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Evaluation of leachate treatment and recycle options using the Static Granular Bed Reactor

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Evaluation of leachate treatment and recycle options using the Static Granular Bed Reactor

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ABSTRACT

Three landfill leachate management strategies were evaluated by comparing simulated landfill columns while studying the application of the Static Granular Bed Reactor (SGBR) to leachate treatment. The three simulated landfill columns were operated in three different strategies. In Column 1 (C1), the leachate was treated in the SGBR reactor and recycled to the top of C1. Column 2 (C2) recirculated the leachate without any treatment. Column 3 (C3) was a simulated conventional landfill without recirculation. With time, the COD concentration of leachate in each column decreased. C1 had the greatest reduction of COD in leachate due to removal in the SGBR and the landfill column itself. Moreover, gas production was accelerated by leachate recirculation owing to enhancement of waste degradation in landfill columns (C1 and C2). The SGBR pre-operating study showed fast acclimation (5 days) to substrate change and short start-up period (10 days) as evidenced by COD removal efficiencies ranging between 84% and 95 % for leachate and non-fat dry milk. Incorporated in a leachate management strategy, the SGBR system was sustained in stability as evidenced by the stable pH and low VFA concentrations. Despite the low organic removal efficiency, the SGBR reactor treating leachate prior to recirculation in the simulated landfill column was effective at reducing the organic matter in leachate within the system. The feasibility of leachate treatment by the SGBR was demonstrated in this study.

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CHAPTER 1. INTRODUCTION

The control of leachate from municipal solid waste (MSW) landfills has been a significant issue for the environment as the generation of MSW has increased. The landfill has been and continues to be the most popular method for disposal of MSW. Leachate must be treated before discharge to the natural environment to prevent soil and water contamination. Leachate recirculation is one of the cost effective alternatives for leachate management. Leachate recirculation means the collected leachate is injected back into the landfill to promote anaerobic biodegradation of solid waste. Moreover, leachate recirculation offers several environmental and economical advantages such as improving leachate quality, reducing leachate treatment cost, increasing waste biodegradation and gas production rates, and maximizing the capacity for waste disposal (Wazinski et al., 2000; Reinhart, 1996; Warith et al., 1999). However, recycled leachate requires treatment before discharge. Biological treatment processes have been evaluated as one of the applicable systems for leachate treatment (Forgie, 1988). Moreover, anaerobic treatment methods are more applicable for the concentrated leachate because they also offer several advantages such as low operating cost and the production of useful biogas from the process.

A new anaerobic treatment system has been developed by Ellis and Mach in the biotechnology research and development group in the Civil, Construction, and Environmental Engineering Department at Iowa State University (Mach and Ellis, 2000). This anaerobic biological process is called the Static Granular Bed Reactor (SGBR). The application of the SGBR to leachate seems to be a good application owing to its high organic removal ability and the concentrated nature and low solids concentration in leachate. Therefore, the combination of landfill leachate recirculation and the SGBR can be an excellent leachate management strategy because it will not only enhance the advantages of leachate recirculation but also treat the leachate.

Based on these considerations, in this study three landfill leachate management strategies were evaluated by comparing simulated landfill columns, while studying the application of the SGBR to leachate treatment. Prior to this study, no research has been done on leachate recirculation with the treatment process. Therefore, this research was conducted in order to study the leachate treatability of the Static Granular Bed Reactor (SGBR) and develop an optimum strategy for the landfill system. Advantages of such a system include improvement of waste stabilization and leachate quality.

CHAPTER 2. LITERATURE REVIEW

Anaerobic treatment of leachate

Anaerobic treatment by methanogenesis has been widely applied to the digestion of waste or primary municipal wastewater sludge, livestock manure and the stabilization of organic solid waste. Besides these applicable fields, this anaerobic treatment technology has attractive potential for the treatment of agro- industrial wastewater, municipal wastewater and some more complex wastewaters such as leachate and those from petrochemical and pharmaceutical industries (Calli et al., 2003). Because leachate generated from landfills includes high organic and inorganic contaminants which are variable during the life of a landfill , the applicability of the leachate treatment relies on the tolerance of the process to the variation of leachate quality (Boyle et al., 1974; Kettuen et al., 1998).

Inanc et al. (2000) reported high-rate anaerobic processes such as upflow anaerobic sludge blanket (UASB) reactors, hybrid bed reactors and anaerobic filter reactors showed high efficiency in the treatment of landfill leachate having a chemical oxygen demand (COD) concentration ranging between 18,800 and 47,800 mg/L and a BOD/COD ratio higher than 0.7 (Inanc et al., 2000). Moreover, owing to their flexibility of operation, sequencing batch reactors (SBRs) were considered for the treatment of leachate which has a high variability of quality and quantity (Kenedy et al., 2000). Timur et al. (1999) reported the SBRs used for leachate had 64-84% COD removal efficiency at wide-range of volumetric (0.4–9.4 g COD/L/ d) and specific (0.2–1.9 g COD/ g volatile suspended solids (VSS) /d) loading rates and COD concentration ranging between 3800–15900 mg /L.

Even though anaerobic treatment so far was not applied in countries at low temperature, owing to lower removal efficiencies, much research has been done at low temperature and has shown successful results ((Elmitwalli et al., 2001; Lettinga et al., 2001). In the case of leachate treatment, Kettuen et al. (1996) reported the use of a laboratory scale UASB for municipal landfill leachate treatment at low temperature (11-24 °C). The UASB reactor was capable of achieving up to 60-65% of COD removal efficiency at a 0.7-1.5 organic loading rate (OLR, kg $COD/m^3/d$) in 11 °C reactor and up to 75% COD removal efficiency in a 24 °C reactor (Kettunen et al., 1996). Moreover, a pilot scale UASB reactor used for leachate treatment at low temperatures (13-23°C) also showed 65-75% COD removal and up to 72% BOD removal at an OLR of 1.4-2.0 kg $COD/m^3/d$ (Kettunen et al., 1998).

Benefits of anaerobic treatment

Landfill leachate has adversely influenced biological treatment processes because it not only contains high concentrations of refractory organics and ammonia nitrogen but also has variable composition and flow (Garcia et al., 1996; Lin et al., 2000). However, in spite of these difficulties, anaerobic processes have shown successful treatment efficiency and applicability for landfill leachate (Henry et al., 1987; Borzacconi et al., 1999). Moreover, high-rate anaerobic processes such as UASB and anaerobic filter reactor can be operated at higher organic loading rates and shorter hydraulic retention times compared to the other systems (Garcia et al., 1996; and Inanc et al., 2000). Therefore, these systems can offer effective benefits for saving construction and operating costs. In addition, anaerobic processes produce valuable biogas containing methane which can be used onsite for fuel (Barlaz et al., 1992). When compared to aerobic processes, the elimination of aeration requirements makes additional energy savings possible in anaerobic processes. Additional benefits include low sludge production and simplicity of sludge disposal (Kennedy et al., 2000; and Zakkour et al., 2001).

General characteristics of the landfill and leachate

Conventional landfills produce leachate characterized as a water-based solution of pollutants including dissolved organic matter, heavy metals, inorganic contaminants, and xenobiotic organic compounds (Christensen et al., 1994). Characteristics of leachate are related with the composition of solid waste and the biological and chemical reactions occurring in the landfill as the waste degradation proceeds (Kettunen et al., 1998). Kjeldsen et al. (2002) reported the composition of leachate changes as the degradation of MSW proceeds.

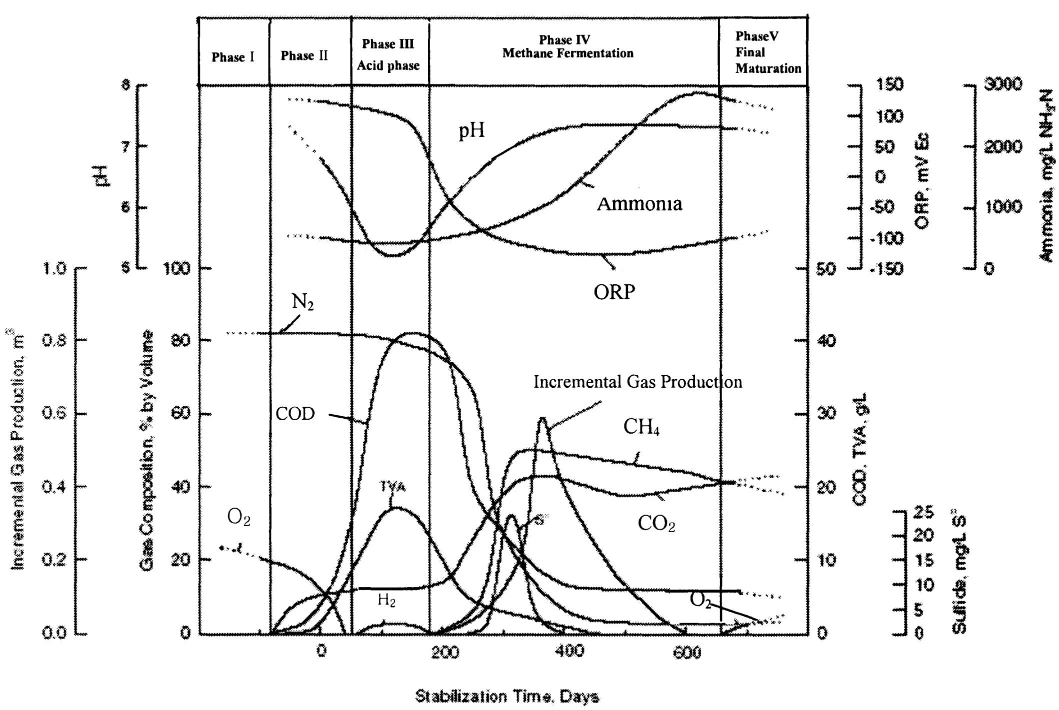

Figure 1. Phases of bioreactor landfill stabilization (Kim et al., 2003)

Pohland et al. (1999) presented the stabilization phases as the landfill bioreactor progresses through initial adjustment, transition phase, acid phase, methane fermentation phase, and maturation phase as depicted by the changes of parameters in leachate and gas (Figure 1). In the acid phase, the enhanced formation of dissolved organic matter and release of ammonia make their concentrations higher than in other phases. In the methanogenic phase, the concentration of dissolved organic matter greatly decreases, which can be indicated through a drop in the BOD/COD ratios below 0.1 (Kjeldsen et al., 2002). The methane production rate reaches to its maximum as the organic matter in landfill is decomposed in the methanogenic phase and decreases thereafter (Kjeldsen et al., 2002).

Leachate recirculation

In order to manage municipal solid waste, mainly two different landfill systems have been applied. One is the conventional landfill system and the other is the landfill bioreactor system which reduces potential environmental risk from the waste management through the control of leachate and gas production (Pohland, 1975). The landfill bioreactor operation system includes leachate recirculation which offers more effective performance for leachate treatment due to the acceleration of methanogenic activity in the landfill. There are several methods to accomplish leachate recirculation. Wazinski et al. (2000) classified leachate recirculation methods according to the distributed points and processes; trench fill method, vertical injection well method, horizontal distribution method, and surface application method.

Because the initial phase of the landfill produces high strength leachate which has significant amounts of BOD, COD, TSS, nutrients, and metals, the attenuation of its constituents by leachate recirculation is considered as an effective way to treat it (Chan et al., 2002; Kim et al., 2003; and Morris et al., 2003). Reinhart (1996) reported leachate recirculation technology provides the flexibility to handle large volumes of leachate from evaluating the eight full scale landfills which have leachate recirculation. The adoption of leachate management and the treatment flexibility from leachate recirculation improves leachate quality and reduces leachate treatment cost (Erases et al., 2003). Moreover, this recirculation is one way to scatter nutrients and microorganisms in solid waste thus preventing stagnant zone development in the landfill cells (Chugh et al., 1998). Therefore, some research has demonstrated that leachate recirculation provides a positive effect on the waste conversion and stabilization owing to the accelerated decomposition of organic matters in landfill reactors (Al-Yousifi et al., 1998; San et al., 2001; and Pohland et al., 1999). This enhanced stabilization of solid waste affects leachate characteristics positivly as the organic strength diminishes owing to methanogenesis (Reinhart et al., 1996). Moreover, rapid decomposition and conversion of waste increases the rate and extent of subsidence which offers a larger potential filling capacity of landfill area (Chan et al., 2002; Townsend et al., 1996; and Wazinski et al., 2000). For instance, a landfill in Buffalo, Minnesota encountered 4-5 feet in additional settlement once recirculation began (Wazinski et al., 2000).

The gas production rate of a landfill site is significantly enhanced as the effect of both the acceleration of methanogenesis activity and the conversion of the organic materials in leachate returned to the landfill through leachate recirculation (Reinhart et al., 1996). It takes over a year to achieve the maximum gas yield rate in the landfill if the landfill does not have optimum condition factors such as temperature, pH, alkalinity, availability of nutrients, microbes and absence of toxic compounds (Kinman et al., 1987; and Chan et al., 2002). Therefore, the dry landfill with limited water input requires a long transitional period for activating methanogenesis (Komilis et al., 1999). El-Fadel (1999) reported the enhancement of gas generation and methane yield from landfill was directly correlated with decomposition and settlement rate of waste in the landfill and gas production increase offered the beneficial aspects for landfill stabilization through extension of potential capacity for landfill in a short time period and compacted methane production. Moreover, faster and higher methane production in landfills can offer the better opportunities for an onsite energy generation (Chan et al., 2002).

Leachate recycle coupled with treatment reactor

The leachate recirculation process enhances the stabilization of waste in the landfill and attenuates the leachate strength (Reinhart, 1996). However, the accumulation of volatile fermentation intermediates such as VFAs can occur by leachate recirculation due to the acceleration of acidification, and this accumulation of VFAs can offer unfavorable conditions to the anaerobic process (Barlaz et al., 1992; and Xu et al., 2002). Therefore, in order to avoid this inhibition, simultaneous treatment and recirculation of leachate was suggested (Xu et al., 2002; and Wang et al., 2003). Xu et al. (2002) reported the methanogenesis process of a food waste landfill bioreactor was enhanced by leachate recirculation coupled with UASB reactor compared to the same recirculation system without any treatment process.

CHAPTER 3. MATERIAL AND METHODS

Analytical methods

To monitor the performance of reactors and landfill columns, chemical oxygen demand (COD), biochemical oxygen demand (BOD), volatile fatty acids (VFAs), total suspended solids (TSS), volatile suspended solids (VSS) were determined according to Standard Methods for the Examination of Water and Wastewater (APHA,1995). The COD tests were performed by the closed-reflux method (Standard Methods, section 5220 C). The BOD method (Standard Methods, section 5210 B) was used to determine BOD concentration. The distillation method (Standard Methods, section 5560 C) was used for measuring the VFA concentrations in leachate from each landfill column, SGBR effluent, and SGBR influent. Total alkalinity was determined according to Standard Methods, section 2320 B. The SGBR influent and effluent pH was measured with using an electronic pH meter (Corning Instruments, Model No. 350). The total suspended solid (TSS) and volatile suspended solid (VSS) measurement was performed by the filtration method (Standard Methods, section 2540 D and E) with glass fiber filter paper (Whatman GF/C, 1.2 *u*m pore size). Gas composition was analyzed by a Gow Mac gas chromatograph.

Three simulated landfill columns

Three landfill columns were constructed for this research to compare and evaluate their performance criteria. Three 36 inch diameter, 6.5 foot long PVC pipes were used for the landfill columns. The tops and bottoms of the columns were capped by PVC circular end caps sealed with melted HDPE plastic rods. Each column was filled with the same mass (375lb) of shredded municipal solid waste (MSW) obtained from the Ames Resource Recover Facility. The MSW was obtained on October 17, 2002 following shredding and classification, and a proportional amount of reject material was also obtained as well to be blended with the shredded waste. Consequently, the MSW placed in each landfill column was similar in composition to the as-discarded waste, with the exception of shredding. At the base of each column, gravel was placed to provide leachate drainage and prevent clogging of the sampling port. The MSW was placed in the landfill columns during the period of October 23-26, 2002. Subsequently, the columns were sealed by melted plastic rods and Epoxy glue. However, there were several difficulties during the first nine months of the project. The first problem was personnel related. The student working on the project initially was not reliable and was relieved of his duties. The second difficulty, related to the first, was with the fabrication of the landfill columns. Due to the method of construction, there were many gas and liquid leaks in the tops and bottoms of the columns and in the gas piping. These leaks resulted in a delay in the initial operation (e.g., water addition and leachate recirculation). In addition, the initial leachate and gas characteristics and quantity data were lost.

Figure 2 shows the schematic diagram of the three simulated landfill columns. The three columns were operated in three different strategies. In Column 1 (C1), the leachate is treated in the SGBR reactor and recycled to the top of C1. Column 2 (C2) recirculates the leachate without any treatment. Column 3 (C3) is a simulated conventional landfill without recirculation. C1 and C2 have been operated with 1L/d recirculation rate.

Table 1 shows the volume of water added and leachate discharged in each of the three landfill columns. Initially, 78 L of distilled water was added to each column to bring the columns up to field moisture capacity. During the initial operation, some leachate was collected from C3 to be used for the SGBR organic loading rate (OLR) study. Leachate (35L) from C3 was also added to C1 since the leachate concentration in C1 was noticeably lower than the other columns. This may have been due to the greater loss leachate in C1 during the first 300 days of the study.

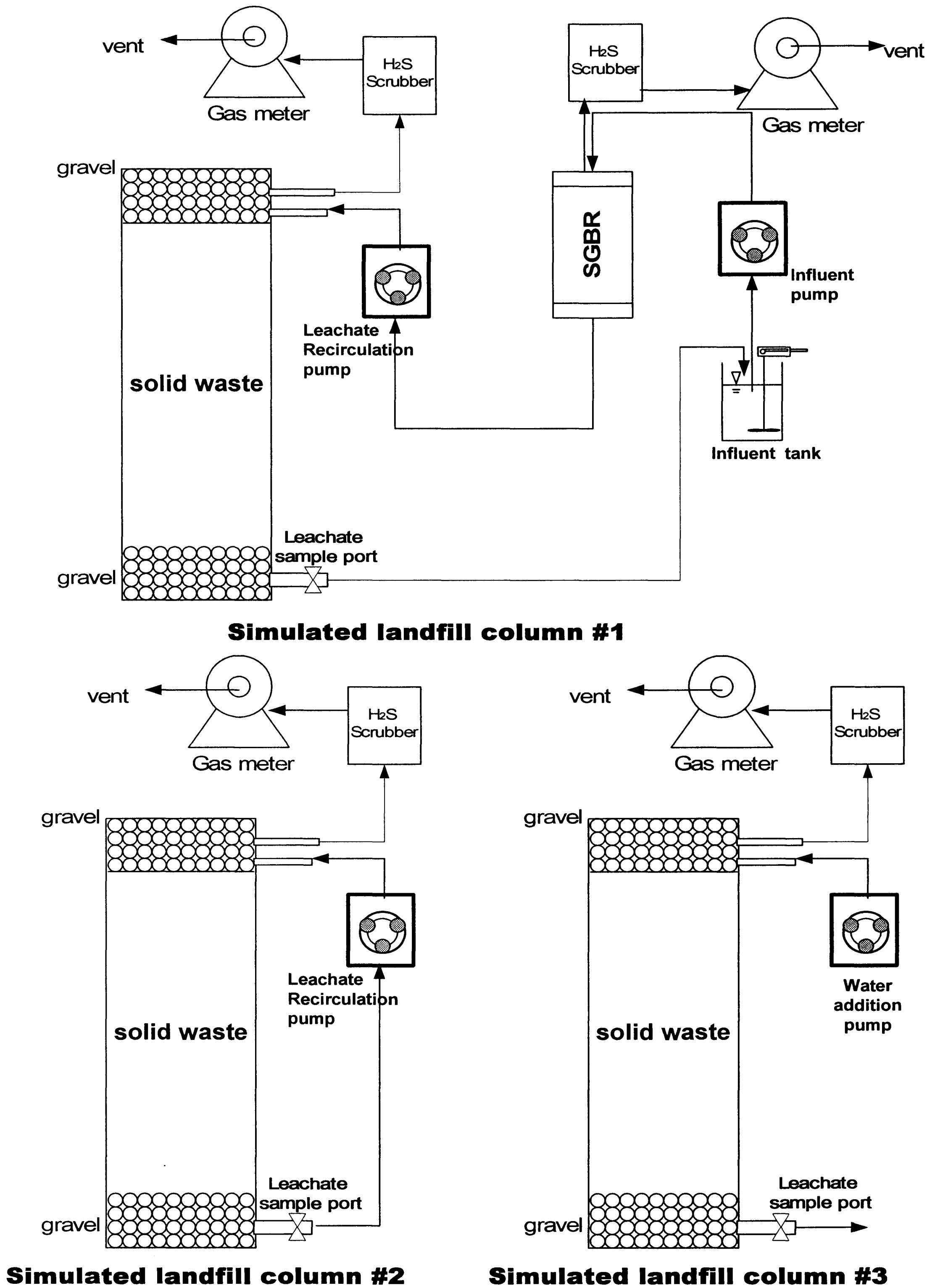

Figure 2. Configuration of simulated landfill columns and SGBR

Table 1. Water or leachate volume added and discharged from the simulated landfill columns (Day 0 corresponds to October 23, 2002)

Days		Volume added(+) and discharged (-)		
		Column 1	Column 2	Column 3
330-340	Water	+ 78L	+ 78L	+ 78L
350-500		+0.3L/d	+ 0.3L/d	+ 0.3L/d
353	Leachate			- 2 L
362				- 6 L
378-379		- 35 L		- 35 L
380		+ 35 L* (from Column 3)		
381			- 6 L	
392				- 1.5 L
396				- 4 L

* leachate from C3 was added to C1 column to increase the concentration of organic matter in leachate(C1).

Overview of the SGBR reactor

The static granular bed reactor (SGBR) is filled with anaerobic granules and operated in a down-flow mode as illustrated in Figure 3. Therefore, the influent wastewater is distributed in the reactor and flows down through the dense active granules. For this study, a 2 L active volume SGBR reactor with 3 L total volume was set-up in the laboratory. Gravel was filled at the base of this reactor to make the granules stable in the system. In order to seed the reactor with granules, anaerobic granular sludge from City Brew Brewery, La Crosse, Wisconsin was used. About 1.5 L of anaerobic granules were used in the SGBR system, and the SGBR has been operated at a 48 hour HRT. For stable startup, dry milk was used as the feed solution at the beginning followed by leachate addition. The leachate used for the SGBR pre-operation was collected from the laboratory landfill columns. The collected leachate was diluted before using it as the influent of SGBR reactor. After pre-operation, the leachate from C1 was use as influent for the SGBR reactor, and its effluent was returned to the top of C1.

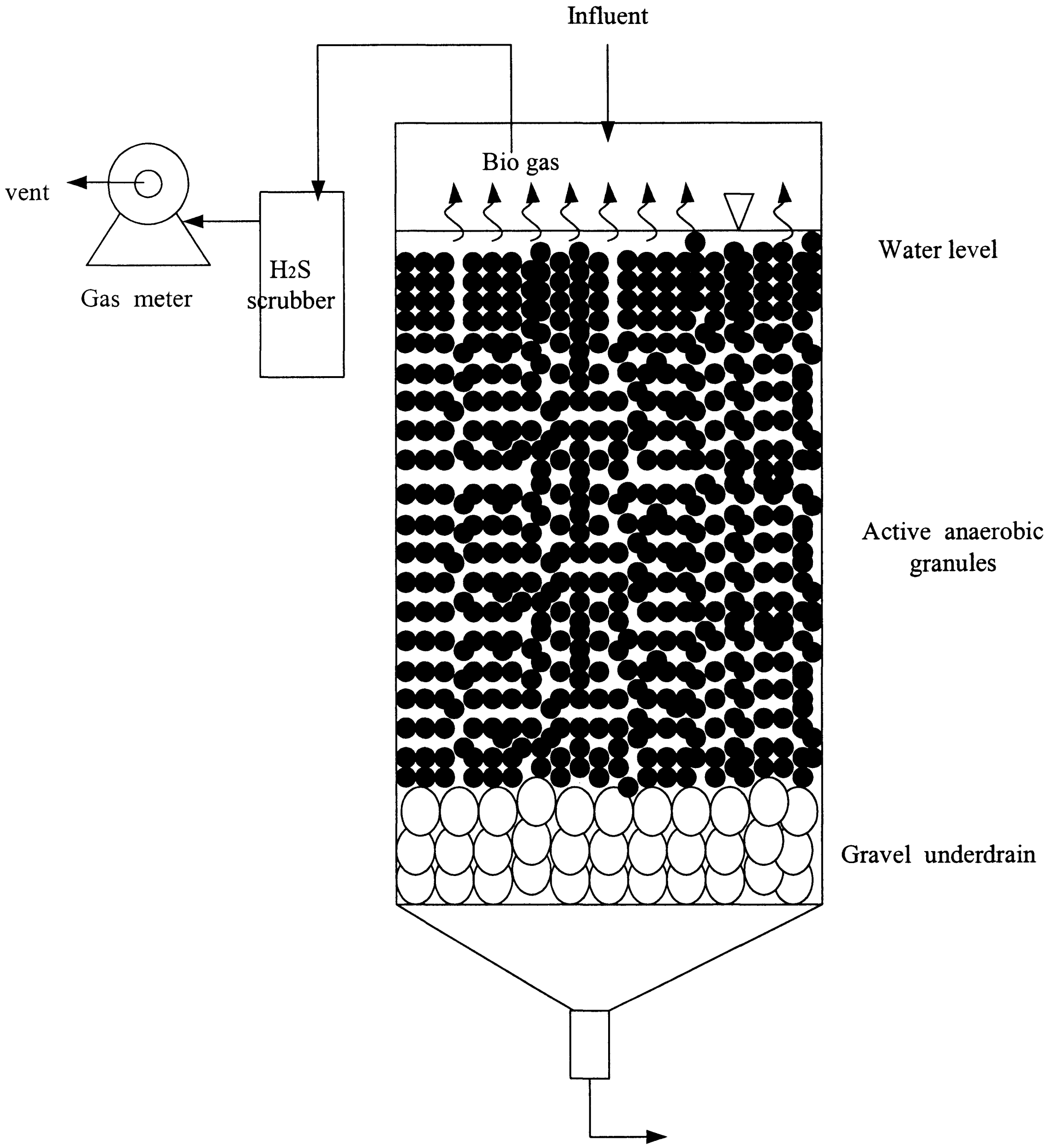

Figure 3. Static Granular Bed Reactor (SGBR) schematic diagram

CHAPTER 4. RESULTS AND DISCUSSION

SGBR pre-operation

The SGBR reactor was initially operated with Non-fat dry milk for system stability and acclimation of the granular sludge. After the startup period, the feed solution was changed to the leachate collected from the simulated landfill column. During this period, the SGBR reactor rapidly became stable and maintained effluent COD concentrations lower than 50 mg/L. Figure 4 shows influent and effluent COD concentrations and the removal efficiency of the SGBR reactor. When the feed condition was changed, the removal efficiency had little decrease and returned to the same value as the previous condition. The pH values of the SGBR were 6.7-7.2 for the two different influent conditions. These values show there was no detrimental effect of pH to the SGBR system in those conditions, particularly to the methanogenesis. Moreover, the average value of VFAs was 10~20 mg VFAs/L which indicated the reactor did not have VFAs accumulation.

In comparison with the SGBR system fed dry milk, the rate of methane conversion from the COD removed in the system fed leachate was similar (Figure 5). After a small decrease in this rate in the beginning, each condition had stable methane production values of

0.26-0.34L CH_4/ g $COD_{removed}$, indicating the methane production rate was stable and similar to the theoretical value (0.35L CH_4/g $COD_{removed}$) for the two different feed conditions. Even though COD removal efficiencies were slightly different for both conditions, methane conversion rates were similar and stable. Therefore, the SGBR maintained similar abilities for organic removal in the two feed conditions. The difference in COD removal efficiencies was likely due to the non-biodegradable portion of leachate. These results show the ability of the SGBR to acclimate to and provide effective treatment of landfill leachate.

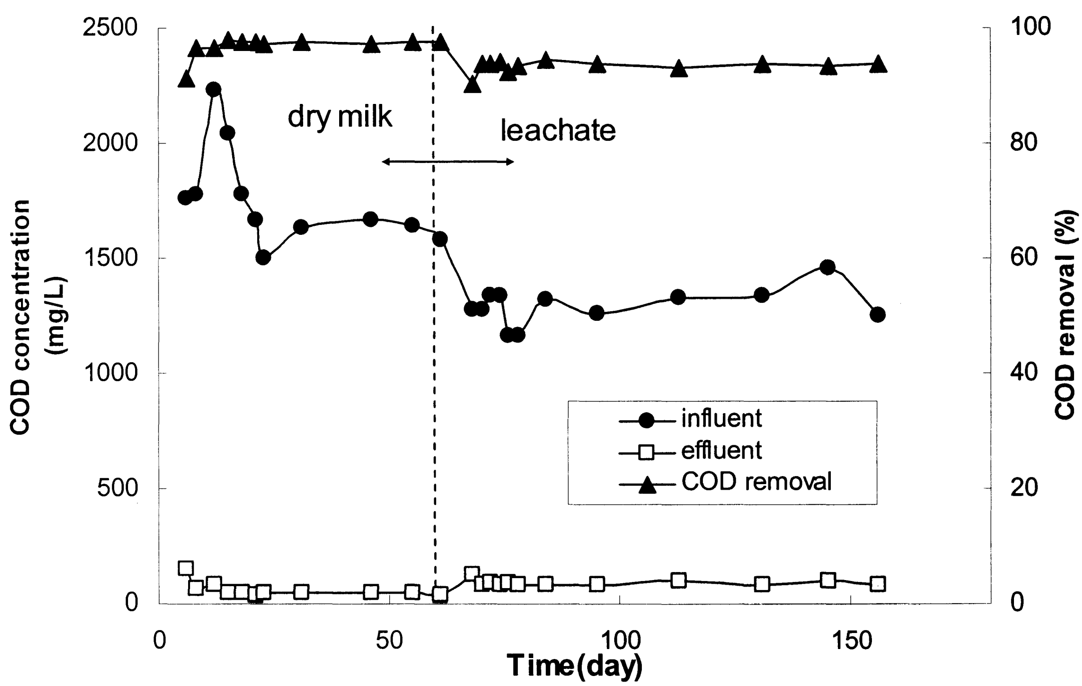

Figure 4. COD results for SGBR pre-operation in the two feed conditions (Day 0 corresponds to March 28, 2003)

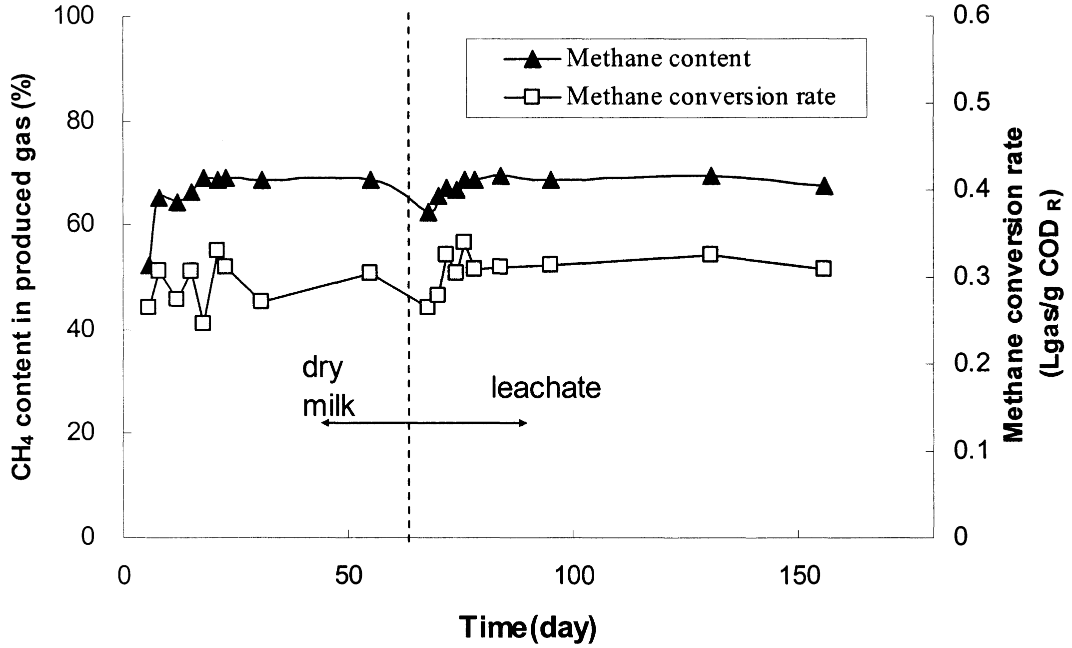

Figure 5. The methane conversion rate and content of the SGBR pre-operation (Day 0 corresponds to March 28, 2003)

Simulated landfill columns

Three different strategies were applied to simulated landfill columns to evaluate their performance and application for leachate management and landfill operation. Each column had somewhat different leachate characteristics during the operating period. Figure 6 shows the variation in the COD concentration for each column. The COD concentration of each column decreased with time as would be expected. Between Day 340 and 400, each column's COD concentration dropped sharply indicating the removal of the readily mobile, soluble organic matter. On approximately Day 390, the maximum COD and BOD concentrations were approximately 12,000 and 8,000 mg/L, respectively for C3. The sharp increase in organic strength was likely due to the fact that some leachate was withdrawn from C3 just prior to this day (i.e., 35L of leachate was withdrawn on Day 378~379). Therefore, newly produced leachate was not diluted with the leachate in the base of the column, resulting in a higher COD concentration at this time.

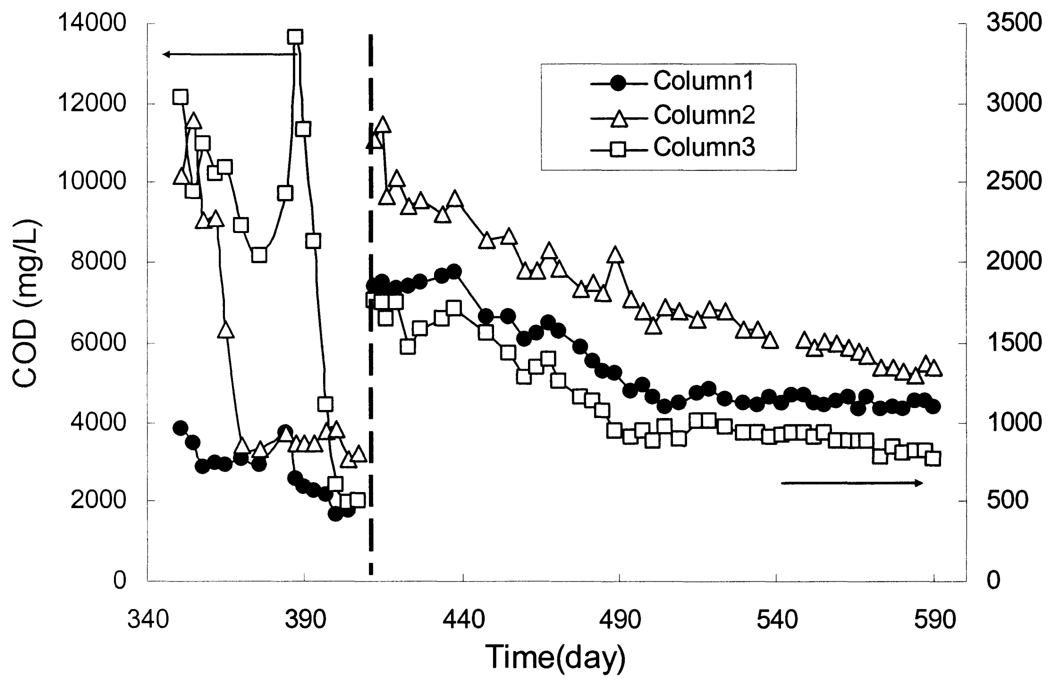

Figure 6. COD results of leachate in three simulated landfill columns (Day 0 corresponds to October 23, 2002)

By Day 400, each column had similar leachate COD concentrations in the 1500 ~ 2800 mg/L range. At this time, C2 had the highest value and C3 had the lowest value. While leachate was withdrawn from C3, the leachate from C2 and C1 was returned to the columns. Therefore, the COD concentration decrease in C1 and C2 was likely due to leachate recirculation. Leachate COD was removed in the SGBR reactor (C1) and the landfill column itself by methanogenesis (C1 and C2). Consequently, these different COD reductions showed the possibility of this leachate management strategy that has the potential for significant cost savings from reduction in surcharges for COD or BOD.

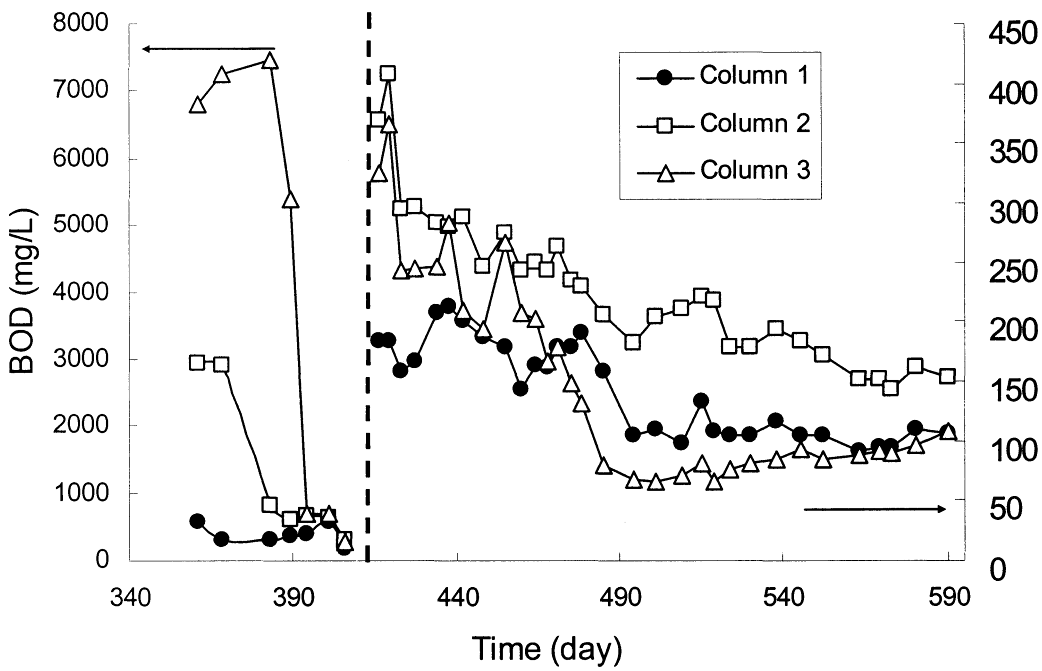

Figure 7. BOD results of leachate in three simulated landfill columns (Day 0 corresponds to October 23, 2002)

The BOD concentrations of leachate from three landfill columns were similar to the COD variation (Figure 7). In the beginning, the BOD_5 concentration in each column decreased sharply, and after Day 400 day, it decreased gradually. This swift decrease in BOD concentration can be explained by the COD: BOD_5 ratio variation as an indication of the relative biodegradability of the organic matter in the leachate. The lowest COD: BOD_5 ratio (C1 for 5.1, C2 for 3.6, C3 for 1.6) was in the initial operating period indicating a high proportion of biodegradable organic matter. However, the COD: BOD_5 ratio increased with time as expected (C1 for 9.8, C2 for 8.2, C3 for 8.4 in Day 580) indicating the increase of non-biodegradable or slowly biodegradable organic matter as a percentages of the total COD. This suggests that the landfill bioreactor systems were effective at reducing the biodegradable fraction of the leachate, and the remaining COD was refractory in nature.

Figures 8 and 9 show the daily gas production and cumulative gas production in each of the three landfill columns, respectively. Each landfill column had similar gas composition and similar variation. The gas produced from the landfill columns was composed of 50-56% methane (CH_4) and 40-44 % carbon dioxide (CO_2) during the operating period. Prior to Day 340, the initial gas production of each column was not measured due to gas leaks in the headspace and gas collection and leachate recirculation piping systems.

However, the peak gas production (Figure 8) was during the period of Day 360-390. This suggests that significant gas production did not occur prior to the addition of moisture to bring the columns up to field moisture capacity. The fact that C3 produced less gas than the other two columns can be explained by the effect of recirculating leachate which accelerated the gas production from C1 and C2 owing to the supply of organic matter and increased moisture. The cumulative gas production of each column (Figure 9) also showed the effect of leachate recirculation on the column with the SGBR treatment prior to recirculation. C2 likely had higher cumulative gas production than C1 due to the fact that a portion of the biodegradable matter was converted to gas in SGBR prior to recirculation to the column C1. This gas production was not included in the cumulative gas production total. It can also be explained by the different leachate COD concentrations in C1 and C2.

An interesting point to note is that C1 had higher gas production than C2 after approximately Day 490 while non-fat dry milk was added in the influent of SGBR in order to supply sufficient growth substrate to the granules. Despite the removal of the COD almost all associated with the non-fat dry milk by SGBR, the SGBR effluent might include a small amount of non-fat dry milk which accelerates the activity of methanogenesis in C1 due to the supply of readily biodegradable substrates. Moreover, SGBR effluent had more favorable conditions such as optimum pH, alkalinity, and low VFA concentrations for methanogenesis, which allowed C1 to accelerate the biodegradation of solid waste due to the recirculation of SGBR effluent to C1.

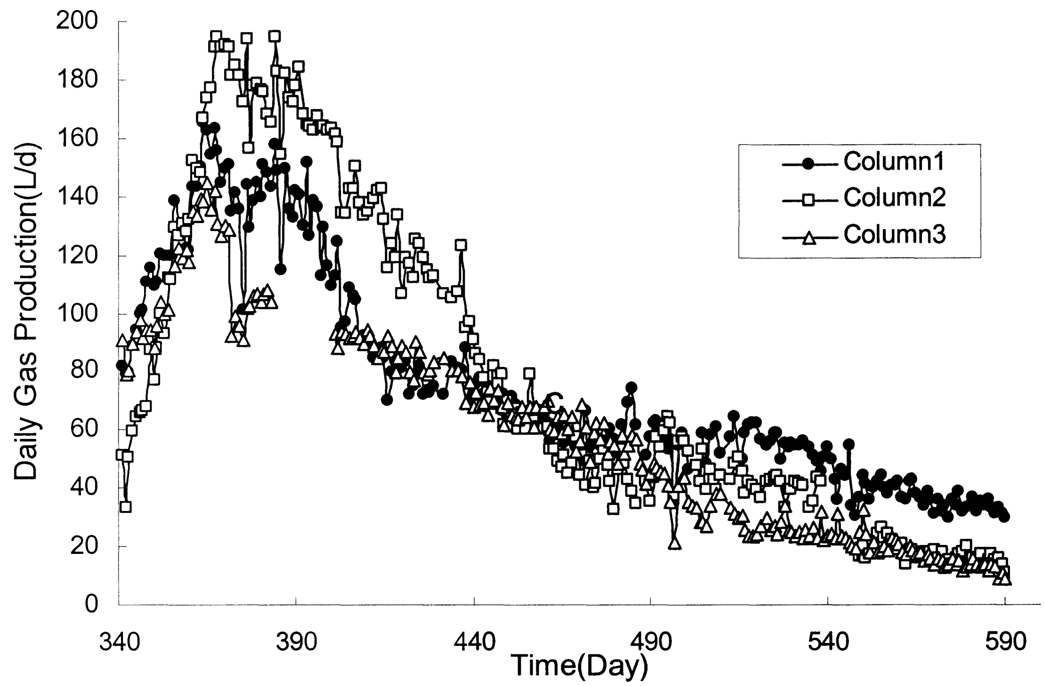

Figure 8. Daily gas production from the simulated landfill columns (Day 0 corresponds to October 23, 2002)

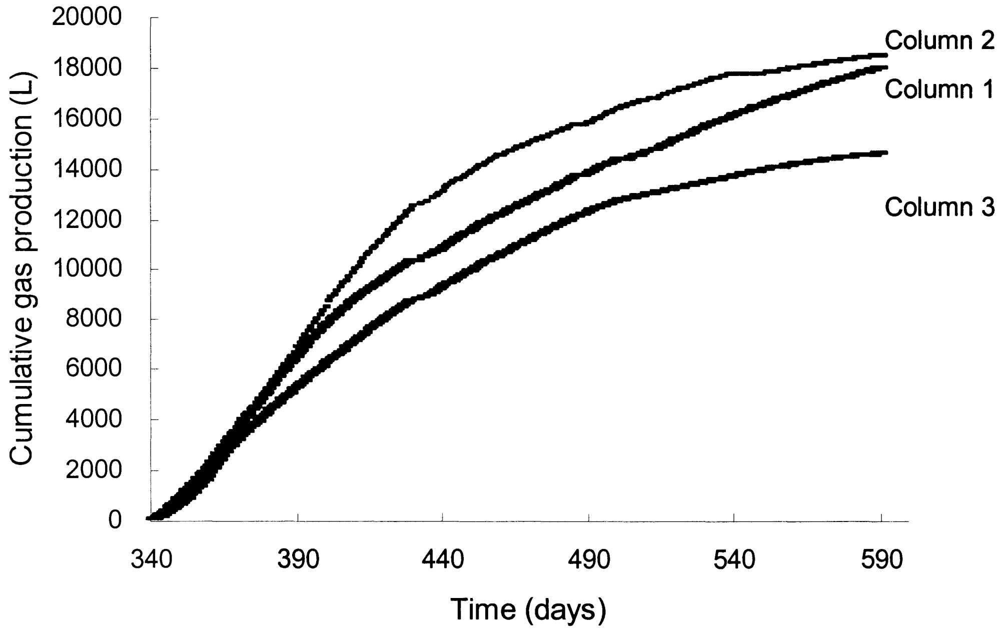

Figure 9. Cumulative gas production of the simulated landfill columns (Day 0 corresponds to October 23, 2002)

SGBR treatment of leachate prior to recirculation in the landfill column

The SGBR reactor was fed with leachate from C1 to treat leachate prior to recirculation in the column. Figure 10 shows the COD concentration of the influent and effluent and, the removal efficiency of the SGBR reactor. Initially, the influent was diluted to avoid shock loading due to the potentially high COD concentration of C1 leachate. However, the influent was not diluted after Day 366 because the COD concentration of leachate from C1 decreased below 2000 mg/L. The soluble COD concentration was similar to the total COD concentration because TSS and VSS concentrations were low compared to the COD concentrations. However, this high soluble COD fraction was fairly nonbiodegradable because the majority of soluble COD was not removed in this system indicating low COD removal efficiency compared to the BOD_5 removal efficiency. With time, the COD concentration of influent decreased as the leachate was treated by SGBR and recirculated in C1. The COD removal efficiency also decreased due to the reduction of the biodegradable portion in the influent. Moreover, the difference between influent COD and effluent COD concentrations in the SGBR reactor became less indicating the shortage of useful substrates for the anaerobic granules in the SGBR. Therefore, in order to supply enough growth substrate to the granules in the SGBR, non-fat dry milk was added in the influent starting on Day 490. During this period, the dry milk was added in the influent as 0.4g/L which increased the COD concentration by 300~400 mg COD/ L. All of the COD from the added non-fat dry milk was removed in the SGBR system as evidenced by the COD concentration of effluent being less than the COD of C1 leachate. Even if the COD removal efficiency was low, the SGBR reactor treating leachate prior to recirculation in the simulated landfill column was effective at reducing the total leachate COD within the system.

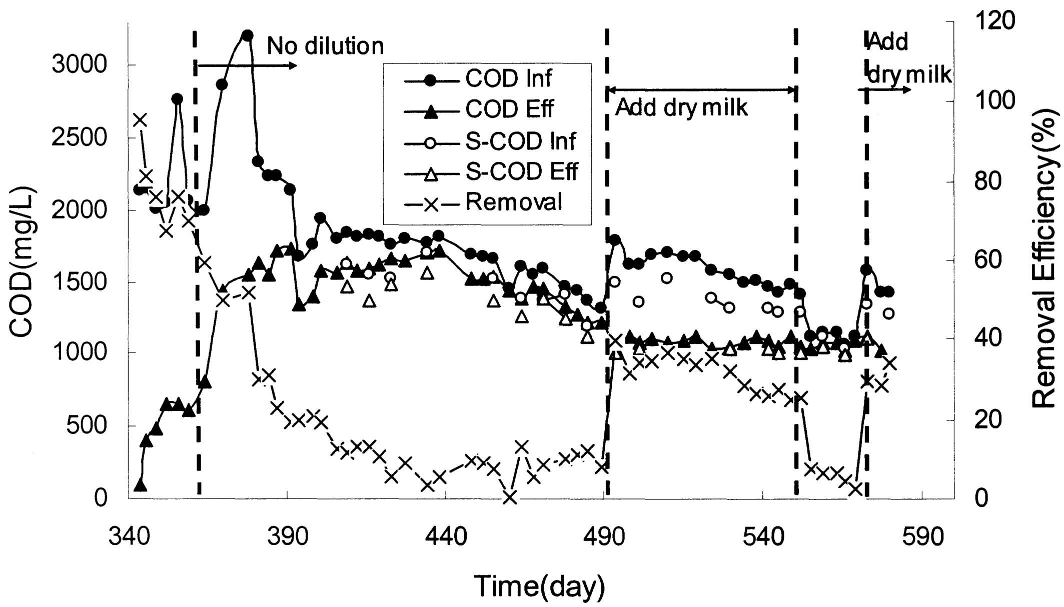

Figure 10. COD, S-COD concentration and Removal efficiency in SGBR reactor (Day 0 corresponds to October 23, 2002)

The influent and effluent BOD_5 variation was similar to the COD variation. Figure 11 shows the BOD_5 concentration of influent and effluent and the BOD removal efficiency in the SGBR reactor. With time, the BOD_5 concentration of influent decreased and the removal efficiency also dropped similar to the response of the COD removal efficiency. However, the BOD_5 removal efficiency was higher than the COD removal efficiency indicating the ability of the SGBR to remove the degradable portion of organic matter in the leachate. Moreover, during the period with dry milk addition, the BOD_5 removal efficiency was about 80 % or more which showed the SGBR system was stable and capable for leachate treatment.

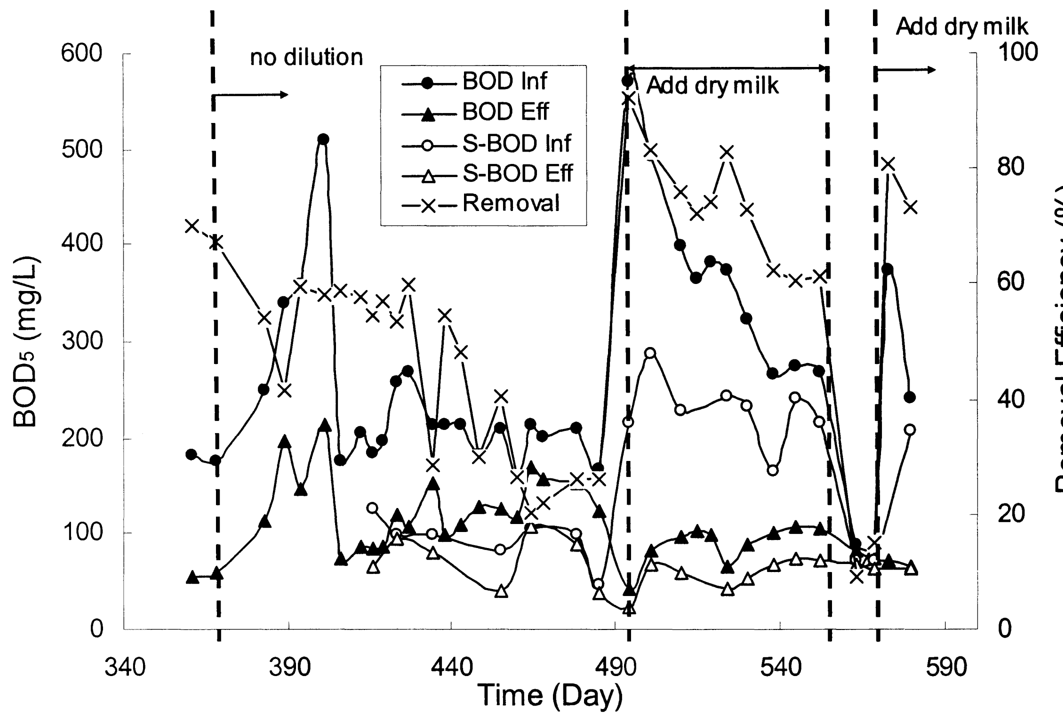

Figure 11. BOD_5, S-BOD_5 concentration and Removal efficiency in SGBR reactor (Day 0 corresponds to October 23, 2002)

Figure 12 shows the pH and VFAs concentrations in the SGBR. Effluent pH and influent pH were 7.6-8.5 and 7.2-8.0, respectively. During this operating period, the VFA concentration did not increase in the SGBR reactor, and the average value was consistently between 60~20 mg VFA/L. The stable VFA concentration of effluent in SGBR reactor indicated the stable performance of system. The low VFA concentration in the influent also showed that the leachate from C1 had low biodegradable portion compared to its COD concentration values, and that acids produced within the solid waste were converted to carbon dioxide and methane within the landfill columns. When dry milk was added to the influent, the VFA concentration of the influent also increased sharply. However, the effluent VFA was maintained below 50 mg/L. Hence, these results suggested that this system was not inhibited by inorganic or organic constituents in the leachate.

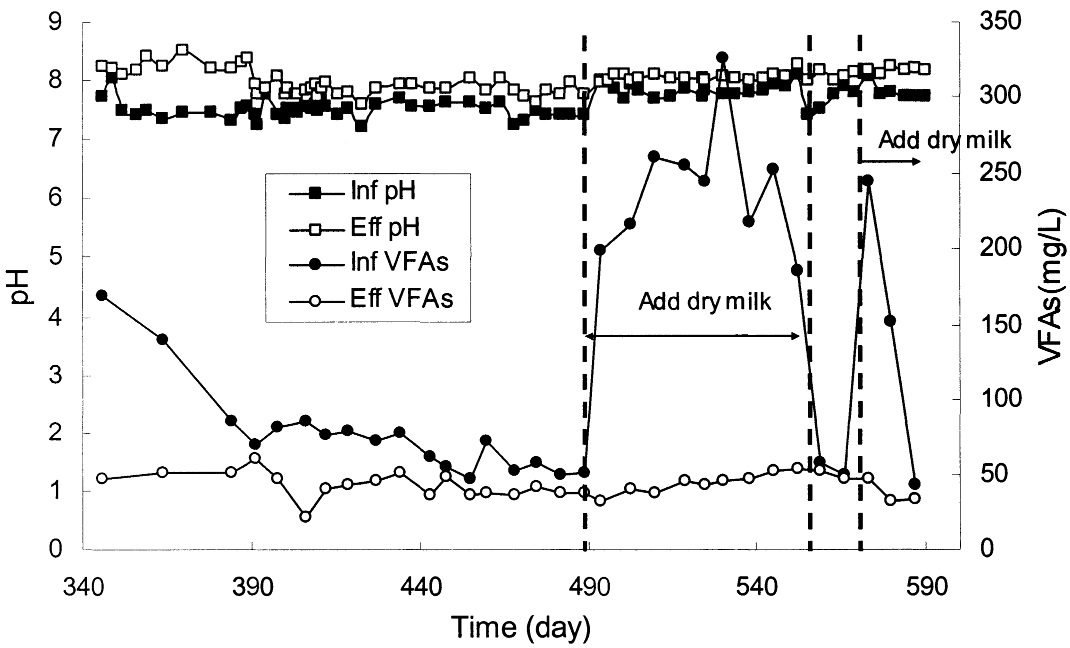

Figure 12. Variations of pH and VFAs in SGBR reactor (Day 0 corresponds to October 23, 2002)

CHAPTER 5. ENGINEERING SIGNIFICANCE

The practical and engineering significance of this study was to demonstrate the SGBR and simulated landfill columns in different operating conditions to evaluate alternative landfill management strategies. In the proposed scheme, leachate was treated in the SGBR and recirculated back through the landfill column. Since the retention time of the leachate in the simulated landfill column was short and columns were not as deep as an actual landfill, essentially the same leachate was recycled over and over again, and the readily degradable matter was quickly removed in the SGBR and solid waste matrix itself. In the field, it is expected that the retention time in the landfill would be significantly longer, due to the greater mass of solid waste in the landfill. Consequently, the leachate being recycled would supply readily degradable organic matter to the SGBR for a longer period of time. Typically, young landfills have leachate with high organic strength which causes difficulty for leachate management (Erses et al., 2003). The application of the SGBR system to the field will potentially have a significant impact on leachate management by providing an alternative organic reduction process or in combination with leachate recirculation for an integrated leachate management strategy.

In comparing the performance of each column, leachate recirculation with SGBR treatment was effective in enhancing the biodegradation of waste as evidenced by the acceleration of gas production. In the field, the leachate recirculation method can be considered to optimize leachate management. Surface application of leachate is recommended for the landfill bioreactor based on the result from the laboratory-scale landfill column (C1) which dispersed leachate directly over a gravel layer on top of the solid waste. This recirculation method provides sufficient moisture to the solid waste immediately prior to compaction due to direct application of leachate to the working space (Warzinski et al., 2000). Moreover, it can make the leachate recirculation with SGBR treatment system simpler and more cost effective than other methods due the ease of pumping and distribution.

The incorporation of SGBR leachate treatment, either with or without leachate recirculation, provides landfill design, management, and operating personnel a unique new tool to lower the organic strength of the leachate generated at the landfill. The system is easy to operate, provides robust and effective treatment, is cost-effective due to its small size when compared to other systems, requires little energy input, and generates biogas which can be combined with the landfill gas to power an engine generator. This laboratory project has provided an important first step in demonstrating the applicability of this exciting new technology in the field.

CHAPTER 6. CONCLUSIONS

Results from the three simulated columns and the SGBR showed effective leachate and waste management strategy. With time, the COD concentration of leachate in each column decreased. In consideration of the leachate withdrawal from C3, C1 had the greatest reduction of COD in leachate due to removal in the SGBR and the landfill column itself. Moreover, gas production was accelerated by leachate recirculation owing to enhancement of waste degradation in landfill columns (C1 and C2). The attenuation of leachate strength and waste reduction through this system offers benefits to the landfill due to an increase of landfill capacity and cost savings for leachate treatment.

The feasibility of leachate treatment by the SGBR was also proven in this study. The SGBR pre-operating study showed fast acclimation (5 days) to substrate change and short start-up period (10 days) indicating significant benefits for leachate treatment due to its variation along with time (Kjeldsen et al., 2002). Moreover, in spite of the low biodegradable portion of the influent, the system was sustained in stability as evidenced by the stable pH and low VFA concentrations. Incorporated in a leachate management strategy, the SGBR offers the potential to reduce high strength leachate prior to recirculation in the landfill. Therefore, recommendations for future research include the application of the new strategy to high strength leachate.

CHAPTER 7. REFERENCES

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APPENDIX A: OPERATING DATA OF LANDFILL COLUMNS AND SGBR

Table A1. Results of the simulated landfill columns

Date	COD(mg/L)			BOD_5(mg/L)			VFA (mg/L)			Gas production (L/d)		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
10/9/03	2871	9060	10960	558	2940	6800	240	340	5742	120	100	104
10/21/03	3072	3430	8912	296	894	7236				165	167	138
11/4/03	3706	3706	9707				86	196	4457	139	178	105
11/17/03	2150	3768	4423	352	592	696	71	197	257	140	183	99
12/2/03	1855	2774	1765	182	308	281	87	117	95	106	142	92
12/15/03	1840	2528	1753	184	408	365	75	108	99	80	133	84
12/30/03	1908	2301	1643	207	283	246	74	121	82	82	108	81
1/13/04	1661	2139	1567	187	246	194	52	103	90	72	61	61
1/29/04	1564	1955	1353	163	250	203	46	78	62	60	49	64
2/12/04	1469	1843	1155	191	230	132	53	77	56	55	48	52
2/28/04	1200	1770	910	104	182	62	46	65	35	59	54	46
3/15/04	1123	1702	898	97	210	71	44	81	42	61	39	48
3/24/04	1210	1710	1010	108	218	66	52	76	40	62	43	24
4/ 4/04	1123	1592	935	105	178	81	47	58	34	55	34	20
4/12/04	1160	1523	909	116	193	84	42	56	36	50	33	19
4/26/04	1116	1473	907	103	182	83	64	88	36	45	24	18
5/ 7/04	1158	1473	877	91	152	87	58	86	34	42	19	20
5/17/04	1089	1352	784	95	144	89	51	80	30	37	14	13
5/24/04	1079	1320	806	109	161	96	48	71	41	34	16	14
6 /3/04	1094	1352	774	137	194	109	53	83	45	30	11	9

C1: Recirculation of leachate treated by SGBR

C2: Recirculation of leachate

C3: Without recirculation

Table A1. (Continued)

Date	pH			Alkalinity (mg/L as $CaCO_3$)			TSS(mg/L)			VSS(mg/L)		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
10/9/03	7.35	7.30	7.56	4760	6040	5560	360	520	440	280	340	290
10/21/03	7.33	7.65	7.31	4600	6160	5240						
11/4/03	7.13	7.49	6.94	4125	6700	5250	410	440	330	280	260	195
11/17/03	7.35	7.28	7.37	4416	6625	5508	360	450	340	220	280	215
12/2/03	7.21	7.34	7.43	4250	5416	4916	340	440	280	230	315	170
12/15/03	7.36	7.39	7.40	4400	4650	4550	420	380	280	300	270	180
12/30/03	7.09	7.20	7.13	4060	4500	4480	380	350	250	300	260	160
1/13/04	7.28	7.35	7.38	4000	4530	4230	270	300	210	190	210	160
1/29/04	7.23	7.29	7.23	4060	4500	3900	240	350	240	150	260	140
2/12/04	7.21	7.30	7.28	4020	4520	3840	230	280	200	140	210	100
2/28/04	7.42	7.36	7.25	3800	4200	3200	108	140	80	72	104	48
3/15/04	7.15	7.25	7.12	3750	4330	3250	110	160	68	65	105	52
3/24/04	7.15	7.20	7.08	3750	4200	3000	95	170	84	65	110	55
4/ 4/04	7.15	7.21	7.09	3920	4170	3000	94	132	70	50	96	46
4/12/04	7.14	7.20	7.01	3830	4000	2920	73	90	50	46	70	40
4/26/04	7.25	7.31	7.10	4080	3830	2670	67	110	60	37	75	45
5/ 7/04	7.18	7.27	7.08	3820	3750	2670	64	87	63	39	51	49
5/17/04	7.12	7.12	7.09	3620	3830	2580	75	105	74	44	63	48
5/24/04	7.36	7.19	7.02	3250	3500	2625	72	92	78	41	48	42
6 /3/04	7.31	7.38	7.11	3750	4160	2580	67	85	71	39	41	42

C1: Recirculation of leachate treated by SGBR

C2: Recirculation of leachate

C3: Without recirculation

Table A2. Results of the SGBR reactor for leachate treatment prior to recirculation

Date	COD (mg/L)		SCOD (mg/L)		BOD_5 (mg/L)		$SBOD_5$ (mg/L)		VFA (mg/L)	
	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
10/9/03	2155	403							180	115
10/21/03	2003	811			183	58			230	195
11/4/03	3200	2417			294	114				
11/17/03	1768	1402			359	146			275	173
12/2/03	1800	1567	1622	1463	175	81	84	48	283	162
12/15/03	1824	1626			258	120	99	94	320	220
12/30/03	1771	1707	1707	1560	215	153	97.6	78.6	260	180
1/13/04	1689	1529			182	127			240	140
1/29/04	1604	1389	1388	1263	213	170	105	106	240	150
2/12/04	1474	1322	1407	1241	209	154	99	88	210	160
2/28/04	1790	1076	1500	1010	570	43	216	23	240	88
3/15/04	1702	1077	1520	1016	399	96	228	58	180	55
3/24/04	1680	1120			381	98			155	65
4/ 4/04	1557	1055	1311	1030	323	88	232	53	155	45
4/12/04	1433	1042	1283	1012	274	108	241	74	165	44
4/26/04	1414	1051	1290	1007	268	104	217	72	120	56
5/ 7/04	1148	1073			89	81	72	68	49	47
5/17/04	1580	1117	1340	1104	373	72	296	61	244	47
5/24/04	3250	3500	1420	939	241	65			152	32
6 /3/04	1170	1064	1126	1048	132	106	86	63	43	34

Table A2. (Continued)

Date	pH		Alkalinity (mg/L as $CaCO_3$)		TSS (mg/L)		VSS (mg/L)		Gas production rate (L/d)
	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	
10/9/03	7.73	8.23	2250	2566	240	160	180	115	0.6(65%CH_4)
10/21/03	7.34	8.24	1760	1960	340	270	230	195	0.2(64%CH_4)
11/4/03	7.47	8.22	3000	3200					0.2(63%CH_4)
11/17/03	7.76	7.88	4333	4791	365	235	275	173	0.1(66%CH_4)
12/2/03	7.56	7.82	4166	4750	375	270	283	162	0.1(66%CH_4)
12/15/03	7.54	7.80	4250	4500	450	290	320	220	0.1(65%CH_4)
12/30/03	7.71	7.94	4060	4120	340	290	260	180	0.1(64%CH_4)
1/13/04	7.63	7.88	3900	4080	340	220	240	140	0.1(58%CH_4)
1/29/04	7.63	8.05	4140	4380	280	230	240	150	0.1(62%CH_4)
2/12/04	7.43	7.82	4080	4210	320	200	210	160	0.1(59%CH_4)
2/28/04	8.01	7.96	3600	3900	350	124	240	88	0.3(67%CH_4)
3/15/04	7.68	8.09	3580	3620	290	105	180	55	0.4(72%CH_4)
3/24/04	7.85	8.04	3500	3660	250	84	155	65	0.4(76%CH_4)
4/ 4/04	7.77	8.08	3580	3670	235	65	155	45	0.3(74%CH_4)
4/12/04	7.92	8.11	3640	3750	230	85	165	44	0.2 (77%CH_4)
4/26/04	8.09	8.27	3790	3750	225	98	120	56	0.2(79%CH_4)
5/ 7/04	7.76	8.02	3660	3830	92	60	54	43	0
5/17/04	8.06	8.18	3330	3540	180	68	145	60	0.1(62% CH_4)
5/24/04	7.80	8.23	3250	3500	120	70	63	50	0.2(77% CH_4)
6 /3/04	7.74	8.16	3750	4120	78	60	60	41	0

APPENDIX B: HYDRAULIC AND ORGANIC LOADING STUDY WITH SGBR

Hydraulic and Organic Loading Study with SGBR

In addition to the SGBR reactor operated with landfill column recirculation, another SGBR reactor system has been operated to conduct a hydraulic and organic loading rate (OLR) study with leachate. Therefore, this OLR-SGBR has been fed leachate at various organic strengths. For stable inoculation, dry milk was used as the feed solution at the beginning followed by leachate addition. During the operating period, the feed solution has been changed several times in order to feed the high organic strength of leachate to the SGBR reactor.

The COD variation and the removal efficiency in the OLR-SGBR reactor are given in Figure B1. Even though the COD concentration of influent fluctuated owing to changing feed solution several times, the effluent COD concentration was maintained at a low value. The COD removal efficiency was higher than 90 % during most of the study at various organic loading rates indicating that the SGBR system can be stable for the high strength leachate (Figure B2). In order to know the pH shock and buffer ability of SGBR, the pH was adjusted to below pH 4 from day 370 to 380. When the influent pH dropped, the treatment ability also decreased and the effluent COD concentration increased at that time. However, the system recovered quickly after the pH was adjusted to the normal condition (pH 7~8).

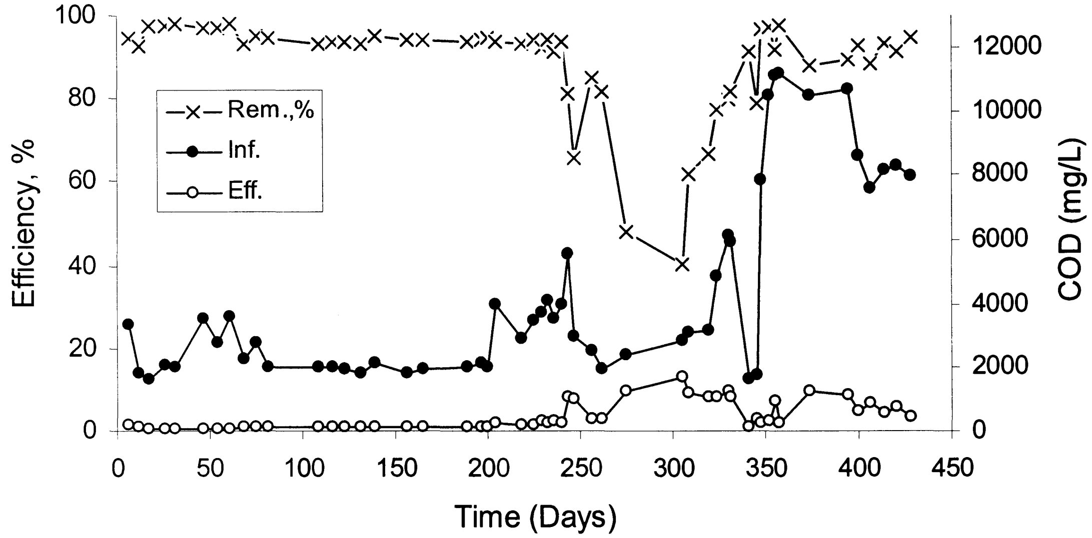

Figure B1. COD concentration and the removal efficiency in SGBR (Day 0 corresponds to February 23, 2003)

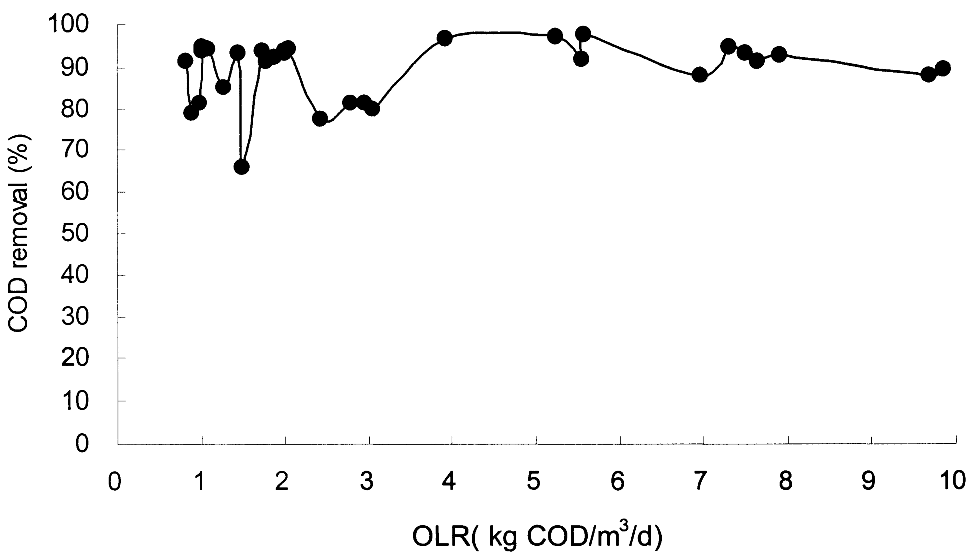

Figure B2. COD removal efficiency of SGBR at various organic loading rates

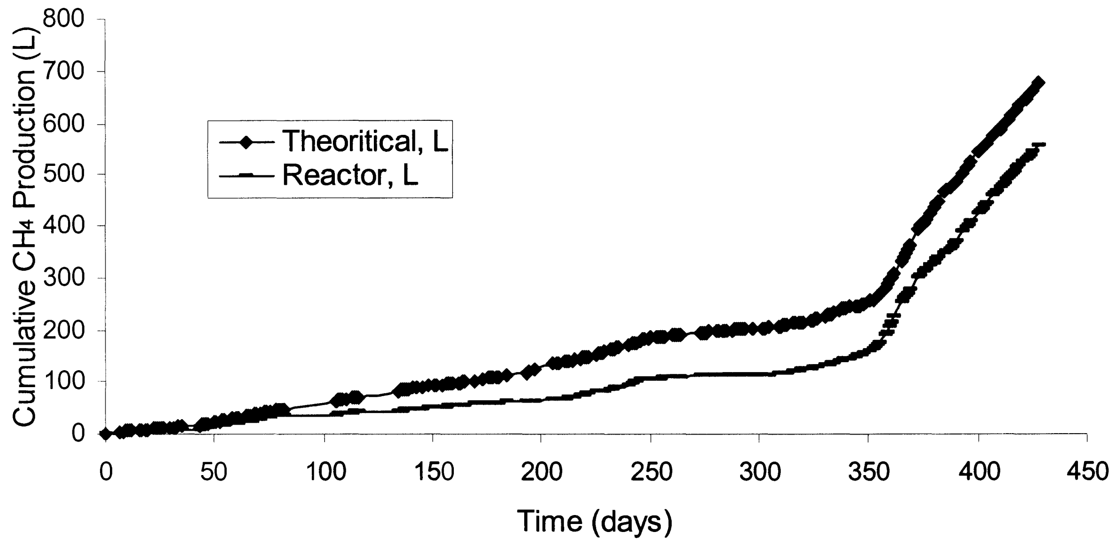

Figure B3. Cumulative methane production (Day 0 corresponds to February 23, 2003)

The cumulative methane production is given in Figure B3. The theoretical methane production was calculated from the daily removed COD and theoretical methane production rate (0.35 L /g removed COD) in order to compare the methane production of the SGBR reactor. The cumulative methane volume produced from the SGBR was lower than the theoretical value. However, the trend of the two values was similar when it considered that the experimental value can not be higher than the theoretical value. Therefore, the cumulative methane production corresponded adequately to the theoretical value. The results demonstrate the system stability and excellent treatment ability of the SGBR fed with leachate. Moreover, there was not a significant change in the methane production rate during the period when the organic loading rate was increased. This result indicated that the SGBR reactor can be applied to the higher strength leachate than tested under these conditions. Hence, this study needs to be continued to get optimal operating information for the leachate treatment with the SGBR reactor.

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