The average pH level of the shredded waste was 7.2; in other words the leachate concentrations were more neutral than the unshredded MSW. Primary sludge was found to be a good source of microbial inoculum. In general, all three bioreactor cells exhibited a higher rate of biodegradation, and achieved a high waste volume reduction in a relatively short duration than previously demonstrated with un-shredded solid waste.

Leachate recirculation at the Trail Road Landfill site enhanced the settlement of the solid waste in Stage III and resulted in the recovery of 25% of landfill air space, which was utilized for landfilling more solid waste. On the other side, leachate recirculation increases the rate of landfill gas generation and pronounces the odor problem, which results from the landfilling operation.

Enhancing and recycling leachate proves to be an effective tool in bioreactor landfill management in the pilot and field scale landfills. It helps lessen the distinctive biological phase, which in return allows for the landfill to reach a state of stabilisation at a quicker rate. The acceleration of MSW biodegradation not only decreases the life of the landfill, but also reduces overall monitoring costs incurred with post-closure of landfill sites.

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