

**Effect of Leachate Blending on Anaerobic Digestion of Organic Fraction of
Municipal Solid Waste**

By

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Abstract

Anaerobic digestion of the Organic Fraction of Municipal Solid Waste (OFMSW) generates a mixture of methane (CH₄), carbon dioxide (CO₂) and water (H₂O). Beyond the field capacity the water generated is collected and recirculated as leachate in Bioreactor Landfills (BLs.) Leachate recirculation has a profound advantage on biodegradation of the Organic Fraction of Municipal Solid Waste (OFMSW) in the landfills. Mature leachate from older sections of landfills (>20 years) and young leachate were blended prior to recirculation in the ratios 3/3 mature, 3/3 young, 1/3 mature-2/3 young and 2/3 old-1/3 young and their effect on biodegradation and biogas production monitored. In addition to analysis of the effect of blending old and new leachates, the study also analyses the effect of an open vs. a closed recirculation loop and the effect of organic loading rates of OFMSW in landfills. Data collected from initial batch tests supplement column bioreactors simulating bioreactor landfills with real world OFMSW from operational landfill facilities in Ontario, Canada. The results are conclusive that the biogas generation can be improved by up to 92% by blending the leachate in an open loop recirculation system as compared to a conventional closed loop system employed in landfills today.

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Chapter 1: Introduction

1.1 Background

The generation of Municipal Solid Waste (MSW) has been increasing due to economic development and rise in population. This increase has demanded organized and comprehensive waste management programs to prevent improper waste handling methods and their environmental consequences, generally known as Integrated Solid Waste Management (ISWM) programs. ISWM evaluates waste management activities including waste prevention, recycling and disposal (Kreith and Tchobanoglous, 2002). Despite increase in recycling and composting, considerable portions of generated MSW have to be disposed of in either landfills or incinerators.

Incinerators convert the organic content into carbon dioxide directly eliminating the production of methane. However, the process of incineration produces carcinogenic toxins such as dioxins and furans. Then there is the problem of air pollution with the emanation of oxides of nitrogen and sulphur, Volatile Organic Compounds (VOCs) and carbon monoxide. For this reason, disposal of MSW by incineration is banned in many parts of the world

(USEPA 2011). Due to these reasons, landfilling continues to be the major component of MSW management in most countries globally which are not constrained for land area. Being the second largest country in the world, Canada mainly utilizes landfills as the solid waste disposal method.

Landfills have evolved from 'open dumps' to the modern day regulated bioreactor landfill since the problems associated with open dumps were profound. The initial problems were associated with odour, spread of diseases and the risk of explosions (Pohland, 1996). The open dumps carried a high risk of explosion due to the methane content and were substituted by the covered dumps. Landfills were covered with a variety of materials, mainly clay.

Following the Resource Conservation and Recovery Act (RCRA) act of 1976 in the United States, all the landfills had to be converted into regulated landfills where the leachate and gas production had to be minimized and controlled in addition to using liners to prevent groundwater contamination. Leachate had to be collected to prevent contamination of groundwater (Themelis and Ullola, 2003). This also meant that the leachate had to be treated to reduce the COD to effluent standards. Hence, diluting through wastewater streams would not solve the problem anymore. This put more emphasis on treating the leachate prior to discharge from the landfill facility. This was due to the 2% rule, whereby the net discharge of leachate from landfills cannot be greater than 2% of the process throughput of the wastewater treatment facility. The main concerns are high concentrations of COD, ammonia, phosphorus and heavy metals. With emerging environmental concerns and the ever increasing need for

energy, modern landfills strive to harness the full methane potential of the solid waste in bioreactor landfills.

1.2 Shift towards Bioreactor Landfills

Organic Fraction of Municipal Solid Waste (OFMSW) is mainly the waste contained in kitchen waste and yard waste which contain organic content from which gas and energy can be tapped and utilized. This portion of the landfilled waste could anaerobically be biodegraded to produce methane which has high energy content and also has a Green House Gas (GHG) potential that is 21 times that of carbon dioxide. This makes it very important to collect and utilize the methane generated for energy generation.

Anaerobic digestion of the OFMSW generates a mixture of methane (CH_4), carbon dioxide (CO_2) and water (H_2O). The methane generated from the waste is of significance, since this is utilized to generate energy. Methane constitutes to anywhere from 40%-60% of landfill gas generated. The methane generated needs to be produced as quickly as possible and at a higher generation for efficient utilization (Townsend and Reinhart, 1996). The potential of energy generation from methane is very high. Canada is one of the largest per capita emitters of greenhouse gas, generating nearly 720 megatonnes (Mt) carbon dioxide equivalents (CO_2e), or per capita emissions of 23.2 t CO_2e . The solid waste sector in Canada alone generated

around 25Mt CO₂e in 2001, of which 23Mt CO₂e were produced by LandFill Gas (LFG) (Mohareb et al., 2008).

In order to utilize the potential of the energy that could be utilized and by understanding of landfill decomposition processes, a shift in the philosophy of landfill design from the storage concept towards a process-based (or bioreactor) approach was inevitable in the recent decades. The concept of bioreactor was first introduced by Pohland in the late 1970's.

Pohland et al. (1996) in their bioreactor approach suggested that leachate recirculation could reduce the time required for biodegradation of OFMSW or organic wastes in landfills by maintaining optimum moisture. Further studies and pilot scale tests revealed that leachate recirculation also has some other advantages which include pH buffering, improving distribution of nutrients and inoculums in the waste matrix, dissolving metabolites and diluting inhibitory compounds (Reinhart, 1996; Reinhart and Al-Yousfi, 1996; Townsend et al., 1996; Pohland and Kim, 1999; San and Onay, 2001; Mehta et al., 2002; Bilgili et al., 2007; Filipkowska, 2008; Benbelkacem et al., 2010).

The research on landfill leachate treatment and management is an emerging field with many studies aimed at recirculation of leachate within the landfill for improving the rate of biodegradation of the waste. The focus from the conception of the Bioreactor LandFills (BLFs) has always been on improving the generation rate and generation of methane by modifying the operational parameters of the BLFs. Much importance has been given to

leachate recirculation in the bioreactor landfills such as the rate of recirculation and modifying leachate characteristics.

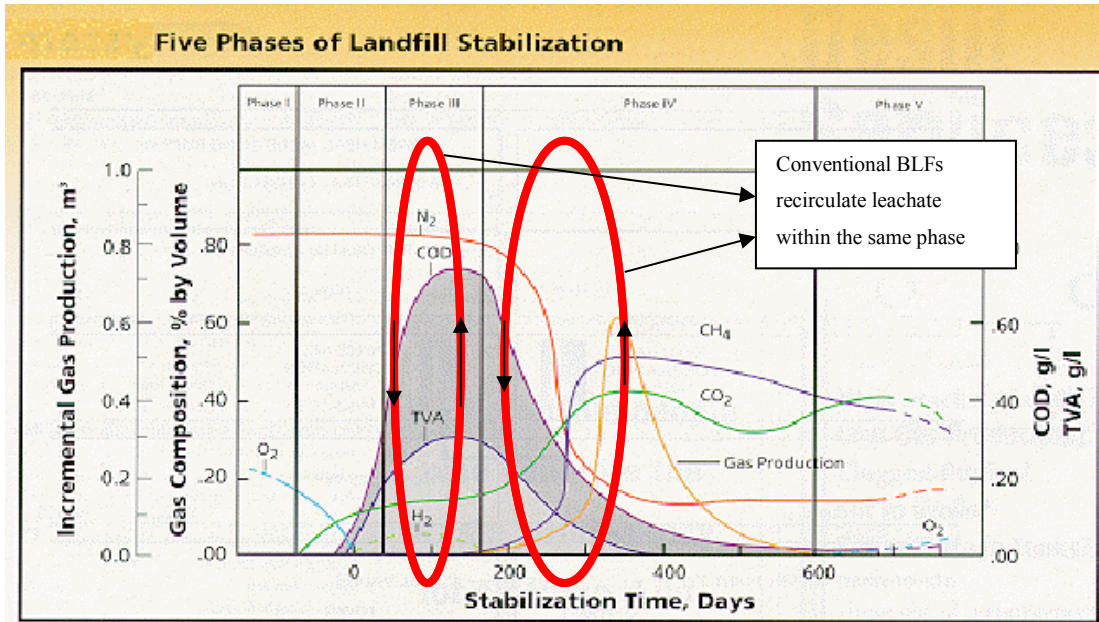
Leachate properties vary greatly with the age of a landfill and also with the type of waste in that landfill. The leachates from fresh OFMSW of young landfills (following a few months after landfilling), have high concentrations of short chain Volatile Fatty Acids (VFAs) inside the landfill. While these are the substrate for methanogenic bacteria, if the concentrations are high, they have a detrimental effect on methanogenesis (generation of methane). This is because it lowers the pH of the leachate due to high acidity. The leachates from older landfills that usually contain cells with stabilized OFMSW have much lower VFAs concentrations which are reflected in terms of the pH of the leachate which is in the basic range.

1.3 Objectives

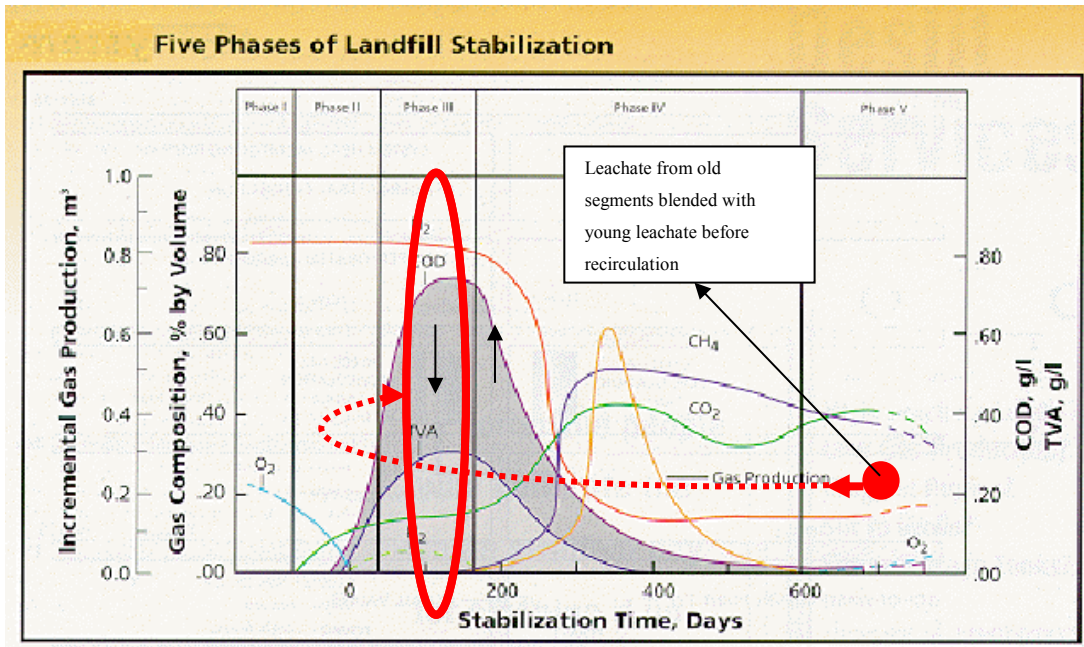
Treating the landfill leachate and recirculating it, has gained much importance over the years. The main underlying target has always been to utilize this waste liquid to enhance the process and to increase the total production of biogas and increase the rate at which it is generated.

Conventional BLFs recirculate the leachate from the same age of the landfill as the OFMSW thereby utilizing the leachate as only a transport media and to provide extra moisture and nutrient distribution. By staging the leachate, i.e using leachate from different ages of the landfill and recirculating through fresh OFMSW, the leachate properties would be enhanced.

The phases in a landfill and recirculation schemes adopted are illustrated in Figure 1.1 and 1.2.



1-1 Leachate recirculation in conventional BLFs (figure adapted and modified from Pohland and Harper, 1993)



1-2 Enhanced BLF with leachate staging (Figure adapted and modified from Pohland and Harper, 1993)

Since their conception, BLFs have always focused on enhancing the rate and generation of methane generation by means of leachate recirculation. The main benchmark of landfill performance has been the methane generation; the total biogas generation and the methanogenic phase duration (Reinhart and Pohland, 2006). The main objective of this research is to further shorten the time taken for the methanogens to start generating methane and to sustain a more efficient methane production phase in BLFs. This is achieved by blending the mature leachate from older segments of landfills containing stabilized OFMSW with the young leachate from segments with fresh OFMSW before recirculating through fresh OFMSW. Providing a better environment for methanogenic bacteria to biodegrade the

OFMSW is achieved by this type of staged recirculation and leads to an increase in rate at which methane is generated as well as an increase in the total yield.

Objectives specific to this thesis include:

Batch Tests – I A

This set of batch biological methane potential (BMP) assays investigates the effect of blending young and mature leachate on biodegradation of OFMSW and biogas production wherein a set of batch reactors was setup with the same organic loads but different leachate blends.

Batch Tests – I B

Leachate blends were biodegraded in this batch BMP test to obtain the cumulative gas production associated from leachate alone.

Batch Tests II

The BMP assay bottles from test IIA were utilized to analyze the effect of a closed and open loop recirculation system (explained in detailed under chapter 3)

Batch Tests – III

Batch test set III was setup with the objective of analyzing the effect of different organic waste loadings with the best leachate blend from batch BMP assay IA

Batch Tests – IV

These batch tests were setup with the objective of analyzing the effect of staged organic waste loading (i.e. load distribution via fed batch loading) with best leachate blend obtained from batch BMP assay I

Column Tests (Simulated Bioreactor Landfills)

Column reactors were setup and operated with different leachate blends. The column reactors try to simulate bioreactor landfills with real world OFMSW. These reactors were setup and operated based on the results from the batch tests.

1.4 Methodology

This research is a two-step process to achieve the research objectives. Initial batch tests to assess the viability of the hypothesis followed by a set of simulated field conditions of a bioreactor landfill filled with OFMSW, i.e. column tests. The four sets of batch BMP assays conducted are aimed at assessing the basic feasibility of the hypothesis i.e whether or not blending the old and new leachate would increase the anaerobic biodegradability of the waste. In both BMP assay and column tests, the net amount of biogas produced is representative of the amount of biodegradation of the waste. The relative destruction of Volatile Solids (VS) and decrease in Chemical Oxygen Demand (COD) also correlate to the extent of anaerobic digestion.

1.5 Thesis Layout

The thesis is divided into five chapters, followed by appendices. Chapter 1 provides an introduction to the research and states the objectives. This is followed by a literature review in Chapter 2. Chapter 3 summarizes the Materials and Methods utilized for the research,

describing the setup, operation of five sets of batch mesophilic BMP assay tests and column tests. It also describes the analytical methods, equipment and testing protocols used for sample analysis. The results and discussions on the experimental work are explained in Chapter 4, which is followed by conclusions and recommendations for future work in Chapter 5.

Chapter 2: Literature Review

2.1 Municipal Solid Waste (MSW)

Solid waste is composed of waste arising from residential households and apartment buildings, commercial and institutional establishments, construction and demolition waste, municipal services, and treatment plants (sludge) (Tchobanoglous, et al., 1993). Typical components of MSW are food wastes, paper, cardboard, plastics, textiles, rubber, leather, yard wastes, wood etc. while construction and demolition waste is tended to be managed separately in industrial mono-landfills (Tchobanoglous et al., 1993). The portion of the MSW that is of significance in this study is the organic portion of this waste which is the biodegradable portion of the waste and is referred to as OFMSW defined as waste containing carbon compounds; derived from animal and plant materials.

2.1.1 Production of MSW: Quantitative and Qualitative Analysis

MSW generation reported at nearly 310 M tonnes in 2011 for N. America (USEPA, 2012) has been a serious concern over the past couple of decades. The USEPA statistics (Fig 2.1) indicate that the rate of MSW generation has been influenced in the past by the surge in

packaging products. In the 80s and 90s there had been a huge demand for packaging materials which ended up in landfills. This trend however was curbed by the recycling boom in the late 90s and early 2000s where recycling fees had been levied and the government policies were in place to promote the three Rs- Reduce, Reuse and Recycle. Material Recovery Facilities (MRFs) became popular and this enabled the landfills to have more organic loads instead of non-biodegradable solid waste.

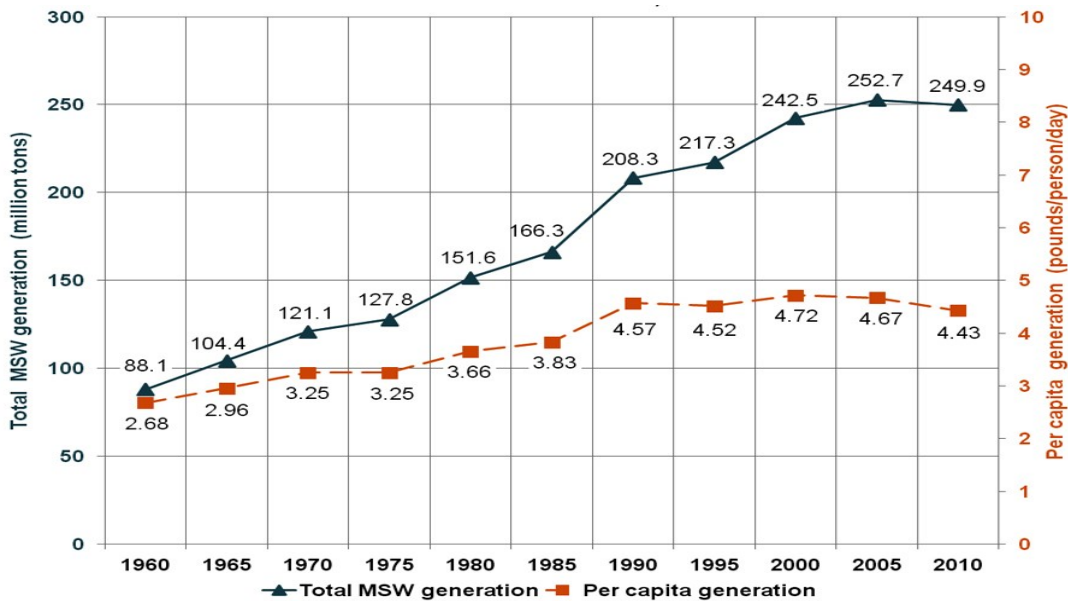


Figure 2-1MSW generation rates in N. America (USEPA, 2011)

The biodegradability of the waste depends quite simply on the type of waste generated. Figure 2.2 depicts the makeup of MSW in N. America. It comes as no surprise that packaging

products such as paper and cardboard form the major portion of this waste, followed by plastics.

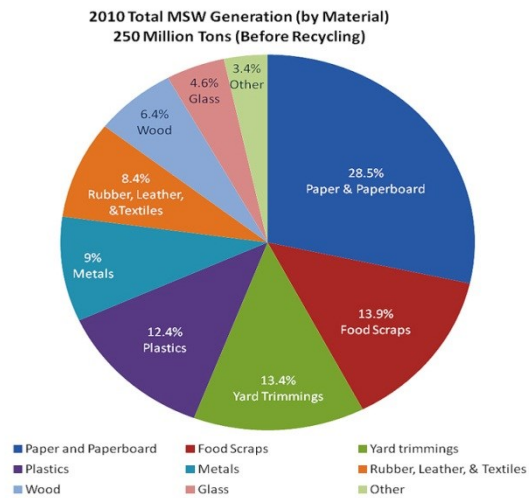


Figure 2-2 MSW composition chart (USEPA, 2011)

In Canada, total quantity landfilling stood at 34 million tonnes and at 1,031 kilograms of waste per Canadian in 2008. These numbers indicate that an average Canadian household produces up to 20% more solid waste than a typical American household. The trend in waste generation rates is also linked to the population density as inferred from Tables 2.1 and 2.2.

Table 2-1 Statistics Canada – Catalogue no. 16F0023X report, 2008

	Residential proportion of waste	Non-residential proportion of waste	Residential sources per capita	Non-residential sources per capita
	%		kilograms	
Canada	33	67	256	520
Newfoundland and Labrador	53	47	429	382
Prince Edward Island	x	X	x	x
Nova Scotia	42	58	158	220
New Brunswick	49	51	313	329
Quebec	33	67	265	530
Ontario	34	66	250	495
Manitoba	41	59	332	469
Saskatchewan	32	68	286	605
Alberta	24	76	267	855
British Columbia	34	66	219	422
Yukon, Northwest Territories and Nunavut	x	X	X	x

The solid waste generation in cities is generally lower owing to recycling programs in cities (Harris, 2004). However, the food waste component of the total waste generated is lesser in urban vs. rural communities. The sources of waste generated for the City of Ottawa is shown in Tables 2.2. Over 70% of the waste generated is sent to the landfill for disposal. Around

23% of the total residential solid waste generated is utilized by the composting and recycling programs. The MSW that is landfilled in Ottawa contains significant quantities of plastics, wood, yard trimmings and aluminum cans. Table 2.2 shows these statistics for the City of Ottawa in 2003.

Table 2-2 Waste generation in City of Ottawa (Harris, 2004)

WASTE SOURCE	AMOUNT (TONNES)
Residential solid waste	308,609
Sent for disposal to landfill	206,307
Waste sent for recycling	68,835
Sent from MRF* to market	66,799
Sent from MRF to disposal	2,036
Leaf and yard waste sent for composting	31,452
Food waste sent for composting	2,015
Compost produced	20,080
Organic waste diverted from backyard	7,400

The total solid waste generation rates vary greatly in composition depending on the type of waste accepted in the landfills. Commercial landfills accept solid waste from a variety of sources, ranging from residential and industrial waste to class B municipal sewage sludge. Table 2.3 gives an account of the source and type of waste accepted in a typical commercial landfill.

Table 2-3 Distribution of waste categorically (Tchobanoglous et al. 1993)

Waste category	Percent by weight
Residential and Commercial, excluding special and hazardous wastes	50-75
Hazardous	0.01-1
Institutional	3-5
Construction and demolition	8-20
Municipal services	6-15
Treatment plants sludge	3-8

2.1.2 Characteristics of MSW

In general of the total MSW generated, less than 55% of the waste can be completely biodegraded. Within this, the easily biodegradable portion includes the food scraps or food waste around 25% followed by yard trimmings which constitutes to another 25% then paper and lastly wood. Biodegradation of the paper and wood component of the OFMSW can take many years due to the presence of lignin a complex compound that requires considerable time to biodegrade (Tchobanoglous et. al., 1993).

Typical composition of waste for the City of Ottawa is shown in Table 2.4. Organic waste, made up of kitchen waste, pet waste, leaves and yard trimmings which is easily biodegraded in landfills with potential for energy generation makes up about 54% of the MSW collected.

Table 2-4 Concentration of MSW for the city of Ottawa, IEWS 2004

Materials	Total refuse collected (kg)(1)	Gross recyclables (and compostables) total (kg)(2)	Total MRF contamination (kg) (3)	Net recyclables and compostables total (kg) [(4)=(2)-(3)]	Total waste generation (kg) [(5)=(1)+(4)]
Paper	551.29	1784.55	25.77	1758.78	4120.39
Old newspaper	60.91	1009.50	4.30	1005.20	2079.91
Magazines and catalogues	22.05	195.70	0.00	195.70	413.45
Old corrugated cardboard	14.24	200.60	1.30	199.30	415.44
Boxboard	69.60	149.21	2.16	147.05	368.02
Telephone books	3.30	2.30	0.00	2.30	7.90
Mixed residential fibre	142.80	185.17	5.12	180.05	513.14
Polycot	9.86	22.03	6.23	15.80	53.92
Tissue	174.80	1.77	1.77	0.00	178.34
Molded pulp	3.82	9.65	0.07	9.58	23.12
Tetra pack	4.43	1.60	0.36	1.24	7.63
Spiral wound	9.88	3.01	0.45	2.56	15.90
Non-recyclable paper	35.60	4.01	4.01	0.00	43.62
Glass	70.07	413.78	2.18	411.60	897.63
LCBO clear containers	6.60	63.00	0.00	63.00	132.60
LCBO coloured containers	9.55	197.40	0.00	197.40	404.35
Clear containers	27.95	125.30	0.20	125.10	278.55
Coloured containers	0.91	2.610	0.00	2.610	53.11
Other glass	25.06	1.98	1.98	0.00	29.02
Metal	63.38	117.57	5.43	112.14	298.52
Steel food and beverage containers ferrous	18.08	79.00	0.00	79.00	176.08
Steel food and beverage containers non-ferrous	2.38	2.86	0.01	2.85	8.10
Aluminum food and beverage containers	6.56	27.52	0.02	27.50	61.60
Aluminum foil and trays	8.00	1.52	0.00	1.52	11.04
Aerosol cans	5.30	1.27	0.00	1.27	7.84
Paint cans	1.50	0.00	0.00	0.00	1.50
White goods	0.00	0.00	0.00	0.00	0.00
Other metal	21.56	5.40	5.40	0.00	32.36
Plastics	257.57	174.18	30.41	143.77	605.93
PET (#1)-polyethylene terephthalate—bottles	5.52	36.85	0.05	36.80	79.22
PET (#1)-polyethylene terephthalate—other	7.85	18.95	0.00	18.95	45.76
HDPE (#2)-high density polyethylene	7.35	24.45	0.10	24.35	56.25
PVC (#3)-polyvinylchloride	0.53	1.52	0.00	1.52	3.57
LDPE (#4)-low density polyethylene	0.92	0.18	0.00	0.18	1.28
PP (#5)-polypropylene	1.50	4.92	0.00	4.92	11.34
PS (#6)-polystyrene	25.85	11.36	0.71	10.65	48.57
Other (#7)	0.45	1.70	0.00	1.70	3.85
Wide mouth tubs and lids (# 2,4,5,7)	14.32	16.80	0.00	16.80	47.92
Recyclable film	66.40	28.82	0.92	27.90	124.04
Waste plastic	126.87	28.63	28.63	0.00	184.13
Organics	1882.71	627.45	3.95	623.50	3137.61
Kitchen organics (food prep.)	1418.26	53.25	1.45	51.80	1524.76
Leaf and yard waste	68.40	571.70	0.00	571.70	1211.80
Pet waste	396.05	2.50	2.50	0.00	401.05
Other materials	659.64	2.70	2.70	0.00	665.04
Disposable diapers/sanitary products	227.17	0.00	0.00	0.00	227.17
Electronics/appliances	31.30	0.10	0.10	0.00	31.50
Tires	0.00	0.00	0.00	0.00	0.00
Textiles	101.20	1.00	1.00	0.00	103.20
Construction and demolition	124.50	0.30	0.30	0.00	125.10
Household special waste	17.93	0.00	0.00	0.00	17.93
Unclassifiable items	157.54	1.30	1.30	0.00	160.14
Total	3484.66	3120.23	70.44	3049.79	6208.40
Total recycled				2426.29	
Total composted				623.50	

2.2 Landfills

2.2.1 Introduction to Landfills

Disposal of solid waste is a major concern globally. Out of the various methods available, landfills are one of the most widely used methods. Landfills are generally classified as:

- Secure modern landfills
- Monofill landfills
- Engineered landfills

The secure landfills are those which are used to prevent any future environmental hazards caused by the landfilled waste and are presently the norm in North America. The monofill landfills accept usually inert materials which could otherwise not be disposed in MRFs, composting or incinerators. The waste that is accepted in these landfills usually tends to be from construction and demolition, yard waste or combustion ash.

Following the RCRA act of 1976, all new landfills in North America had to be regulated landfills constructed with appropriate liners and where the leachate had to be collected to prevent contamination of groundwater. This also meant that the leachate had to be treated to reduce the COD to effluent standards and diluting through wastewater streams would not solve the problem anymore (Tchobanoglous et. al., 1993). Emphasis then shifted to treating the leachate onsite. The leachate from landfills tend not be treated in conventional wastewater

treatment plants since they have extremely high concentrations of ammonia, phosphorus and heavy metals and are limited to 2% of the wastewater treatment plant flow to minimize inhibition of the activated sludge process (Qasim and Chiang, 1994).

2.2.2 Bioreactor Landfills

Bioreactor landfills are an enhancement of regulated engineered landfills where leachate is collected and effectively recirculated through the waste. The leachate recirculation in bioreactor landfills provides quite a few advantages. For one it improves nutrient transfer to the microbial population which aids their growth rate and hence has a profound impact on anaerobic biodegradation. It also improves the moisture in the waste and this is important because water is essential for microbial biodegradation. Recirculating the leachate also solubilises organics in the waste which in turn accelerates the biodegradation process. USEPA also reports that the toxicity levels in the leachate from bioreactor landfills are significantly lower than those of regular landfills that do not practice recirculation.

The recirculation of leachate aids in transport of essential nutrients to the microorganisms and also helps to maintain the bacterial balance. In addition over time as biodegradation proceeds, the density of the waste becomes higher in bioreactor landfill which enhances landfill space recovery. Another significant advantage is the reduced leachate disposal and treatment cost. Bioreactor landfills are easier to close out since the waste is stabilized more quickly.

A schematic of the bioreactor landfill is shown in Fig. 2.3. The striking difference in a bioreactor landfill compared with a conventional regulated landfill is the leachate recirculation and accompanying LFG collection and utilization.

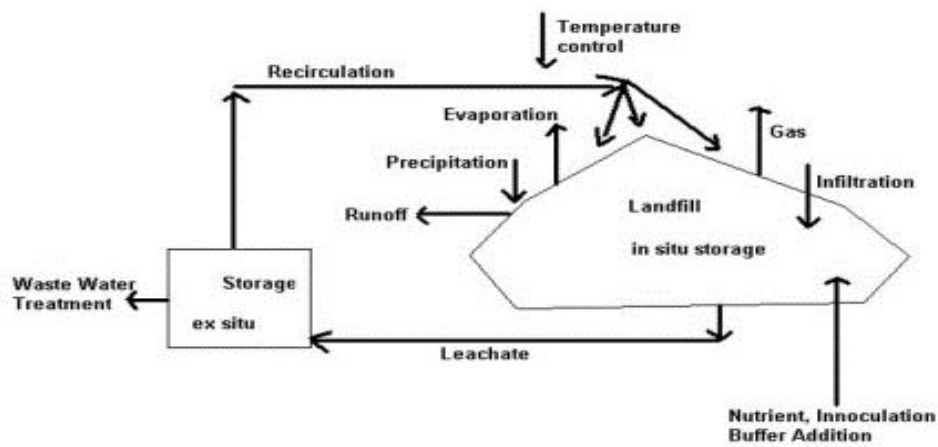


Figure 2-3 Bioreactor landfill Schematic (Reinhart and Townsend, 1998)

Bioreactor landfills revolve around the concept of leachate recirculation and biogas collection and utilization. Landfill leachate is the endogenous liquid associated with the waste which seeps through the solid waste and also includes a percentage of rainwater and runoffs (Kostova, 2006; Reinhart and Townsend, 1998). In a broader perspective, leachate is generated as a result of water contacting with waste. Leachate quality in landfills can vary in strength and composition. Most of these variations are based on the age of the landfill, the operation type of the landfill, the waste makeup and leachate capture, recirculation and

treatment system if any and also on certain geographical and topographic factors such as rainfall, runoff design and ambient temperatures.

Of the leachate parameters, the most significant ones are the high COD and the high concentration of ammonia which prevents it from being treated in a regular landfill. Typical landfill leachate would have anywhere between 1000 mg/L up to 100,000 mg/L of COD and ammonia concentrations ranging from 500 mg/L to 20,000 mg/L (Reinhart and Townsend, 1998). With such high concentrations, it is practically impossible to treat the leachate in conventional wastewater treatment plants (Reinhart and Townsend, 1996; Rowe, 1994). Dilution could have been a solution but the extent to which leachates have to be diluted makes it uneconomical and non-environmentally friendly. The leachate also contains relatively high concentrations of heavy metals and this is another major obstacle.

2.2.3 Leachate Generation

Rainwater seeps through the landfill cover and generates leachate. The leachate also contains a percentage of water generated within the landfill due to biodegradation of the waste itself. Baghchi, (1990) defines leachate as a contaminated liquid that contains a number of dissolved or suspended materials. The rainwater increases the moisture content in the waste which is critical for Anaerobic Digestion (AD). This in turn causes the OFMSW to be biodegraded into water and biogas. The water balance in a modern day landfill is shown in Figure 2.4. In

modern day landfills, the water that infiltrates through the landfill either gets absorbed by the waste (if field capacity is not reached) or gets collected at the liner after field capacity is exceeded. The amount of leachate generated in a landfill depends on the annual rainfall in the area, the landfill morphology, the density and compaction of waste, number of lifts, the texture and nature of the MSW and most importantly the leachate recirculation system (Reinhart and Townsend, 1996).

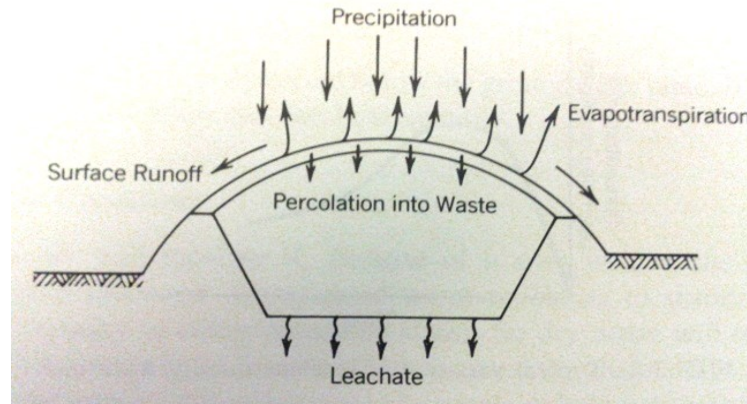


Figure 2-4 Landfill water balance (Baghchi et al., 1990)

Leachate Collection Systems (LCS) is implemented in all landfills post 1976 as per the RCRA subtitle D landfill regulations (USEPA, 2011). The leachate collection and storage systems are made up of a series of piping systems embedded into the bottom of the landfill just above the liner system. The leachate generated in the landfills is trapped and flows through the installed perforated pipes. This arrangement is shown in Figure 2.5.

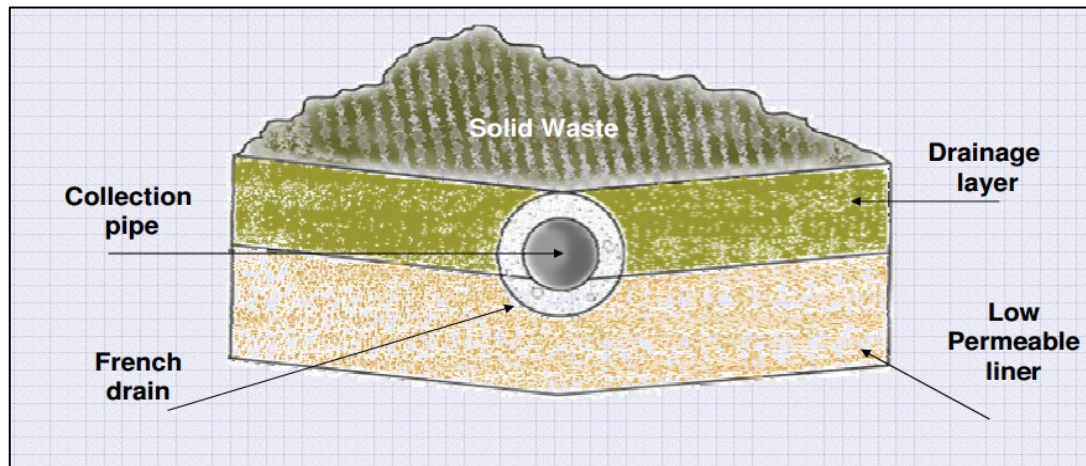


Figure 2-5 Leachate collection system profile (Kostova, 2006)

The main stipulation for landfill design is that the leachate level above the liner should be restricted to 30 cms. Needless to say, the landfills could no longer be used to store the leachate. Hence the leachate generated in excess of 30 cm must be removed from the landfill. This means that leachate will have to be collected and disposed of.

2.2.4 Young Leachate Characteristics

Leachate has distinct properties which are indicative of the age of the landfill and the age of the waste that is landfilled. By young leachate, we refer to the leachate that is generated from fresh OFMSW from newer segments of landfills having two or three lifts. Typically young leachate has higher concentrations of COD, lower pH and lower concentrations of heavy metals. This is because as water seeps through fresh waste that is being stabilized by

microbial biodegradation, there will be a significant component of soluble organics that would be assimilated by the leachate before being collected. The high organic content of the leachate also includes a large VFA component as a result of acidogenesis. High VFA concentrations mean that the leachate is more acidic with pH in the range of 4.5 to 6.5 as depicted in Figure 1.1 and another characteristic listed in Table 2.5.

Table 2-5 Young leachate characteristics (Kostova, 2006)

Leachate constituent	Concentration (mg/L)	
	Transition phase	Acid-formation phase
	Years 0-5	Years 5-10
BOD ₅	100 -11 000	1 000-57 000
COD	500 -22 000	1 500-71 000
TOC	100 -3 000	500 - 28 000
NH ₄ -N	0 -190	30-3 000
NO ₃ -N	0,1 - 500	0,1 - 20
Total diss. solids	2 500 -14 000	4 000-55 000

2.2.5 Mature Leachate Characteristics

Mature leachate has completely different properties. It is observed that with the exception of ammonia in anaerobic bioreactor landfills, the concentration of all the components of leachate increases rapidly during the initial (0-3 years) and young (3-10 yrs) phases and then starts to decline as the landfill matures through to the final old stages (>10 years) (Figure 1.1).

Landfill age has a profound impact on the bacterial consortia within the leachate. The older the leachate, the more acclimatized is the bacteria in the leachate with a more balanced mixture of acidogenic and methanogenic populations (Pohland, 2003; Reinhart 1998). The acidogenic/methanogenic consortia ratio is balanced and since the endogenous decay of anaerobes is so low the matured leachate has inventory of methanogens that can be easily activated if exposed to short chain VFAs. This is a desirable property for anaerobic biodegradation and leachate staging.

The COD content in old leachate is considerably lower than young leachate as is the case with the VFAs. Mature landfill leachate has a higher pH as a result of this since the lower the VFA the higher is the pH. Most studies report that the soluble organic content in the leachate vs. the particulate organic in the MSW is the component that is biodegraded the quickest since it is in solution and the COD is already solubilised. This is one of the reasons why the COD of mature landfill leachate is low, most of which is non-biodegradable. Mature landfill leachate properties are shown in Table 2.6

Properties of mature leachate have been studied over the last couple of decades. One probable reason for this is that these segments of landfills were constructed with no proper leachate collection systems and impervious liners installed at the time. This meant that the leachate arising from these landfill cells could possibly affect groundwater quality by causing contamination.

Table 2-6 Mature leachate properties from studies (Sponza and Ozman, 2003; Kostova, 2006)

Parameter Units	pH	COD mg/L	VFA mg/L	TP mg/L	TN mg/L	ORP mV	Alkalinity mg CaCO ₃ /L
Erses and Onay (2003)	7.76	721	-	30	-	-234	4829
Jianguo <i>et al.</i> (2007)	7.37	13890	856	64	2499	-	-
Filipkowska (2008)	8.87	3915	-	21	442	-	-
Benbelkacem <i>et al.</i> (2010)	8.5	-	35	-	-	-	-
Kostova,(2006)	-	30-900	-	-	6-430	-	-

2.2.6 Classification of Bioreactor Landfills

Bioreactor landfills are classified based on their type of operation as Aerobic, Anaerobic or Facultative (or Hybrid) bioreactor landfills. Aerobic bioreactors (Figure 2.6) are also called aerated bioreactor landfills where in addition to controlled leachate recirculation, air is injected into the landfill waste mass using blowers, to promote aerobic activity and accelerate waste stabilization (USEPA, 2011). The rate of waste stabilization in the first stages of the landfill is relatively quick owing to aerobic bacterial consortium. However, the later stages require much longer.

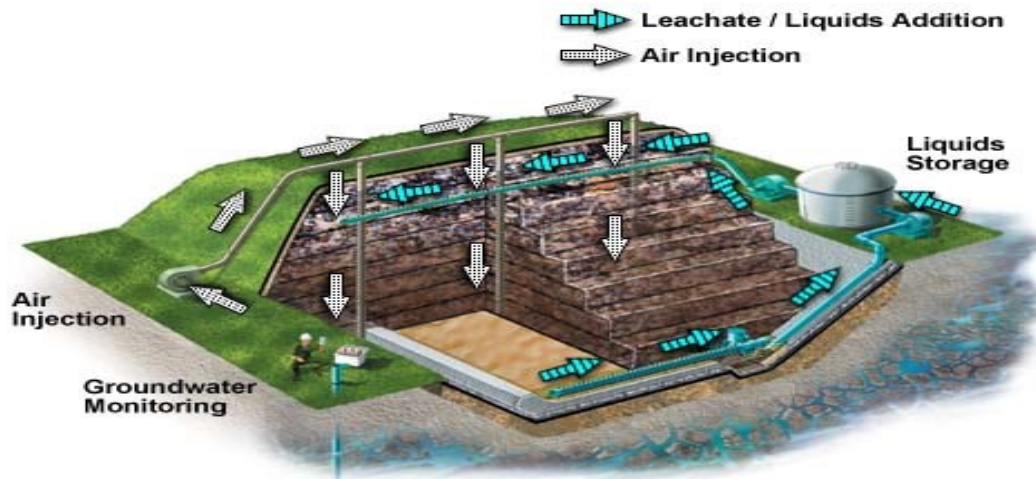


Figure 2-6 Typical Aerobic Bioreactor Landfill @Waste Management

The hybrid bioreactor landfill accelerates waste degradation by employing a sequential aerobic-anaerobic treatment to rapidly degrade organics in the upper sections of the landfill and collect gas from lower sections. Operation as a hybrid results in the earlier onset of methanogenesis. There are several advantages with hybrid bioreactors though they are more difficult to operate and quite obviously have higher installation cost. Maintenance of these landfills is also not easy because of clogging risks of the gas and leachate collection and recirculation lines.

Anaerobic bioreactor landfills are those which are operated in the absence of air/oxygen. Methane gas which constitutes around 50-60% of the biogas generated from landfills is trapped to utilize its high calorific value of 55.3 KJ/Kg.

An anaerobic bioreactor landfill is depicted in Figure 2.7. They are more efficient and have a shorter stabilization time compared to conventional engineered landfills but longer than aerobic bioreactor landfills. Anaerobic bioreactor landfills are more of a treatment system than a typical landfill (Pohland and Kim, 2003). The entire landfill works as an anaerobic digester and accelerates the waste decomposition by maintaining a healthy anaerobic bacterial consortium.

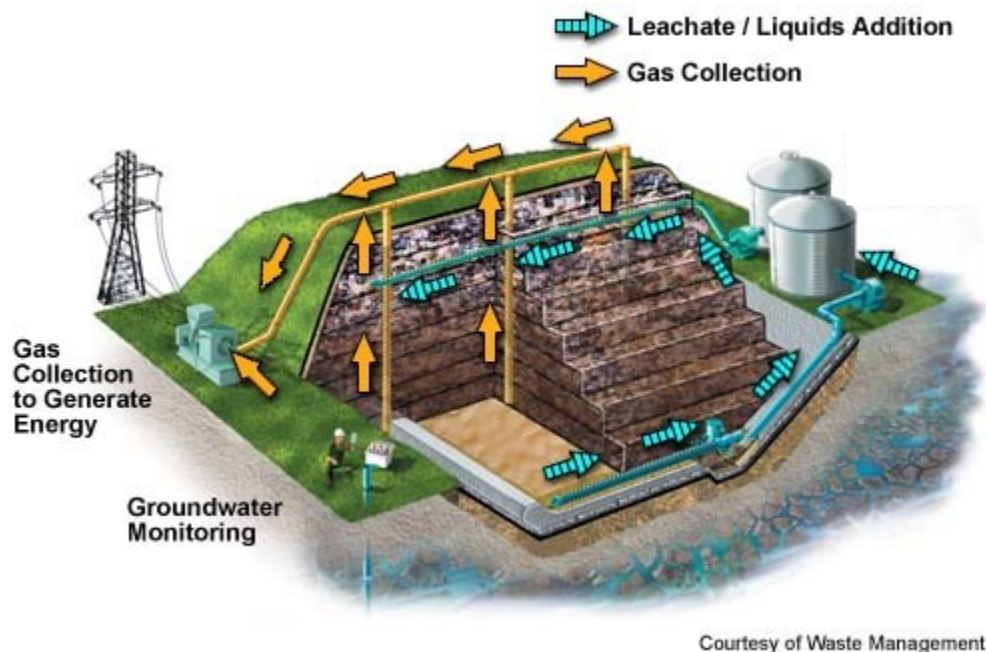


Figure 2-7 Typical Anaerobic Bioreactor Landfill @Waste Management

Anaerobic landfill bioreactors are easier to operate and more cost effective since there is no energy requirement for aeration. However, anaerobic bioreactor landfills have distinct

problems arising from high ammonia accumulation, higher VFAs, and from higher GHG (Green House Gas) emissions (Bilgili et al., 2007; Gianis et al., 2006).

2.2.7 Anaerobic Digestion in Bioreactor Landfills

Anaerobic digestion of the OFMSW generates a mixture of methane (CH_4), carbon dioxide (CO_2) and water (H_2O). The methane generated from the waste is of extreme importance since this is utilized to generate energy. Methane constitutes anywhere from 40%-60% of landfill gas generated. The reactions taking place in an anaerobic landfill have been analyzed over the last few decades and can be summarized as a five phase process as outlined by Pohland and Kim (2003) and shown in Figure 2.7

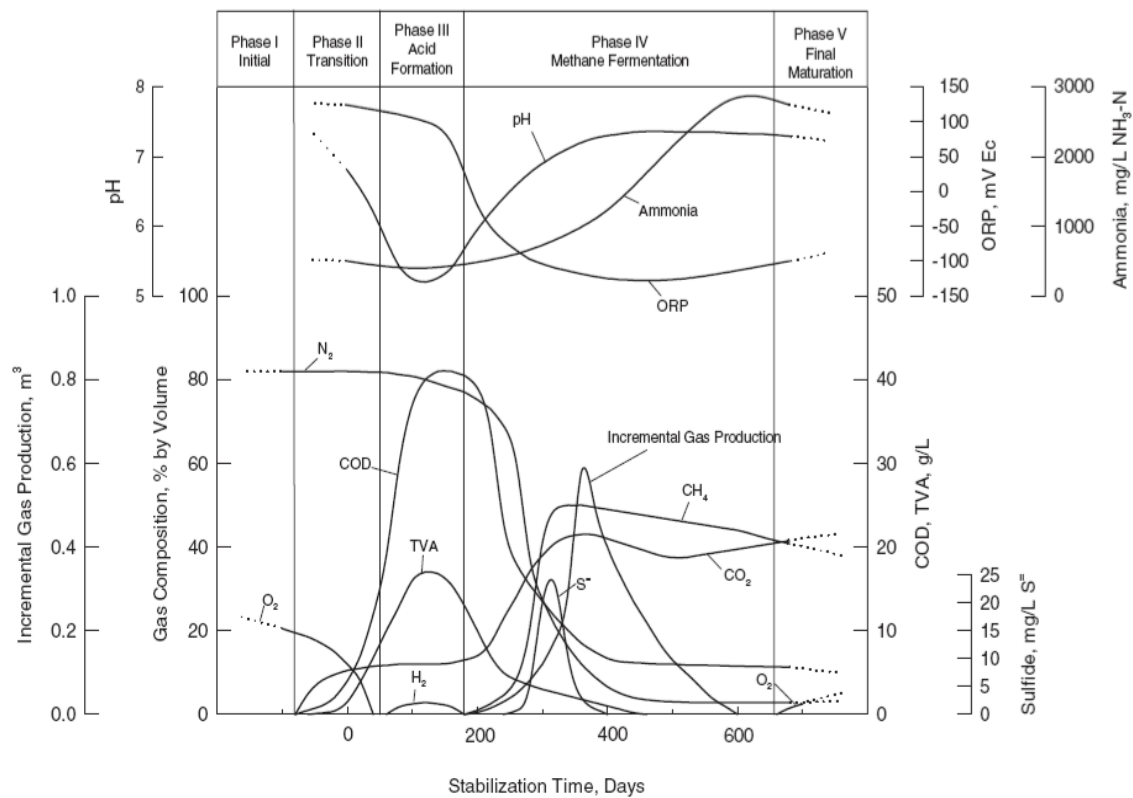


Figure 2-8 Phases of waste decomposition in bioreactor landfills (Kim and Pohland, 2003)

Phase I: Lag or Initial Adjustment:

This is the phase that starts after a waste lift is placed in a landfill and covered with a layer of topsoil. There is still moisture and sufficient trapped air to start aerobic microbial decomposition of the waste. The duration of the phase depends on two main factors- waste compaction and moisture content.

Phase II: Transition:

Once the oxygen in the waste is depleted as a result of compaction and aerobic microbial activity, the entire process shifts from aerobic to anaerobic and thus the transition phase begins. Under aerobic conditions, the primary electron acceptor is oxygen, while under anaerobic it is mainly nitrates. The organic compounds are thereby hydrolysed and the long chain hydrocarbons are broken down. There is significant change in the leachate COD, TKN and volatile organic acids at the end of this phase (Shahriari and Abdallah, 2009).

Phase III: Acid Formation:

In this phase, the hydrocarbons that were broken down by hydrolysis are converted into volatile fatty acids (VFAs), mainly acetic acid (CH_3COOH), butyric acid and also hydrogen gas. It then goes without saying that there is a reduction in pH which drops from an average of 7.5 to approximately 5.6. This phase also sees a marked change in the consumption of substrate and nutrients (Shahriari and Abdallah, 2009).

Phase IV: Methane Fermentation or Methanogenesis:

During this phase, microbes called methanogens break down the intermediate compounds formed in the acid forming state into methane (CH_4), carbon dioxide (CO_2) and water (H_2O .) Because the intermediates are now being consumed to produce methane, the pH rises back to an average of 7.0. By the end of the methanogenesis, the organics are converted into methane, carbon dioxide and water thereby removing the need for oxygen to satiate the BOD of the leachate. This is one of the most critical stages of anaerobic digestion in a landfill. This also is

the most important stage for tapping the methane potential of the OFMSW (Reinhart and Townsend, 2004)

Phase V: Maturation and Stabilization:

The last stage of the OFMSW biodegradation in the landfill which is maturation and stabilization does not have the same level of microbial activity as the previous two stages. This is because the whole process of biodegradation is limited by available carbon substrates and essential nutrients like phosphorous both of which are essential for cell growth and synthesis. As a result, the methane produced in this stage is low and is associated with the difficult to biodegrade residual organics in the OFMSW. Waste stabilization is then said to have occurred wherein there is little or negligible methanogenic activity in the landfill. This makes collection of food waste from older sections of landfills that are dormant rather difficult.

2.3 Recent Studies on Leachate Recirculation

As mentioned before, leachate recirculation has been identified as the main component of bioreactor landfill operations. Mehta et al. (2002) determined a relationship between the moisture content and the rate of anaerobic digestion of the waste and found that the higher the moisture content of the OFMSW, the faster is the anaerobic decomposition of the waste.

Reinhart and Yousifi (1996) stated that the bare minimum for operating a landfill as a bioreactor is 40% moisture content.

Leachate recirculation has its distinct advantages. In a study by Wang et al. (2006) who studied the influence of leachate recirculation with simulated landfills suggested that recirculation of leachate had both advantages and also a few disadvantages. The study simulated four bioreactors loaded with simulated OFMSW. The first anaerobic reactor C1, percolated water until stabilization of MSW occurred, following which high strength leachate would be percolated. Reactor C2 used a similar regime to C1 with the difference that C2 had been aerated with openings at the top and bottom. Anaerobic reactor C3, was similar in construction to C1, but had leachate being recirculated in a closed loop simulating an anaerobic bioreactor landfill. The control reactor, C4 had no leachate recirculation. The summary of the experimental setup is shown in Fig 2.9 and Table 2.7. Following the stabilization of the waste in the reactors, high strength leachate was passed through reactors C1, C2 and C3 to observe the effect of further waste biodegradation on the leachate. The results are summarized in Table 2.8 and Figure 2.10, which shows the COD curve for the leachate in the reactors. Bioreactor landfill C3 was observed to have had waste stabilization in 33 weeks as compared to C1, C2 and C4 which required over 49 weeks stabilizing the MSW. In conclusion, it was stated that leachate recirculation could significantly shorten the stabilization time required in landfill bioreactors. The downside to leachate recirculation was

the accumulation of ammonia in the leachate of anaerobic bioreactor landfills which could result in microbial inhibition.

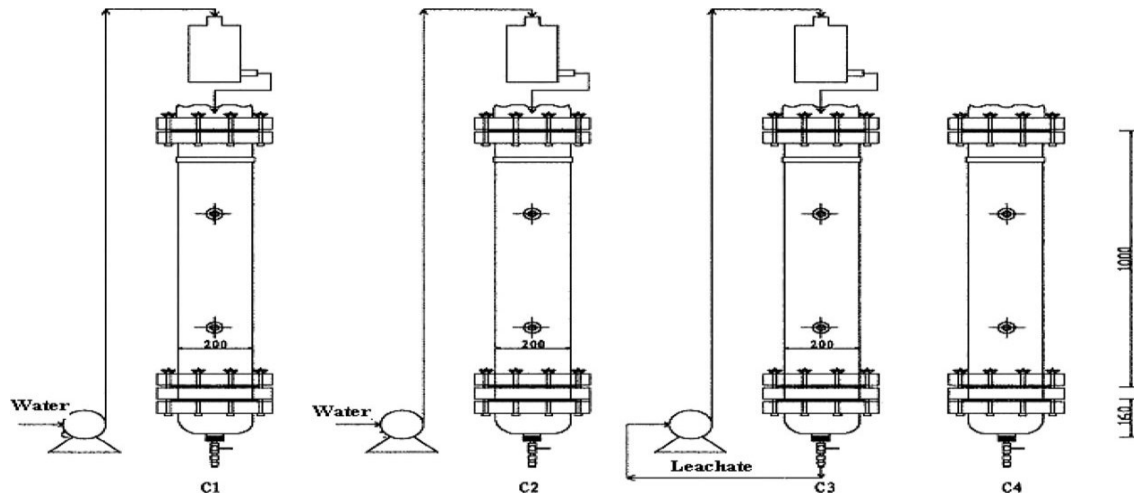


Figure 2-9 Schematic experimental setup (Wang et al., 2006)

Table 2-7 Experimental conditions adapted from Wang et al. (2006)

Condition	Column C1	Column C2	Column C3	Column C4
Top air access	No	Yes	No	No
Bottom air access	No	Yes	No	No
Top input flow				
Earlier stage	Tap water	Tap water	Re-circulated leachate ^a	No
Later stage	High concentration leachate ^b	High concentration leachate ^b	High concentration leachate ^b	No
Feedback amount	500-ml/week	500-ml/week	500-ml/week	-

^a Re-circulated leachate was generated from C3 and C1, and collected at the bottom of Column C3.

^b High concentration leachate was collected from other test columns with raw MSW.

Table 2-8 Leachate quality and stabilization time, adapted from Wang et al. (2006)

Column	Status of leachate		Leachate quality (mg/l)				Date (month/year)
			COD ₅	BOD	NH ₃ -N	pH	
C1	Landfill initial phase		70,200	44,000	2900	6.03	05/1998
	Stabilized phase		592	81	320	8.06	05/1999
C2	Landfill initial phase		77,000	61,000	2880	6.03	03/1998
	Stabilized phase		398	18	2.43	8.32	03/1999
C3	Landfill initial phase	In	80,500	60,100	3020	6.01	03/1998
		Out	81,700	54,000	3340	6.02	
	Stabilized phase	In	92,000	43,000	3000	6.69	11/1998
		Out	3300	380	3100	8.59	
C4	Landfill initial phase		77,000	44,000	3500	5.97	03/1998
	Stabilized phase		26,000	12,200	3400	8.53	03/1999

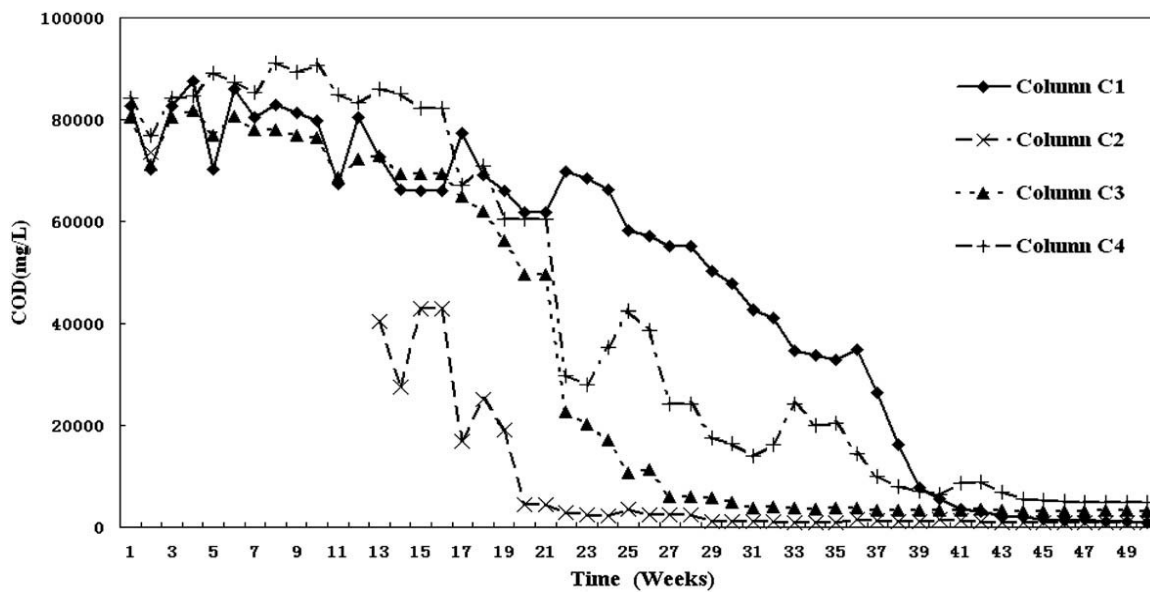


Figure 2-10 COD curve (Wang et al. 2006)

Leachate recirculation and dilution prior to recirculation was shown to produce better results in terms of waste stabilization as observed by Sanphoti et al. (2006). Three reactors were setup to simulate landfills, of which the control reactor RC was a single pass leachate reactor;

R1 simulated an anaerobic bioreactor landfill with leachate recirculation and R2 leachate recirculation wherein the leachate was diluted before recirculation.

Biogas production and COD removal rates observed with leachate recirculation and supplemental water addition, R2 was highest followed by R1 in which the leachate was recirculated as produced and the lowest in the single pass reactor, RC. Sanphoti, et al. (2006) attributed the enhanced waste stabilization in the reactors with leachate recirculation to the fact that the substrates for methanogens in the leachate recirculation reactor get captured, reapplied and utilized by the microbes. In a single pass reactor however, the substrates and essential nutrients for methanogens get washed out due to leachate drainage. Contact time for the methanogens to work on the substrates was higher in case of leachate recirculation. Leachate recirculation with buffer addition was also shown to accelerate MSW stabilization as well as enhance gas production in the simulated landfill reactor. Increases in methane content after buffer addition to the reactor were indicative of the presence of a substantial inventory of methanogens in the system.

Leachate recirculation with supplemental water addition produces faster waste stabilization since the water addition dilutes the total VFAs and moderates the pH which makes the substrate and conditions in the landfill more conducive for the methanogens. In addition to diluting the VFA concentrations, dilution also reduces the toxicity levels of any methanogenic inhibitors such as ammonia and/or heavy metals which results in a net higher biogas yield and enhanced COD removal as shown in Table 2.9

Table 2-9 COD removal comparison, adapted from Sanphoti et al. (2006)

Day	COD removal (%)		
	RC	R1	R2
344	65.62	67.45	73.67
351	79.31	81.20	85.01
356	89.54	91.02	91.22

Studies conducted on the effects of leachate recirculation in simulated landfills by Bilgili et al., (2007) have shown that leachate recirculation also has an impact on the net leachate generation within the waste. The experimental procedure compared the effect of leachate recirculation on both anaerobic and aerobic reactors treating OFMSW. In the four reactor setup, two were aerobic (A1 and A2) and two anaerobic (AN1 and AN2); with recirculation (A2 and AN2) and without recirculation (A1 and AN1).

The results from the study showed that the reactors with leachate recirculation produced more biodegradation from the waste. One of the primary reasons for this could have been that a more even moisture and nutrient distribution occurs when there is leachate recirculation which enhances biodegradation and water is one of the by-products of anaerobic biodegradation (Mehanta R. et al., 2002). The study reported highest biodegradation and waste stabilization for the aerobic landfills owing to faster bacterial growth and activity in the aerobic mode of operation. While the aerobic reactors did not seem to benefit much from leachate recirculation in terms of leachate quality, the anaerobic reactors showed enhanced leachate quality (improved COD removal) and biogas production with leachate recirculation

as shown in Figure 2.11. Leachate recirculation therefore is best suited for anaerobic bioreactor landfills.

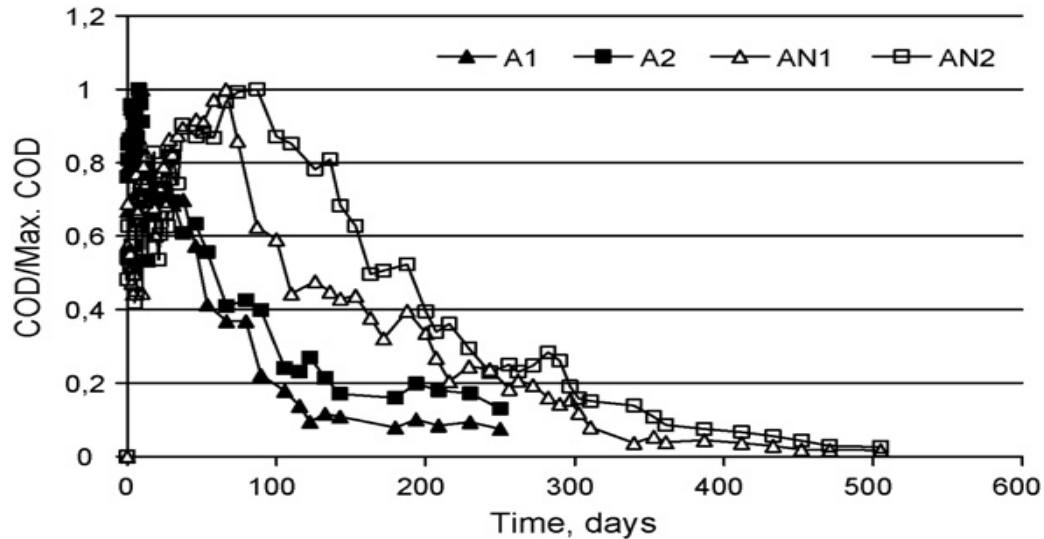


Figure 2-11 COD removal profile, adapted from Bilgili et al. (2007)

Sponza and Ozman (2003) studied the effect of leachate recirculation rates on bioreactors. Their experiments utilized domestic kitchen waste along with anaerobic digested sludge. Their kitchen waste had an approximate composition of 75-95% organic component with the remaining part made up by 2-6% paper and nearly 1-2% plastics and textile. The experimental setup is depicted in Fig. 2.12 The parameters monitored included pH, COD, VFA, ammonium-nitrogen and methane gas. Methane was checked only during the first 60 days due to gas leaks in the reactors. The maximum COD removal and therefore maximum treatment efficiency was observed for reactors with leachate recirculation at 13% v/v as shown in Table 2.10. The extent of methanogenesis was also reported to be highest at 13% v/v recirculation which can be observed from the maximum COD reduction and VFA utilization. The higher

methane content in the biogas also shows the greater methanogenesis obtained in the reactor. The higher pH suggests higher waste stabilization. From the study, it was understood that for achieving higher rates and extent of biodegradation and methane generation, recirculating leachate is beneficial. In addition, it was also concluded from the study that recirculating lower volumes of leachate would be a better option.

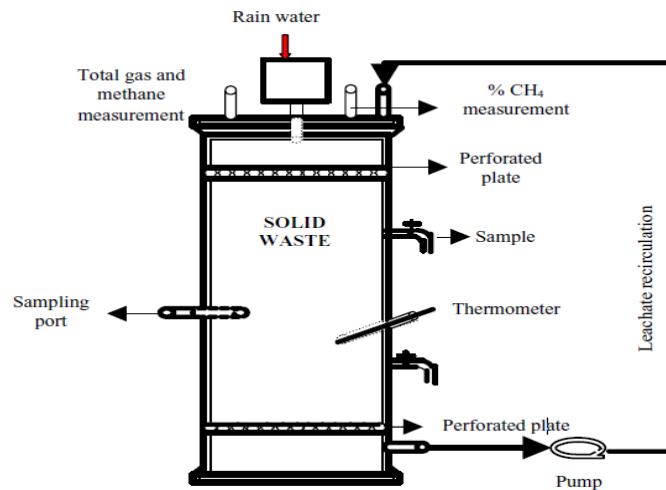


Figure 2-12 Experimental Setup (Sponza and Ozman, 2003)

Table 2-10 Rate of leachate recirculation as observed by Sponza and Ozman (2003)

	Single Pass	Reactor R9	Reactor R21
Recirculation rate	-	13% v/v	30% v/v
pH	5.89	6.44	6.16
COD	47,000 mg/l	39,000 mg/l	52,000 mg/l
VFA	15,000 mg/l	13,000 mg/l	21,000 mg/l
% CH ₄ in gas	30%	50%	40%

The recirculation was done by means of a pump with a reservoir column outside the main reactor to ensure that there is no dry pumping during continuous operation. Sanpoti et al. (2006) suggests that such a kind of continuous recirculation is not practical in landfills owing to uneven compaction of the waste, i.e. the waste around the areas with leachate contacts with the waste and those areas would have more compaction and that particular portion would arch inwards. Another issue with this kind of recirculation makes the landfill prone to horizontal flow of leachate outside the perimeter of the landfill. In order to avoid these issues, the same volumetric recirculation ratio is maintained but the recirculation is done every alternate day in lab scale reactors simulating the biweekly landfill recirculation adopted in real BLFs.

It can be concluded from the study that lab scale bioreactor performance is dependent on the leachate recirculation rate and the volume of leachate generated. In a simulated landfill bioreactor, it would be critical to calculate the amount of leachate that has to be generated since, in lab scale experiments, the leachate quantity depends on the amount of water added into the waste. The amount of leachate recirculated should exceed the field capacity of the waste or at least be close to the field capacity so as to avoid losing leachate to compensate for the moisture absorbed by the waste (Mehanta R. et al., 2002).

The properties and characteristics of the recirculated leachate also vary vertically and horizontally in landfill bioreactors. A 50 year old operational landfill was monitored by Sormunen et al. (2008) for horizontal and vertical variations in terms of leachate quality inside the landfill where cells were being used as bioreactors. Monitored over two years, the

studies were able to conclude that the leachate quality varied greatly both horizontally and vertically. The variation is hypothesized to be brought about by the spread of leachate and conductivity close to the leachate recirculation drains.

This study established the fact that the leachate quality can change a lot within the landfill bioreactor cells. The leachate recirculation regime has a major impact on the leachate quality in a bioreactor landfill. Hence in any study, the leachate recirculation regime adopted can either improve or worsen the activity in a landfill.

Leachate recirculation is, thus an extremely efficient method for changing the operational parameters in a landfill bioreactor. The rate and type of leachate recirculation regime adopted changes the characteristics of the bioreactor landfill.

2.4 Leachate Treatment and Modification

Leachate properties vary greatly depending on the landfill. Toxicity levels of the leachate determine the type of treatment that is required before disposal. In bioreactor landfills, the need for special treatment trains for leachate removal is eliminated since recirculation more or less reduces the toxicity of the leachate.

Owing to the successful studies with leachate recirculation, several studies focused on modifying and pre-treating the leachate before injection for recirculation. Pre-treating the

leachate is done mainly to relieve the ammonia build-up in anaerobic BLFs and also to improve conditions for methanogenesis. The growth rate of methanogens is inhibited by parameters such as high ammonia concentration, lower pH, high VFA concentrations and heavy metal contamination. In order to offset these problems researchers have been focusing on alleviating the inhibitory effect caused by components in the leachate. The other reason why leachate is pre-treated is to provide a secondary treatment before disposal.

Experimental work by He et al. (2005) focused on leachate treatment and recirculation by subjecting the leachate to a pass through a UASB (Up-flow Anaerobic Sludge Blanket) reactor thereby aiming to reduce the solubilised COD in the leachate. A schematic of this experiment is shown in Fig 2.13. R1 was the control reactor simulating a regular bioreactor landfill setup with regular recirculation. R2 included using the UASB reactor for the leachate line in and R3 was fed with leachate which was modified with inoculums generated separately.

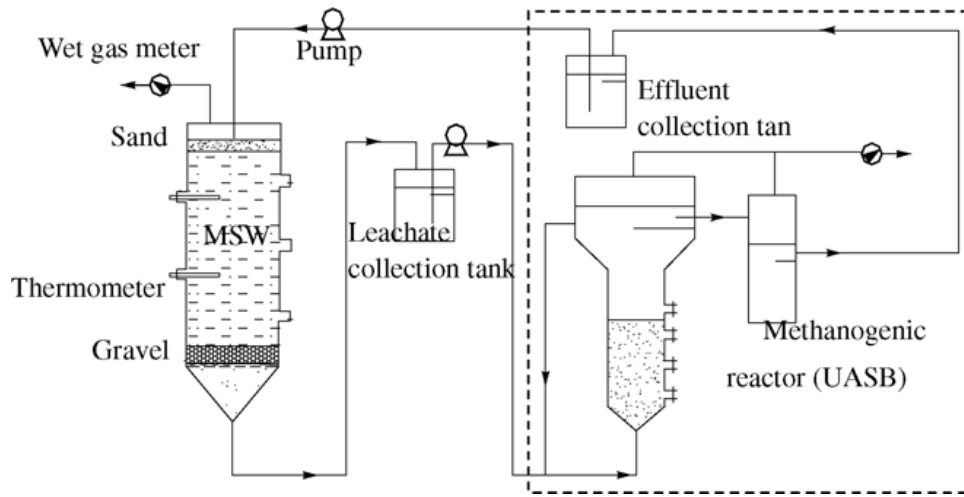


Figure 2-13 Experimental Schematic, adapted from He et al. (2005)

The fundamental basis of the study was that the leachate recirculated would contain active microorganisms upon reinsertion into the MSW bed. This would result in a stable microbial balance within the MSW layer. The UASB reactors have significant operational advantages in terms of methanogenic bacterial growth rates (Kennedy, 2001). The results from their experiments showed significant improvement in the COD removal rates and thus higher gas yields could be achieved by passing the leachate through the active sludge layer in the UASB reactor before recirculation. The cumulative gas production increased significantly in R3. However, since the entire recirculation loop is closed, it would be important to realize that the increase in the cumulative gas production could be attributed to the AD of the leachate in the UASB reactor which was dissolved within the leachate. Additionally, the UASB had no effect on reducing ammonia concentrations.

Pre-treatment options for the leachate also include various other types of anaerobic bioreactors being used in-line to treat the leachate before recirculation. In their experimental work, He et al. (2007) compared the result of leachate recirculation with single pass leachate pre-treatment in an anaerobic UFB (Up-flow Filtration Bioreactor) and recirculation with single pass leachate pre-treatment in an aerobic SBR (Sequential Batch Reactor). The anaerobic UFB enhanced the time required to shift into the methanogenesis phase with marked methane yields within 11 weeks of recirculation compared to 20 weeks in the other reactors. They claimed that such an enhanced rate of waste stabilization occurred in the anaerobic reactors with UFB because the excess VFA build up was removed with the anaerobic UFB and also since the inoculums in the UFB was acclimatised to high strength leachate. In the case of the bioreactor with leachate pre-treatment using aerobic SBR, the COD reduction was extreme and also was effective at reducing ammonia concentrations. However, the SBR forced a delay in phase shift to methanogenesis in the BLF.

In certain cases where landfilled waste has high volatile solids content that can be easily hydrolysed, having a normal leachate recirculation is not sufficient since it could inhibit the anaerobic consortia especially the methanogens in the system (He et al., 2007). If the concentration of inhibitory leachate components spike up, there can be a net detrimental effect on the rate of acidogenesis which in turn significantly affects the methanogenesis (He et al., 2007). In such landfills, even dilution has not been shown to be successful (Kim et al., 2001).

Lozecznik et al. (2010) utilized an Anaerobic Sequential Batch Reactor (ASBR) to pre-treat leachate from the Brady Road landfill facility, Winnipeg, Canada, to reduce COD and VFA concentrations. Leachate with lower COD and VFA concentrations showed better results with recirculation by improvements in methane production of up to 34% compared to controls. The ASBR in this study also decreased the Ca^{2+} ions in the leachate by 60%, which reduces the clogging rate of the pipelines in the LCS.

Mature landfills have a severe problem with leachate disposal. Collection and treatment is a very critical issue. Despite the fact that mature landfill leachate contains relatively low COD, it is still not treated in wastewater treatment plants mainly owing to contamination by heavy metals, and high ammonia content (Rowe, 1997; Li, 2009).

With extensive research in leachate treatment and disposal, Li et al., (2009), devised proprietary treatment trains for mature landfill leachate. A combination of SBRs, Fenton® process, Poly Ferric Sulphate (PFS) coagulation and UFBS the process is one of a kind devised to achieve up to 97.8% COD removal and 99% ammonia removal from mature leachate.

Pre-treating the leachate to decrease ammonia concentrations and reduce the dissolved COD loading has gained importance over recent years. In a study conducted by Gianis et al. (2008) dealing with pre-treatment using leachate aeration, in an aerobic bioreactor landfill as shown in Figure 2.14. They were able to achieve faster COD reduction of the waste in the bioreactor

landfills with aeration of the leachate. This study gives another option as to how leachate pre-treatment could be utilized to modify the rate and path of a bioreactor landfill operation.

Sun Y et al. (2011) performed tests by recirculating the leachate derived from fresh waste after treating it by passing through a column of aged landfill refuse. It was suggested that the aged refuse would semi aerobically treat and nitrify the leachate. The control reactor was loaded with fresh refuse with no leachate treatment. The experiments were based on utilizing a bed of naturally aspirated aged refuse to aerobically decrease high ammonia concentration in the leachate derived from fresh OFMSW as shown in Figures 2.15 and 2.16.

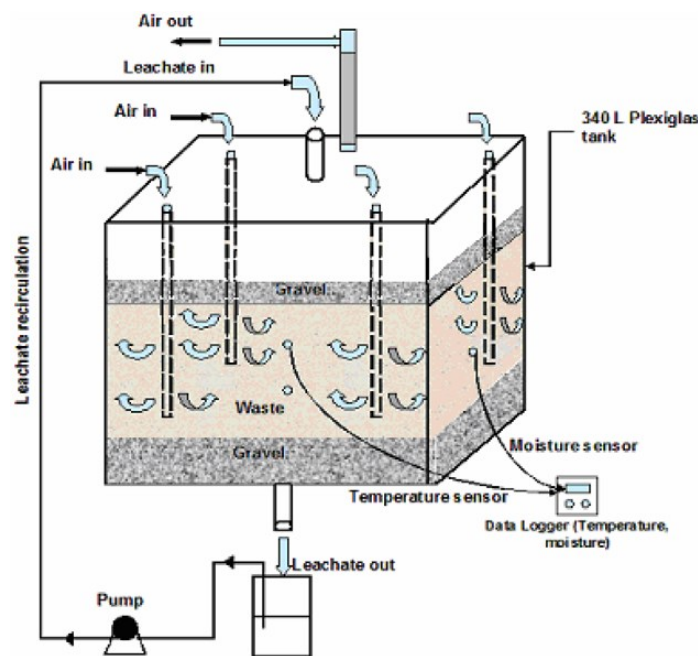


Figure 2-14 Schematic of aerobic bioreactor landfill with aerated leachate adapted from Gianis et al. (2008)

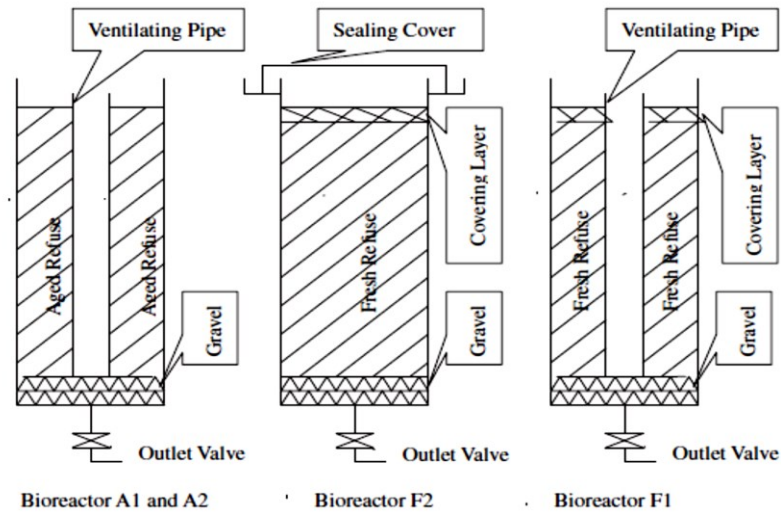


Figure 2-15 Experimental setup, adapted from Sun Y et.al. (2011)

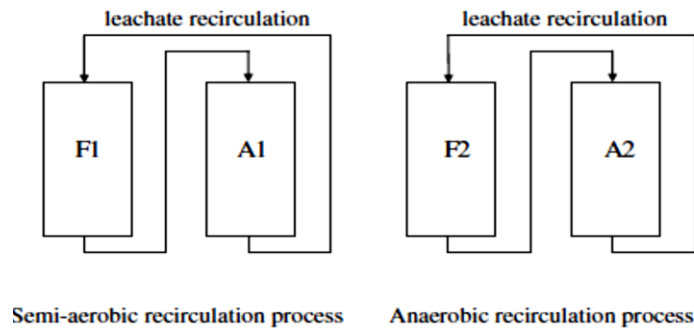


Figure 2-16 Leachate recirculation regime, adapted from Sun Y et al. (2011)

The study measured the changes in COD, TOC, pH, Total N, Total P and conductivity of the leachate samples. From their analyses, they were able to deduce that the quantity of leachate generated was directly proportional to the COD reduction of the fresh waste. They were able

to also conclude that a semi-aerobic recirculation process was able to achieve better results; which they ascertain is due to the fact that in the semi-aerobic recirculation process, there is evaporation of leachate by natural ventilation. The COD and pH analysis showed considerable difference in leachate quality. From their study it was inferred that leachate from older segments of landfill bioreactors have specific properties which differentiate them from young leachates. Their results showed that treating the leachate in semi-aerobic condition by passing through aged refuse yielded a 35% improvement in COD reduction. However, this approach might not be best suited for operational landfills which work based on anaerobic degradation.

In another study conducted by Dong et al. (2006) the effect of phase separation (between the phases in a landfill) separation to optimize simulated bioreactor landfills to achieve enhanced biogas production and waste stabilization was reported. Three bioreactors A, B and C were setup with compost and gravel in an attempt to actively aerate the leachate in the gravel under-drain in order to achieve faster and a more distinct landfill phase separation. Their secondary objective was to remove the ammonia by aeration. Characteristics of the leachate that they utilized are shown in Figure 2.17. With aeration and leachate treatment they were able to achieve faster stabilization and ammonia removal in their bioreactor. The reactor setup A had only leachate recycling with no aeration, while in B there was leachate recycle and intermittent aeration. Reactor C had the addition of activated sludge with leachate recycle and active sludge addition. The COD stabilization was achieved quickly as shown in Figure 2.18.

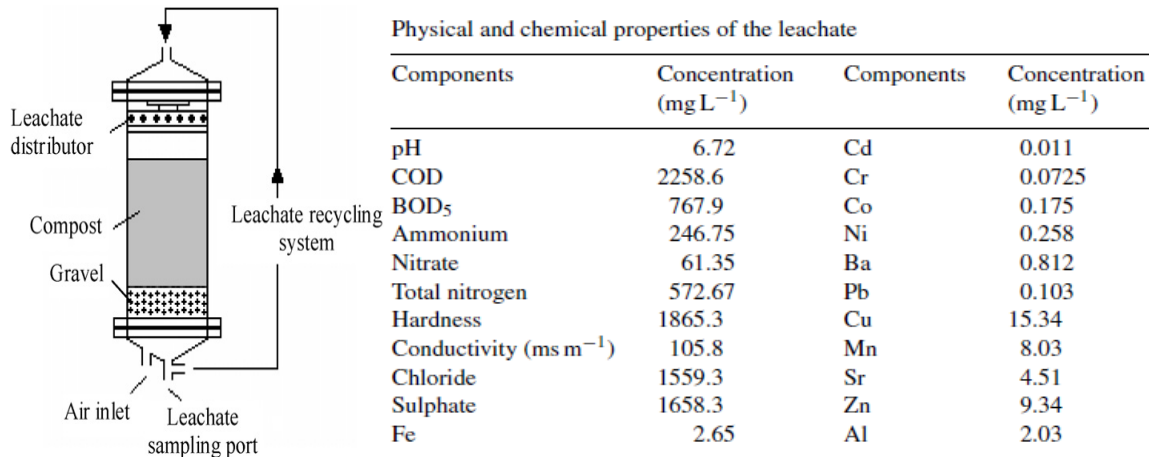


Figure 2-17 Bioreactor setup and leachate properties Dong et al. (2006)

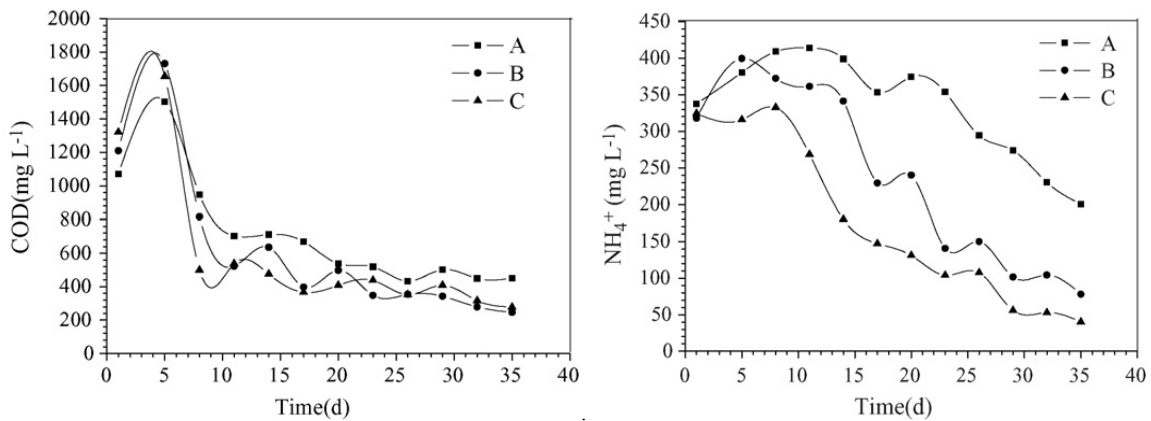


Figure 2-18 COD and Ammonia removal in bioreactor landfill (Dong et al., 2006)

Improved ammonia removal was also observed as a result of aeration of the leachate. The aeration of the leachate however, as illustrated by Dong et al. (2006) is best suited for hybrid bioreactors which are very few compared to the more common anaerobic bioreactor landfills. In addition the cost of aeration in bioreactor landfills is expensive and also has a lot of

operational issues mostly pertaining to clogging of aeration lines, additional energy requirement for blowers and so on.

2.5 Research Gaps

It has already been established that leachate properties in an anaerobic bioreactor landfill vary greatly depending on which phase of anaerobic digestion it is in and so recirculating in each phase has a different impact on the overall functioning of the landfill. If a landfill bioreactor is in hydrolysis, then recirculating the leachate would mean that there would be the accumulation of shorter chain organic compounds; the substrate for acidogens. Since the specific growth rate for acidogens are significantly higher than methanogens, VFA accumulation causes the pH to drop which proves detrimental to the methanogens. Similar is the situation if the recirculation is done in the acidogenic phase wherein the high concentration of VFAs lowers the pH throughout the bioreactor landfill. The recycled leachate should ideally have a balanced anaerobic microbial consortia (old leachate), low VFA concentrations and higher pH in order to moderate the effects of the VFAs in new landfill leachate. Old or mature leachate has these characteristics and could be used.

Therefore, it would be beneficial if the mature leachate from older sections of landfill (>10 years in age) can be utilized to enhance the performance of the new bioreactors in which case, the need for expensive processes for treating this leachate can be more or less

reduced(Kostova, 2006). If this process proves to be advantageous, then it would be a big breakthrough for bioreactor landfill operation. These landfills if possible could look forward to an expansion project with the fresh landfill leachate being blended with mature leachate from older segments of the same landfill so as to increase the rate of waste stabilization and biogas yield. There have not been studies done on blending (staging) mature and young leachate to observe the advantages of this in terms of stabilization time and methane yield.

One possible advantage of using a blend of mature and young leachate is that while the mature leachate portion has microorganisms that are starved for substrate, the young leachate portion brings in the substrate. As a result of the symbiotic substrate-microorganisms melange, the leachate would not have to be continually modified before reinjection into the BLF. On the other hand if the mature leachate has high ammonia concentrations some inhibition may occur that may require an ammonia removal step.

Chapter 3: Materials and Methods

3.1 Introduction

The experimental work in this study is divided into two parts: batch tests (BMP assays) and column reactors simulating landfills. The batch tests aid in providing a foundation to the initial hypothesis of feasibility of enhancing AD of OFMSW by blending young and mature leachate in a controlled and accelerated environment. These tests were performed in duplicates. The data and inference from batch tests are the basis for setting up column reactors which simulate bioreactor landfills. Testing protocols were as per standard code of practice. Appendix I provide hyperlinks to the online editions of the user manuals for the equipment used in this research.

3.2 Organic Fraction of Municipal Solid Waste (OFMSW)

MSW was collected from Lafleche Environmental landfill facility at Moose Creek, Ontario. The facility operated by Lafleche Environmental is a state of the art bioreactor landfill accepting residential waste since 2001. The solid waste was collected in two batches five

weeks apart. Nearly 90Kgs of organic waste (from the green box program in Ontario) was collected following hand sorting from the output of the shredder at the solid waste processing facility in Ottawa, ON in 15L plastic pails, transported and stored at University of Ottawa, at -4 °C. When required the MSW was removed from the cold storage and thawed for 24 hours at 35 °C before being used in column bioreactors.

Once thawed, the waste was hand sorted to remove non-biodegradable and difficult to degrade materials such as plastics and wood. The waste collected was mixed thoroughly using the quartering technique to ensure good mixing before use in the column reactors. This waste was characterised for COD, alkalinity, Moisture Content (MC), Total Solids (TS) and Volatile Solid (VS) content. The results and standard deviations are tabulated in Table 3.1. The characteristic properties of the anaerobic inoculums (Digested anaerobic sludge) obtained from ROPEC (Robert O. Pickard Environmental Center, Ottawa) are also given in Table 3.1

Table 3-1 Properties of prepared OFMSW and Inoculums

	Alkalinity as CaCO ₃ mg/l	COD mg/l	Ammonia as N mg/l	Moisture Content %	Total Solids mg/l	Volatile Solids mg/l	pH
OFMSW	1,600	536,317*	779	65.4	305,100	268,200	4.9
Anaerobic Inoculums	4,250	26,500	990	na	20,900	11,800	7.3

* The COD value measured by diluting sample with distilled water followed by blending and then centrifuging it. The COD of the centrate

is measured and used to calculate the COD of the OFMSW itself.

3.3 Prepared Food Waste

Organic fraction of municipal solid waste simulating domestic kitchen waste and industrial food processing waste used to supplement the MSW was prepared according to Shahriari, (2012). This waste would be used for the batch tests which simulates a controlled environment.

Food waste consisted of cooked rice (27.5 w %) cooked pasta (17.5 w %), carrot (11 wt %), apple (11 wt %), banana (11 wt %), cooked ground beef (10 wt %), dog food (10 wt %) and cabbage (2 wt%). The food waste was prepared weekly and stored at 4°C. The composition of the food waste had a standard composition of protein, hydrocarbon, vegetable and fat as suggested by the Canada Food Guide (CFG, 2007).

3.4 Mature Leachate

Mature landfill leachate was obtained from the municipal landfill at Carp Road, Carp Ontario. Leachate from the Carp road landfill was collected on July 28th, 2011. The landfill leachate collected was aged between 15-25 years. The leachate was collected in six 19L gasoline containers and transported to University of Ottawa and stored at a temperature of -4° C until used. The leachate was thawed at 35°C and used when required. A sample of the leachate was

sent for analysis to Exova testing laboratories, Colonnade road, ON and its characteristics are shown in Table 3.2.

Table 3-2 Mature leachate parameters, Exova Accutest results

PARAMETER	UNITS	MEASUREMENT
Alkalinity as CaCO ₃	mg/L	8200
Biochemical Oxygen Demand	mg/L	81
N-NH ₃ (Ammonia)	mg/L	1410
Sulphate	mg/L	48
Total Kjeldahl Nitrogen	mg/L	1450
Total Phosphorus	mg/L	18.3
Arsenic	mg/L	0.12
Cadmium	mg/L	0.04
Iron (total)	mg/L	14.0
Lead	mg/L	0.04
COD	mg/L	11,040
VFA as Acetic Acid	mg/L	868.4

3.5 Young Leachate

The young leachate for the study was generated by continuously percolating distilled water under anaerobic conditions through 100L of loosely packed MSW at a recirculation rate of 3L per hour over 3 recirculation cycles. Approximately 35L of fresh leachate was generated this way. The characteristics of young leachate are shown in Table 3.3. Figure 3.1 shows the visual appearance of the young leachate collected. The leachate quality started getting diluted

with every cycle of water addition which is reflected in lighter looking leachate as the cycles of water addition increased. This leachate was stored in the refrigerator at 2 °C.

Table 3-3 New leachate characteristics

	Alkalinity as CaCO ₃ mg/l	COD mg/l	Ammonia as N mg/l	VFA as Acetic Acid mg/L	Total Solids mg/l	Volatile Solids mg/l	pH
New Leachate	5,300	56,800	2,360	19,514	287	230	5.4



Figure 3-1 Leachate collected from percolating water through MSW

3.6 Batch Reactors (BMP Assays)

Two hundred and fifty mL Kimax® glass bottles capped with butyl rubber stoppers were used to perform mesophilic BMP assays. Total working volume was 200 mL consisting of OFMSW and leachate (discussed below) and included 70 mL of mesophilic anaerobic inoculums. Equal portions of NaHCO_3 and KHCO_3 were added to each bottle to achieve an alkalinity concentration of between 4000 and 6000 mg/L as CaCO_3 . This also buffered the pH in the bottles which was between 7.8 and 8.1. The bottles were subsequently sparged with nitrogen gas for two minutes to produce anaerobic conditions and then sealed. Assay bottles were brought to atmospheric pressure prior to incubation by inserting a BD 21G1½ needle connected to a U-tube manometer allowing the bottle pressure to equilibrate with atmospheric pressure. Bottles were incubated at $35 \pm 1^\circ\text{C}$ in a New Brunswick Scientific Controlled Environment Incubator Shaker model G-25 at 80 rpm, to keep bacteria and substrate in suspension. Figure 3.2 shows the sealed batch bottles on the shaker (Angelikadi, 2010). The measurement of the gas produced by the batch BMP bottles were monitored on a daily basis using a tube in tube manometer.



Figure 3-2 Mesophilic batch BMP bottles in fixed speed shakers

3.6.1 Batch Tests – I A

In order to investigate the effect of blending young and mature leachate on AD of OFMSW, batch test IA reactors were setup with the configuration as shown in Table 3.4. The organic loading consisted of OFMSW with different leachate blends. Batch tests were setup in the following format in duplicate:

- 30mL of leachate blend as explained in Table 3.4
- 3g of OFMSW(prepared food waste)
- 100mL of buffered distilled water
- 70 mL of anaerobically digested sludge.

Table 3.4 shows the nomenclature for the batch reactor bottles in batch test IA, IB and II. Parameters such as COD, pH, ammonia and VFA of the mixture in the bottles were measured at the start of the experiment, after 30 days and at the completion of the experiment. Biogas produced was measured with a manometer. The control reactor with inoculum control represents BMP of inoculum alone, while the control reactor with OFMSW contains inoculum and OFMSW. This control reactor simulates a batch BMP assay of a conventional regulated landfill with no recirculation.

Table 3-4 Batch bottles IA contents

3N:0O	3 parts new leachate
3N:0O duplicate	3 parts new leachate <i>duplicate</i>
2N:1O	2 parts new leachate + 1 part old leachate
2N:1O duplicate	2 parts new leachate + 1 part old leachate <i>duplicate</i>
1N:2O	1 part new leachate + 2 parts old leachate
1N:2O duplicate	1 part new leachate + 2 parts old leachate <i>duplicate</i>
0N:3O	3 parts old leachate
0N:3O duplicate	3 parts old leachate <i>duplicate</i>
Control (OFMSW only)	Control reactor with OFMSW plus water
Control (OFMSW only) duplicate	Control reactor with OFMSW plus water <i>duplicate</i>
Control (Inoculum only)	Control reactor with only Inoculum
Control (Inoculum only) duplicate	Control reactor with only Inoculum <i>duplicate</i>

3.6.2 Batch Tests – IB

In order to analyze the gas production from the leachate blends alone, a set of batch tests were conducted with the different combinations of the leachate used in the previous test. Batch BMP assays were setup in the following format in duplicates:

- 30mL of Leachate blend as explained in Table 3.5.
- 100mL of distilled water (dilution)
- 70 mL of anaerobically digested sludge.

Biogas produced was measured with a manometer. The biogas measured from this set of experiments gave the gas produced solely from the leachate.

Table 3-5 Batch bottles IB contents (leachate only)

3N:0O	3 parts new leachate
3N:0O duplicate	3 parts new leachate <i>duplicate</i>
2N:1O	2 parts new leachate + 1 part old leachate
2N:1O duplicate	2 parts new leachate + 1 part old leachate <i>duplicate</i>
1N:2O	1 part new leachate + 2 parts old leachate
1N:2O duplicate	1 part new leachate + 2 parts old leachate <i>duplicate</i>
0N:3O	3 parts old leachate
0N:3O duplicate	3 parts old leachate <i>duplicate</i>

3.6.3 Batch Tests II

In order to analyze the effect of closed recirculation system vs. an open recirculation system, the batch tests from IA were extended as a fed batch tests, with addition of additional

leachate. The leachate recirculation loop is explained in detailed under the section on column reactors. Batch bottles from test IA were modified in the following format:

- 30ml additional leachate blend added to the reactors as explained in Table 3.6.

Table 3-6 Batch bottles II contents

2N:1O OL	2 parts new leachate + 1 part old leachate blend addition
2N:1O CL	2 parts new leachate + 1 part old leachate no change to original bottle
1N:2O OL	1 part new leachate + 2 parts old leachate blend addition
1N:2O CL	1 part new leachate + 2 parts old leachate no change to original bottle
0N:3O OL	3 parts old leachate addition
0N:3O CL	3 parts old leachate no change to original bottle

During loading of the bottles (fed batch) 30ml of air was syringed out prior to injecting the leachate blend to ensure that there was no residual pressure during the addition of leachate. 30mL of leachate blend was injected into the bottles. The bottles with the leachate addition represent an open system wherein the leachate addition in a bioreactor landfill would be done in cycles, i.e. intermittent recirculation, and the bottles without any leachate addition represents a closed system in which the original leachate was continued to be recirculated. Biogas produced was measured with a manometer.

3.6.4 Batch Tests – III

Batch test set III was setup with the objective of determining the effect of different organic waste loading with the best leachate blend obtained from the first stage of batch tests. The leachate blend used was 1 part of young leachate and 2 parts of old leachate (1N:2O). Batch BMP assays were setup in the following format:

- Prepared food waste loads as shown in the Table 3.7
- 30mL of Leachate blend (10mL new leachate+20mL old leachate).
- 100mL of distilled water (dilution)
- 70 mL of anaerobically digested sludge.

Table 3-7 Batch bottles III contents

1	3g of OFMSW
2	3g of OFMSW duplicate
3	6g of OFMSW
4	6g of OFMSW duplicate
5	9g of OFMSW
6	9g of OFMSW duplicate

The measurement of the gas produced by the batch BMP bottles were monitored on a daily basis. The gas measured from this set of experiments gives an indication as to whether or not a bioreactor landfill can achieve better biodegradation with larger or smaller waste lift size. Biogas produced was measured with a manometer.

3.6.5 Batch Tests – IV

These batch tests were setup with the objective of analyzing the effect of distributed loading of OFMSW with the best leachate blend obtained from batch test I. The leachate blend used was 1 part of young leachate and 2 parts of old leachate (1N:2O). Batch tests were setup with the following format:

- 3 different OFMSW loading strategies as shown in the table 3.8
- 30mL of leachate blend (10mL new leachate+20mL old leachate).
- 100mL of distilled water (dilution)
- 70 mL of anaerobically digested sludge.

Table 3-8 Batch bottles IV contents

1	3g of food waste
2	3g of food waste duplicate
3	1.5g food waste on day1 + 1.5g food waste on day 20
4	1.5g food waste on day1 + 1.5g food waste on day 20 duplicate
5	1g food waste on day1 + 1g on day 20 + 1g on day 40.
6	1g food waste on day1 + 1g on day 20 + 1g on day 40 duplicate

The quantity of gas generated in these batch bottles were measured on a daily basis with the U-tube manometer. However, during the first week of operation, gas measurements had to be more frequently due to large biogas production in the 1.5g and 1g bottles. During loading of the bottles (fed batch) the biogas production was measured twice to ensure that there was no retention of any gas. The stopper was then removed while simultaneously sparging the bottle

with nitrogen as the rubber stopper was replaced. The system was vented via the manometer to ensure that there was no residual pressure in the bottles as a result of the nitrogen sparging.

The results from this batch BMP assay would give an estimate as to what kind of waste filling pattern (i.e. shallow vs deep lifts) might enhance biogas generation in a bioreactor landfill.

3.7 Column Reactors: Simulated Bioreactor Landfills

Six (6) sealed column bioreactors were setup made with 15mm Plexiglas that were 120mm X 120mm X 1200 mm with a bottom reservoir capacity of 2.9L wherein the leachate would be collected and stored prior to recirculation. Ceramic beads were used as a support media on which a perforated acrylic plate was mounted after which MSW and OFMSW was loaded into the columns. A schematic of the setup is explained in Fig. 3.3.

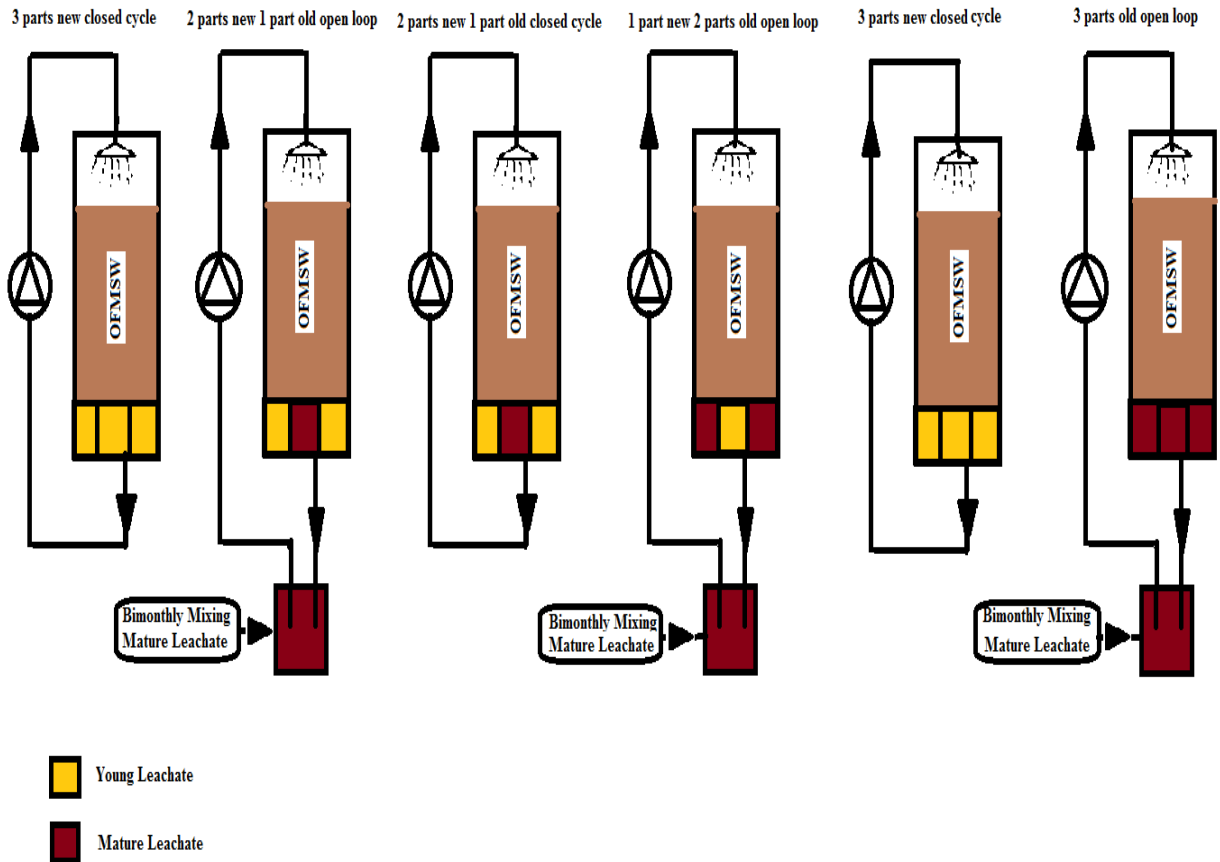


Figure 3-3 Experimental setup for column bioreactors

The collected MSW was mixed with the remaining portion of the prepared food waste (mixture of rice, pasta, carrots, potatoes and cabbage.) Using the quartering method, the waste was well mixed before filling the column bioreactors.

Using a compaction tool, the waste was compacted to between 500-550 kgs/m³ in all the reactors. The experimental setup after loading the reactors is shown in Figure 3.6. Characteristics of the MSW-OFMSW mixture used in the columns is shown in Table 3.9.

Table 3-9 Characteristics of OFMSW

	Total Solids (mg)	Volatile Solids (mg)	Organic Content (%)	Moisture Content (%)	COD (mg/L)
OFMSW	2,031	1,620	79.6	32.3	536,300

Masterflex© pumps were used to recirculate the leachate in the columns based on the strategy presented in Table 3.10. Old leachate was 20-25 years old collected from the Carp landfill. The young leachate used was generated by percolating water through collected OFMSW as previously explained. The gas produced by the column reactors was collected in tedlar® bags (Figure 3.3) which would then be precisely measured with a U-tube manometer coupled to a peristaltic pump



Figure 3-4 Tedlar ® bags for gas measurement

Table 3-10 Reactor Configuration and Nomenclature

Reactor number	Nomenclature	Parts of young leachate	Parts of mature leachate	Loop-Open/Closed
I	3N:00-CL Control	3	0	Closed
II	2N:1O-CL	2	1	Closed
III	2N:1O-OL	2	1	Open
IV	1N:2O-OL	1	2	Open
V	3N:00-CL Spare control	3	0	Closed
VI	0N:3O-OL	0	3	Open

Reactor 3N:00-CL: This reactor was a control reactor which was operated with water without any additional leachate mixture. 3L of water was added to bring it to the field capacity. Once the leachate was generated, it was recirculated at 6L/hr for one hour twice-weekly. Since there was no external leachate mixture being recirculated in this reactor, it would represent a control closed loop bioreactor landfill with leachate as produced recirculation.

Reactor 2N:1O-OL: This reactor was operated with 3L of a leachate blend (2L of young and 1L mature) that was recirculated. Once the leachate was generated in the reservoir, it was recirculated at 6L/hr for one hour twice-weekly. Once every four recirculation cycles (once every two weeks), 1L of the leachate was removed from the 3L mix and was replaced by 1L mature leachate. This reactor simulated a fresh landfill recirculating young leachate supplemented with old leachate and follows an open loop system as shown in Figure 3.8 as a

portion of the leachate is replaced. The reactor simulates a fresh landfill utilizing a blend of young and old leachate aged approx.4-5 years.

Reactor 2N:1O-CL: This reactor was operated with 3L of a leachate blend (2L of young and 1L mature) recirculated. Once the leachate was generated in the reservoir, it was recirculated at 6L/hr for one hour twice-weekly. The reactor was operated as a closed loop system with no additional leachate introduced into this reactor. The reactor simulates a fresh landfill utilizing a blend of young and old leachate recirculating in a closed loop as shown in Figure 3.8. The reactor simulates a fresh landfill utilizing a blend of young and old leachate aged approx. 2 years.

Reactor 1N:2O-OL: This reactor was operated with 3L leachate blend (1L of young and 2L mature) recirculated. Once the leachate was generated in the reservoir, it was recirculated at 6L/hr for one hour twice-weekly. Once every four recirculation cycles (once every two weeks), 2L of the leachate was removed from the 3L mix and was replaced by 2L mature leachate. The reactor simulates a fresh landfill utilizing a blend of young and old leachate aged approx.10 years and follows an open loop system as shown in Figure 3.8 as a portion of the leachate is replaced.

Reactor 3N:0O-CL Spare control: This reactor was operated similar to reactor I and served as a second control.

Reactor 0N:3O-OL: This reactor was operated with 3L of old leachate recirculated. Once the leachate was generated in the reservoir, it was recirculated at 6L/hr for one hour twice-weekly. This reactor was operated in the open loop mode and once every four recirculation cycles (once every two weeks); 1L of the leachate was removed from the 3L mix and was replaced by 1L of mature leachate. This reactor simulates a fresh landfill recirculating leachate obtained from older segments of the landfill aged at least 15-20 years

Figure 3.5 depicts the two leachate recirculation loops. In the closed loop system, there is no addition of any leachate externally during the mixing cycles. In case of drop in leachate levels as observed in the reservoir, either water in case of controls or corresponding leachate blend was added to compensate for loss of the leachate. In the open leachate recirculation loops, a component of the spent leachate was replaced with the corresponding component of the mature leachate.

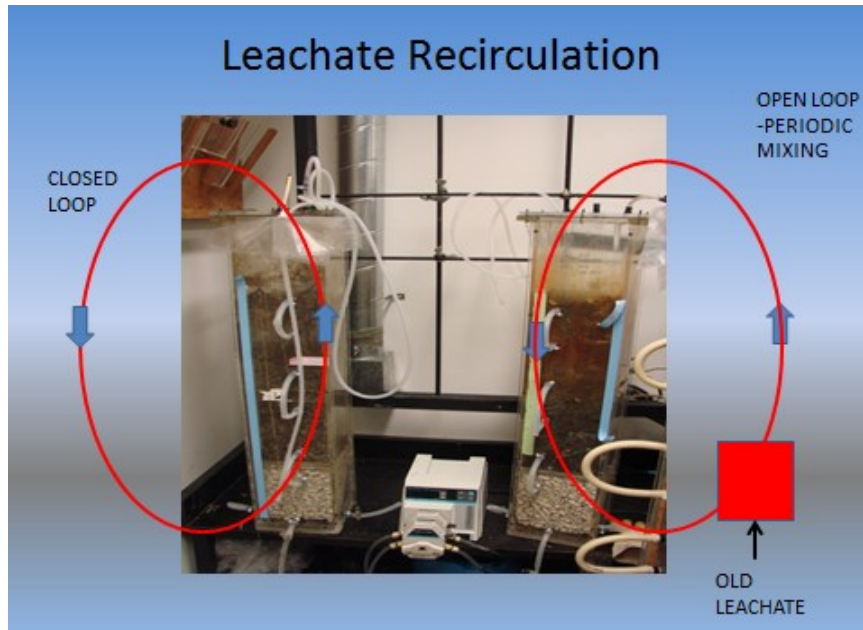


Figure 3-5 Open and closed leachate recirculation loop



Figure 3-6 Column reactors with loaded OFMSW

3.8 Analytical Equipment and Methods

Gas samples were analyzed for gas composition with thermal conductivity gas chromatograph (series 400, Gow-Mac Instrument Co., USA) as shown in Figure 3.7. The detector, injection port and column temperatures were 130°, 130°, and 120°C, respectively, and the carrier gas was helium at inflow rate of 30 mL/min. The instrument contains two sampling columns; column A measures N₂, O₂ and CH₄ while column B measures N₂, CH₄ and CO₂ percentages in the gas sample. The samples injected were in duplicates. Tedlar® bags were used to collect the gas in the column reactors. The gas was measured by draining the tedlar bags using a peristaltic pump into a manometer to measure the gas.



Figure 3-7 GOW- MAC GC Equipment- gases

Leachate samples were analyzed in triplicates for chemical oxygen demand (COD), ammonia nitrogen (NH₃-N); in duplicates for total alkalinity (TA) and volatile fatty acids (VFAs). COD was measured with the reactor digestion method (5220-D, APHA, 2005) using TNTplus™822

high range reagent vials (Method 8000, Hach, USA). Ammonia was measured with the salicylate method using TNTplus™ 832 reagent vials (Method 10205, Hach, USA). The Hach DR 5000 UV-VIS spectrophotometer, Figure 3.8, was used to analyze the reagent vials of COD and Ammonia. The DR200 heating block for COD vials was used to heat and digest the Hach TNT 822 test vials.



Figure 3-8 Hach DR5000 Spectrophotometer with bar code scanner

VFAs were measured using the gas chromatographic method (5560-D, APHA, 2005) with an Agilent-6890 gas chromatograph Figure 3.9 (HP-Agilent Technologies, Inc., USA) equipped with a Flame Ionization Detector (FID).

Total Alkalinity was determined by titration to pH = 4.50 (2320-B, APHA, 2005). pH was measured using a Fisher Accumet model XL25 dual channel pH/ion meter equipped with a glass electrode.

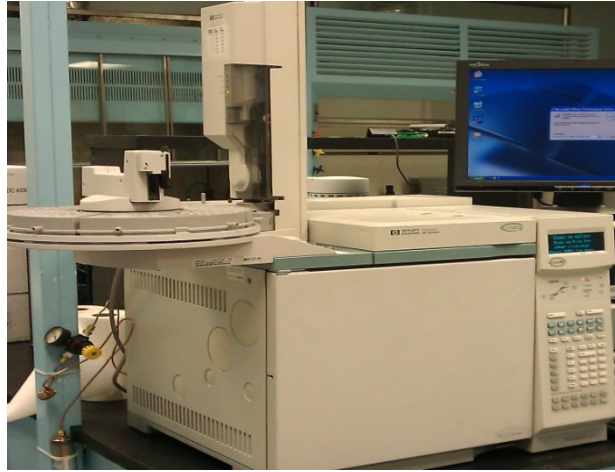


Figure 3-9 HP- Agilent VFA gas chromatograph

Chapter 4: Results and Discussion

The results from the batch tests were able to provide a better understanding as to whether or not the blending of the leachate had a positive effect on the anaerobic biodegradation of OFMSW. It also provided an estimate to the type of quantitative loading that would be optimal to run such systems. The batch BMP assays conducted also showed the effect of staged organics loading rate as well as the effect of operating the system under open/closed scheme.

The column reactors on the other hand would give a better understanding of how real world landfill bioreactors operate and the processes and bacterial activity and whether or not leachate blending had any effects in a real world bioreactor landfill. The results from the column reactors also would aid in strengthening the results from the batch tests and the hypothesis that staged leachate recirculation aided in improving the gas production from bioreactor landfills.

4.1 Batch Tests – IA

The objective of batch tests - IA was to assess if blending mature and young leachate would enhance anaerobic biodegradation of OFMSW and the rate and generation of biogas production. Leachate blends with mature and young leachate can vary in biodegradability owing to the difference in organic contents and characteristic between the blends as is observed from batch tests IB. Leachate recirculation alone has been proven to improve the overall biogas production and speed up OFMSW stabilization from both pilot studies and actual landfill operations.

The biogas generated in batch tests IA would be representative of the biogas contribution from both the leachate as well as the OFMSW. The biogas generated from the leachate blends component (analyzed from batch tests IB) was then subtracted from the total biogas generated in batch tests IA, to get the actual biogas production from the OFMSW. Based on the results from this data, it would be possible to infer whether or not the leachate blending has any considerable enhancement in anaerobic biodegradation. The control reactor with inoculum control represents BMP of inoculum alone, while the control reactor with OFMSW contains inoculum and OFMSW. This control reactor simulates a batch BMP assay of a conventional regulated landfill with no recirculation.

The cumulative gas production for all reactors in batch tests IA is shown in Figure 4.1. It was observed that the reactor configuration 2N:1O had the highest total biogas generated.

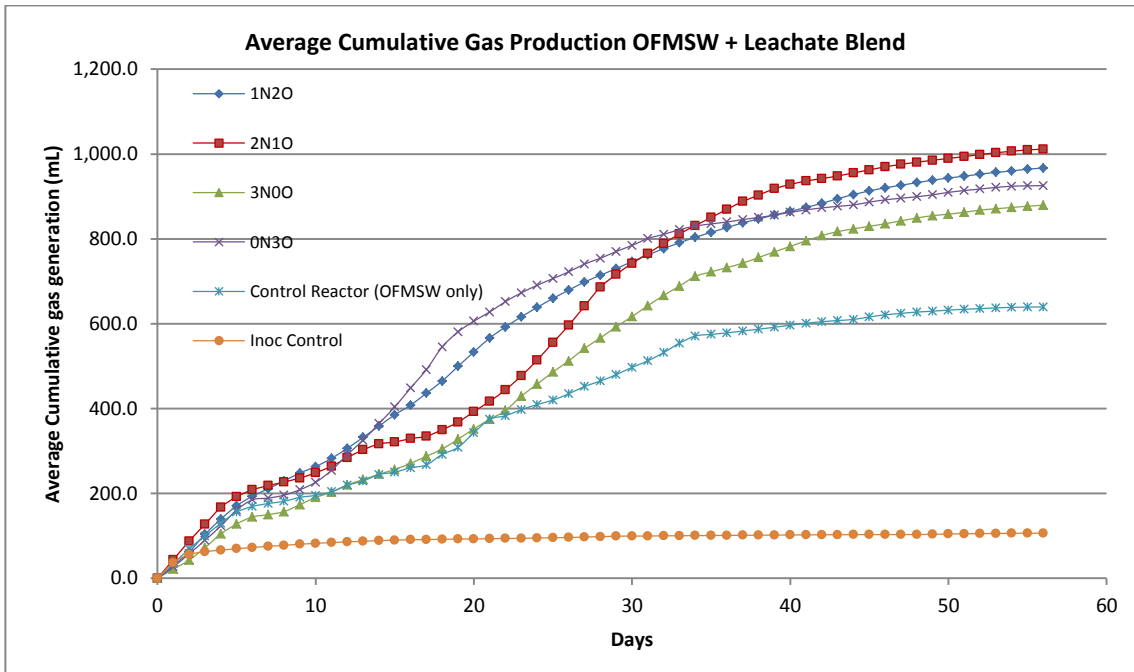


Figure 4-1 Average cumulative gas production batch tests IA

4.2 Batch Tests – IB

Batch Test-IB analyzed the biodegradation of the different leachate blends only. The results shown in Figure 4.2 give an account of the total biogas production contribution by the leachate blends only. Table 4.1 summarizes the characteristics of the mature and young leachates used for the blending leachate, as previously discussed in details in Chapter 3. It is observed that the mature leachate has almost no biodegradable organic material in it (COD of 11,040 mg/L and BOD of only 85mg/L) as a result of which there was not much biogas observed in the leachate blends bottle 0N:3O containing only mature landfill leachate (160mL of biogas, see Figure 4.2). The young leachate however, had a high COD load of 56,800mg/L

(Table 4.1), most of which was biodegradable. Therefore, it was reasonable to find that the batch bottle 3N:0O, containing 30mL of only young leachate produced 1,487mL of biogas.

Table 4-1 Characteristics of mature and young leachate

	Alkalinity as CaCO ₃ mg/L	COD mg/L	BOD Mg/L	Ammonia as N mg/L	VFA as Acetic Acid mg/L	Total Solids mg/L	Volatile Solids mg/L	pH
Young Leachate	5,300	56,800	22,500	2,380	19,514	287	230	5.4
Mature Leachate	8,200	11,040	85	1,410	868.4	96	22	8.9

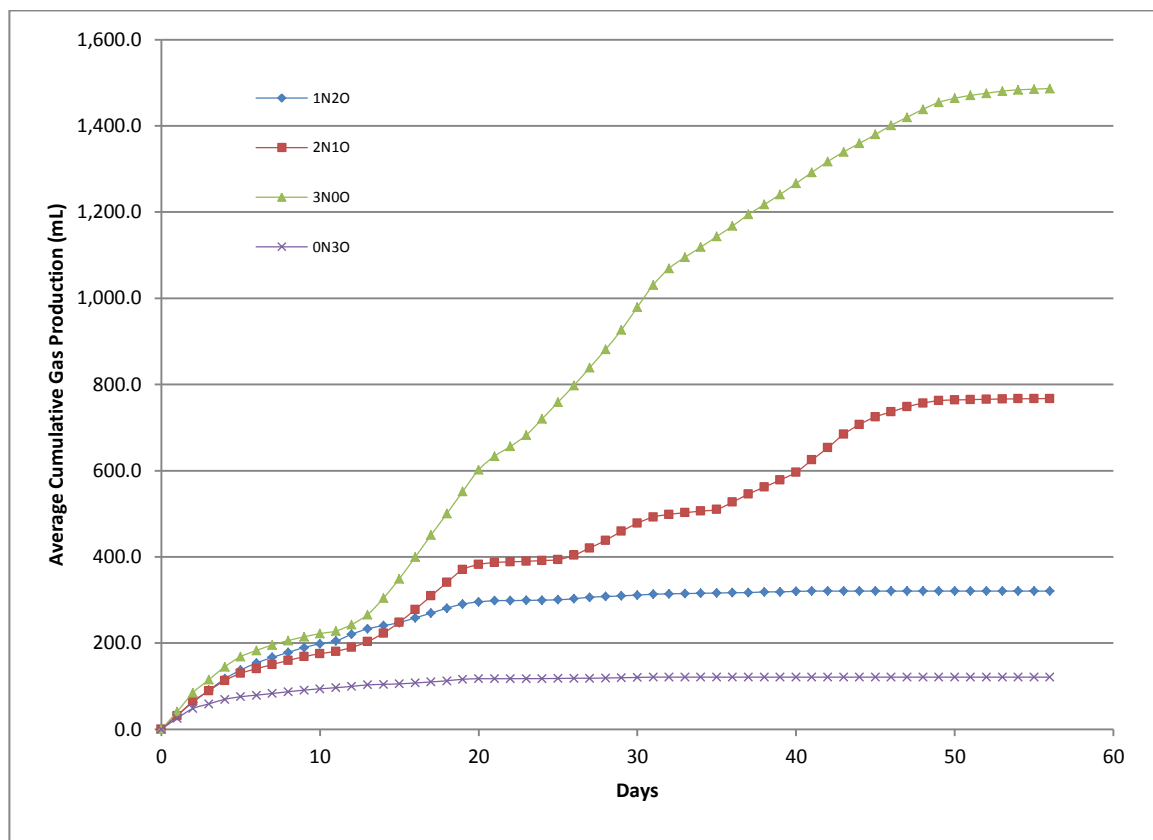


Figure 4-2 Cumulative gas production from pure leachate blends- Batch tests IB

The amount of gas produced is reflective of the extent of biodegradation of the leachate. This shows that the higher the percentage of new leachate in the leachate blend, the higher is the gas produced due to the biodegradation of leachate alone. The bottles with the blends 0N:3O, 1N:2O, 2N:1O and 3N:0O produced biogas at 160 mL, 321mL, 767 mL, and ~1500 mL, respectively, which correlated with the component of young leachate present in them. However, it was observed that there were days wherein the biogas production in the bottles 3N:0O and 2N:1O were erratic. This was observed in the cumulative biogas production curve (Figure 4.2.)

The biogas produced initially contained as little as 20% of methane for the first four days following which the methane content had increased to 59.8% and stayed consistent since 14 days at 61.4%.

The batch bottles in batch tests IA contained 3 g OFMSW, 10 mL of leachate blend, 70 mL of inoculum, and 100 mL dilution water, as was discussed earlier in Chapter 3. In order to estimate the contribution of biogas generated from the OFMSW alone due to the leachate addition in batch tests IA, the net and corrected (based on the amount of leachate used) gas production data from batch tests IB was subtracted from the total cumulative gas produced from the mixture of OFMSW and leachate blends in batch tests IA. It is to be kept in mind that while subtracting the biogas generation due to leachate, we automatically removed the component of biogas produced from the inoculum.

In batch tests IA, the leachate that was added was 10mL, while the leachate quantity added in batch tests IB was 30mL. In order to remove the component of biogas generated from the same amount of leachate blends, a correction was made to the amount of biogas generated from 10mL of the leachate blends. The final plot of net biogas production after correction is shown in Figure 4.3. This gave an account of the biogas production from OFMSW alone.

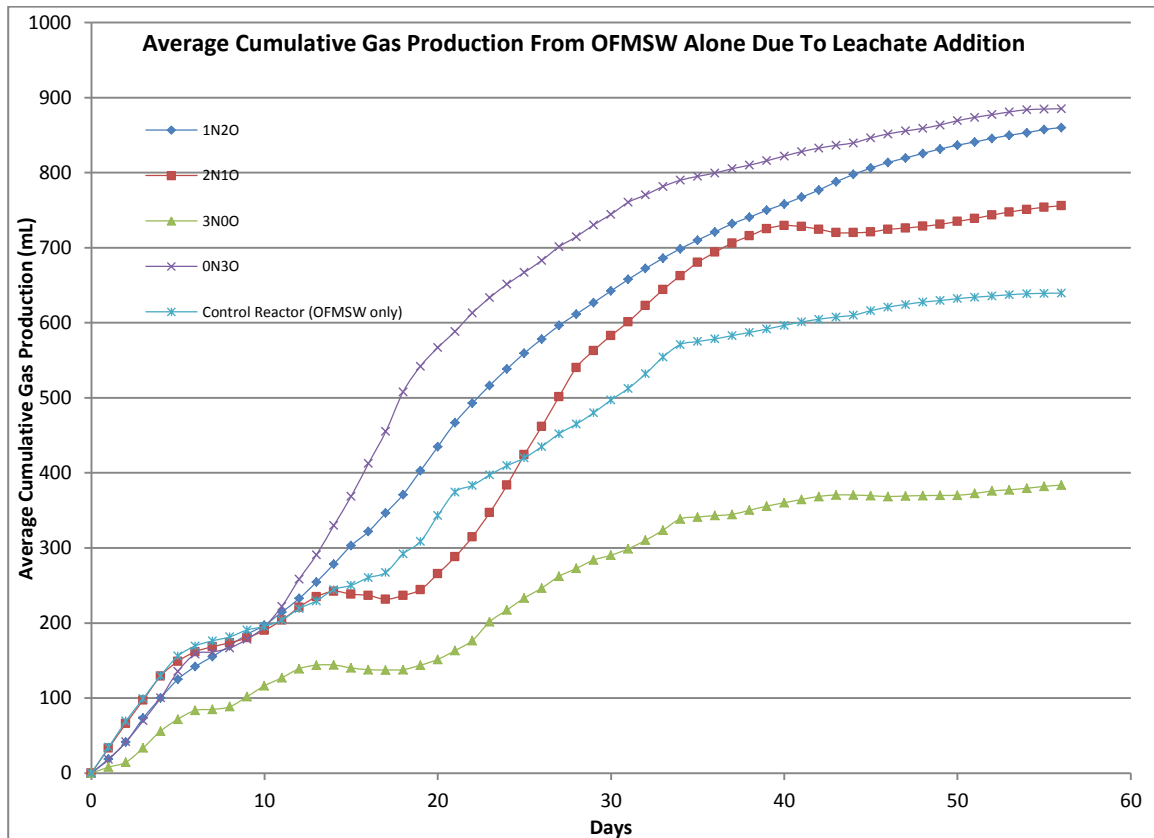


Figure 4-3 Average Cumulative net Gas Production from OFMSW due to Leachate Blending/Staging

These results showed that blending mature and new leachate had a positive effect on biogas production. The reactors with higher proportions of mature leachate, i.e. 0N:3O and 1N:2O, had higher total biogas productions compared to 2N:1O and 3N:0O which had lower proportions of mature leachate. Though the results seem to suggest that 0N:3O was the best leachate combination to use since it produced the most gas; from a practical perspective the leachate blend 1N:2O would be more suitable. This was due to the following reasons:

1. The results show that the difference in cumulative is negligible (less than 3%)
2. The leachate blends 1N:2O has a higher COD content. Hence, the total organic loading can be more efficiently increased with this leachate blend over the complete mature 0N:3O leachate in a working BLF. As a result there is a higher potential for biogas production,
3. By blending old and new leachate the new leachate is treated and managed at the same time in terms of organic contents. If only mature leachate were to be used in a large scale operational BLF, the generated leachate would need to be treated before disposal because of the 2% rule previously discussed and
4. This study is based on enhancing biogas production via leachate blending wherein the leachate 0N:3O contains only mature leachate and is not a blend. Figure 4.4 shows the final biogas yields from the OFMSW+ leachate mixture, leachate only and from OFMSW due to the addition of leachate blends.

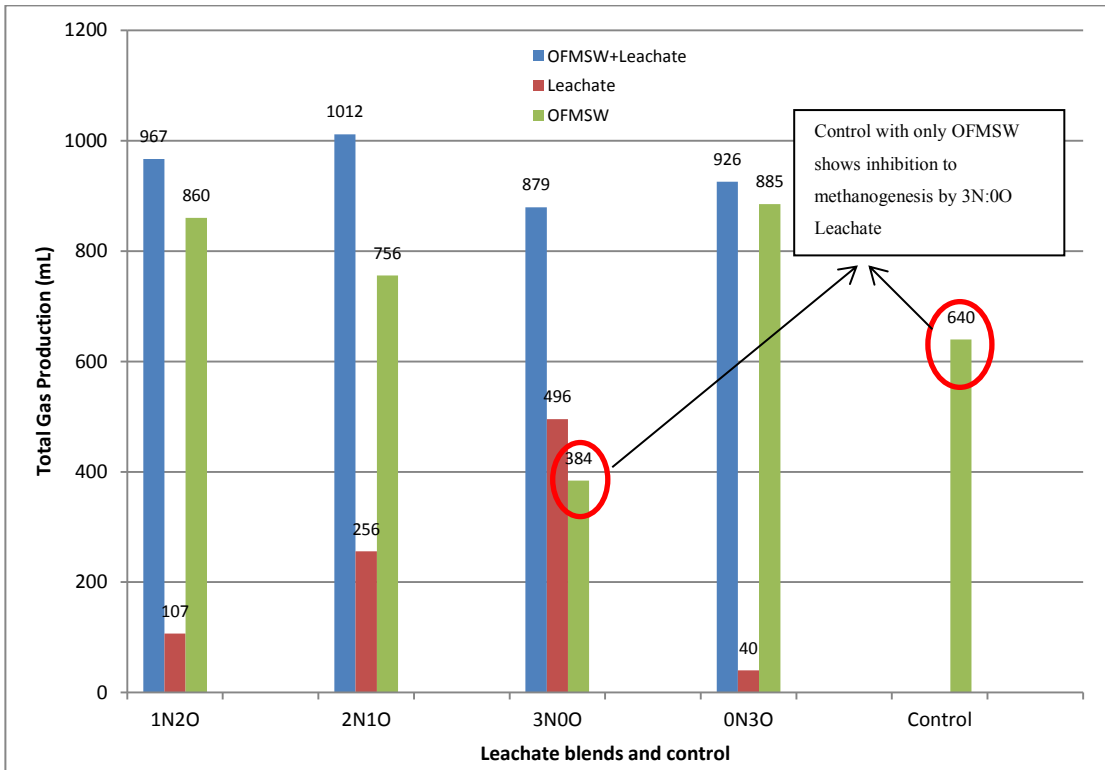


Figure 4-4 Total Gas Production Split up

As seen from Figure 4.4, the presence of mature leachate component enhanced the total biogas produced from OFMSW showing that blending and recirculating mature leachate through fresh waste results in a more efficient biodegradation. The reactors with higher proportion of mature leachate, i.e. 0N:3O and 1N:2O had higher total biogas productions contributed by OFMSW at 885mL and 860mL, respectively, compared to 2N:1O and 3N:0O which had total biogas productions at 756mL and 384mL, respectively. Comparing these results with the biogas production for the control reactor (640 mL) shows 38%, 34%, and 18% increase for 0N:3O, 1N:2O, and 2N:1O combinations, respectively, and a decrease of 40% for

3N:0O, which could be attributed to the inhibitory effect of some constituents such as ammonia in the young leachate. In modern day landfills, blending old and fresh leachate is a viable strategy, i.e. to blend of mature and young leachate before recirculation than recirculating only mature leachate. If this can be applied to landfill bioreactors, the fresh cells can prove to be a good management option for treating leachate as well and increase the biogas generation total and the rate of biogas production at the same time.

Comparing the effect of a conventional bioreactor landfill with recirculating only fresh leachate (3N:0O) with a bioreactor landfill with mature leachate addition (0N:3O), there is a significant enhancement in the biogas generation in the reactors of nearly 130%. Comparing the leachate blend 1N:2O with the conventional BLF (3N:0O), the enhancement brought about by blending (staging) is 124%. The percentage improvements brought about by the 0N:3O mature leachate compared to 1N:2O leachate blend is negligible and less than 3%; so for the reasons stated above it was concluded that the best leachate blend is the 1N:2O.

A possible reasoning for observing higher gas production in batch bottles with higher fractions of mature leachate is that as hypothesized, the presence of the mature leachate has a stabilization effect on the system which is probably brought about by the higher pH (pH of mature leachate was 8.9) and also the fact that it contained more microbial consortium than fresh or young leachate. The VFAs was also significantly lower in the mature leachate. The acetic acid component for the mature leachate was at 868 mg/L compared to 19,514 mg/L for the young leachate. Several studies conducted on mature leachate substantiate the advantages

of recirculation of leachate at a higher pH (7-9) (Chugh et.al, 2003; Reinhart and Townsend, 2006). With an increased pH alone, studies have shown that there is quicker phase shift into methanogenic phase from acidogenesis.

Once the VFAs stabilization is achieved, it enhances the methanogenic activity and in this study it is evident that it brings about an enhanced reaction rate for the biodegradation of the food waste. The methanogenesis is retarded also by the amount of ammonia in the mixture. In the fresh leachate, the ammonia levels were as high as 2,380 mg/L which is inhibitory to methanogenesis (Reinhart and Townsend, 1999). The mature leachate had an ammonia level of 1,410 mg/L which was high compared to the mature leachate used in other studies (in the range of 6-500 mg/L) (Chugh et.al, 2003; Kostova, 2006; Rowe, 1993). However, these values were within the toxic levels for methanogenesis which is stated to occur at concentrations over 1,500 mg/L (Angelikadi et.al, 2009).

Most studies dealing with fresh leachate state that young leachate contains relatively lower concentrations of ammonia in the range of 700 mg/L to 1,500 mg/L (Dong et.al, 2007; Kostova, 2006; Bilgili et.al, 2007). With the young leachate having ammonia levels of 2,380 mg/L, it could be expected that the addition of young leachate alone would result in inhibition to methanogenesis. As stated above this was distinctly observed in from the results shown in Figure 4.4 where 67% decrease in biogas production was observed in 3N:0O leachate blend compared to the control reactor having OFMSW alone. It could be hypothesized that the methanogenic bacteria utilized the solubilised organic material in the leachate prior to the

COD in the OFMSW by which time the VFA would have increased, and ammonia levels being toxic could have brought about a retardation which was why the biogas production from leachate alone in 3N:0O batch bottles was higher (496mL) compared to the biogas from OFMSW alone (384mL).

In the first week of batch tests IA, almost all batch bottles showed similar behaviour with the reactors having leachate blends (1N:2O and 2N:1O) producing biogas at a faster rate compared to the control bottles and the reactor bottles with no leachate blending (3N:0O and 0N:3O). An explanation for this behaviour could be due to the fact that while the young leachate component in the blends contained a higher concentration of VFA, the mature leachate component contained more stable methanogenic consortia. So even with the acidogenesis of the food waste dropping the pH to as low as 6.8, the biogas production still continued because of acclimatized bacteria from the mature leachate was still active. Further on the methanogenic activity acted like a buffer and brought the pH back to 7.5.

On completion of methanogenesis indicated by very low cumulative biogas generation, it was observed that higher yields were observed for the reactors that had higher slopes during weeks 2 and 3 of operation. This meant that the reactors that produced gas fastest also produced most biogas (1N:2O and 0N:3O). Hence, the blending achieves remarkably better results compared to the control reactors in terms of total biogas generation. It can be said that the presence of the mature leachate would have enhanced the rate of biodegradation which in turn makes the gas production higher.

4.3 Total Biogas Generation- Batch Test IA Blending Effect Analysis

In this section, the individual bottles from the batch BMP test IA for each of the leachate blends were analyzed along with the control for the total biogas generation with leachate blend and OFMSW were analyzed. Variations in critical parameters such as COD, VFA and ammonia levels were also analyzed for each leachate blend.

4.3.1 3N:0O Leachate Blend:

The results from the batch test IA for the bottles with 3N:0O and control are presented in Figure 4.6. This shows the total biogas generation for the blend as compared to the control reactor. These batch test bottles are representative of a conventional bioreactor landfill once the newly generated leachate is recirculated (with no leachate blending). The results also show good repeatability in the tests. The values with the duplicate bottles are very close to each other.

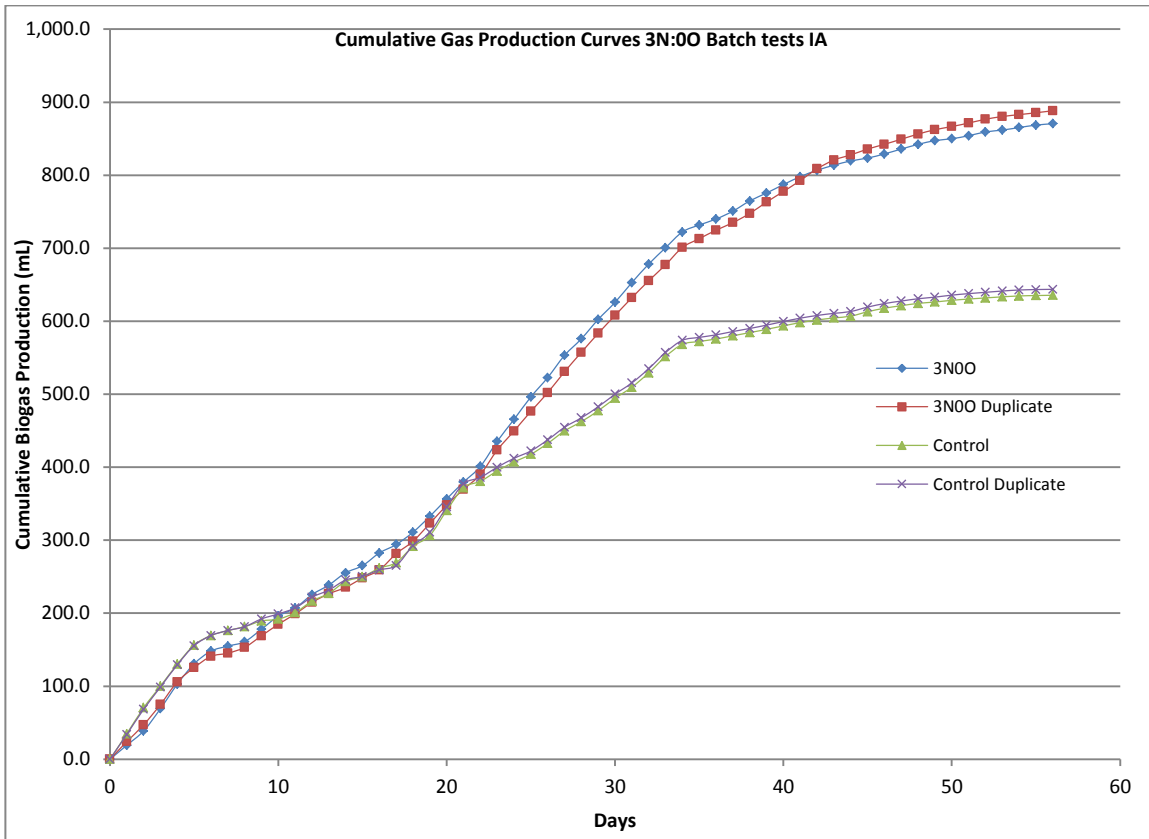


Figure 4-5 Cumulative Gas Production Curves 3N:0O

It is to be noted however, that the additional biogas generation in this bioreactor was due to the additional organic loading in the form of young leachate which contained quite a high organic load since the COD of the young leachate was 56,800 mg/L. Studies related to young leachates suggest that the COD levels in the young leachate are significantly higher than older leachates, with a reported range of 10,000-60,000 mg/L. (Kim and Pohland, 1997; Kostova, 2006; Bilgili et.al., 2009). The generated young leachate had similar properties as the leachate

used by studies which generated leachate from real OFMSW, like the study on S.M.A.R.T bioreactors (Abdallah et.al, 2012).

Figures 4.6, 4.7, and 4.8 show the COD, VFA (including Acetic Acid, Propionic Acid and Butyric Acid concentrations), and ammonia concentrations, respectively, of the bottles containing only young leachate at the start of the batch test, at the end of week 3 and at the end of day 60.

During the start-up of the bottles, the COD concentration in these reactors was highest at 4,120 mg/L. The starting ammonia concentration was also the highest for young leachate at 503 mg/L (This is different from the ammonia concentration of the leachate due to dilution.) The VFA had the highest concentrations of propionic and butyric acids at 40 mg/L and 90 mg/L, respectively, and also had high concentrations of acetic acid at 830mg/L. The higher the concentrations of propionic and butyric acids, the longer it takes for the onset of methanogenesis. The propionic and butyric acids are the most difficult VFAs to biodegrade anaerobically.

Following the 3rd week of the operation cycle, the acetic acid component of the total VFAs had risen to 1,510 mg/L while the propionic and butyric acid concentration had increased to 260mg/L and 170 mg/L, respectively. As a result of the high acid content, the pH had dropped to 7.2.

The COD concentration in reactors 3N:0O had reduced from 4,120mg/L to 3,570 mg/L at the end of week 3. It was already observed that the leachate component biodegrades comparatively quicker than the OFMSW component mainly because all the COD in the leachate was in the soluble form. It was observed that by the end of week 3, almost all of the biogas produced from the leachate was negligible. The concentration of ammonia in reactors 3N:0O had increased to 546 mg/L from 503mg/L as a result of hydrolysis of the OFMSW. In anaerobic digestion, there is no aeration and hence, ammonia does not reduce.

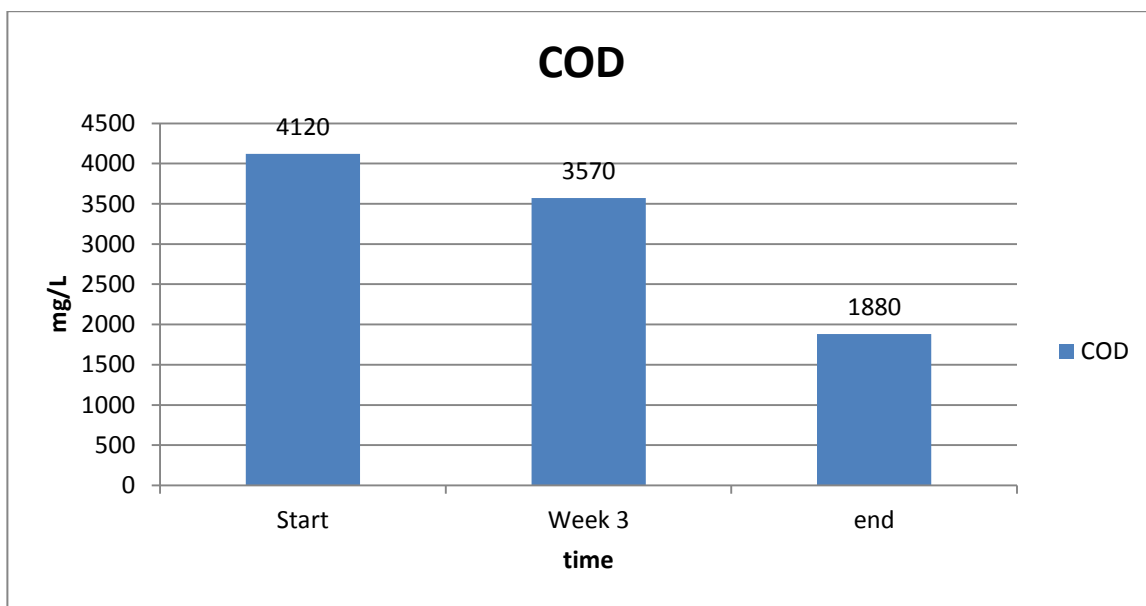


Figure 4-6 3N:0O: COD – start, after 3 weeks and completion

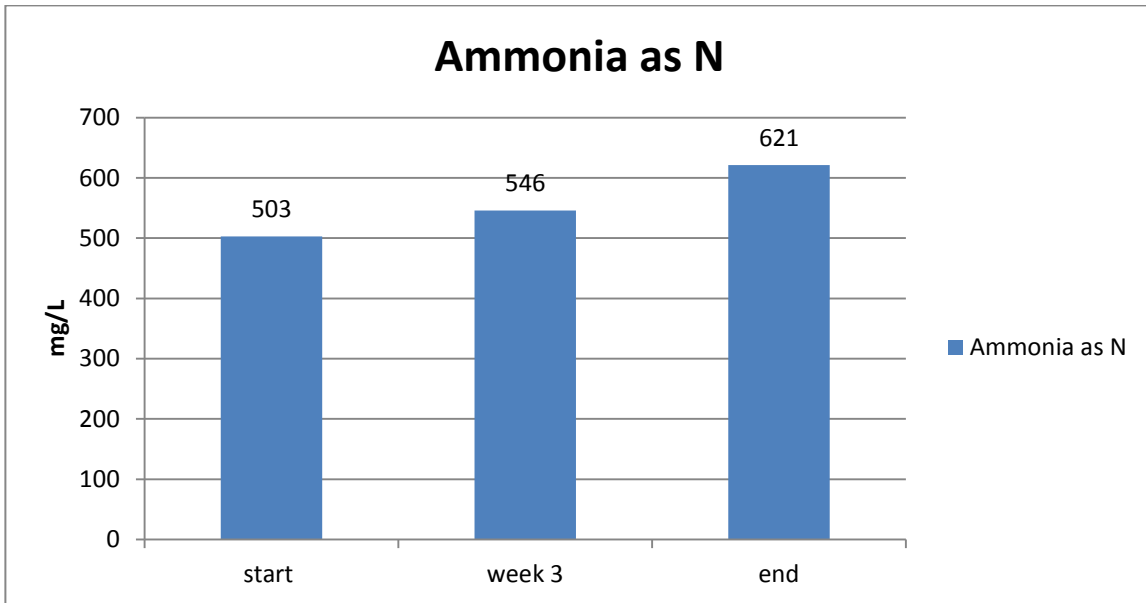


Figure 4-7 3N:0O Ammonia – at start, after 3 weeks and completion

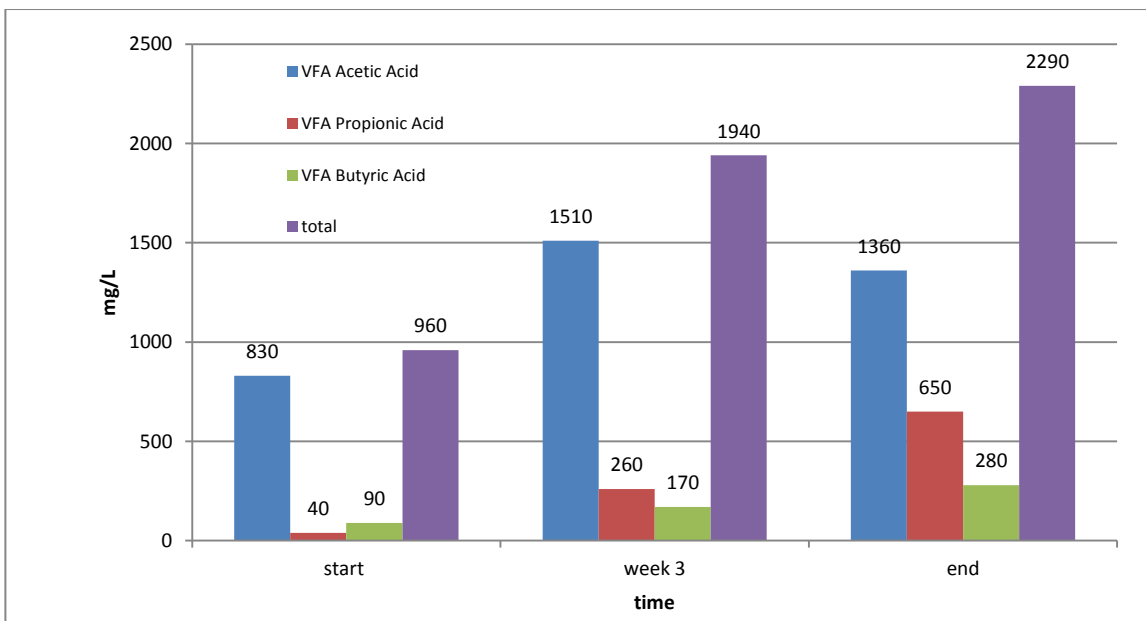


Figure 4-8 3N:0O VFA – at start, after 3 weeks and completion

The COD value had dropped in the batch bottles 3N:0O to 1,880 mg/L at the end of day 60. There was almost negligible biogas generation from these reactors which indicated that the activity was almost over. The residual organic content or the COD on day 60 can be interpreted as the non-biodegradable portion.

The ammonia concentration had increased to 621 mg/L. The high ammonia content in these reactors 3N:0O is due to the fact that they contain 10mL of leachate which has a high ammonia content of 2,380 mg/L. The increased ammonia concentration after 60 days of operation is from the hydrolysis of the OFMSW as previously stated.

The VFA concentrations revealed that while the concentration of acetic acid had dropped to 1,360 mg/L from 1,510 mg/L at the end of 3 weeks indicating that the readily biodegradable component in these batch bottles had decreased. However, the acetic acid concentration at 1,360 is extremely high and when there is no biogas being produced. i.e the substrate concentration is high while there is no methanogenesis occurring which indicates that there is an inhibition in methanogenesis. It is also to be noted that the propionic and butyric acid concentrations had increased to 650 mg/L and 280 mg/L respectively indicating that there was accumulation of less biodegradable organic materials in these batch bottles. While the ammonia and VFA concentrations in the bottles 3N:0O due to the diluted leachate are lower

than the inhibitory ranges observed in pilot plants and BLFs, there is a marked inhibitory effect caused in the accelerated environment.

4.3.2 0N:3O Leachate Blend Discussed:

The total biogas generation for the batch bottles with leachate blend 0N:3O with control reactor is shown in Figure 4.9. The cumulative biogas generated in these reactors is higher (920 mL) compared to the control reactors (643 mL) which simulate conventional regulated landfills. While the biogas generation is higher, the component of biodegradable organic material in the mature leachate is low compared to young leachate as previously discussed. Any reactor producing more biogas compared to the control is better than a conventional BLF. In this case, the biogas generation is 43% more than the control. Thus staged leachate recirculation is more beneficial to the conventional BLF. The results show good repeatability.

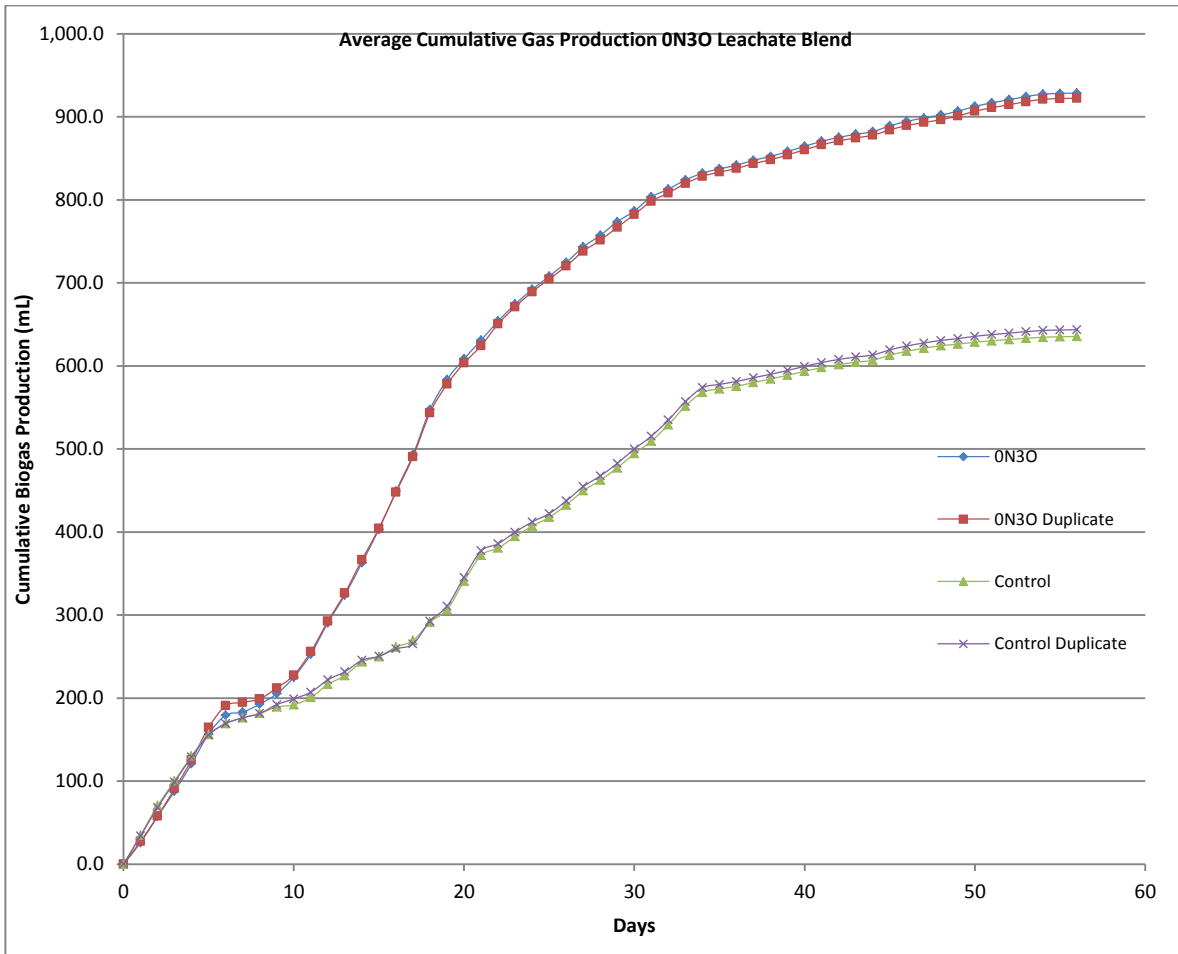


Figure 4-9 Cumulative Gas Production Curves 3N:0O

The batch BMP assay on the reactors (in duplicate) shows a steep slope during the initial week, beyond which there is a lag phase prevailing for two days as observed from Figure 4.9. This indicated a phase shift from acidogenesis to methanogenesis. The methanogenic phase is very consistent as observed from the smoother curve compared to the control. In addition to

producing substantially higher biogas than the control reactor (43% enhancement in total biogas generated), the methanogenic phase is seen to last longer than the control reactor.

Figure 4.10 shows the COD concentrations of these bottles at the start of the batch test, after week 3 and at the end of day 60 while Figure 4.11 shows the ammonia concentrations of 3 parts of mature leachate also at the start, after week 3 and at the end of day 60. Figure 4.12 shows the VFA concentrations of Acetic Acid, Propionic Acid and Butyric Acid at the start of the batch BMP test, week 3 and at the end of day 60.

The COD concentrations in the batch bottles 0N:3O reduced consistently compared to the control and much lower compared to the bottles with 3N:0O (young leachate). The initial concentration of COD was 3,350 mg/L. The initial COD was lowest in concentration compared to other leachate blends. This is attributed to the fact that the mature leachate component has a lower COD content of 11,040 mg/L.

The initial ammonia concentration in these reactors was the lowest at 315 mg/L compared to the other batch reactor bottles with leachate blends. The mature leachate had a concentration of ammonia at 1,410 mg/L which is why the ammonia level in the batch reactors 0N:3O was the lowest at 315 mg/L. These reactor bottles also showed lower initial total VFA of 160 mg/L which was comprised of only an acetic acid component. After week 3, the COD concentration in these batch bottles had decreased to 2,520 mg/L from 3,350 mg/L and at this

stage had produced nearly 500 mL of biogas. The ammonia concentration had increased to 368 mg/L from 315 mg/L from the hydrolysis of OFMSW.

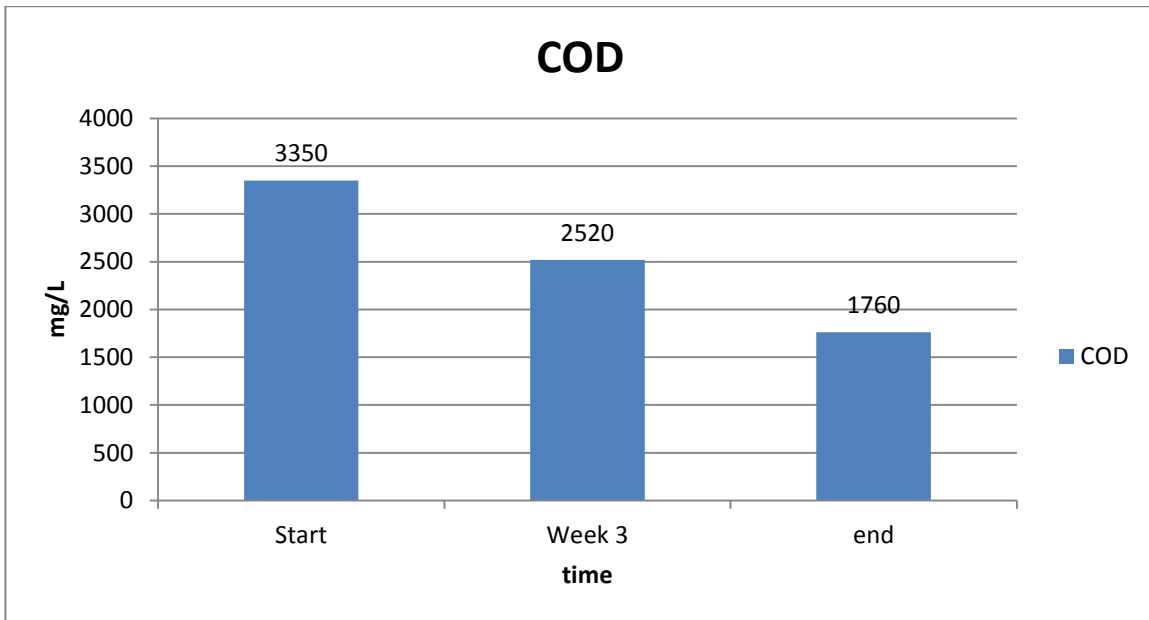


Figure 4-10 0N:3O: COD – start, after 3 weeks and completion

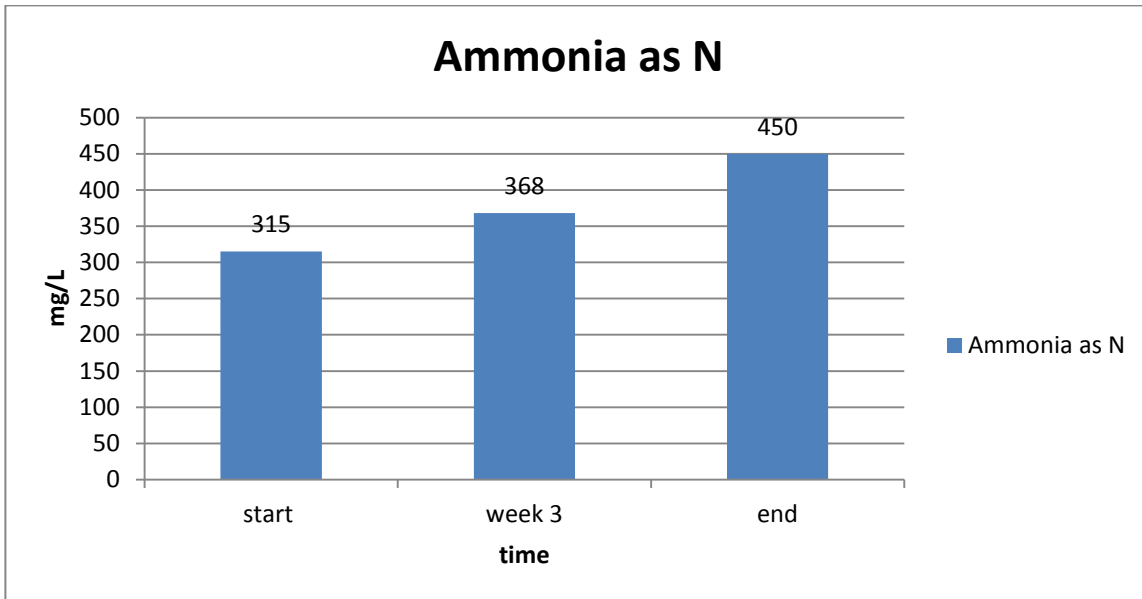


Figure 4-11 0N:3O: Ammonia – start, after 3 weeks and completion

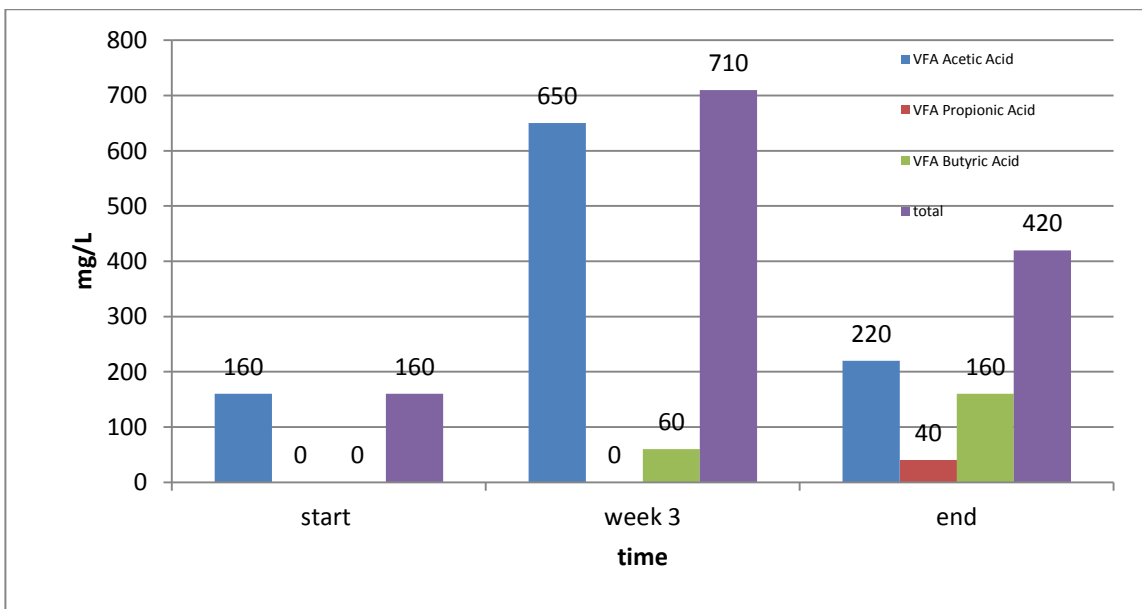


Figure 4-12 0N:3O: VFA- start, after 3 weeks and completion

After day 60 of the batch test IIA, the COD concentration in the batch bottles with 3 parts of mature leachate had dropped down to 1,760 mg/L clearly indicating that there was a bigger component of non-biodegradable organics in these reactors. The reasoning is that the COD coming from the mature leachate component is higher in non-biodegradable organics.

The Ammonia concentration in these reactors at the end of day 60 was measured at 450 mg/L. The VFA had an acetic acid component of 220 mg/L, propionic acid at 40 mg/L and butyric acid at 160 mg/L.

4.3.3 1N:2O Leachate Blend Discussed:

In these batch reactor bottles, the effect of 1N:2O leachate blend was analyzed on the biodegradation of OFMSW. The batch test analyzed whether or not there was an advantage of using one part of young leachate with two parts of mature leachate on enhancing the biodegradability of OFMSW.

This reactor presented the highest biogas generated and also had a steep biogas production curve (Cumulative) indicating faster phase shift into methanogenesis. Figure 4.13 shows the plot for the cumulative gas production in these reactors compared with the control reactor. The gas production in these batch BMP bottles was over 1017mL compared to the control

reactor's 635mL (containing diluted food waste and inoculum.) A 60.15% increase in cumulative biogas generation was observed in these reactors with OFMSW and leachate blends as compared to the control reactor with only OFMSW.

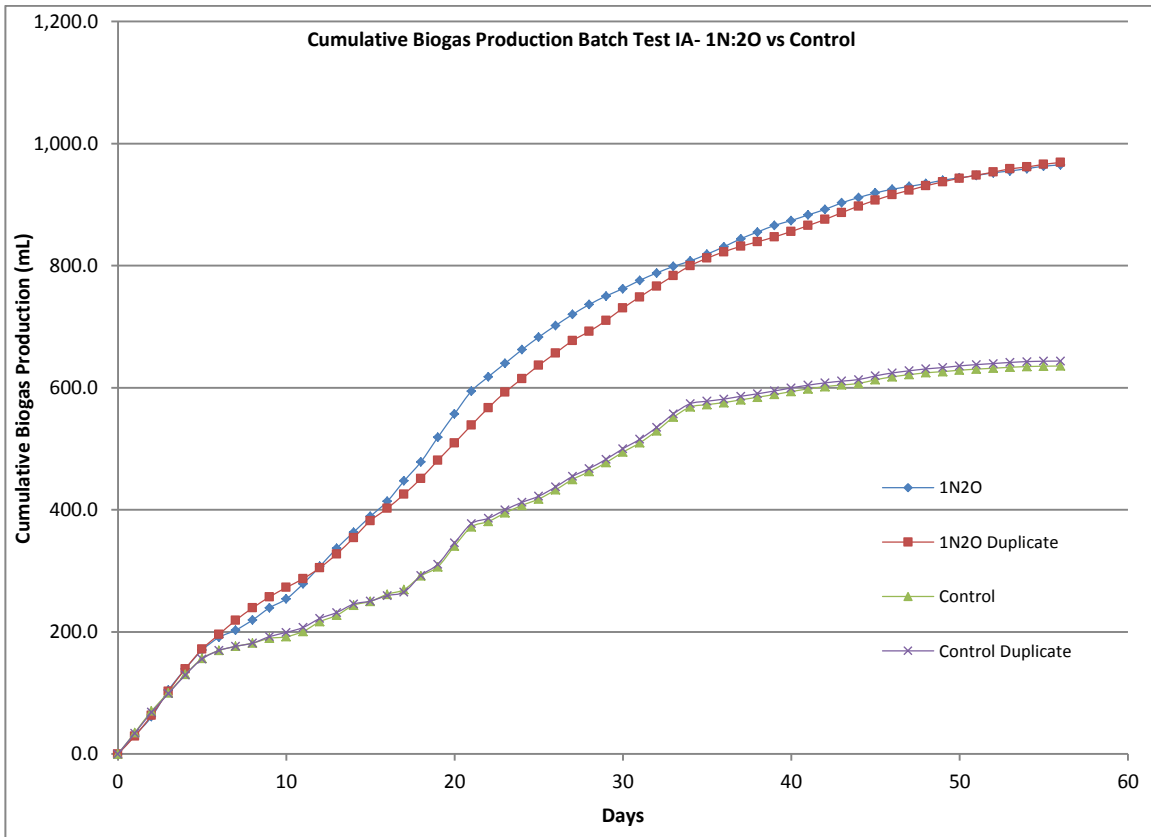


Figure 4-13 Cumulative Gas Production Curves 1N:2O

Figure 4.14 shows the COD concentrations of these bottles at the start of the batch test, after week 3 and at the end of day 60 while Figure 4.15 shows the average ammonia concentrations of the bottles 1N:2O leachate blend at the start, after week 3 and at the end of day 60. Figure

4.16 shows the VFA concentrations of Acetic Acid, Propionic Acid and Butyric Acid at the start of the batch BMP test, week 3 and at the end of day 60.

During the start-up of the reactors, the average COD concentration in the bottles with 1N:2O leachate blend was found to be 3,690mg/L. The differences in COD values are mainly brought about by the organic content in the leachate blends. The ammonia concentration in these bottles during startup was 405 mg/L. The concentration of ammonia was comparatively lower than the bottles with 3N:0O and slightly higher than that of the bottles with 0N:3O. The higher the component of young leachate, the higher is the ammonia concentration since most of the initial ammonia concentration is due to the ammonia coming in from the young leachate which has an ammonia content of 2,380 mg/L while the mature leachate component has an ammonia content of 1,410 mg/L.

The bottles had high initial concentrations of acetic acid at 280 mg/L with no traceable content of propionic acid. The concentration of butyric acid was found to be 10 mg/L. The higher the percentage of young leachate, the higher is the total acids during start-up.

After 3 weeks of biodegradation, the COD concentration had dropped down to 2,770 mg/L of COD from 3,690 mg/L. Though the decrease is not very high till the end of the third week, the biogas generation curve gives an explanation as to why the decrease is not that high. The biogas generation rate till the end of the third week is comparatively lower (452 mL of biogas) which explains why there is not much of decrease in the COD concentration.

The average ammonia concentration in these batch bottles was noted to be 479 mg/L at the end of 3 weeks of operation. There is a significant amount of hydrolysis taking place as a result of which the VFA concentration is comparatively higher at this stage and the net acetic acid concentration is 1,160 mg/L, while the propionic and butyric acid concentrations are 20 mg/L and 80 mg/L respectively. Since the propionic and butyric acids are much lower compared to the acetic acid, there should be a significant rate increase in biodegradation and hence biogas generation which is observed in Figure 4.17.

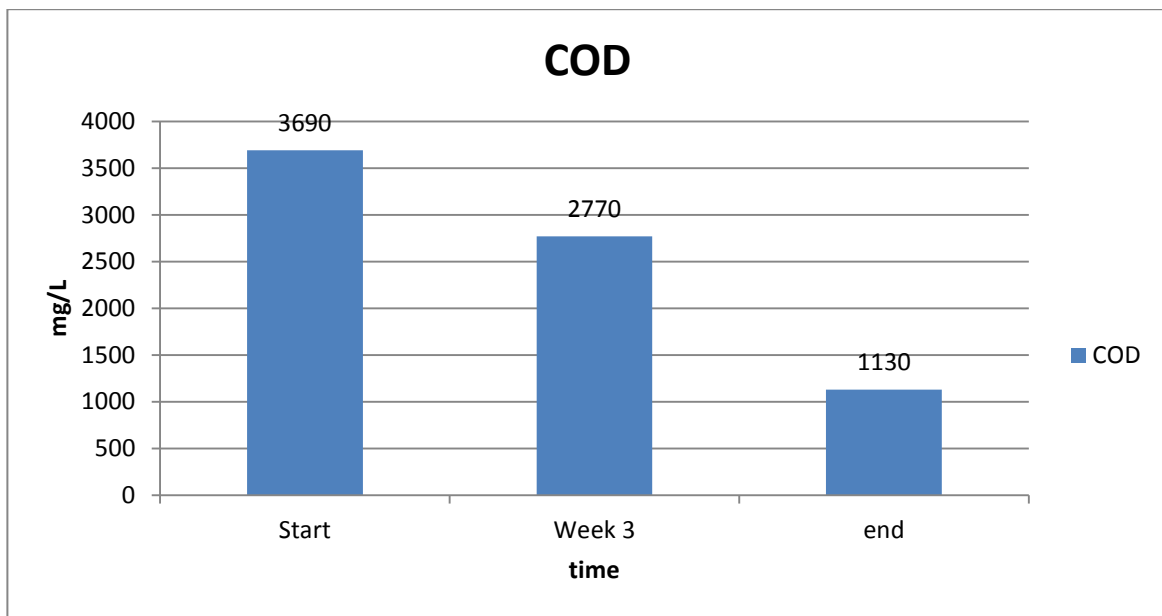


Figure 4-14 1N:2O: COD – start, after 3 weeks and completion

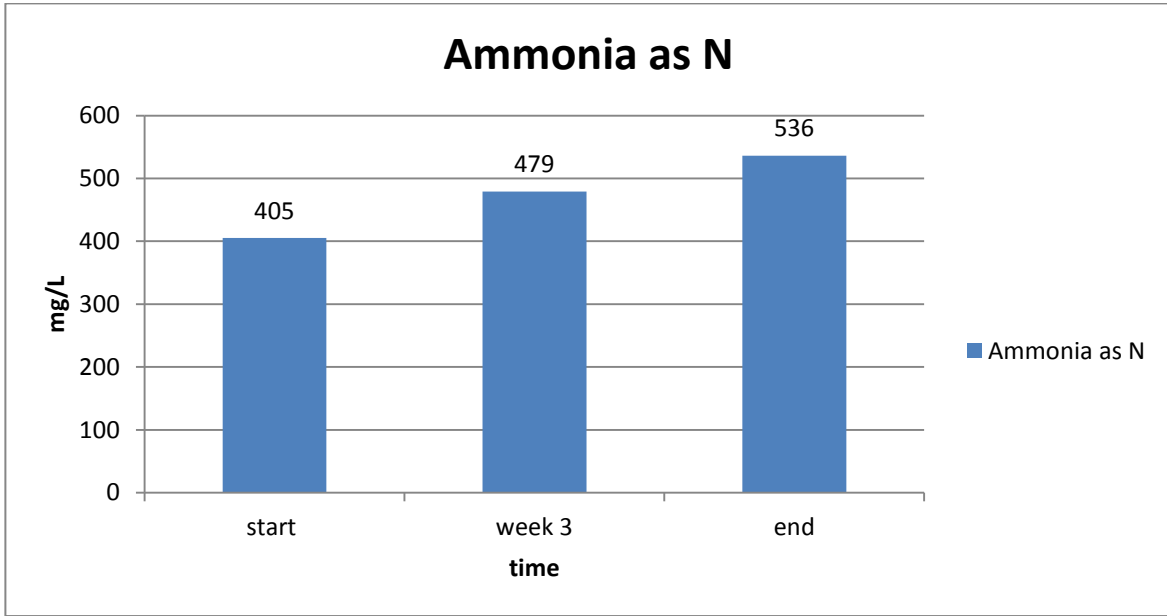


Figure 4-15 1N:2O: Ammonia – start, after 3 weeks and completion

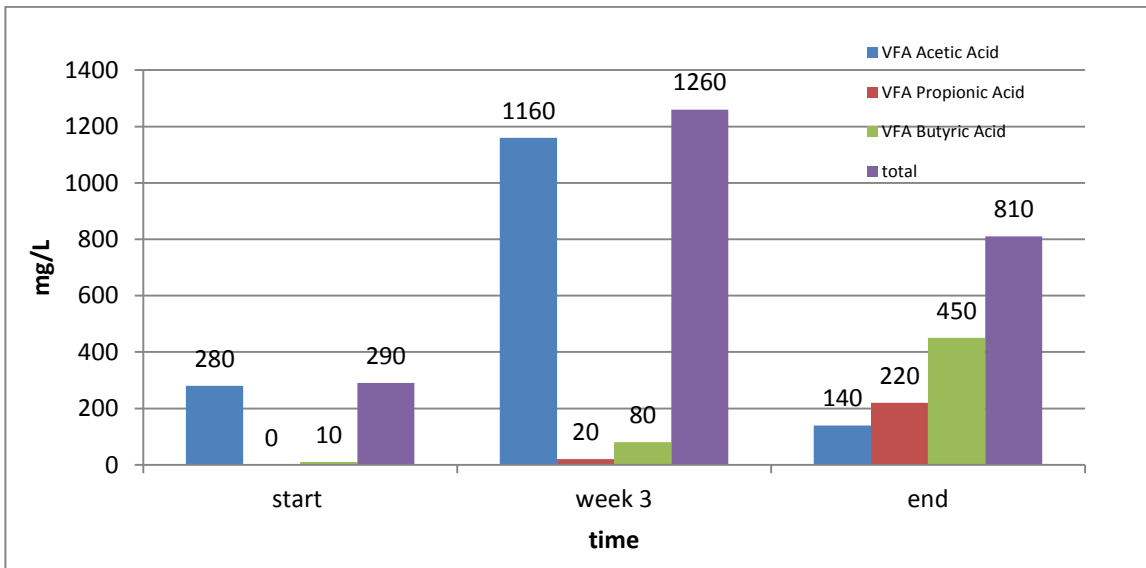


Figure 4-16 1N:2O: VFA – start, after 3 weeks and completion

After day 60, the biogas generation in these reactors were negligible which indicated inactivity, which was mainly due to the exhaustion of substrate by the bacteria. The COD concentration had dropped in these bottles to 1130 mg/L of which most part was non-biodegradable. The ammonia concentration was 536 mg/L.

Interestingly the VFA concentration showed extremely low acetic acid levels of 140 mg/L and higher propionic and butyric acid levels of 220 mg/L and 450 mg/L. It can be concluded from this that any further biodegradation would be extremely slow or negligible.

4.3.4 2N:1O Leachate Blend Discussed:

In these batch reactor bottles, the effect of 1 part of mature leachate and 2 part of young leachate was analyzed on the biodegradation of OFMSW. The batch test analyzes if there was any advantage to blending the leachates, both mature and young leachates and whether a higher component of younger leachate would be beneficial. Figure 4.17 shows the total biogas generation from the leachate blend 2N:1O and also shows the comparison with the control reactor which contains only OFMSW. The control reactor simulates a regulated landfill wherein there is only water seepage from rainwater runoffs.

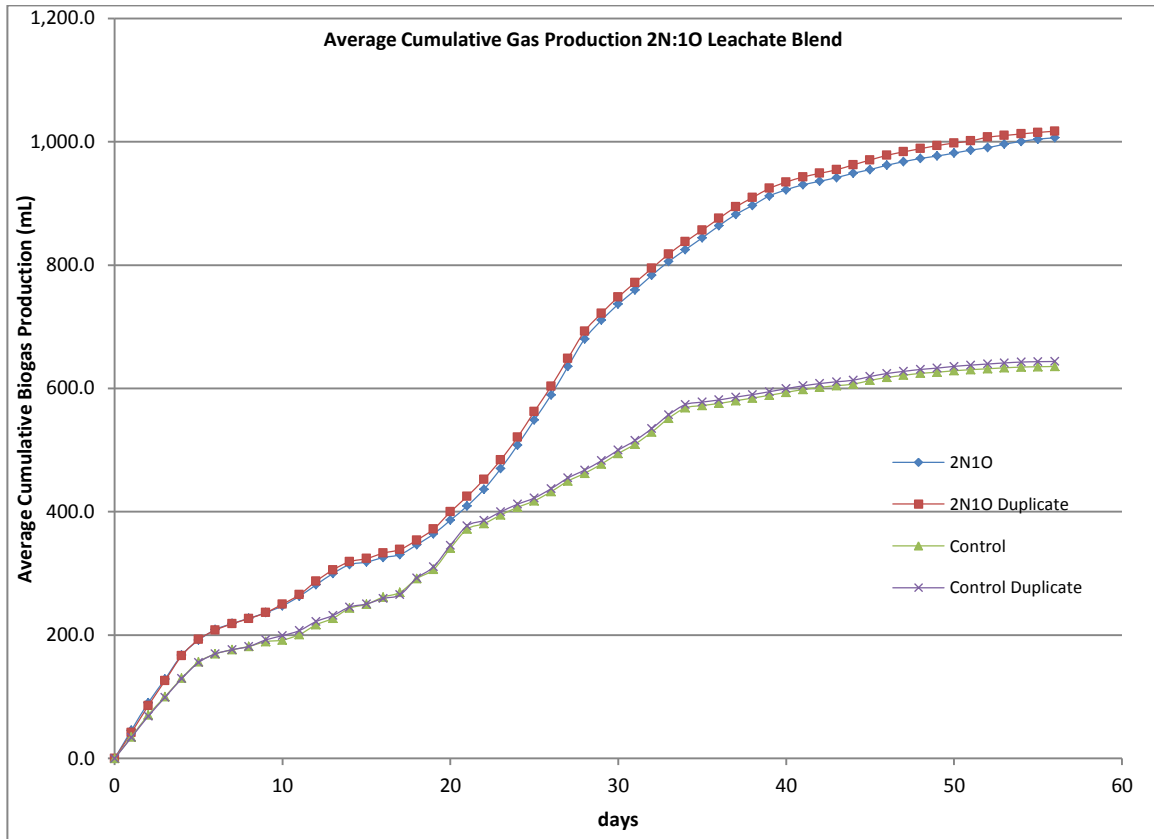


Figure 4-17 Cumulative Gas Production Curves 2N:1O

The slopes were moderate and there were few data points where the duplicates were not completely in sync and had a deviation of up to 10mL on certain days. However, this did not significantly affect the total biogas generated or the gas production rate.

While the gas production in these reactors was much higher than the control reactors (635mL) and slightly higher than the reactors containing 0N:3O (927mL). Previously discussed, the

leachate blend acts completely as a different leachate rather than showing behaviour closer to either young or mature leachate.

Figure 4.18 shows the COD concentrations of these bottles at the start of the batch test, after week 3 and at the end of day 60 while Figure 4.19 shows the ammonia concentrations of 2 parts of young leachate and 1 part of mature leachate at the start, after week 3 and at the end of day 60. Figure 4.20 shows the VFA concentrations of Acetic Acid, Propionic Acid and Butyric Acid at the start of the batch BMP test, week 3 and at the end of day 60.

The COD values at the start of the batch tests were 3,990 mg/L. The ammonia concentration for these reactors was 466 mg/L and the VFA had higher acetic acid content of 560 mg/L and 10 mg/L of butyric acid.

Following week 3, the COD concentration increased to 5,010 mg/L. while in all other reactors, the COD concentration decreased after week 3, in this reactor the COD concentration increased from 3,990 mg/L to 5,010 mg/L. One possible reason could be that the measured COD concentrations are all soluble COD concentrations and there could have been more COD solubilized in these reactors after 3 weeks. The ammonia concentration increased to 516 mg/L while the VFA concentration increased in acetic acid to 1,100 mg/L, while propionic and butyric acids increased to 120 mg/L and 268 mg/L respectively.

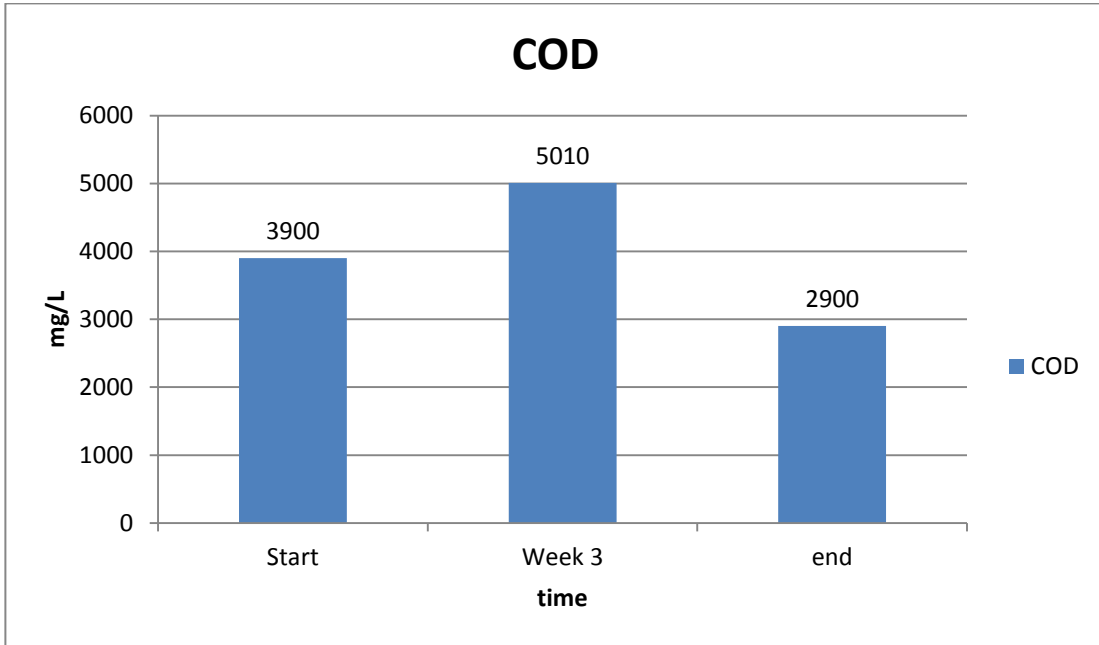


Figure 4-18 2N:1O: COD – start, after 3 weeks and completion

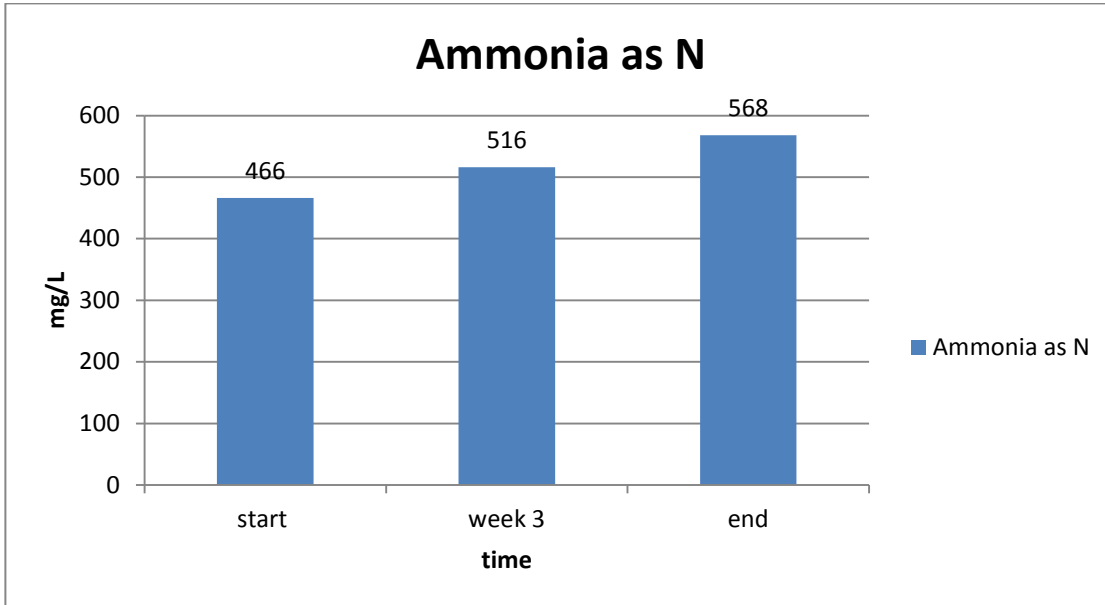


Figure 4-19 2N:1O: Ammonia – start, after 3 weeks and completion

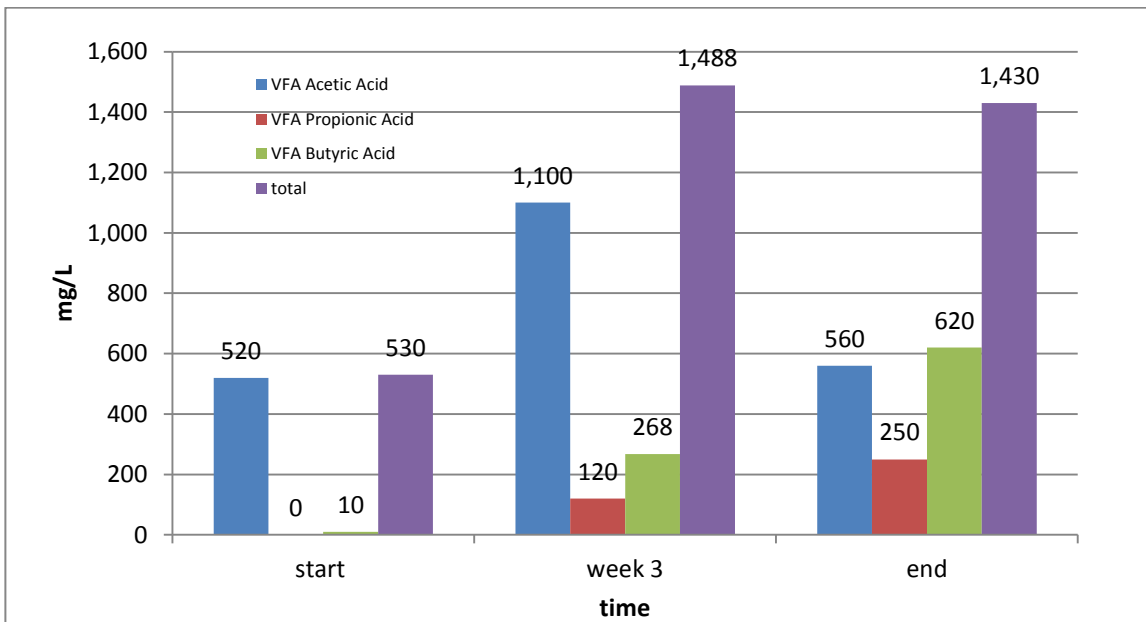


Figure 4-20 2N:1O: VFA – start, after 3 weeks and completion

On completion of biodegradation after day 60, the VFA levels showed higher residual acetic acids concentration of 560 mg/L while the propionic acid concentration increased to 250 mg/L and the butyric acid levels increased from 268 mg/L to 620 mg/L.

The COD concentration dropped down to 2,900 mg/L and the ammonia levels in these reactors increased to 568 mg/L after day 60.

4.4 Batch Tests – II

Batch test-II was aimed at predicting how a closed loop system and an open loop system with replacement affect the rate and total biogas production in a functional bioreactor landfill. Chugh et al., (2003) had analysed leachate recirculation with open and closed loop recirculation loops with regards to drop in COD.

Batch tests II were conducted in continuation with batch test IA wherein some of already spent leachate batch bottles were replenished with leachate blends in an open and closed loop simulation. These set of batch tests were conducted in order to see the effect of an open loop and closed loop recirculation. The principle of open and closed loop systems have already been discussed under chapter 3. Following batch test IA, the bottles that had a component of mature leachate was used for this set of batch BMP assay i.e 2N:1O, 1N:2O and 0N:3O batch bottles. From the two bottles of each blend, 30mL of the same leachate blend was added to one of the bottle while its duplicate's contents remained unchanged.

The plot shown in Figure 4.21 indicates the overall result of the open and closed loop systems. The reactors with additional leachate blend added to them simulate an open loop while the others were a closed loop system. It was observed in reactors with 2 parts of new leachate (2N:1O), the biogas production was highest in addition to quicker gas generation rates. The batch bottles which had an addition of leachate showed an increase in biogas generation.

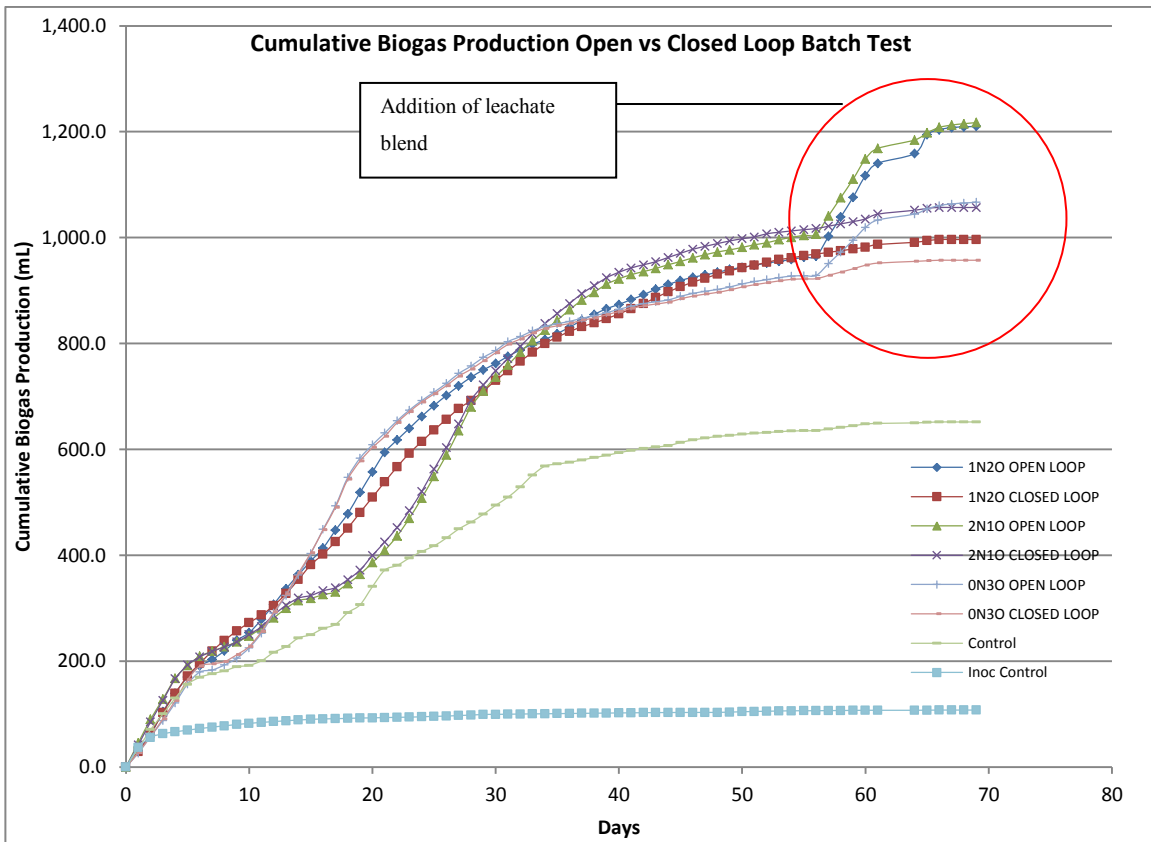


Figure 4-21 Cumulative Biogas Production Batch Test II

The leachate contains biodegradable organics which are solubilized and hence, are easily biodegradable as can be observed from the plot in Figure 4.21. There was a slight lag observed for the first two days during the introduction of the leachate in the second stage of the batch bottles. Figure 4.22 shows a comparison of the biogas generation from pure leachates vs. the open loop leachate blends. There is an obvious difference noticed in that there was a lag in batch test II where the leachate blends were added. This said, the specific growth rate for the bacteria in the open loop systems was much higher compared to the batch tests IB where the system was started with leachate blends.

The total biogas generation was also higher in case of the open loop bottles compared to the pure leachate blends. It was observed that the time taken for the biogas generation to move towards completion was the same in both batch tests IB and II despite the initial lag which indicates that there was an accelerated rate of biodegradation observed in the case of the batch test II open loop systems.

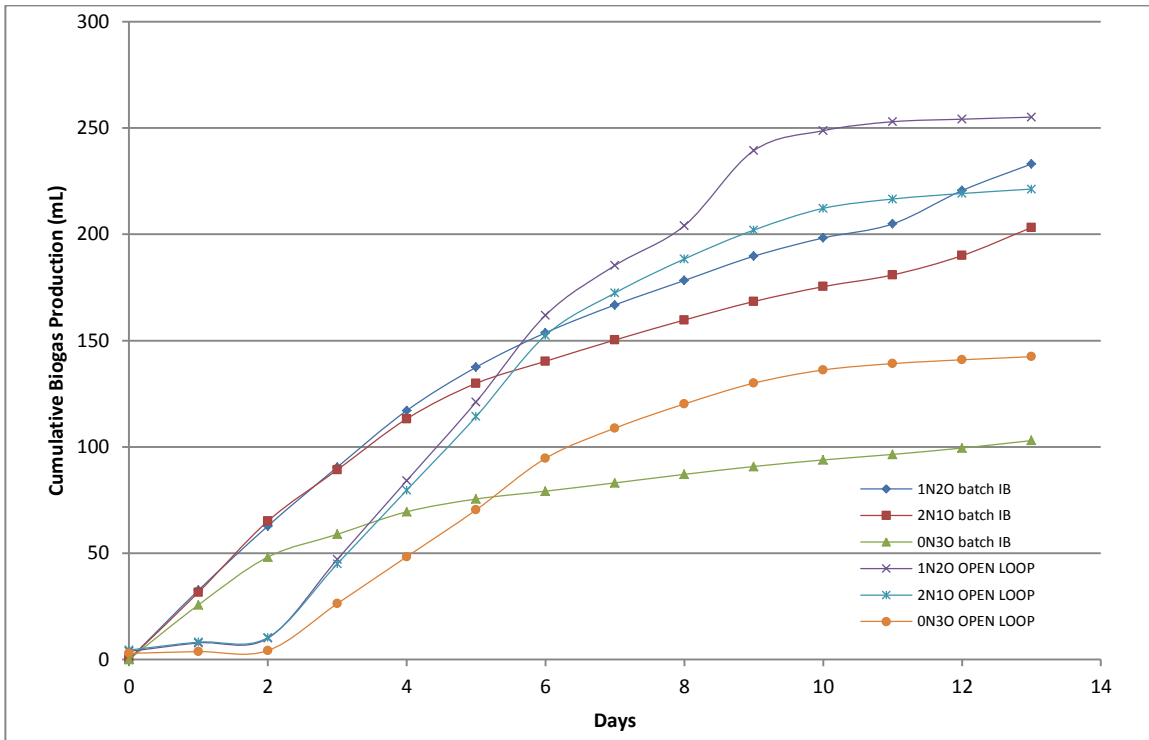


Figure 4-22 Batch Test II Open Loop Vs. Batch Test IB Pure Leachate Blend

4.4.1 1N:2O Leachate Blend:

It can be observed from Figure 4.21 and 4.22 that the leachate blend 1N:2O had the highest performance change between the open loop recirculation (255.1mL) and the closed loop recirculation mode (37.9mL). The addition of the leachate blend was able to provide conditions to produce 217.2mL of biogas over the closed loop system as can be observed from Figure 4.21. This translated to a 5.7 fold increase in performance of an open loop system over a closed loop system. It is to be noted that the increase was solely due to the presence of

organic biodegradable material in the fresh leachate blend introduced in the open loop systems. It was also observed that the addition of the leachate in an open loop produced biogas at a much faster rate than a pure leachate blend. This is observed from Figure 4.22. The rate and biogas generated was the highest for the leachate blend 1N:2O in an open loop recirculation system.

4.4.2 2N:1O Leachate Blend

This blend of 2 parts of young leachate and 1 part old leachate (2N:1O) when in an open loop showed a significant increase in biogas production as can be observed from Figure 4.21. What was interesting in this case was that even though this reactor had a higher component of young leachate, the biogas generation was not as high as the reactor with 1N:2O. It would have been expected that this reactor in an open loop would have produced most biogas after the addition of leachate blend. However, this produced a total of 221.3mL of biogas which was lower than the leachate blend 1N:2O. The leachate blend in closed loop produced 46.8 mL of biogas which gave a difference of 174.4mL between open and closed loops systems. The improvement in performance of open loop system for this particular leachate blend was 3.7 times over the closed loop system for the same leachate blend. It is to be noted that the increase was solely due to the presence of organic biodegradable material in the fresh leachate blend introduced in the open loop systems.

The leachate blend 2N:1O also had a slight lag initially but a steeper biogas generation rate and a better overall performance compared to the pure leachate blend in batch test IB as was observed from Figure 4.22.

4.4.3 0N:3O Leachate Blend:

The leachate blend with only mature leachate 0N:3O, in the open loop showed more promising results than expected because there was almost no biodegradable organic material in the additional leachate blend since the BOD₅ of mature leachate was 85mg/L. In the open loop the biogas production after addition was at 142.4 mL as compared to the closed loop system which had a total biogas production of 39.1mL which is shown in Figure 4.21. The increase in performance for the leachate blend 0N:3O with only mature leachate in an open loop with leachate addition was 2.6 times the same leachate blend in a closed loop system. It is to be noted that the increase was solely due to the presence of organic biodegradable material in the fresh leachate blend introduced in the open loop systems.

The leachate blend also had a steeper biogas generation rate and total biogas generated compared to the pure leachate blend 0N:3O in batch test IB (103.4mL). The additional biogas generation can be assumed to have been from the residual OFMSW biodegradation.

Overall, batch bottles with higher percentage of young leachate produced more gas while the mature leachate did not have much of biodegradable organic fraction so the gas production

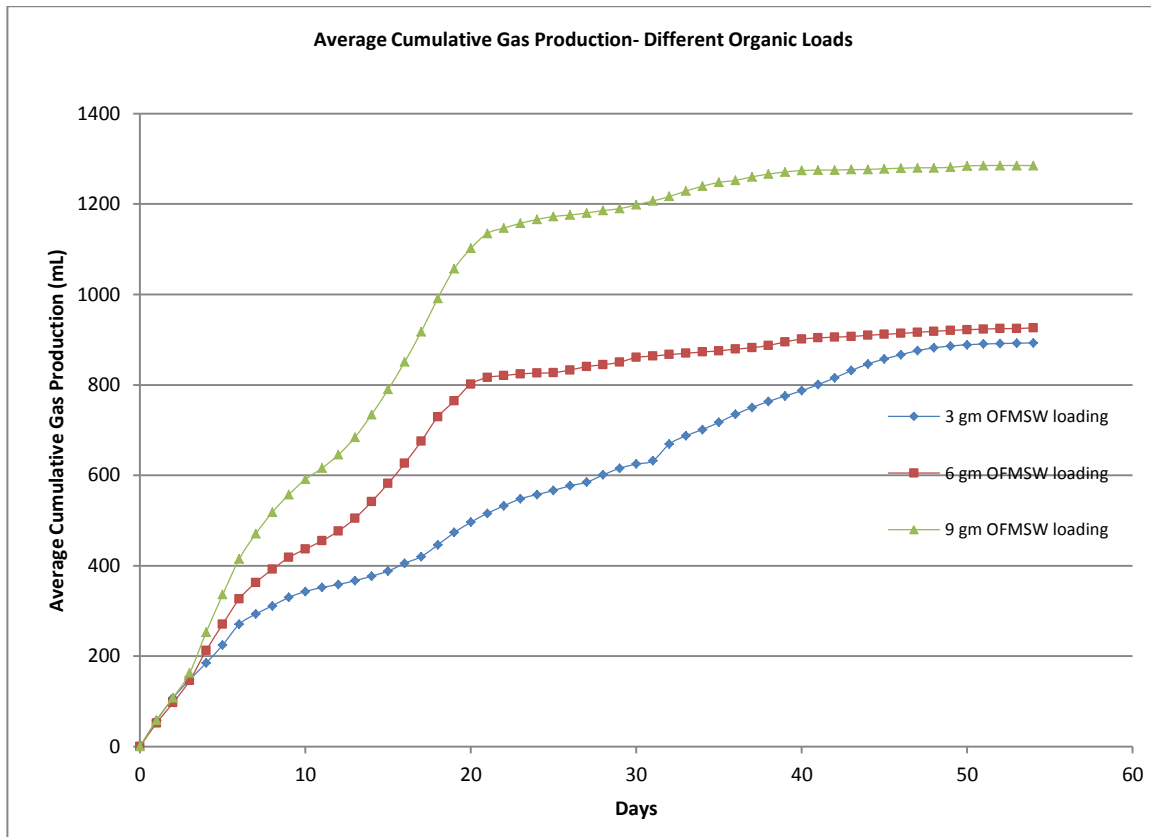
was more or less limited in case of completely mature leachate as was observed from batch test IB.

The reactors with an addition of leachate blend (replacement) simulated an open loop type of leachate recirculation while the bottles without any leachate addition showed a closed loop system. The open loop system of recirculation with replacement of leachate is superior because it contains more soluble organics from the portions of the young leachate. For practical applications, an open type of recirculation system is more preferred since the system provides COD removal and organic destruction for the leachate which otherwise would have required more treatment trains before disposal.

4.5 Batch Tests III: Impact of Organic Loading on Methane Generation

This set of batch tests, was focused on understanding whether or not a higher organic load in bioreactor landfills would lead to a higher biogas generation or not. The results from the batch tests are shown in Figure 4.23. The graph in Figure 4.23 shows the total biogas generated (average of the two duplicates) from the OFMSW and 30mL of the leachate blend 1N:2O for all reactors. The total yields were used to compare the performances of the reactors with the three different organic loads of 3 g, 6 g and 9g. The biogas produced from the reactors with 9

g of prepared food waste had an initial surge in gas production which saturated after day 21 producing nearly 1200 mL of biogas in total as seen in Figure 4.23.



4-23 Average cumulative gas production for different organic loading- Batch test II

The reactors with 6 g of waste on the other hand produced nearly 900 mL of gas. Based on the data for 6 g and 9 g, the average gas production under these conditions per gram of waste was anywhere between 142 mL and 154 mL. Based on this, the reactor with 3 g should technically have produced only 450 mL of gas. On the contrary, the reactor with 3 g of waste actually

produced 890 mL of gas. This indicates that the biodegradable portion in the reactors with 6 g and 9 g of waste was not completely utilized.

The specific biogas generation for all three loading rates was as follows:

- Batch bottle with 3 g organic load: 297 mL/g
- Batch bottle with 6 g organic load: 154.5 mL/g
- Batch bottle with 9 g organic load: 142.2 mL/g

The specific gas generation for the batch bottles was highest in case of 3 g organic loading with 297 mL/g of biogas, while the 6 g organic loading had 154.5 mL/g and the 9 g loading had the least specific biogas generation at 142.2 mL/g of biogas. This meant that in terms of performance, the lower the organic load, the higher was the performance in terms of methane generation. One possible reason for this is that as the amount of food waste increases, the methanogenic bacteria experience a lower pH because of the increased acidogenesis in case of higher organic loading and as a result do not perform to the full potential.

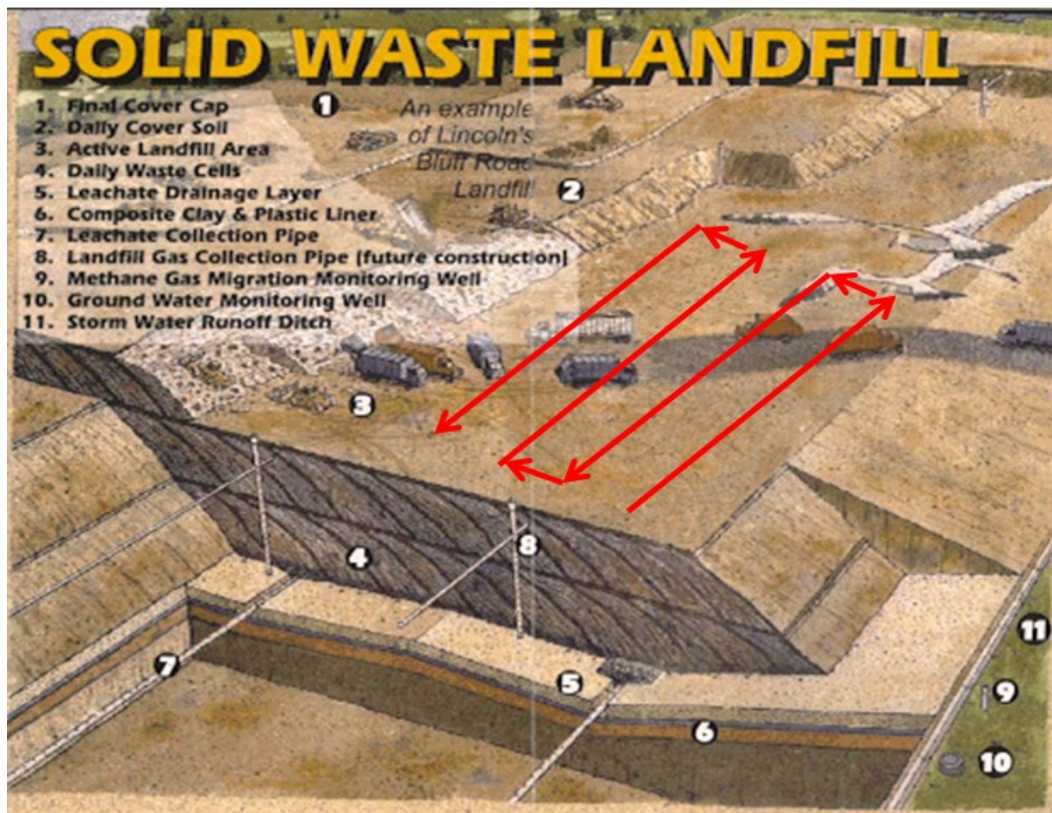
Methanogenic bacteria have a lower specific growth rate compared to acidogenic bacteria and due to this, the acid formation happens quicker which in turn drops the pH. This also makes available an excess substrate for methanogenic bacteria in cases of higher organic loads and this shock loading cannot be well received by the methanogenic bacteria. This explains why the initial rate of gas production was higher for the higher organic loads of 9 g and 6 g bottles while the 3 g reactors had a more consistent production curve.

The results observed in this study indicated that the reactors having an organic loading rate of 3 g had the highest efficiency in terms of biodegradation. This however, is not to be mistaken as a standard value of organic loading or optimal loading for all bioreactor landfills. From this set of batch tests, it can be observed there is a limit on the amount of loading which can be effectively utilized by the methanogenic bacteria within the bioreactor landfill. This is more or less a threshold beyond which there is an inhibitory effect caused by the either the additional organic load which increases the VFA content and drops the pH or possibly even the increase in ammonia to inhibitory levels. From the operational perspective of a landfill, it would be interesting to extend this study to the compaction rate since it is directly related to the total organic load in the bioreactor.

4.6 Batch Tests IV: Influence of Fed-Batch on Methane Generation:

Landfills used as bioreactors, are loaded in lifts of OFMSW. Depending on the nature of the landfill and the operating conditions, the lift size varies. Some landfills utilize higher lift sizes, spread over a smaller area as shown in Figure 4.25 while the others use lower lift sizes spread over a larger area as shown in Figure 4.24. The results from this set of batch tests help in predicting which one of these filling patterns would enhance biodegradation.

To simulate these with a fed batch system, the same total organic load of 3 g of prepared food waste was added to all reactors in different time intervals. In the first case, the entire 3 g of organic load was applied right at the start of the batch test, in the second case; the initial load of 1.5 g was supplemented by a second load of 1.5 g at the end of day 16. And finally in the third set of reactors, the initial load of 1 g was supplemented by two loads of 1 g each at the end of day 16 and day 29. The first case simulated a bioreactor landfill with small fill areas and higher lift's size. The third case simulated a bioreactor landfill with larger fill areas and lower lift's size. The results from the tests are shown in Figure 4.26.



4-24 Landfill loading pattern I - horizontal loading (adapted from <http://lincoln.ne.gov>, (2008))



4-25 Landfill loading pattern II-vertical loading (adapted from <http://lincoln.ne.gov>, (2008))

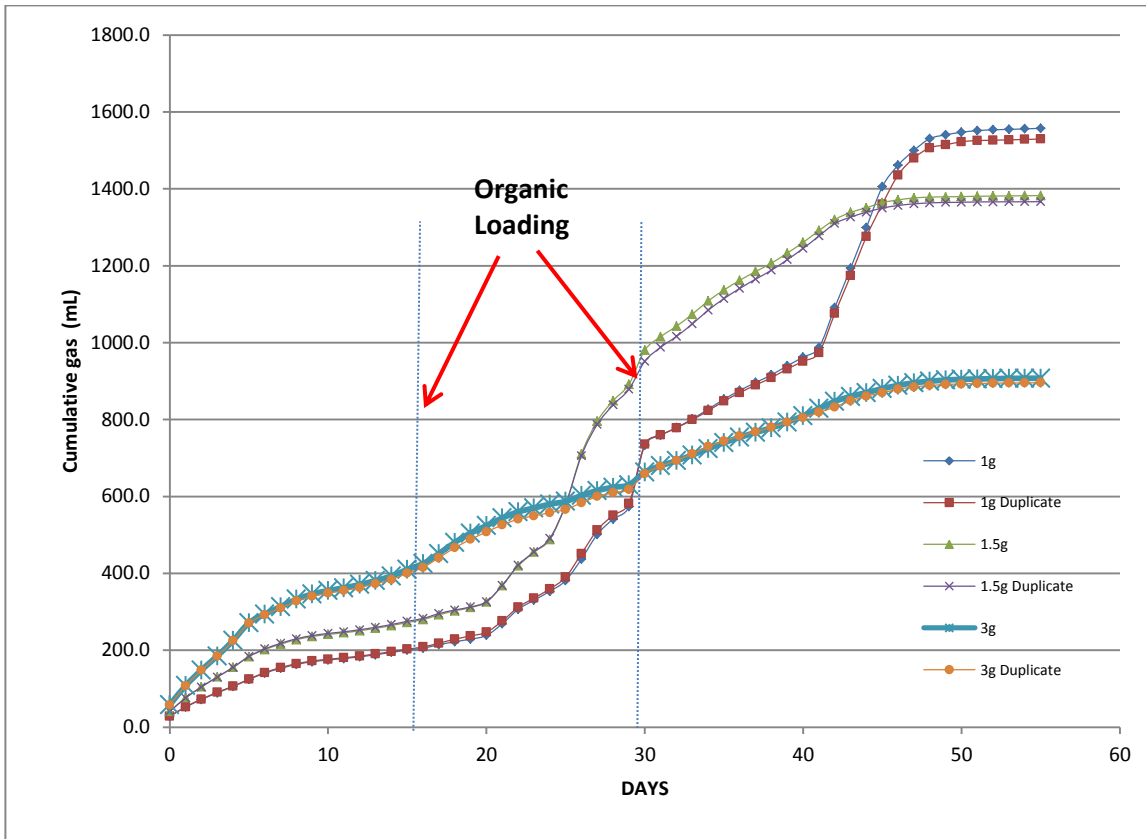


Figure 4-26 Cumulative gas production for loading rates (Fed batch) - Batch test IV

The test results shown in Figure 4.26 indicate that there is a distinct advantage in a staged fed batch BMP assay with faster biodegradation and a higher biogas generation with increasing intervals of loading. It was observed that the reactors with three loads of 1 g (3 X 1 g) spread over the duration of the test started producing biogas at a rate corresponding to the total biodegradable portion of the food waste. Immediately after a loading, the biogas generation curve for 3 X 1 g showed much steeper curves and by day 30 the reactor had produced the same biogas generation (618 mL) as the reactors loaded once with 3 g (1 X 3 g)

of food waste. With every subsequent loading, the rate of gas production had increased and by day 45, the reactor with 3 X 1 g loading rate had yielded the same amount of gas (1400 mL) produced by the reactor with 2 X 1.5 g loading rate. In addition to producing biogas faster, the reactor with 3 X 1 g loading also produced a higher total biogas generation of 1530mL compared to the 1 X 3 g and 2 X 1.5 g loading which produced a total of 896 mL and 1367 mL, respectively.

The reactors with the 2 X 1.5 g loading showed similar characteristics to the 3 X 1 g loading reactors with the exception that the biogas production rate was very high after the second loading. These reactors equalled the biogas generation(560 mL) from the 1 X 3 g reactors on day 24; soon after the second loading was applied.

The reactors with the 1 X 3 g single loading reactors showed a very smooth and consistent curve with the least generation and the slowest rate compared to the other reactors. The cumulative biogas generation curve resembles a standard batch BMP assay curve.

The results observed in this batch BMP assay indicate that there is a clear advantage in terms of rate of biogas generation (30 days faster than 1 X 3 g loading and 4 days faster than 2 X 1.5 g loading reactors in terms of time to attain the same yield.) The reactor with 3 X 1 g loading also achieved higher yields (produced 73% more biogas than 1 X 3 g loading and 14% more biogas than 2 X 1.5 g loading.)

A possible explanation for this increased performance with smaller loads spread out over time is that the bacteria responsible for biodegradation have already acclimatized to the food waste. In addition to this, the acidogenic and methanogenic bacterial consortia are at a better balance which results in more conducive pH stability and a good VFA balance. The methanogens would have been able to utilize the substrate since the methanogenic bacterial population would be well acclimatized which is the rate limiting step for organic biodegradation.

The results indicate that the preferred loading pattern for enhanced biodegradation is the horizontal type of loading shown in Figure 4.24. This is also the most commonly followed loading pattern in operational landfills.

4.7 Column Reactors:

In order to simulate real world landfills, the OFMSW collected from a landfilling facility in Ottawa, Ontario was used for laboratory experiments. Landfill bioreactors are analyzed in terms of leachate quality since the leachate is representative of the extent of biodegradation occurring in the landfills.

Six column reactors were set up to simulate operational bioreactor landfills, a schematic of which is shown in Figure 4.27. The columns recirculated different leachate blends and also simulated the open and closed loop recirculation systems. The closed loop system did not get

any addition of leachate within the recirculation loop. The leachate absorbed by the leachate was only replenished. The open loop recirculation on the other hand replaces a component of the mature leachate depending on the blending ratio. The open and closed loop systems (previously discussed under chapter 3), is shown in Figure 4.28. In the closed loop system, there was no addition of any leachate externally during the mixing cycles. In the open leachate recirculation loops, a component of the spent leachate was replaced with the corresponding component of the mature leachate.

The leachate properties that were analyzed for the column reactors included COD, ammonia and the pH of the leachate as shown in Figures 4.29, 4.30 and 4.31. In case of the duplicate control reactor, the average values were used. In addition the VFA concentrations and the biogas generated were also monitored for the column reactors.

The gas production in the reactors was observed initially in the first week after loading and starting up in reactors 2N:1O-CL (2.8L), 1N:2O-OL (3.6L) and 3N:0O-CL (5.3L) bioreactors, following which there was no gas production noticed. The initial biogas production could have likely come from aerobic biodegradation since there was no significant methane concentration in this collected biogas (CO₂ upto 30% and remaining N₂ and O₂).

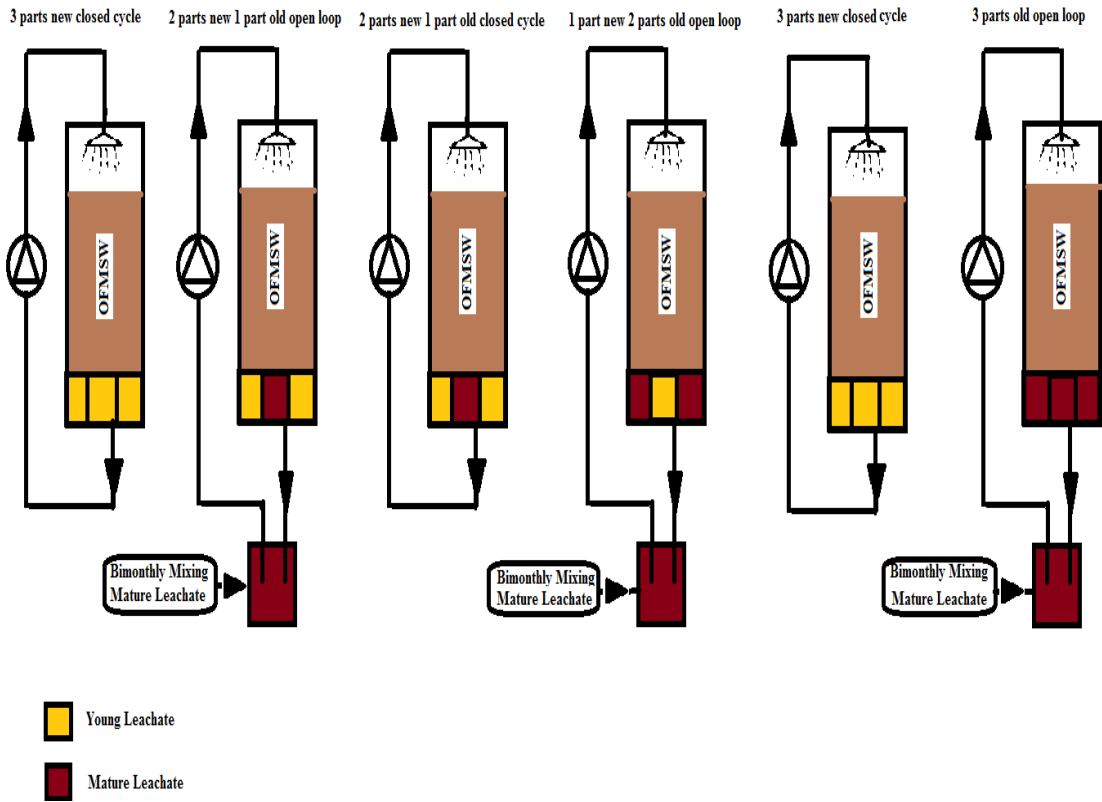


Figure 4-27 Schematic column reactors

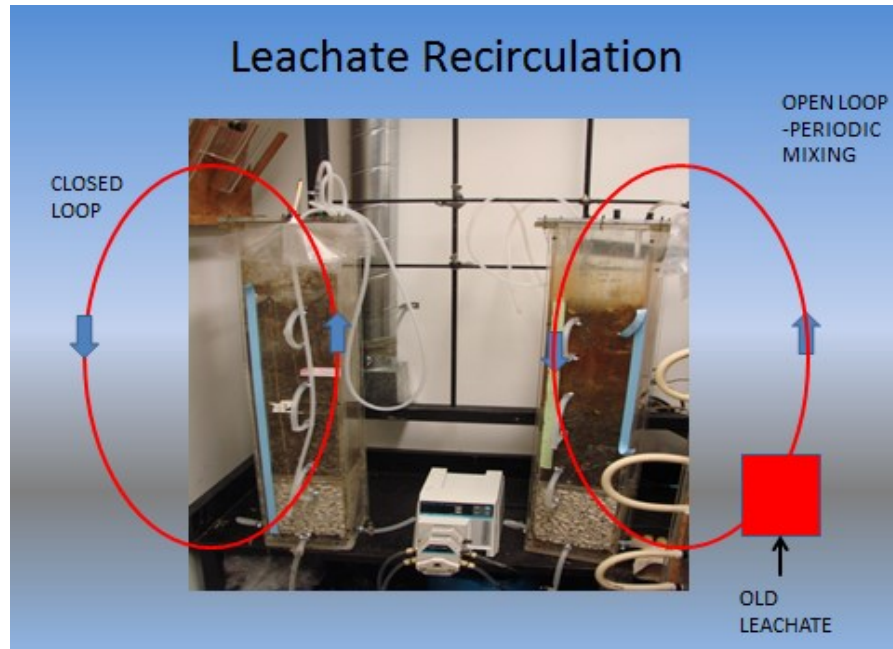


Figure 4-28 Open and closed leachate recirculation loop

4.7.1 Reactor COD Curve

The COD analysis for the column reactors were conducted every alternate day for the first 2 months of operation following which the tests were done every alternate week for all reactors. The first 2 months of operating the column reactors showed that there were no fluctuations observed in the COD values and ammonia values except during cyclic mixing. The cyclic mixing in the reactors showed slight variations in terms of the COD values immediately after the mixing but returned to an average value within two recirculation cycles (one week after mixing) as shown in Figure 4.29.

The COD values for all the columns were very erratic during the first month and dropped with every recirculation which was not expected. (Reinhart, 2006) This initial drop in COD values was not a result of VOC destruction because there was no indication of any methanogenic activity. An explanation of this kind of behavior by the reactors is that the OFMSW adsorbed the solubilized organic material from the leachate during recirculation.

In addition to the variation in COD values, the ammonia concentration was also unusually high for the fresh leachate generated and there seemed to be some component in the OFMSW in the column reactors. Therefore, to provide a reset for all the columns, a flushing cycle was done wherein all the reactors were flushed with 9L of distilled water each (3 passes of flushing with 3L each pass.) After the flushing the COD valued in all the reactors had almost stabilized except for the reactors containing 2 parts of new leachate in closed loop (2N:1O-CL). Two more passes were required to reset this particular reactor.

It was observed that all the reactors with a component of mature leachate being replaced had typically lower COD values, perhaps because of the lower COD values of the mature leachate (11,000mg/L) there was also a higher degree of stability in these reactors.

The COD values shown in Figure 4.29 clearly showed that there was no onset of methanogenesis and no organic biodegradation. There was also minimal gas production during the initial week which dropped to zero gas production. Perhaps the total organic loading in the reactors were too high as was evidenced in the batch test III conducted wherein high organic loading retards the biodegradation.

In order for the reactors to achieve faster stabilization the recirculation schedule was increased to thrice a week from twice a week after 6 months of operation of the column bioreactors. The results suggest that the stabilization could take long periods of time despite increasing the factors conducive to landfill stabilization.

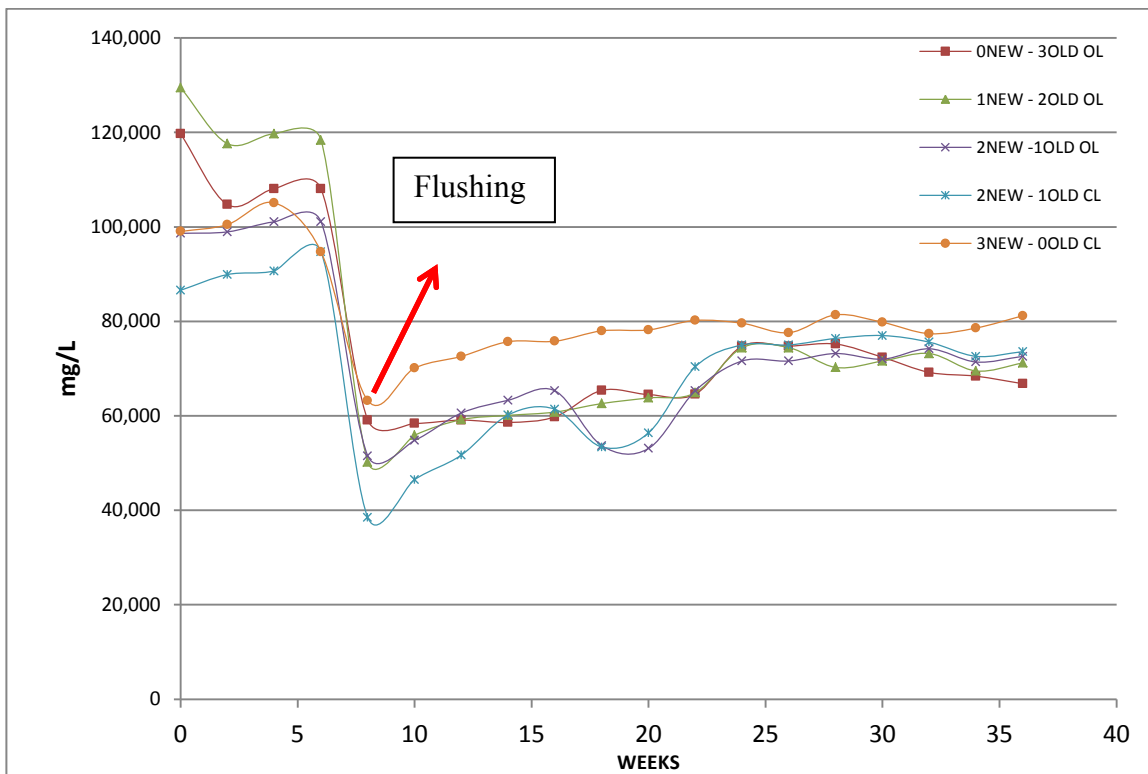


Figure 4-29 Column reactor COD curve

4.7.2 Reactor Ammonia Curve

Ammonia is a very serious inhibitor to methanogenesis. In most studies that have analyzed the peak levels of ammonia beyond which methanogenesis is retarded, state that at concentrations

around 1,500 mg/L, ammonia has a considerable inhibitory effect on methanogenesis. (Reinhart and Townsend, 2006; Berge, 2006) The ammonia concentrations for the reactors are shown in Figure 4.30. During the first month of operation, wherein the leachate was recirculated, the ammonia picked up by the leachate was extremely high. Within four passes, the ammonia levels in the control reactor 3N:0O-CL had increased to 4,170 mg/L and was rising uncontrollably in the other reactors as shown in Figure 4.30. Ammonia destruction in the system requires either oxygen (aerobic stripping) or an open loop recirculation for removal through dilution. Since neither of these exists in the case of the closed loop systems, the ammonia levels in these reactors would only increase as the leachate trickles through the OFMSW, which was of serious concern. The ammonia buildup that occurs in the bioreactor landfills has been explained by Berge(2007), as ammonification. The ammonia buildup in the reactors with closed loop recirculation also interfered with the COD values and a reset was imperative. Hence a flushing was performed as previously discussed.

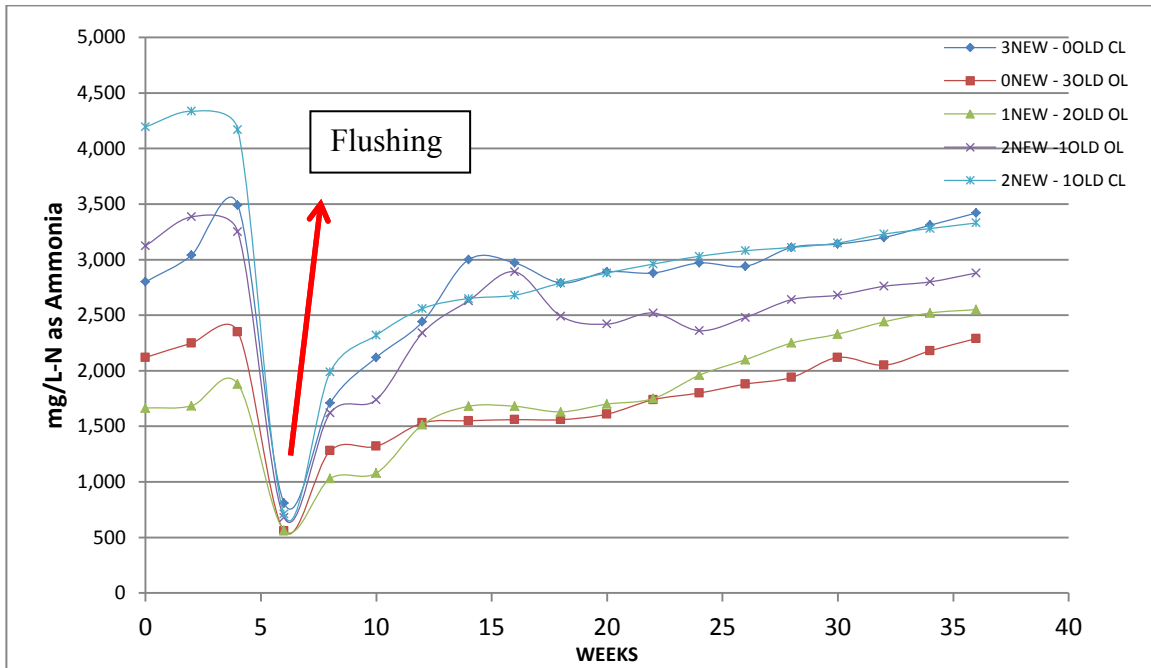


Figure 4-30 Ammonia curve column reactors

The flushing cycle provided the column reactors a reset also for the ammonia concentrations which were reaching critically inhibitory levels in the closed loop reactors. The objective of the flushing was also to remove the existing leachate with high ammonia concentration, dilute the ammonia causing material in the recirculation pathway and stabilize the OFMSW and by keeping the leachate levels in the non-inhibitory range. Following the flushing, the ammonia levels dropped to as low as 564mg/L. Following the flushing, the reactors picked up ammonia levels within a week of recirculation though not as high as before the flushing. The reactors which had an open loop recirculation cycle showed distinctly lower ammonia values (67% difference in ammonia levels between the reactors with 3 parts old leachate in open recirculation and 3 parts of new leachate in closed recirculation.) However, it is to be assumed

that the open loop dilution of the ammonia was probably not enough to offset the inhibition caused by the ammonia.

The observed results clearly indicate that the higher the component of old leachate recirculated in the landfill the lower is the ammonia. This however, need not be the case in every landfill bioreactor. The tendency is for the mature leachate to have a higher ammonia concentration than the fresher portions of the waste since in anaerobic digestion that takes place with the OFMSW, the ammonia stays within the system and is not removed by microbial activity. However, Berge et al., (2006) states that the ammonia concentrations in the mature leachate can also be drastically low depending on the type of infiltration of surface water sources (assuming that there is no ground water regurgitation).

In all of the reactors, the ammonia levels increased at a steady pace even after the flushing cycle. In the reactors with open loop recirculation the ammonia levels was found to drop a little immediately after replacement and within a week the ammonia levels would return to higher values as is observed in the plot (Figure 4.30) The high ammonia concentrations in excess of 2,500 mg/L could have been one of the main inhibitors to methanogenesis. The ammonia concentrations in the column reactors could not be adjusted despite the flushing cycle. One of the main reasons as discussed earlier is the fact that there is negligible ammonia removal in anaerobic bioreactor landfills.

4.7.3 Reactor pH Curve

The pH of the reactors was monitored on a weekly basis. Though it was not an indicator as to whether or not there was biodegradation, the pH is critical for creating favorable conditions for methanogenic bacterial growth. The pH curve is shown in Figure 4.31

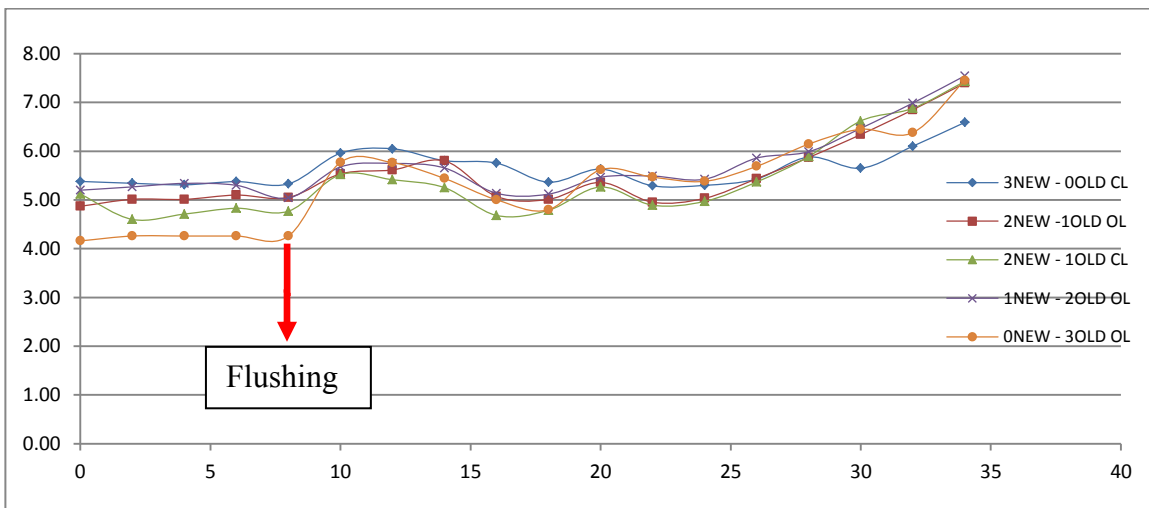


Figure 4-31 pH curve column reactors

The initial pH of the leachate generated with addition of water was highly acidic in the range of 4-5 for all reactors. From the very first percolation of water through the OFMSW, the pH after the first pass dropped from 7 to less than 5. During the flushing, the pH increase was noted by nearly 1 unit. The pH unlike the ammonia or COD did not drop after recirculation following the flushing.

The pH of the reactors was dependent on the component of mature leachate in the leachate blend. This is because the natural pH of the mature leachate is in the basic range at 7.9.

During every replacement cycle however, the leachate pH varies by a few decimal points in the reactors having an addition of mature leachate.

It has been concluded from studies that methanogenic bacteria is very sensitive to pH and the methanogenic activity is best at pH ranges of 7-8. The natural alkalinity of the leachate blends vary from 4500mg/L to 6,800mg/L. In order to promote the methanogenic activity of the bacteria additional buffers were added to raise the pH within the range of 7-8. The buffer (4g of Na_2CO_3 and 1g K_2CO_3) was added to every recirculation cycle following the flushing. The pH was noted to start increasing tangibly from week 23 onwards presumably as a result of the breaking of the natural acidic buffers in the leachate by the addition of prepared buffer. The reactors showed similar properties with regards to the pH.

4.7.4 Reactor VFA

The phase shift in bioreactor landfills are seldom identified in bioreactor landfills (Reinhart, 2006). The phase shift between acidogenic phase and methanogenic phases in a bioreactor landfill could take up to a few decades and during the process of OFMSW stabilization the point of phase shift cannot be distinctly noted. In terms of methanogenic activity, the phase shift may never be identified even in a bioreactor landfill.

The sharp drop in leachate COD levels and biogas generation are characteristic of phase shift into methanogenic phase in a bioreactor landfill. In most studies, the phase shift is accelerated

by using kitchen waste (Sun Y. et.al, 2011; Jiangbo, 2008; Bilgili, 2009). These studies utilize high organic content food waste alone as OFMSW in the simulated bioreactors. With pure organic waste, it is possible to observe a phase shift within a year of operation characterized by Volatile Solids (VS) removal and biogas generation. In operational bioreactor landfills, the OFMSW stabilization and phase shift could take decades.

The VFA distribution in leachate can be helpful in predicting the rate of waste stabilization in bioreactor landfills. (Abdallah and Shahriahri, 2009; Abdallah, 2012; Sanphoti, 2006). Figure 4.32 shows the pathway of VFA generation leading to anaerobic digestion.

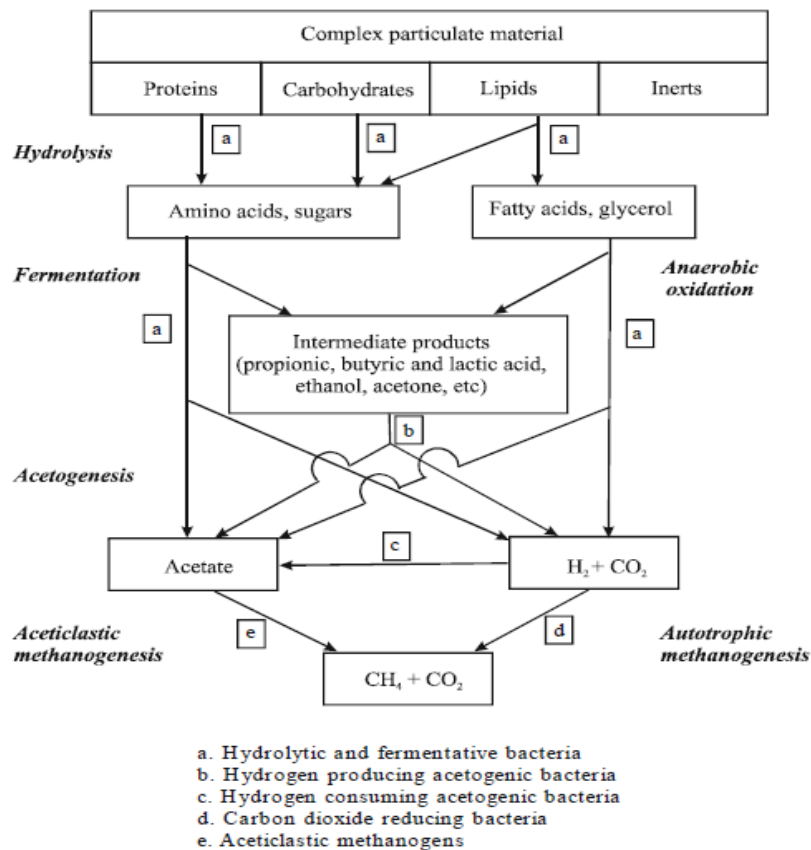


Figure 4-32 Pathway of Anaerobic Digestion, adapted from Manariotis et.al, (2010)

It is observed that in a mix of volatile fatty acids, the higher the acetic acid, the more is the biogas generation potential and the higher the amount of propionic acid and butyric acid, the longer it would take to achieve anaerobic biodegradation or methanogenesis.

Higher VFA content in leachates can prove inhibitory to methanogenesis (Shahriahri, 2011).

This is well substantiated by batch test III where higher organic loading show that bacteria are

overwhelmed by the high amount of substrate available for biodegradation and this in turn inhibits methanogenesis.

It can therefore be stated that in a bioreactor if there is a higher concentration of acetic acid, the biogas generation would relatively be higher and also that lower concentrations of propionic and butyric acids, indicates faster rates of phase shift into methanogenesis.

Figure 4.33 shows the VFA split up for the different leachate blends as analysed under the GC immediately after flushing the column reactors. It is observed that in the reactors that had mature leachate components had different characteristics from the ones that had only young leachate while the other reactors were in between.

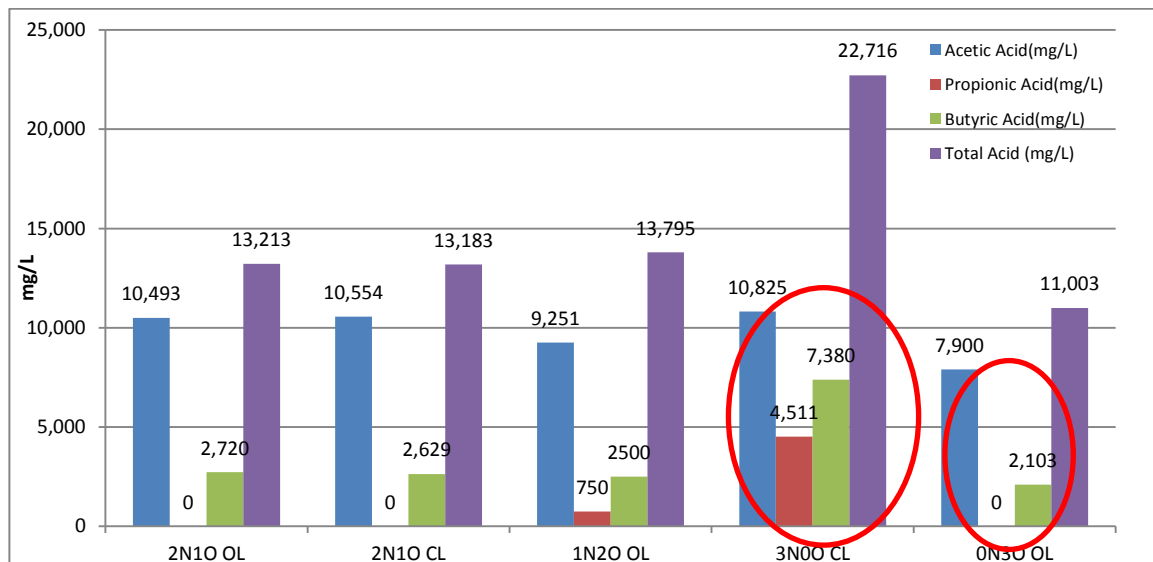


Figure 4-33 VFA analysis for column reactors after flushing.

It is interesting to observe that the recirculated leachate in bioreactor with 3 parts of young leachate had the highest proportion of butyric and propionic acids. The acetic acid

concentration was also the highest at the start of the reactors immediately after the flushing cycle. This indicated that the reactors would have a high generation potential with respect to biogas generation. However, the rate of generation will be lower because of the high proportions of butyric and propionic acids. The pathway for biodegradation of these two types of acids takes much longer and is essentially a critical path in the anaerobic biodegradation as explained in Figure 4.32. Studies with organic loading rates with high VFA contents show that the high total acids would inhibit the methanogens. (Manariotis et. al., 2010) this fact is also evident from the results of batch test III.

The reactors with higher components of mature leachate showed relatively lowest levels of acetic acid and lowest levels of butyric acid and propionic acid was undetected at the end of the first month's run immediately after the flushing cycle. This indicates that there was potential for a higher rate of biodegradation. This supplements the results from batch test IA wherein the bioreactors producing methane faster has the maximum generation as well. This however, is a hypothesis since the bioreactors had not matured enough for a phase shift into methanogenesis. It is suggested from the results that the higher the component of mature leachate in the leachate recirculated, the biogas generation tends to be increased and the rate of biogas generation.

The VFA in the leachates from the reactors were analyzed after 20 weeks of operation. These results observed were found to have a significant difference compared to the VFA analysis during start-up. Figure 4.34 shows the VFA split up.

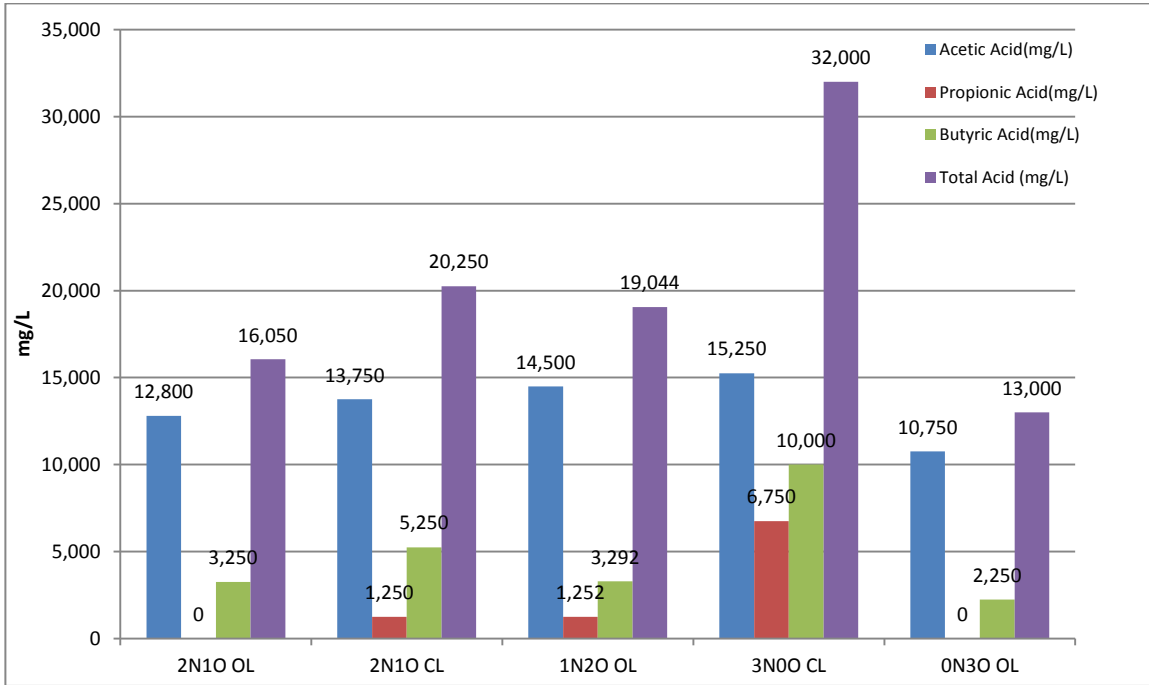


Figure 4-34 VFA analyses for column reactors after week 20

The VFA analyses after week 20, bears a lot of similarity with the batch test VFA results between the reactor with 3 parts of young leachate and reactor with 3 parts of mature leachate during the middle of the operation cycle. However, it is observed that the reactor with only 1 part mature leachate and 2 parts of old leachate in open loop performs better in terms of VFA analysis to the reactor with 2 parts of mature leachate and 1 part of new leachate in open loop system. This is contrary to the results observed in the batch test IA where the reactors with more component of mature leachate showed higher acetic acid concentration and lower propionic and butyric acid concentrations.

One of the reasons for this behaviour can be attributed to the open loop and closed loop being applied in the column reactors, in addition to the type of waste and the recirculation in the column reactors. Another possible explanation is that there is no biogas generation in the column reactors and there would only be accumulation of acids because of active acidogens. This would not yield any conclusive results till the phase shift occurs into methanogenesis. High acid content also inhibits the methanogenesis as is observed from batch test III.

Figure 4.35 shows the VFA distribution following week 36. It shows high degree of acidogenesis.

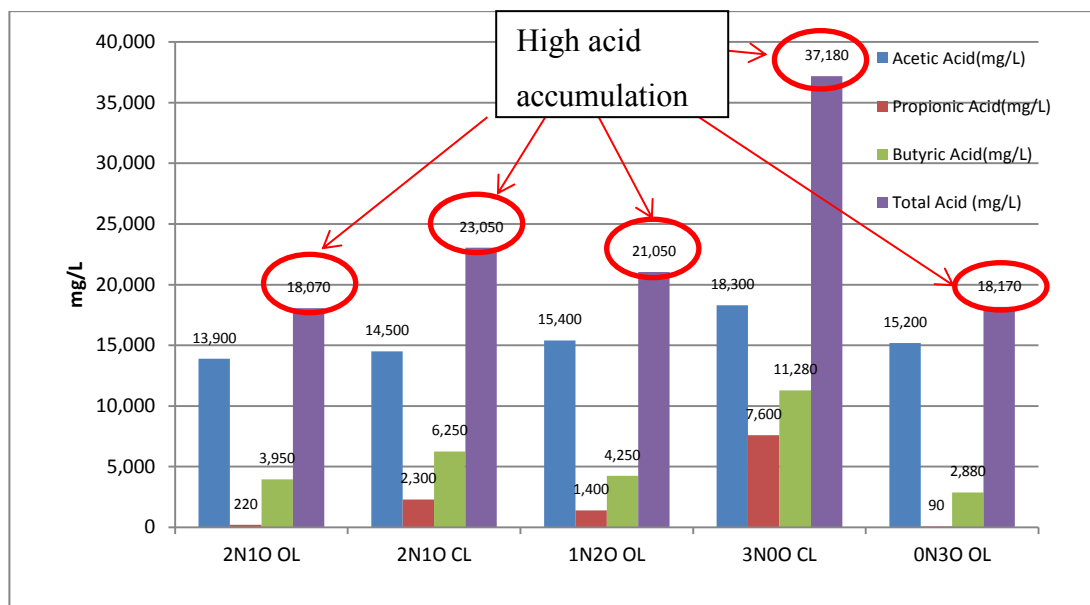


Figure 4-35 VFA analyses for column reactors week 36

Since there is no methanogenesis, as is evident from no biogas being generated, the substrate is not getting utilized and shows up as acid accumulation. However, what can be inferred from the VFA analysis is that once the methanogens are active, the reactors most likely to

perform best in terms of biogas generation and rate of biogas generation, it would be the reactors with highest acetic acid content and least butyric and propionic acid content.

The column reactors despite flushing would not produce gas but at the same time had produced a high amount of VFAs. This indicated that there was an inhibition in the phase shift from acidogenesis to methanogenesis. Reinhart (1997), states that the process of this phase shift in working bioreactor landfills could take anywhere between 1-5 years. Due to time restrictions, the column bioreactors would be analyzed for factors of inhibition and removal of ammonia and pH adjustment in another study on the same column bioreactors.

Chapter 5: Conclusions and Future Work

5.1 Conclusions from Batch BMP Assays

The batch test IA concludes that the leachate blending shows significant improvement in terms of biogas generation, both from a generation perspective and from a rate perspective as the reactors with more component of mature leachate produces biogas faster and in case of the leachate blend with 2 parts of mature leachate and 1 part of young leachate the rate of biogas generation is increased by nearly 7 days to produce the same amount of gas as a conventional bioreactor landfill using 3 parts of young leachate.

Batch test IB establishes the fact that there is a high amount of biodegradable organic material in younger leachate compared to mature leachate. The leachate from younger segments of landfills, or the landfill segments where there is loading of fresher organic waste, will contain more organic material. Of this organic material, the younger leachates will contain a higher

percentage of biodegradable organic material over the mature leachate which has a higher percentage of organic materials that are non-biodegradable.

Batch tests IA and IB combined establishes that the initial hypothesis to be true that blending leachates can increase the rate and extend of anaerobic biodegradation in bioreactor landfills. The leachate blend with 1 part of new leachate and 2 parts of old leachate blends showed a 98.9% higher biogas generation over using 3 parts of generated leachate as in conventional landfill bioreactors.

It is inferred from batch test II that there is an advantage in terms of operational standpoint in using an open loop recirculation system over a closed loop recirculation system. The leachate addition in the open loop system ensures that there is a treatment protocol for the additional leachate since it was observed that the leachate biodegrades faster than the OFMSW and the biodegradation of the leachate can produce a considerable amount of methane. An open loop system produced up to 5.7 more biogas compared to the same closed loop system as a result of the leachate replenishment.

The batch test III concludes that the full potential of organic material cannot be utilized if the organic loading in the bioreactor landfills exceeds the threshold for a particular bioreactor landfill and the leachate recirculated. It was observed that the specific biogas generation per gram of organic load was highest for the reactors with 3 g organic load at 297 mL/g which

was double the specific biogas generation for the reactors with 9g of waste. Hence it can be concluded that a higher organic load does not necessarily mean that there is a higher rate of biogas generation.

Batch test IV concludes that there was an advantage in distributing organic loading over time. Bioreactor landfills can stand to gain in reducing the lift sizes and spreading out the loading spatially. The reactors which had a distributed loading representing lower lifts had a biogas generation of 1,526 mL/3g of loading while the reactors which had a one-time loading representing highest lift sizes had a biogas generation of 896mL/3g of loading, This conclusion also supports the findings from the study conducted by Reinhart and Townsend (1999) on COD loading patterns in bioreactor landfills. (Reinhart and Townsend, 1999)

5.2 Conclusions from Simulated Landfills- Column Bioreactors

The column bioreactors, simulating real world bioreactor landfills, support the hypothesis that blending mature leachate with the generated leachate in bioreactor landfills improves the performance of the bioreactors. Though the column reactors did not produce biogas and had not yet achieved a phase shift into methanogenesis, the parameters monitored such as VFA analyses, pH, COD and ammonia suggest that the rate and generation of the biogas can be

increased by blending mature leachate within the leachate recirculation loop in a bioreactor landfill.

The VFA analysis shows significant rate retardation in the column reactors with 3 parts of young leachate (representing a conventional bioreactor landfill) compared to the column with 3 parts of mature leachate. The rate retardation would be brought about by the amount of butyric and propionic acids which in case of column with 3 parts of mature leachate has a 5 fold reduction in the total propionic and butyric acid production compared to the column with 3 parts of mature leachate.

5.3 Future Work

From this study it is evident that blending mature and young leachates in bioreactor landfills can improve the performance of the landfills by increased biogas production and faster waste stabilization. This said, there are many inhibitory factors in biogas generation such as ammonia toxicity, threshold organic loading and acidity build up.

The operation of the column bioreactors would have to be continued with increasing alkalinity and continued leachate recirculation and blending till a phase shift is observed into methanogenesis. The ammonia concentration in the bioreactors should also be reduced from

building up beyond 3,000mg/L and a cheap and efficient alternative of removing ammonia should be developed without altering any of the other parameters such as COD and pH.

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