JBLD, SPECIAL ISSUE, NOVEMBER 2014, pp. 106-119

Pilot-scale experiment on anaerobic landfill bioreactor in Tanzania

F. SALUKELE*

ABSTRACT

Landfill bioreactors have been developed in industrialized countries as a long-term municipal solid waste (MSW) management option, but in East Africa no landfills have yet been designed and operated as recirculated landfills or bioreactors. Treatment of leachate and landfill gas emanating from landfilling remains a major environmental concern despite improved techniques of landfilling of solid wastes. This paper presents findings from a comparative study of a pilot scale landfill bioreactor and sanitary landfill conducted in Dar es Salaam city, Tanzania, to study the effect of leachate recirculation on waste degradation and acidification, landfill gas production, and in situ leachate treatment to provide insights for the successful operation of landfill bioreactors in developing countries. Two reactors R1 and R2 were built and each filled with about 2.3 tons of wet waste predominantly food waste (about 60%) of moisture content about 64% collected from municipal waste transfer stations. R1 was operated as a control reactor simulating a sanitary landfill and R2 was a simulated landfill bioreactor (LFB). Throughout the study of 52 weeks R1 was run as a flow through system whereas R2 was broken into two phases. During phase one of R2 the leachate was recirculated directly to the top of the reactor and phase two involved recirculation of leachate after treatment via an Up-flow Anaerobic Sludge Blanket reactor as an in-situ pre-treatment measure of the leachate. The study revealed that acidification of the leachate in the LFB without production of landfill gas (LFG) during a certain period is possible and that the LFB can be used for the first two steps of anaerobic digestion (i.e. hydrolysis and acidification) and then the remaining step of methanogenesis can be carried out in a separate reactor to produce biogas at a shorter period. The study also showed that biogas production in the reactor with recirculation of leachate strongly increases the total biogas production compared to the reactor with no recirculation of leachate. Overall, this study indicated the feasibility of operation of the LFB with waste characteristics of Tanzania to accelerate the stabilization of organic-rich wastes, enhance LFG production and achieve a degree of leachate treatment.

Keywords: Landfill Bioreactor, anaerobic digestion, leachate, landfill gas

INTRODUCTION AND LITERATURE REVIEW

Landfill bioreactors have been developed in industrialized countries such as the U.S.A, Australia, Japan and some European countries, as a long-term municipal solid waste (MSW) management option. Treatment of leachate and landfill gas emanating from landfilling remains a major environmental concern despite improved techniques (i.e. from controlled dumping to sanitary landfilling) of disposal of solid wastes. Long-term performance of landfill bioreactors (LFB) are yet to be fully understood but the advantages associated to operating landfills as bioreactors include increased potential for waste to energy conversion by optimizing the landfill gas (LFG) generation rate; storage and/or partial treatment of leachate, increased landfill capacity due to enhanced settlement and; reduced waste decomposition time from several decades to 5–10 years thus reduced land use costs (Reinhart et al. 2002).

Studies on LFB have been conducted by some researchers in different parts of the world

*F. Salukele is a Lecturer, Department of Environmental Engineering,, Ardhi University, Dar es Salaam, Tanzania. His contact address is P.O. Box 35176, E-mail: Fredrick.salukele@gmail.com

using characteristics of waste almost similar to that of Tanzania. San and Onay (2001) filled a simulated recirculated landfill reactor with a synthetic mix of Municipal solid waste (MSW) whose characteristics were mostly food waste being 76% on dry basis and initial moisture content of 80%. They researched the impact of various leachate recirculation regimes on waste degradation in landfills and in situ leachate treatment to provide data for successful operation of landfill sites in the Istanbul metropolitan area. The study showed that landfill leachate recirculation is a feasible way for in situ leachate treatment decreasing the cost of further external treatment (San and Onay 2001). Sponza and Ağdağ (2004) evaluated the impact of leachate recirculation and recirculation volume on stabilization of MSW in simulated anaerobic bioreactors. In their study, the waste had a moisture content of 75-86% and organic waste constituting 75-90% of the wet waste. The results showed that despite very high chemical oxygen demand (COD) and volatile fatty acids (VFA) concentrations in leachate an optimum leachate recirculation volume contributes to enhanced COD removal, decreasing VFA, and effective methane gas production. Another study was a pilot-scale experiment on anaerobic bioreactor landfills in China conducted by Jiang et al. (2007) using fresh waste unloaded from daily municipal waste collection trucks with physical properties of 60% moisture content (wet weight basis) and 75% volatile solids (VS, dry basis). Findings from the study by Jiang et al. (2007) showed that leachate recirculation with a high rate can be adopted as an effective in situ pre-treatment approach to remove organic pollutants in leachate and notably ammonia-nitrogen, phosphorus and some persistent organic compounds can be accumulated in the effluent leachate that need further treatment. These promising studies were conducted in regions other than East Africa thus there is limited data on the performance of LFBs in tropical developing countries such as Tanzania. In East Africa no landfills have yet been designed and operated as recirculated landfills or LFBs. It is important to better understand the possibilities of LFBs in situations with waste having a high organic matter and moisture content and a high temperature.

In this study, findings from a comparative study of a pilot scale landfill bioreactor and sanitary landfill are presented. This pilot scale experiment was conducted in Dar es Salaam city, Tanzania, East Africa, to study the effect of recirculation on waste degradation and acidification, landfill gas production, and in situ leachate treatment as the main objective. In order to achieve this objective the following were the specific objectives: (1) study of the variations of the effluent leachate characteristics as an indicator of waste stabilization, (2) evaluate the effects of leachate recirculation on leachate COD removal, (3) evaluate the landfill gas generation rate and composition, (4) monitor the settlement of waste due to the organic matter degradation, (5) investigate the possibility to keep the landfill acidified for a certain period.

MATERIALS AND METHODS

Description of the pilot-scale LFB setup

The pilot setup consists of two reactors without (R1) and with (R2) leachate recirculation. R1 was operated as a control reactor simulating a sanitary landfill and R2 was considered as a simulated landfill bioreactor. The reactors were each built in a concrete structure with a square horizontal cross section of 1m by 1 m and 2.5 m deep to represent a landfill cell. The depth of the cell is in conformity with the landfilling requirements according to the excavated cell method recommended by Tchobanoglous et al. (1993, p. 374) whereby the cell depth should range from 3 to 10 ft (0.9 to 3 m). Practically a landfill site consists of such cells one deposited on top of the other to a height of about 10 to 15 m. Figure 1 illustrates a schematic representation of the experimental setup showing waste in reactors, leachate collection, leachate recirculation system comprised of a storage tank and small diameter leachate inlet pipes, LFG extraction pipes and temperature monitoring ports at different heights. Leachate recirculation pipes were laid in R2 only to recirculate leachate. At the bottom of both reactors, there is an outlet for the generated leachate to be collected. The bottom of the reactor was slightly slanted to direct the generated leachate towards the outlet and at the outlet a wire mesh was placed to prevent the waste from being washed out with the leachate. Installation of LFG extraction pipes was done during the filling of the reactors with waste. Between the waste and the LFG pipes, 25-35 mm granite - gravel media were placed as drainage layers for leachate in downward direction and landfill gas in upward direction. The gravel was held in place by the aid of a PVC casing whereby the LFG pipes were enclosed between the casing and gravel. After the casing was fully surrounded with waste it was removed to leave the gravel in contact with the waste while shielding the LFG extraction pipes from direct contact with the waste. The waste was capped by compacted clay soil in which the leachate distribution system was laid with leachate inlet pipe running approximately 100 mm into the waste.

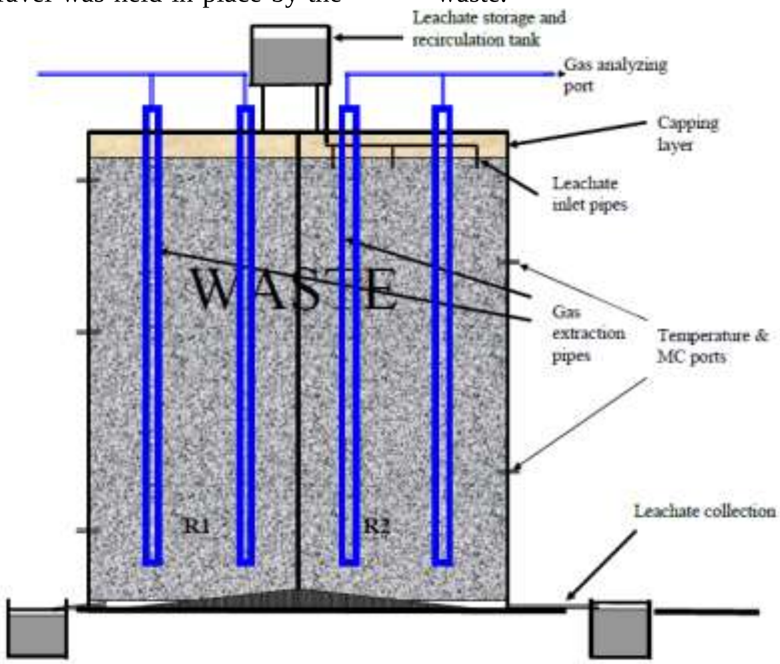

Figure 1: Schematic representation of the pilot scale LFB

Loading and operation protocol

Each of the reactors were simultaneously filled with about 2.3 tons of wet waste of moisture content about 64% collected for several days from municipal waste transfer stations in Mwenge area in Kinondoni municipality, Dar es Salaam city. The collected waste was predominantly food waste (about 60%) and was sorted to remove glass, metals, plastics and any other non-biodegradable materials. The relatively high proportion of organic waste is considered to be characteristic of MSW in Tanzania, as well as several other developing countries (San and Onay 2001; Sponza and Ağdağ 2004; Mbuligwe et al. 2002; Kassim and Ali 2006; Jiang et al. 2007). The sorted waste was loaded into the reactors and compacted manually using a sledge hammer to a density of nearly 900 ton/m^3. Table 1 shows the loading protocol of the LFBs. Leachate from R1 was collected and samples for measurement were drawn but not included in the recirculation leachate. After drawing samples for measurement, all the remaining leachate from R2 was manually transferred to the storage tank at the top of the reactors and allowed to flow back into R2.

Table 1: Loading protocol of the landfill bioreactors

	Reactor without Recirculation R1	Reactor with Recirculation R2
Quantity of waste (kg)	2394	2342
Recirculation	Without	With
Recirculation rate (mm/day)	-	13 (average)
Moisture content (%)	64.07	64.38
Operation time (day)	378	365

Initially the waste was kept in a static state for five days before recirculation of leachate began in R2 at an average rate of 13 mm/day. At this rate the hydraulic retention time of recirculated leachate in R2 would be 230 days if plug flow would be assumed. The actual hydraulic retention time of the recirculated liquid is not known but probably less with possible short circuiting taking place.

Throughout the study of 52 weeks R1 was run as a flow-through system. The study with R2 was broken into two phases. During phase one the leachate was recirculated directly to the top of the reactor. COD, pH, temperature, conductivity, nutrients, volume of leachate generated, waste settlement and gas production were monitored frequently. After 120 days of leachate recirculation in R2 the pH was observed to be too low for methanogenesis. Then phase two of the study began which involved recirculation of leachate after treatment via an Up-flow Anaerobic Sludge Blanket (UASB) reactor as an in-situ pre-treatment measure of the leachate. The UASB reactor used was a 15.7 litre PVC reactor of 2 m height, 0.1 m diameter, hydraulic retention time of 1.15 days, filled with 6.75 L anaerobic sludge obtained from an existing UASB reactor whose sludge age is more than 5 years with a specific methanogenic activity of about 0.17 g COD/gVSS/day. Monitoring of the same parameters as for phase one were continued to be monitored for both R1 and R2. Figure 2 depicts the flow diagram showing the pilot scale experiment during the two phases and the two distinct regimes of leachate flow of R2.

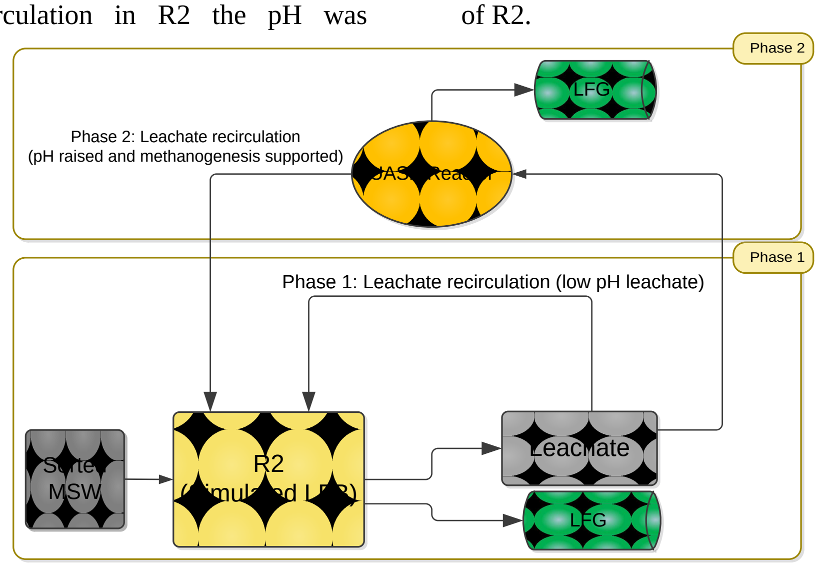

Figure 2: Flow diagram phase 1 and 2 of R2 (simulated LFB)

Analytical procedures

Temperature of the waste in the reactors was monitored weekly using Hanna Instruments Inc. 16.34 K-thermocouple thermometer with built-in microprocessor that has temperature probes specially designed to measure the temperature in compost. The probe was inserted into the reactor through the temperature/moisture content sampling ports and left for half a minute before readings were recorded. The ambient temperature was measured by a simple thermometer near and around the reactor. The temperature readings were all taken daily at 10:00 am throughout the operation time of the reactor.

pH of the leachate was determined daily for 13 weeks and thereafter weekly for 39 weeks making up a total of 52 weeks. pH was measured using SensIon pH meter model 156 Hach.

Leachate was analyzed for COD, Nitrogen-Ammonium and Phosphates. COD was analyzed using the dichromate method. Before analysis the samples were filtered with 4.4 µm folded paper filter (Schleicher & Schuell 595½). Phosphates and Nitrogen-Ammonium, were analyzed by spectrophotometry following the procedures as described in the Standard Methods (APHA 2005).

Samples for moisture content analysis of the incoming waste were taken during filling of the reactors and from the already filled waste, samples were taken after every four weeks for first three months of the study. In order to determine the moisture content the collected waste sample was weighed and oven dried at 103-105 ^{o}C after which the dried sample was weighed for quantification of evaporated water content.

The volume of gas generated was measured by displacement method. One inverted bottle filled with water was connected to the reactor via a 5 mm plastic pipe while another bottle received displaced water due to gas being bubbled into the inverted bottle. The volume of water displaced was measured and represented the volume of gas bubbled.

The gas composition methane and carbon dioxide (CH_4 and CO_2) was measured by using the inverted serum bottle liquid displacement technique. The displaced liquid was a strong 15% sodium hydroxide (NaOH) solution. A syringe was used to take a sample of biogas and injected into the serum bottle and as the biogas passed through the solution, the CO_2 was converted to carbonate and absorbed into the liquid. The CH_4 passes through the solution and an equivalent volume was pushed out of the top serum bottle. The displaced liquid was measured as the volume of CH_4 present in the biogas under the assumption that 1 ml CH_4 displaces 1 ml NaOH solution.

Results and discussion

COD concentration variations in leachate produced from the reactors

The COD concentrations of the leachate collected at the bottom of the reactors as function of the time of stabilization are as shown in Figure 3. The COD concentrations of leachate in both R1 (control) and R2 (simulated LFB) were observed to increase from the initial 49,800 mg/l and 60,600 mg/l to 151,200 mg/l and 79,800 mg/l, respectively through the first 6 weeks.

The COD of R1 remained between 140,000 mg/l and 160,000 mg/l for 18 weeks in the 6th until the 24th week and began to fall to about 29,000 mg/l in the 33rd week and from there the COD was at an average of 30,000 mg/l. The COD concentration pattern of the leachate exhibited by R1 was somewhat different from what is theoretically expected of a sanitary landfill. In the aerobic phase in the beginning of the experiments the COD concentration is expected to rise but this aerobic phase only lasts a few days as the oxygen is depleted. Then, the waste becomes anaerobic and moves into the acidic phase and supports hydrolytic and fermentative reactions resulting in carboxylic acids and alcohols. During this phase the highest COD concentration is expected and as the acetogenic bacteria begin to convert these acids and alcohols to acetate, hydrogen, and carbon dioxide the COD is expected to begin to drop. However, the COD concentration of R1 took longer than expected to begin to drop as the phase was changing from aerobic to acidic and fermentation phase.

For R2 with recirculation, the COD concentration exhibited a pattern that conforms much more with the theoretical expectations. After the initial rise to 79,800 mg/l in the early phases of degradation, acids accumulated, pH dropped and remained low (as shown in later subsections of this section) and the COD concentration rose as high as 143,200 mg/l in the 16th week. At this point the reactor has become thoroughly acidified with a leachate pH so low that it inhibited methane production. A UASB reactor filled with anaerobic sludge was introduced to produce biogas from the already acidified leachate and to pre-treat the leachate before recirculation. From there on, the COD concentrations began to drop until levels as low as 8,500 mg/l in the 52nd week because of biogas production from the volatile fatty acids in the leachate. However, separate effects of the UASB on the COD concentrations of the recirculated liquid were not established because only the leachate collected at the bottom of R2 was monitored The findings from this study exhibited COD concentration patterns similar to the studies by San and Onay (2001) and Sponza and Ağdağ (2004) and Jiang et al.(2007).

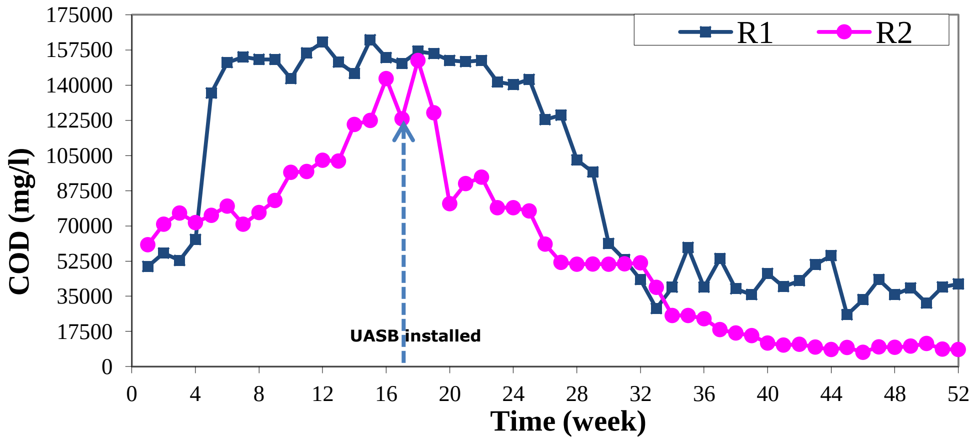

Figure 3: COD concentrations in leachate of R1 (control) and R2 (simulated LFB) as a function of time

pH variation in leachate

The pH in the leachates of R1 and R2 as a function of time is presented in Figure 4. The initial pH in the leachate from R1 was 7.1. The pH value decreased for the first three weeks which was expected but then rose to 8.5 in the 10th week. The observation we have not been able to explain. Then a drop of pH to 5.2 by 15th week occurred probably due to imbalance of acidification and methanogenesis in the reactor. After the drop, the pH began to increase gradually and stabilized between 8.0 and 8.1 in the 46th week and onwards indicating utilization of VFA. The pH trend exhibited by R1 was typical for sanitary landfill leachate which was also observed by Jiang et al. (2007). An exception was the period between the 4th and 10th week with a temporary rather high pH value above 8.0.

The initial pH in the leachate from R2 was almost neutral at 7.2 as it was for R1. The pH values then decreased sharply to 5.5 until the 3rd week. The pH then maintained within a slightly acidic range of 5.2 and 5.6 for 18 weeks. pH in the acidic range is detrimental to methanogenic activity. Such low pH values could be attributed to the production of low alkalinity, which is not enough for maintaining the neutral pH and buffering the VFA produced (Sponza and Ağdağ 2004). The low pH was presumably due to a constant dissolution and accumulation of VFA suggesting that acidogenic bacteria were governing the system (Veeken et al. 2000; Dinamarca et al. 2003; Valencia 2008). After introduction of the UASB reactor in week 17 the acids in the leachate were converted to methane in the UASB reactor and the resulting pH of the leachate began to increase to 7.3-7.7. The values were above neutral from the 32nd week onwards. Note that such pH conditions would then start favoring methanogenesis in the reactor now considered as a representative section of a cell would no longer be used for acidification purposes but rather for in-situ production of LFG.

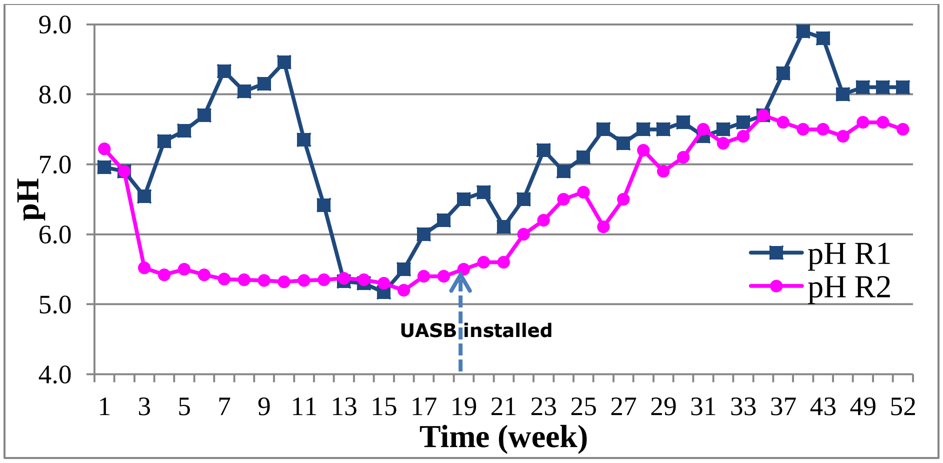

Figure 4: pH variations of the leachate in R1 and R2

Both R1 and R2 began with almost the same neutral pH and in the initial three weeks pH in both reactors dropped indicating the beginning of the acidic phase. As the degradation and low rate biogas production took place the pH of leachate from R1 began to rise while that of R2 maintained a low level in the acidic region and no gas was being produced. The pH of R1 due to acidification of the waste as a result of anaerobic condition, the pH dropped into the acidic region to values the same as that of R2. The pH of R1 once again began to rise as was for R2 but the latter was due to the introduction of the UASB reactor coupled with recirculation of leachate. The pH in both reactors rose to above neutral and within the conditions favorable to methanogenesis.

Nutrients variation in the leachate

The ammonia-nitrogen (NH_3-N) concentration found in the leachate of R1 and R2 as a function of time is given in Figure 5. The initial concentrations were found to be 324 mg/l and 432 mg/l for R1 and R2 respectively as a result of decomposition and leaching of organic nitrogen. The initial concentrations were more or less the same but due to heterogeneity of the conditions in the waste there was a difference in the concentration despite both reactors being loaded simultaneously with almost the same mixture of waste. As a result of the decomposition, ammonia nitrogen concentrations in the leachate from R1 and R2 increased from the initial values of about 400 mg/l to a maximum of 538 and 1230 mg/l after 19 and 16 weeks of the study period respectively. The observed higher concentration in R2 is attributed to the recirculation of leachate which reintroduced ammonia back to the system and thus resulted in accumulation. Due to the fact that 100% of the collected leachate was recirculated, all the available nutrients in the leachate were contained and recirculated within the reactor.

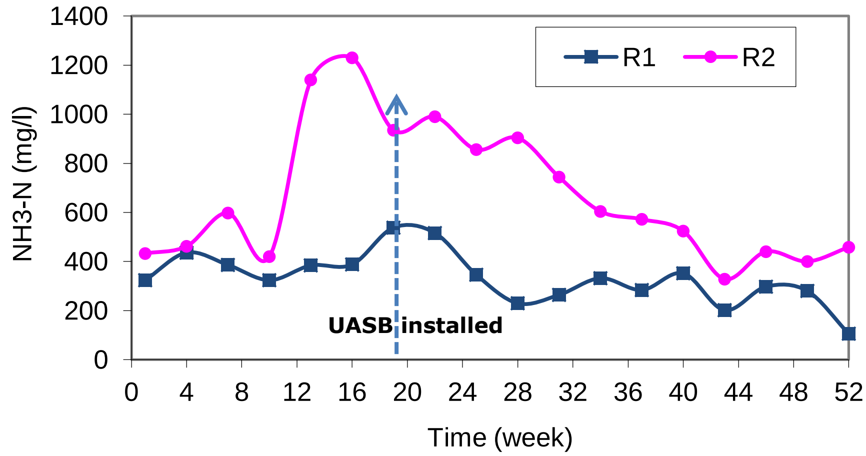

Figure 5: Ammonia-nitrogen variations in R1 and R2

After the 22nd week, the concentration of NH_3-N in the leachate in R1 began to decrease and reached 106 mg/l after the 52nd week due to possible depletion of nitrogenous organic matter in the waste. Similarly in R2, NH_3-N concentrations which were as high as 1,230 mg/l began to decrease in the 19th week that is after the introduction of the UASB reactor and remained at levels above 450 mg/l through to the 52 weeks of the study period. A gradual increase was expected but the NH_3-N concentrations dropped and continued to drop. The reason of the downward trend after the 18th week in R2 is not clear, but a similar trend of decrease in concentration was observed by San and Onay (2001) and Sponza and Ağdağ (2004) whereby both studies had different recirculation rates and in some cases addition of water was done. It can be said that in landfills, the release of soluble nitrogen from solid waste into landfill leachate continues over a long period (Sponza and Ağdağ 2004). Leachate ammonia-nitrogen is a significant long term pollution problem that may cause inhibition of methanogenesis and may greatly determine when post-closure care of a landfill may be ended or reduced. This was also noted by Kjeldsen et al. (2002) and Berge et al. (2007).

Phosphorus occurs in wastewaters almost exclusively as phosphates (PO_4). Figure 6 shows the variations of the phosphate concentration in the leachate with time. The concentration of phosphates in the leachate of both reactors was more or less the same during the first 16 weeks. With the introduction of the UASB reactor to pre-treat leachate from R2 before recirculation, the phosphates concentration in the R2 leachate began to increase. This increase is mainly due to the recirculation of leachate which introduces back the phosphates that had already been released from the UASB reactor thus causing accumulation and further release of bound phosphorus. After the 16th week, while the concentration in R1 remained unchanged, the concentration in R2 increased which could be in part explained by the accumulation of phosphate due to recirculation. In the 40th week the concentration gradually began to drop as the pH was increasing to above 7.5 and phosphates were removed from the liquid phase by precipitation.

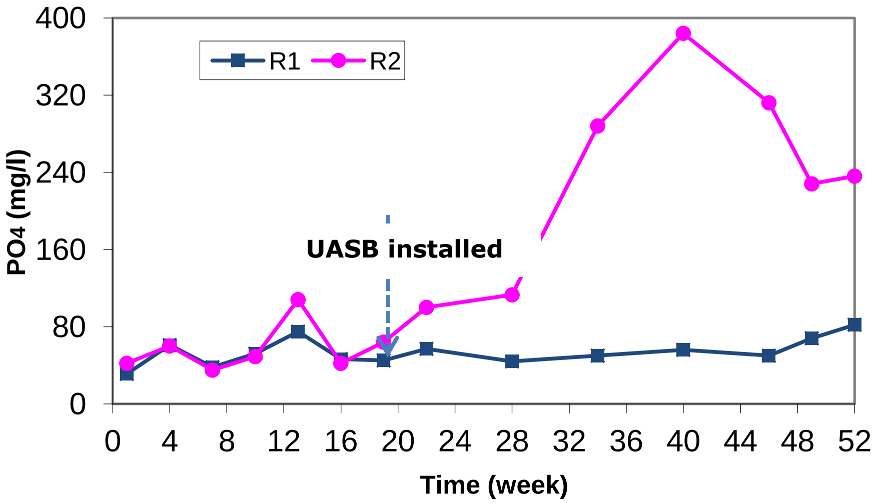

Figure 6: Phosphate variations in the leachate from R1 and R2

Temperature variation of the reactors

Variation of temperature of leachate from the reactors is shown in Figure 7. Both reactors exhibited a more or less a similar pattern. For both reactors R1 and R2, temperature initially increased to between 28 °C and 29 °C after 13 weeks of operation which indicated that the some heat was also being generated by the metabolism of microbes. As for R2, the temperature continued to rise and reached values between 36 °C and 37 °C (temperature optimum for methanogenesis) in the 34th to 40th week. The increase in temperature is probably due most importantly to the heat of the recirculated leachate. This heating is brought about by insolation of the exposed leachate storage and the UASB reactor during day time. However, during the 49th – 52nd week, the temperature in R2 was remarkably high despite the fact that the conversion was lower than during the previous weeks.

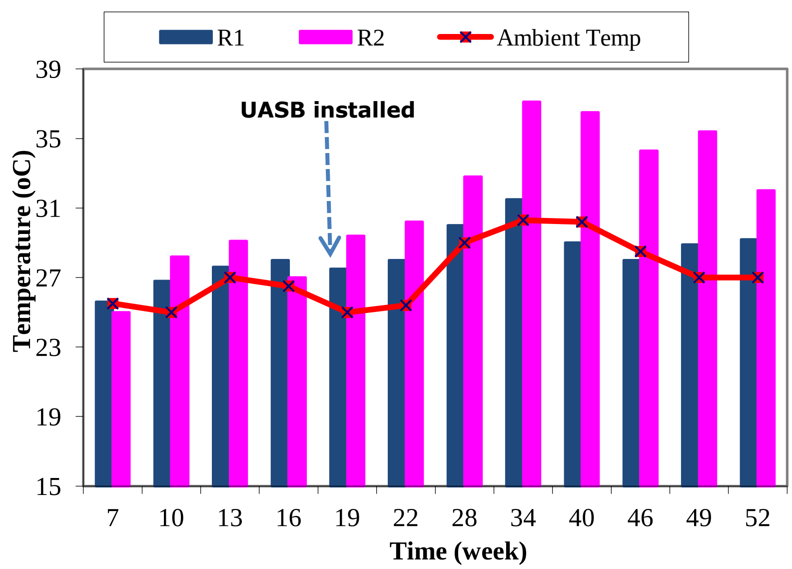

Figure 7: Temperature variation in the reactors and ambient temperature

LFG generation

The cumulative landfill gas (LFG) generation of reactor R2 is presented in Figure 8. R1 began to generate LFG after 4-5 weeks while there was a lag in R2 which began to produce LFG after the 26th week of reactor operation. The generation of LFG in R1 was at a relatively low rate. The lag of LFG generation in R2 was mainly due to prolonged acidification of the reactor by recirculation of acidified leachate. This resulted in a pH below 6 (see Figure 4).

After the 16th week the introduction of the UASB reactor for in-situ treatment of leachate from R2 brought about biogas generation via the UASB reactor. With the treatment of leachate, the pH of the leachate changed from acidic to near neutral. On the 26th week with the introduction of the UASB reactor, biogas began to be generated at an average rate of 15 l/day as depicted in Figure 8. After 52 weeks of operation of the UASB reactor coupled to R2, this LFB produced cumulatively 12 m^3 of biogas and R1 about 0.15 m^3. It should be noted that, the low volumes of gas generated from the UASB coupled to R2, may be due to problems of inadequate sealing of the reactors to avoid losses or leakages.

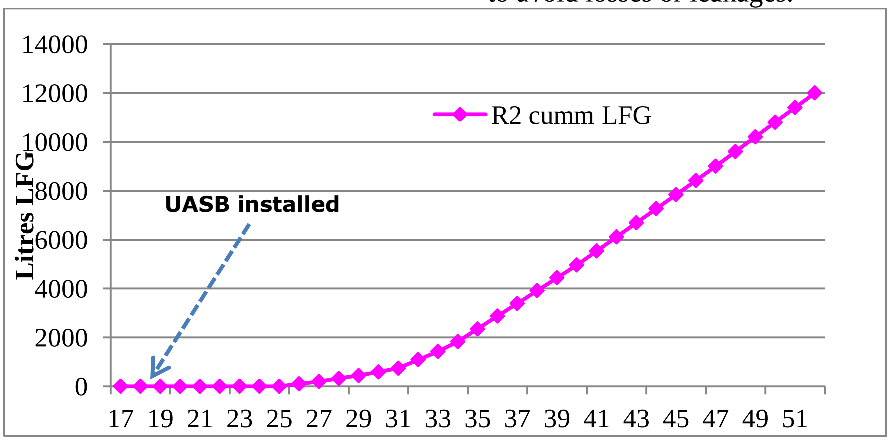

Figure 8: Cumulative LFG volume from UASB reactor coupled to R2 (simulated LFB**)**

Methane percentages for several LFG samples are shown in Figure 9. The gas samples were taken after every 10 weeks of operation. The analysis shows that the typical composition of LFG was in the range of CH_4 35-46% for R1 and 48-55% v/v for R2, with an annual average of 42% and 51% v/v for R1 and R2 respectively.

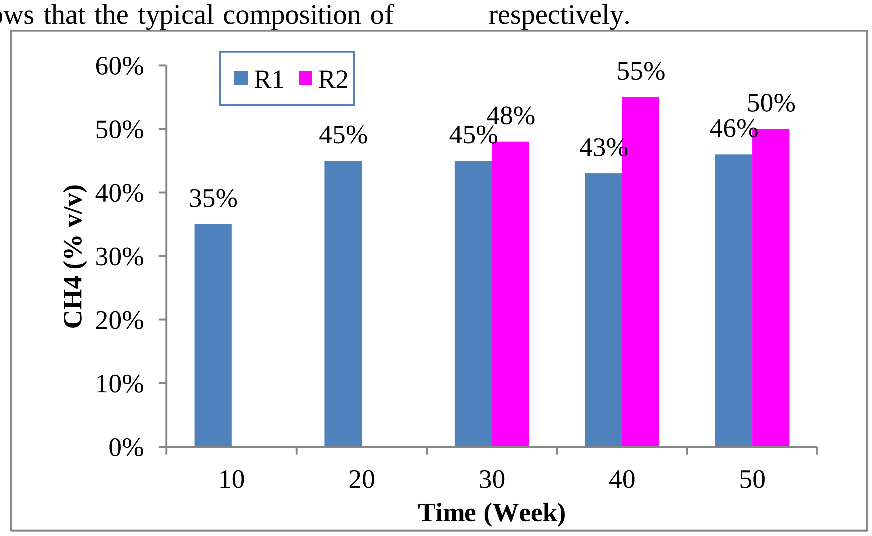

Figure 9: Methane percentages of several LFG samples

Waste settlement and volume reduction

Settlement patterns observed for the reactors are illustrated in Figure 10. Initially, the settlement rate of the waste for the first three months in R1 and R2 was 0.75 cm/week and 1.59 cm/week respectively. Gradually the settlement rate dropped and no further settlement was observed after the ninth month of operation.

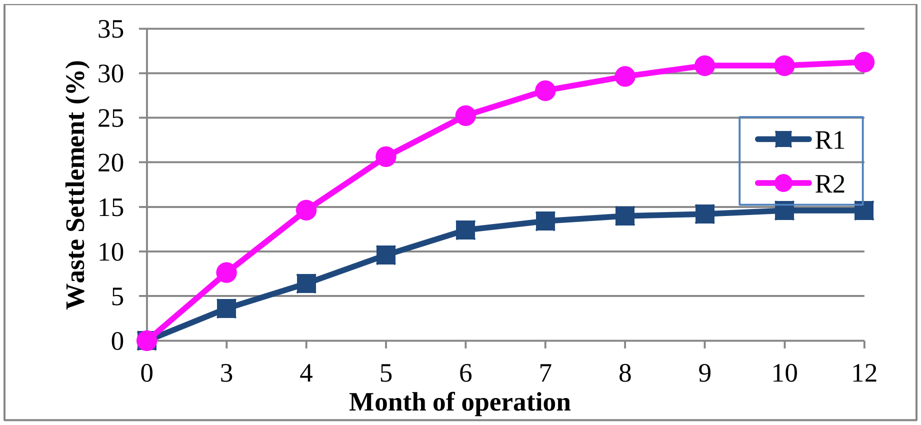

Figure 10: Settlement of the deposited waste with time

After one year of operation a total reduction in waste volume of 14.6 % in R1 and 31.2 % in R2 was observed. Waste settlement is a function of factors such as thickness and weight of cover and compaction, waste density and composition (particularly moisture), climate, etc. (Zhao et al. 2002). Settlement of waste in LFBs is a result of reduction in void space and compression of loose material due to overburden weight, volume changes due to biological and chemical reactions and dissolution of waste matter by leachate, movement of smaller particles into larger voids and settlement of underlying soils (McBean et al. 1995; Reinhart and Townsend 1998). In this study, availability of void spaces was limited by the compaction that was done during filling the reactors and due to leachate drainage. Settlement is also a result of the decrease of the remaining solids in the waste mass caused by degradation. COD reduction in the leachate is an indicator of the advanced degradation of the waste taking place in the reactor. The settlement of waste provides an opportunity to utilize valuable air space prior to closure of the cell thus extending the life span of the entire landfill site.

Leachate generation

The leachate produced in the reactors as mentioned in section 2.1 was collected once a week from the bottom of each reactor and the volume was measured. Figure 11 presents the amount of leachate collected per week from each reactor during the entire period of study. The amount of leachate production per week from R1 reached a maximum in the second week operation and decreased afterwards as expected in a sanitary landfill where leachate production will be high in the beginning and the volume will gradually decrease until eventually no leachate was produced anymore. This point was reached after about 45 weeks. It may be assumed that at this point the field capacity of waste would have been reached. The cumulative amount of leachate collected from R1 throughout the study period added up to 702.15 litres from an initial amount of waste of 2394 kg wet waste. This figure means that the leachate production amounted to 293 l/ton of wet waste starting from an initial water content of 640 l/ton. Neglecting rainfall having entered the reactor and the mass reduction of waste due to degradation, the moisture content of the waste after about one year equals 640-293= 347 l/ton or 34.7%. This is within the 30 – 50% range of field capacity values of landfilled waste presented in the literature.

In reactor 2 leachate production comprised the original leachate production that was also found in R1 and the recirculated leachate which may also influence the original amount of leachate produced. The latter amounted to a constant 91 l/week. The observed leachate production in R2 initially increased to about 110 l/week, then decreased and increased again to reach a level that varied between about 90 and 105 l/week after about 20 weeks. The decrease to a level of less than 80 litre/week during the period week 6 – 8 could not be explained but possibly clogging of the leachate collection system was the reason. Finally, after about 37 weeks a stable level of around 90 l/week was reached. This amount corresponded to the amount of recirculated leachate. From the leachate production figure R2 can be concluded that the recirculated leachate had reached the bottom of the reactor after about 2 weeks.

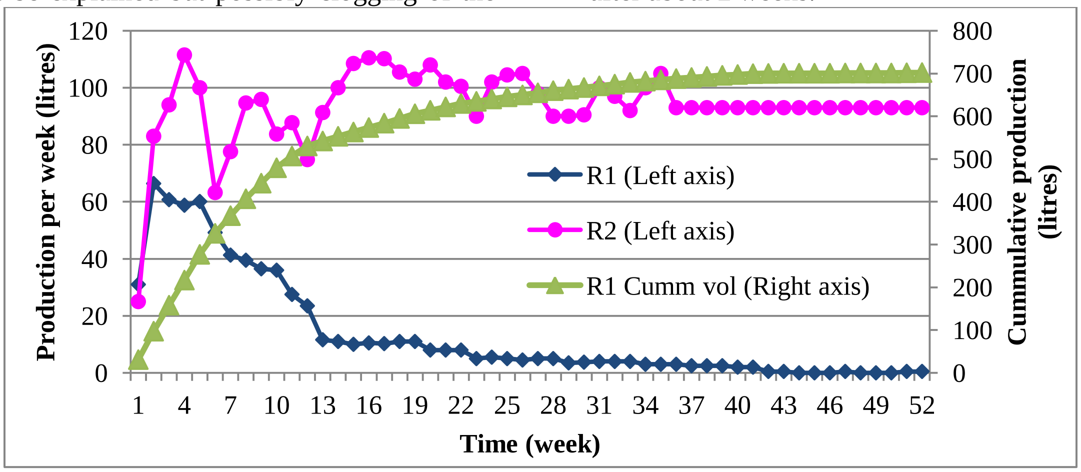

Figure 11: Leachate production in R1 (control) and R2 (simulated LFB) as function of time

CONCLUSIONS

The objective of this study was to identify the impact of leachate recirculation on waste degradation, methane production, and in situ leachate treatment, and to provide insights for the successful operation of LFBs in developing countries. The main results of this study indicate the validity and feasibility of operation of the LFB with waste characteristics of East Africa to accelerate the stabilization of organic-rich wastes, enhance LFG production and achieve a good degree of leachate treatment. Based upon results obtained during the study, the following specific conclusions are drawn:

1. The study confirms the literature with respect to the feasibility of the operation of a landfill as a controlled anaerobic bioreactor with leachate recirculation.
2. Leachate recirculation enhanced waste stabilization as reflected in higher gas production in R2 (simulated LFB) than in R1 (control) and more waste settlement.
3. Controlled acidification of the leachate is possible. The lesson learnt from the extended acidification of leachate in R2 and introduction of the UASB reactor can be taken as positive evidence that the LFB can be used for the first two steps of anaerobic digestion (i.e. hydrolysis and acidification) and the remaining step of methanogenesis can be carried out in a separate reactor.
4. In practice, this two stage approach of extended acidification means that no biogas is generated within the landfill so that there is no loss of methane from the landfill. Accordingly the two-stage process may result in a lower overall loss of biogas to the atmosphere.
5. Management of nutrients (N and P) requires attention because neither degradation nor removal of these parameters was observed in both R1 (control) reactor and R2 (simulated LFB).
6. The results obtained from this study come from a pilot-scale experiment. To confirm these results more experiments and probably a full-scale study are necessary to elucidate more precisely the LFB phenomenon.
7. The results obtained in this study are in general in agreement with results mentioned in literature for comparable experiments.

ACKNOWLEDGEMENT

This study is part of a larger interdisciplinary programme – Partnership for Research On Viable Infrastructure Development in East Africa (PROVIDE) project with a long term objective to help realize the Millennium Development Goals (particularly MDG7) by improving the sanitation and solid waste management in Tanzania, Kenya and Uganda funded by Interdisciplinary Research Fund (INREF). I wish to acknowledge Prof. dr. ir. W. H. Rulkens, Professor of Environmental Technology and Dr. ir. J. C. L. van Buuren, Assistant Professor, both from Sub-department of Environmental Technology, Wageningen University for their supervision and guidance during the entire study. Furthermore, I extend my gratitude to Mr. R. Mbulume of Ardhi University Environmental Engineering laboratory who provided technical assistance during the daily and weekly collection of data.

REFERENCES

Apha, (2005). *Standard methods: For the examination of water and wastewater*. Edited by A. D. Eaton, L. S. Clesceri, E. W. Rice and A. E. Greenberg. 21st ed. Washington D.C.: American Public Health Association, American Water Works Association, Water Environment Federation.

Berge, N. D., D. R. Reinhart, J. D. Dietz, and T. Townsend. (2007). The impact of temperature and gas-phase oxygen on kinetics of in situ ammonia removal in bioreactor landfill leachate. *Water Research* 41 (9):1907-1914.

Dinamarca, S., G. Aroca, R. Chamy, and L. Guerrero. (2003). The influence of pH in the hydrolytic stage of anaerobic digestion of the organic fraction of urban solid waste. *Water Sci Technol* 48 (6):249-54.

Jiang, J., G. Yang, Z. Deng, Y. Huang, Z. Huang, X. Feng, S. Zhou, and C. Zhang. (2007). Pilot-scale experiment on anaerobic bioreactor landfills in China. *Waste Management* 27 (7):893-901.

Kassim, S. M., and M. Ali. (2006). Solid waste collection by the private sector: Households' perspective--Findings from a study in Dar es Salaam city, Tanzania. *Habitat International* 30 (4):769.

Kjeldsen, Peter, Morton A. Barlaz, Alix P. Rooker, Anders Baun, Anna Ledin, and Thomas H. Christensen. (2002). Present and Long-Term Composition of MSW Landfill Leachate: A Review. *Critical Reviews in Environmental Science and Technology,* 32 (4):297-336.

Mbuligwe, S. E., G. R. Kassenga, M. E. Kaseva, and E. J. Chaggu. (2002). Potential and constraints of composting domestic solid waste in developing countries: findings from a pilot study in Dar es Salaam, Tanzania. *Resources Conservation and Recycling* 36 (1):45-59.

McBean, E.A., F.A. Rovers, and G.J. Farquhar. (1995). *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall.

Reinhart, D, and T. Townsend. (1998). *Landfill bioreactor design and operation*. New York: Lewis Publishers.

Reinhart, D. R. , P. T. McCreanor, and T. Townsend. (2002). The bioreactor landfill: Its status and future. *Waste Management and Research* 20:172–186.

San, I., and T. T. Onay. (2001). Impact of various leachate recirculation regimes on municipal solid waste degradation. *Journal of Hazardous Materials* 87 (1-3):259-271.

Sponza, D. T., and O. N. Ağdağ. (2004). Impact of leachate recirculation and recirculation volume on stabilization of municipal solid wastes in simulated anaerobic bioreactors. *Process Biochemistry* 39 (12):2157-2165.

Tchobanoglous, G., H. Theisen, and S. Vigil. (1993). *Integrated solid waste management: Engineering principles and management issues*. International ed. Boston, USA: McGraw-Hill.

Valencia, R. V. (2008). Enhanced stabilization of municipal solid waste in bioreactor landfills, UNESCO-IHE Institute for Water Education, Technical University, Delft, The Netherlands.

Veeken, A., S. Kalyuzhnyi, H. Scharff, and B. Hamelers. (2000). Effect of pH and VFA on hydrolysis of organic solid waste. *Journal of Environmental Engineering-Asce* 126 (12):1076-1081.

Zhao, Y. C., L. C., Wang, R. H., Hua, D. M. Xu, and G. W. Gu. (2002). A comparison of refuse attenuation in laboratory and field scale lysimeters. *Waste Management* 22 (1):29-35.