EFFECT OF MANURES ON FOOD WASTE DEGRADATION IN BIOCELL

by

MD NUR BASIT ZAMAN

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Abstract

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Md Nur Basit Zaman, MS

The University of Texas at Arlington, 2016

Supervising Professor: MD Sahadat Hossain

Proper disposal of food waste is a challenge due to adverse effect on the environment through generation of excessive leachate and greenhouse gas (CH_4). After food loss through the food supply chain, the food waste ends up mostly in landfills. A study by EPA showed food waste to be the second largest component found in landfill. However, food waste imposes major cost on landfill management, and demands a potential alternative disposal solution that can negate the adverse effects. Though anaerobic digester and composting are possible solutions for food waste disposal, the former is highly expensive while in later solution, a valuable portion of energy is lost. Among other existing alternatives biocell landfill might offer a sustainable benefit for food waste disposal by retrieving valuable energy in a cost efficient way. In addition of being capable of handling high moisture, the addition of nutrients (e.g. livestock manures) used in biocell accelerates decomposition of waste. For organic waste especially pure food waste, addition of nutrients is necessary to prevent excessive volatile fatty acid (VFA) accumulation and thus reduction of microbial activities. However, limited studies have been conducted to evaluate the effect of nutrients (livestock manure) on food waste degradation and gas generation. Therefore, the major objective of the current study was to find out the potential of nutrient (different types of manures) addition on food waste decomposition and gas generation in biocell.

Current research was conducted by preparing laboratory simulated biocell food waste reactors with four combinations; a pair of control reactors containing only food waste and the other combinations including 6% cow manure, pig manure and horse manure respectively in addition to sludge as inoculum. The reactors were operated at 37°C in an environmental growth chamber. Over the operation period, the reactors were monitored for leachate and gas measurement. For leachate, pH, volume, COD and BOD_5 tests were conducted while composition and volume measurements were done for the gas generated. Based on the experimental results, it was found that all the food waste reactors showed an extended lag period (more than 100 days) before methane generation. Reactors with cow manure as nutrient presented better result compared to pig manure and horse manure. However, the lag period for the reactors with food waste and cow manure were 100 days and 135 days while the other reactors were still in lag period. During about 180 days of operation peak methane generation rate for these two reactor were 350 mL/wet-lb/day and 355 mL/wet-lb/day while the cumulative methane generation was 16 liter/wet-lb and 9.5 liter/wet-lb respectively and they were still just at the rising stage of methane generation phase; percentage of methane found in these two reactors were 75.9% and 73.4% respectively. However, methane generation from other reactors were found to be negligible; in fact most of the reactors were still in the initial lag phase.

Results from the current study suggested cow manure to be a possible nutrient on food waste degradation in biocell landfill. Presence of extended lag period was an issue associated with food waste, however, methane generation was satisfactory and the percentage was comparable to that of anaerobic digester.

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Chapter 1

Introduction

1.1 Background

According to Food and Agriculture Organization (FAO) (1981), food waste is the edible portion of the produced consumables that instead of being consumed either gets discarded, lost, degraded or affected by pests. Food waste is reported to be the second largest component (14%-21%) of the waste stream in USA (USEPA, 2013). Globally around one third of the food produced goes to waste even before reaching to the consumer. This wasted food is amounted for 1.3 billion tons per year (FAO, 2011). Figure 1.1 shows the regional per capita food loss, which is as high as 650 lbs. per capita per year in North America & Oceania and the lowest amount is 276 lbs. per capita per year in South & Southeast Asia (FAO, 2011).

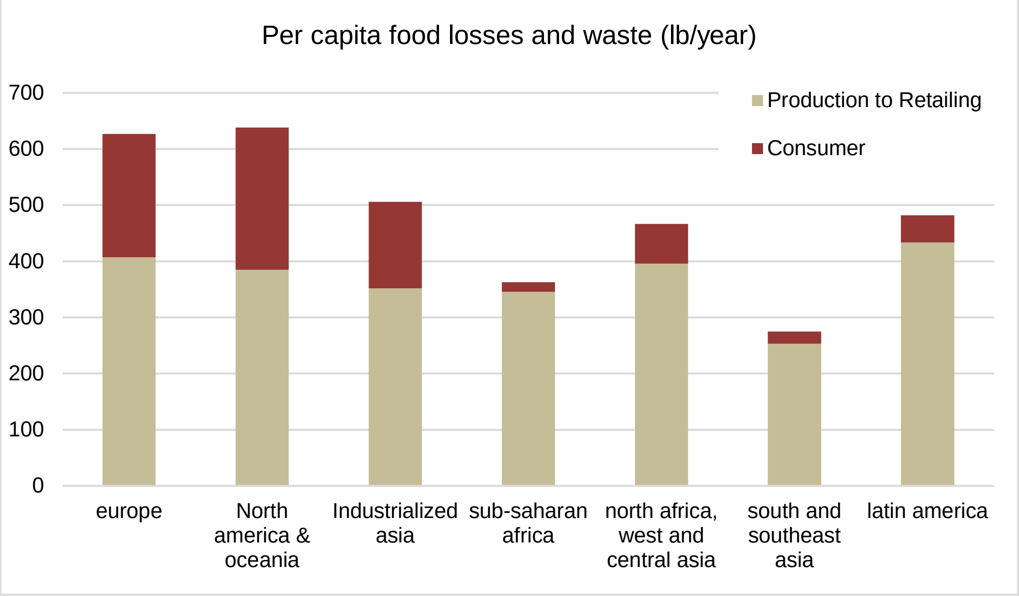


Figure 1.1 Per capita food losses and waste, at consumption and pre-consumptions stages, in different regions (FAO, 2011)

Throughout the entire process of food supply chain, from production to the fork of the consumer (growing & harvesting, postharvest, processing, retail and consumption), food is wasted. The amount varies in different stages of the process and with the component of food. A global scenario of food waste is presented in Figure 1.2.

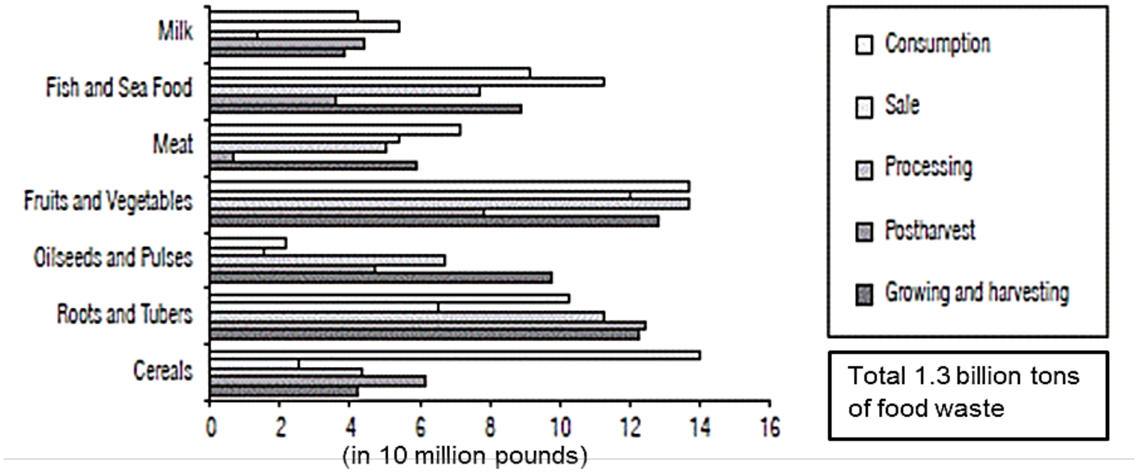


Figure 1.2 Comparison between food waste components in different phase of food supply chain (source: Gustavsson, 2011)

Food loss is a common scenario for both developed and developing countries. In industrialized countries the loss of food occurs at the retail and consumer level and 97% of this huge amount of food waste finds their way into the landfill (Buzby et al., 2011).

On the contrary, food loss in developing countries occur mainly due to poor storage condition even before reaching the retail or consumer. In developing countries, these food wastes are the largest portion of the municipal solid waste that is approximately 70% of the waste stream (Waste Concern, 2009).

Food waste has adverse effect on the environment through the excessive methane generation and leachate production. In addition, food loss accounts for significant economic loss in both developed and developing countries. However, food waste can be used for composting or converted to energy if diverted from the main waste stream. Many US states already started food waste diversion and using this organic waste in composting or in anaerobic digester (AD) for energy production. Since, food waste is one of the largest component in MSW, if all food waste is diverted from the landfill a lot more anaerobic digester will be required. Currently, only a limited number of AD’s are operating in the states and the initial investments and operating costs are significantly high for AD’s. Therefore, an alternative option for this diverted food waste management is becoming very critical.

1.2 Biocell for Food Waste

Biocell concept first introduced by Hettiaratchi et al. in 2005, proposes a modified bioreactor technology with addition of nutrients for enhanced degradation of the waste. Biocell can be considered as a promising alternative for organic waste diversion since it has the ability to handle waste with high moisture content, facilitate faster degradation through the addition of nutrients (e.g. manures) and possibly capture almost all the methane (CH_4) generated. The major advantages of biocell landfill are energy recovery, greenhouse gas (GHG) emission control, groundwater as well as surface water contamination control, resource recovery and airspace recovery. Considering all these, rather than a waste disposal facility, biocell can be a possible alternative for waste processing facility where organic contents of MSW will be processed after being diverted from a recycling facility.

1.3 Problem Statement

In developing countries the lion’s share (70% or more) of the MSW is food waste which contains a significant amount of moisture (70~90%). Developing countries do not have well-built infrastructure for proper collection and disposal of waste. Most of these food waste ends up in the open dumps due to lack of proper collection and disposal of waste. These uncontrolled dumping of food waste leads to contamination of water sources and contributes to the greenhouse gas emission having high methane generation potential.

In developed countries such as US, 40% of the food produced are unconsumed (Gunders, 2012), and eventually ends up in the landfill, which is the second largest component (14%-21%) of MSW generated. Presence of this high volume of food waste in MSW presents adverse environmental and economic effects since food waste is responsible for generating higher leachate and higher gas resulting in extra monitoring cost and migration issues. Therefore, many US states like Connecticut, Vermont and Massachusetts started to ban food waste from landfill which calls for the need of an alternative and efficient diversion solution for food waste.

At present, anaerobic digester is becoming very popular alternative for food waste processing and disposal. Currently there are approximately 645 anaerobic digester operating in US (American biogas council, 2016) which processes only a small fraction (<3%) of the high amount of food waste produced. However, to divert all the food waste from the landfill a lot more anaerobic digester will be required and the initial investments and operating costs are significantly high for anaerobic digesters. Therefore, biocell landfill could be effective and economically viable alternative concept. However, no study to date has been conducted on biocell with 100% food waste; in addition, no study has been done to compare the performance of different manures on food waste degradation. Therefore, to evaluate the concept it is important to conduct a research by introducing nutrients as inoculum for food waste degradation in biocell landfill.

1.4 Research Objective

The goal of current research was to determine the effect of nutrients (e.g. manures) on food waste degradation in biocell. An extensive experimental program was prepared to evaluate the results collected from gas and leachate generation data.

The specific objectives of the current study were as follows:

1. Determine the effect of manures on food waste degradation and gas generation
2. Compare the effects of different manures on gas generation
3. Determine the best possible manure for maximum gas generation from food waste.

1.5 Thesis Outline

This thesis is organized in five chapters that can be summarized as follows:

Chapter 1 offers general introduction to the study and presents the problem statement along with objectives of the research.

Chapter 2 presents literature review on problems associated with food waste and previous work and studies conducted related to current research, influencing factors in waste degradation and gas generation, manure as source of inoculum and a promising concept for food waste processing alternative to landfill – Biocell.

Chapter 3 describes the experimental procedure followed to collect food waste samples and inoculum to build laboratory scale simulated biocell reactors, experimental setups and laboratory test methodologies to address the research objectives.

Chapter 4 focuses on the experimental results from the laboratory tests, discussion on the results analyzed and comparison with the existing literature.

Chapter 5 summarizes the results, offers conclusion based on the results found from current study and provides recommendation for future work.

Chapter 2

Literature Review

2.1 Background

Food waste is becoming increasingly important issue which incurred with the world's growing population (FAO, 2011). Food waste is a term that can be defined as an edible item that goes unconsumed from either retailer end due to undesirable color or consumer's end as plate waste (Buzby et al, 2014). According to Parfitt et al. (2010), food loss is the edible sum for human consumption which gets wasted at production, postharvest and processing stages in the food supply chain and which relates to retailers' and consumers' behavior.

Loss of food or food waste takes place in different stages throughout the food supply chain (FSC) from initial agricultural production down to consumer end. Globally around one-third of the edible parts of food produced for human consumption, gets lost or wasted, which sum upto about 1.3 billion ton per year (FAO, 2011). Food waste is becoming a major concern in all sectors especially from the economic and health perspective. According to Economic Research Service's (ERS), for providing an affordable, diverse and safe supply to the consumer, some amount of food loss is unavoidable and/or necessary; but the biggest challenge remains in reducing food waste is to identify and quantify the point/s where food loss occurs in the food system. However, reduction of food waste is not easy and needs immense planning and implementation. Hence, food waste find their way into landfill before being diverted as animal feed, composting, incineration and anaerobic digester. Incineration is not very popular for food waste diversion because of extremely high moisture content. Presence of excessive moisture demands higher energy for incineration.

2.2 Food Waste: Global Scenario

Among the basic needs for human survival, food is the most important of all. This basic need reaches the consumer through a series of stages commonly known as "Food Supply Chain"

(FSC). The FSC can be divided into five different stages: agricultural production, post-harvest handling and storage, processing, distribution and consumption. In each of these stages a considerable amount of food is wasted due to mechanical damage during operation, spillage and degradation during processing and storage, mishandling, loss in market system and during consumption (FAO, 2011; Galanakis, 2012). Figure 2.1 shows different stages involved in producing food waste.

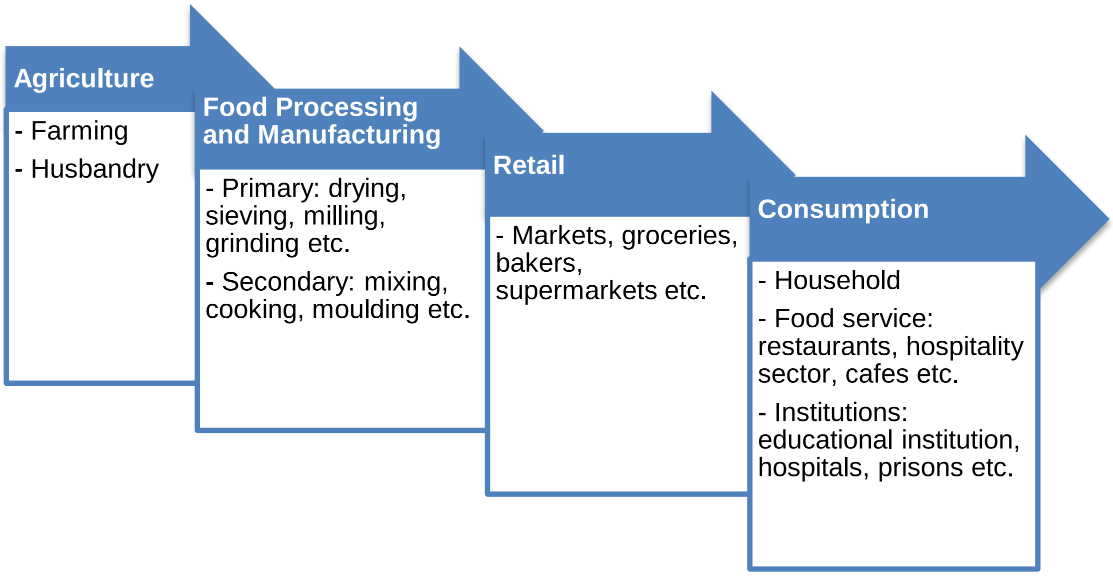


Figure 2.1 Activities giving rise to food losses and waste in the food supply chain (Parfitt et al., 2010; Smil 2004; Papagyropoulou et al., 2014)

One of the major influencing key factor in food waste generation is the economic condition of the people. Countries with higher income index tend to waste more food than countries with low income index; and a significant part of food waste from higher income countries are often found in consumable condition (FAO, 2011). In industrialized countries, food wastage is found to be as high as developing countries; however, the waste scenarios are quite different. In industrialized countries more than 40% food waste occurs at retail and consumer level while in developing countries the same loss happens at post harvesting and processing levels mostly due to poor storage and inefficient processing. Moreover, the most tragic scenario is that the consumer level waste of industrialized countries (222 million ton) is almost same as the total net production in sub-Saharan Africa (230 million ton) (FAO, 2011). Figure 2.2 shows the food waste per capita per year for different regions including developed and developing countries. The figure presents that each year as high as 600 - 650 lb per capita food is wasted in Europe, North America & Oceania, whereas in Sub-Saharan Africa, South & Southeast Asia the amount is almost half (260 – 370 lb). Table 2.1 shows the numeric values of food loss per capita per year at retail and consumer level for different regions.

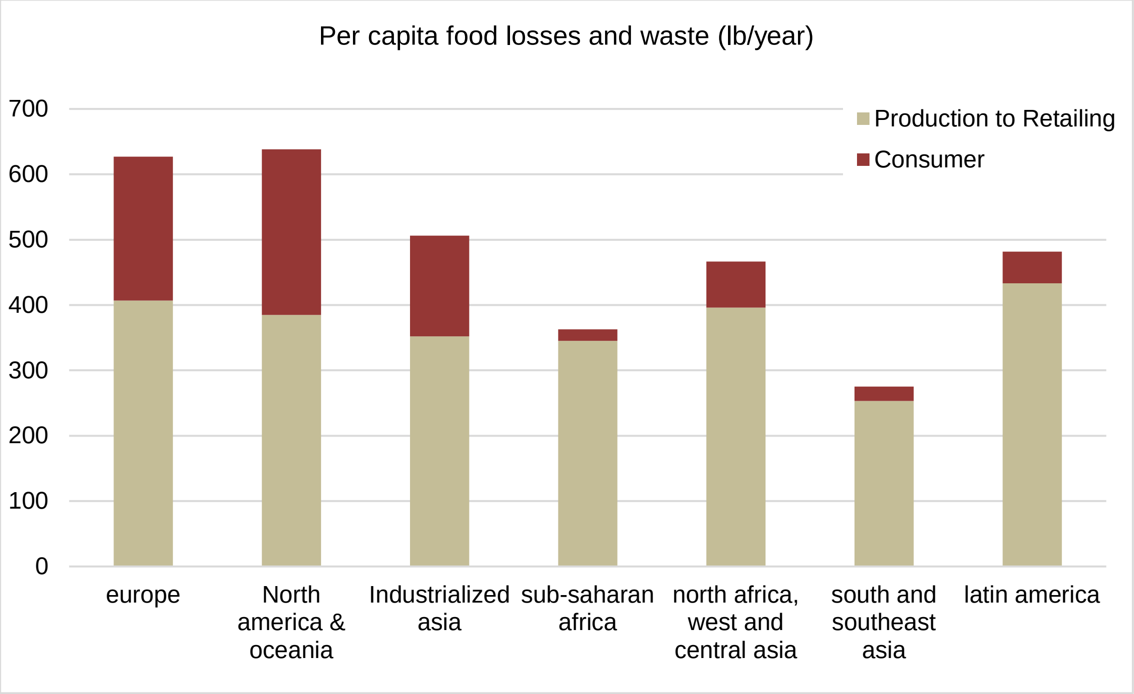
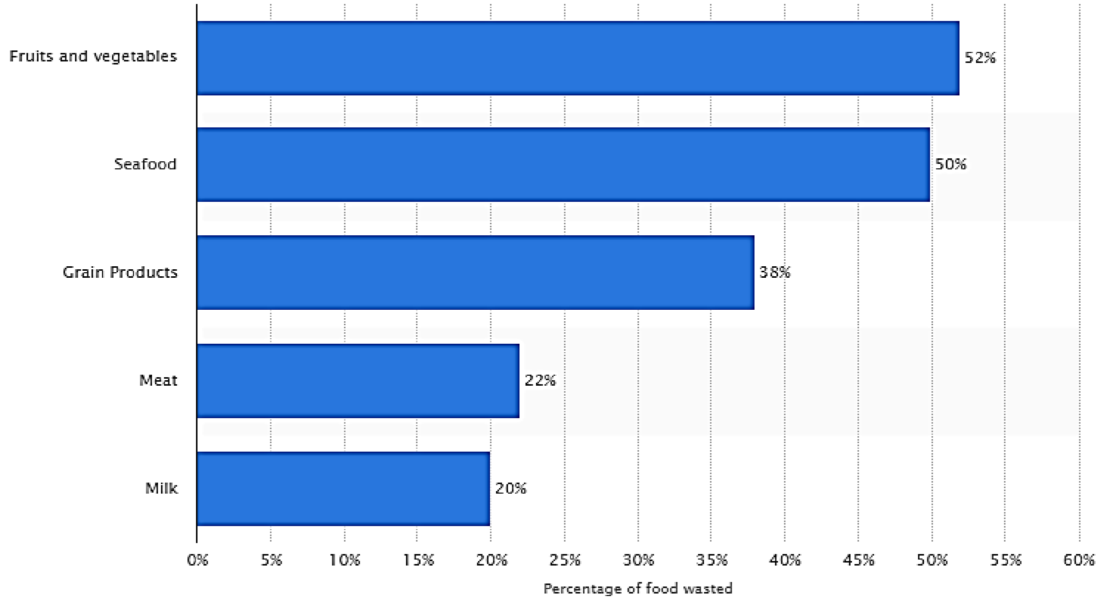


Figure 2.2 Per capita food losses and waste, at consumption and pre-consumptions stages, in different regions (FAO, 2011)

Table 2.1 Per capita food loss each year in different regions of the world (FAO, 2011)

Food loss & waste per capita per year	**Total**	**At the production & retail stages**	**By consumers**
Europe	280 kg (620 lb)	190 kg (420 lb)	90 kg (200 lb)
North America and Oceania	295 kg (650 lb)	185 kg (408 lb)	110 kg (240 lb)
Industrialized Asia	240 kg (530 lb)	160 kg (350 lb)	80 kg (180 lb)
sub-Saharan Africa	160 kg (350 lb)	155 kg (342 lb)	5 kg (11 lb)
North Africa, West and Central	215 kg (474 lb)	180 kg (400 lb)	35 kg (77 lb)
South and Southeast Asia	125 kg (276 lb)	110 kg (240 lb)	15 kg (33 lb)
Latin America	225 kg (496 lb)	200 kg (440 lb)	25 kg (55 lb)

A study conducted by the Swedish Institute for Food and Biotechnology (SIK) in 2011 showed that about one third of food produced for consumption goes to waste resulting in about 1.3 billion tons of food waste per year globally. A statistics by FAO (2011) reported that fruits and vegetables have the highest percent of waste (about 52%). According to the source, percentage of losses by category of foods were calculated collectively for the United States, Canada, Australia and New Zealand (Statista, 2016) as represented by Figure 2.3.



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Additional Information:
Worldwide; FAO; 2011

Sources:
Natural Resources Defense Council; FAO

Figure 2.3 Food waste in United States, Canada, Australia and New Zealand by category (FAO, 2011)

2.3 Food Waste in Landfill

Landfill is a disposal site for the refuse and other waste material which is also the oldest and most popular waste disposal system. Food waste is the second largest component in the landfill. It has been noted that globally along the food supply chain food is being wasted and the amount is not negligible, about 1.3 billion tons per year (FAO, 2011), most of which (more than 95 percent) goes into the landfill. According to Chen et al. (2010), through composting less than only three percent of the food waste is being separated and treated primarily and the rest is being sent to the landfills. This scenario is more or less similar in both developed and developing countries although the stage where the loss occurs is quite different.

2.3.1 Developed Countries

According to USDA's Economic Research Service (ERS) (2010), at the retail and consumer level, food of approximately $161.6 billion was not available for human consumption;

which is about 31% (133 billion pounds) of the food produced by developed countries (Buzby et al, 2014). In US, before food reaches to the consumers about 10 percent of the total food supply is wasted in the food chain. 40 percent of the food produced are unconsumed (Gunders, 2012), and eventually ends up into the landfill and contribute to methane emission. It has been found that, food waste is the second-largest component of municipal solid waste generated from the United States. According to the U.S. Environmental Protection Agency (EPA), in 2010 a total of around 250 million tons of municipal solid waste (MSW) was generated, out of which almost 14 percent (34 million tons) were food waste (EPA, 2011). When recyclable materials e.g. paper, paperboard and other materials are being recycled, food waste was found to be the single largest amount (almost 21 percent) of MSW categorized by EPA in 2010. Figure 2.4 shows the composition of MSW before and after recycling.

Physical composition of MSW in U.S. shows that in landfill the second highest component is food waste and highest when recyclables are being removed.

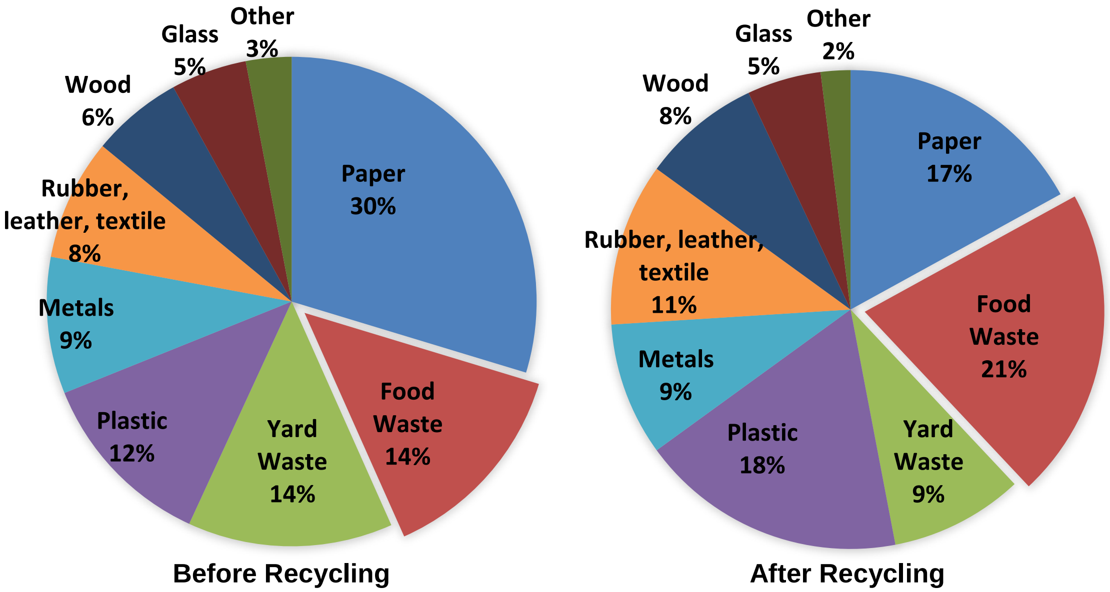


Figure 2.4 Municipal Solid Waste composition before and after recycling (Source: EPA, as of September 17, 2012)

Food waste scenario in North America shows that about 30 to 40 percent of the food supply is being wasted which equals to approximately 20 pounds of food per person per month.

2.3.2 Developing Countries

Developing countries do not have well-built infrastructure nor have a well-organized distribution network like most of the developed countries, which accounts for a large percentage of food waste occurrence. Almost fifty percent (50%) of the food produced are lost in the supply chain and accounts for billions of dollars of monetary loss. In India, annually over 60 million tons of fruits and vegetables are produced of which only 1 % is processed in the fruit and vegetable processing industries (Krishna Nand & Manjrekar, 1988). In Bangladesh, food loss in consumer level is minimum while crop losses at pre and post-harvest are extreme. According to waste data base of Bangladesh (Waste Concern, 2009) food and vegetables residues are the major portion of solid waste stream, approximately 68%. Figure 2.5 shows the average physical composition of solid waste of urban areas in Bangladesh.

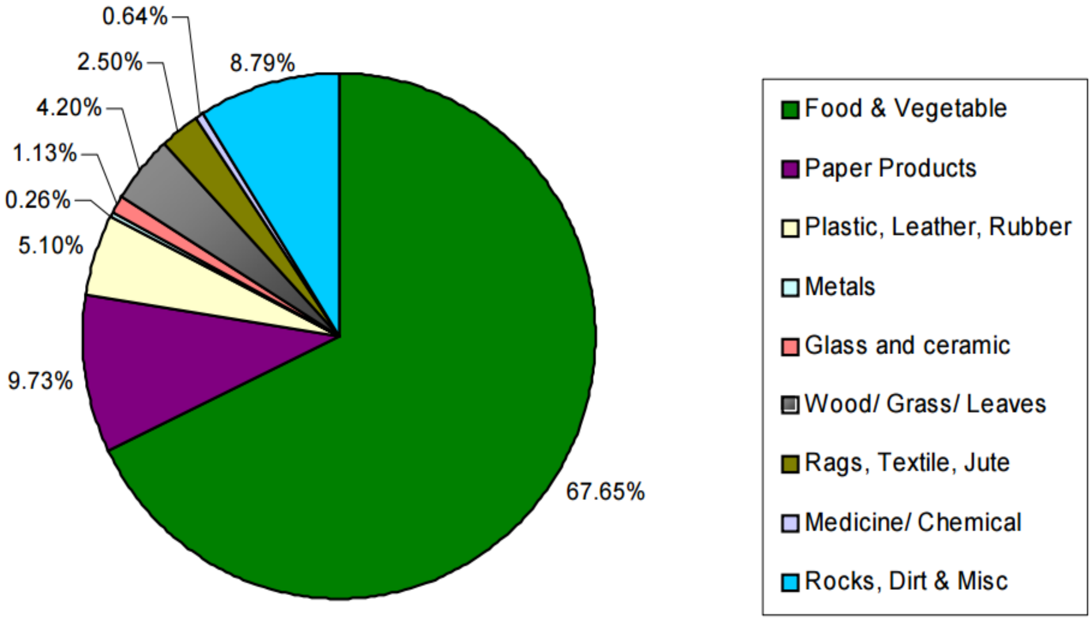


Figure 2.5 Average physical composition of Urban Solid Waste in Bangladesh (Waste Concern, 2009)

A comparative analysis (waste concern, 2009) of landfill waste composition of Dhaka, Bangladesh between 1992 and 2005 also shows that the lion's share is comprised of food waste (Figure 2.6). In different sectors of Bangladesh the percentage of food waste can be as high as 70 percent of the total solid waste generated which is very similar to any other developing countries around the world.

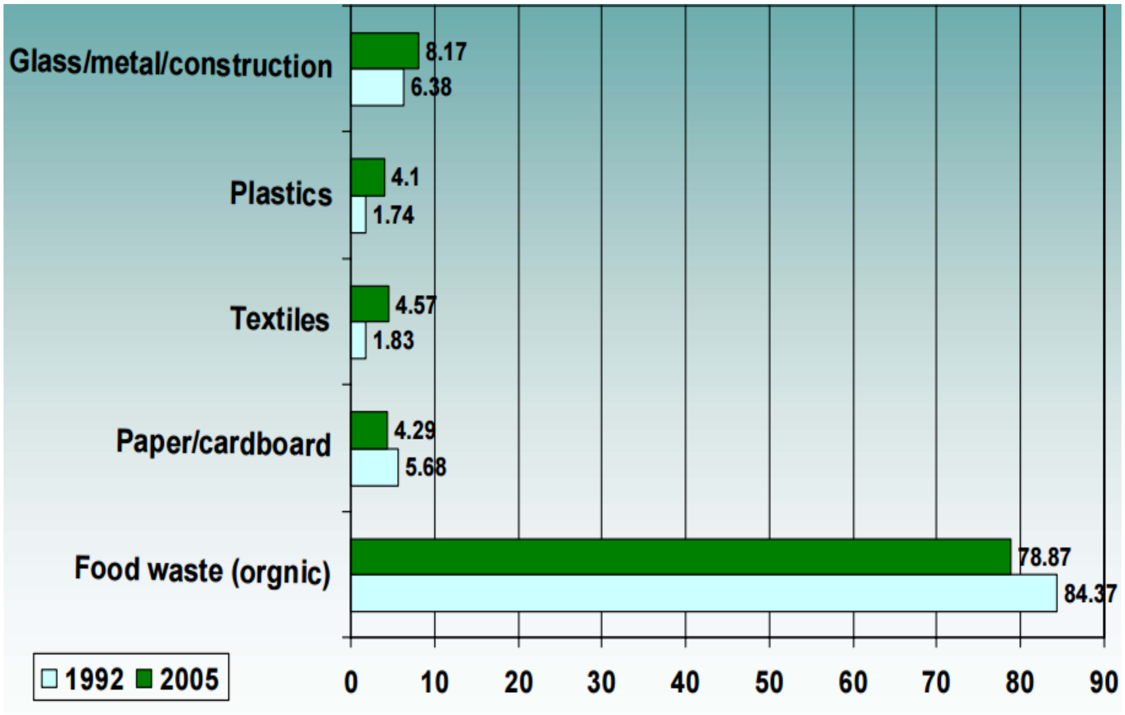


Figure 2.6 Comparative Analysis of Composition of Waste Dhaka City Between 1992 & 2005 (Waste concern, 2009)

This huge amount of food waste ends up in the open dumps or landfills since these are the most common practices of waste disposal system in the developing countries.

2.3.3 *Composition of Food Waste*

Food waste is the discards generated along all stages of the food supply chain from production to the plate of the consumer which can be any solid or liquid food substance and can be cooked or uncooked. Composition of food waste includes complex ingredients that have been discarded from the source material compared to other components of MSW. Based on the origin food waste can be divided into two main groups (Galanakis, 2012):

a. Plant origin

b. Animal origin

These two main group can be sub-categorized into seven groups, four from plant origin: i) Cereals, ii) Roots & tubes, iii) Oil crops & pulses, iv) Fruits & vegetables, and three from animal origin: v) Meat, vi) Fish & seafood, vii) Dairy (Galanakis, 2012). Although these are the most common constituents, the percentage of these varies significantly. The primary food waste generating stage is during agricultural production and secondarily the postharvest handling & storage while consumer level wastage is minimum in the low income/developing countries. However, in industrialized countries food loss occurs in both agricultural and consumption stage where consumer level wastage is the dominating one (Gustavsson et al., 2011). Table 2.2 shows global scenario of ranges of different components of food waste.

Table 2.2 Ranges of different components in food waste: global scenario (Gustavsson, 2011)

Commodity group	**Total in chain (minimum)**	**Total in chain (maximum)**
Cereals	19 % (SSA[i])	32% (NAm&Oce[ii])
Oil crops and pulses	18% (Ind. Asia[iii])	29 % (NAf, WA& CA[iv])
Roots and tubers	33% (NAf, WA&CA[iv])	60 % (NAm&Oce[ii])
Fruit and vegetables	37% (Ind. Asia[iii])	55% (NAf,WA&CA[iv])
Meat	20% (S&SE Asia[v])	27% (SSA[i])
Fish and seafood	30% (LA[vi])	50% (NAm&Oce[ii])
Milk	11% (Ind.Asia[iii])	25% (SSA[i])
Egg	12% (SSA[i])	20% (NAm&Oce[ii])

i) SSA: Sub-Saharan Africa, ii) NAm&Oce: North America & Oceania, iii) Ind. Asia: Industrialized Asia, iv) NAf, WA & CA: North Africa, Western Asia & Central Asia, v) S&SE Asia: South & Southeastern Asia, vi) LA: Latin America

According to food and agriculture organization, 2011, the average American consumer wastes are as high as 10 times the average Southeast Asian food waste generation. However, this loss is lower at production and processing stages compared to low income countries. Table 2.3 shows the retail, consumer and total food losses as per United States Department of

Agriculture (USDA). A pie chart in Figure 2.7 shows a simple representation composition of food waste in USA. USDA divided the food waste in nine groups as shown in the same Figure 2.7, while FAO simplified that into five groups: fruits and vegetables, grain products, meat, seafood and dairy products.

Table 2.3 Retail level, consumer level and total food losses by food groups in USA (Buzby et al., 2013)

Food groups	**Retail level**		**Consumer level**		**Total loss**
	Billion pounds	**%**	**Billion pounds**	**%**	**%**
Grain products	7.20	5.42	11.30	8.50	13.92
Fruit	6.00	4.51	12.50	9.41	13.92
Fresh	4.40	3.31	9.50	7.15	
Processed	1.60	1.20	2.90	2.18	
Vegetables	7.00	5.27	18.20	13.69	18.96
Fresh	5.20	3.91	12.80	9.63	
Processed	1.80	1.35	5.30	3.99	
Dairy products	9.30	7.00	16.20	12.19	19.19
Fluid milk	6.50	4.89	10.50	7.90	
Other dairy products	2.80	2.11	5.70	4.29	
Meat, poultry & fish	2.70	2.03	12.70	9.56	11.59
Meat	1.40	1.05	7.20	5.42	
Poultry	0.90	0.68	3.90	2.93	
Fish and seafood	0.40	0.30	1.50	1.13	
Eggs	0.70	0.53	2.10	1.58	2.11
Tree nuts and peanuts	0.20	0.15	0.30	0.23	0.38
Added sugar & sweeteners	4.50	3.39	12.30	9.26	12.64
Added fats & oils	5.40	4.06	4.50	3.39	7.45
Total	43.00	32.36	89.90	67.64	100

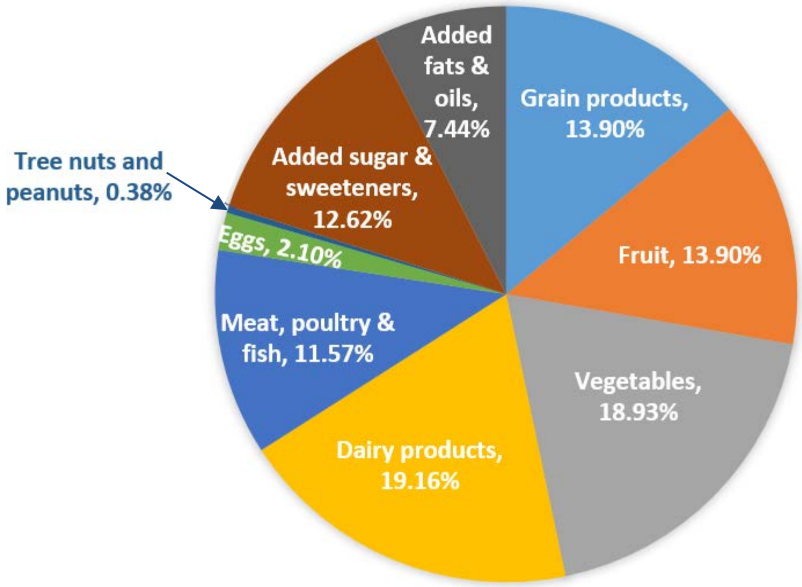


Figure 2.7 Food waste composition of USA (Buzby et al., 2013)

2.4 Food Waste Diversion from Landfill

Food waste consists of a considerable portion of municipal solid waste in both developed and developing countries and is one of the largest degradable component in the waste stream. Food waste is typically the wettest portion of municipal solid waste with a moisture content of 50 to 80 percent (Tchbanoglous, 1993). Disposal of these wet, putrescible organic refuse presents formidable environmental and economic problems since it generates higher leachate and higher gas generation resulting in extra monitoring cost and migration issues. According to the endorsement for food recovery hierarchy by the U.S. Environmental Protection Agency (EPA), source reduction deemed as the ideal situation at all points in the food supply chains followed by feeding hungry people. Food that fails to reach the consumer can still be utilized as food for livestock as the second best option. Recycling food waste for industrial purpose can be another solution (EPA). Anaerobic digester plants and composting are most preferred options these days to reduce the waste as well as benefit the environment. On the other hand, the least preferred option pointed out by EPA for food waste disposal is landfill. Figure 2.8 shows the food recovery hierarchy according to EPA.

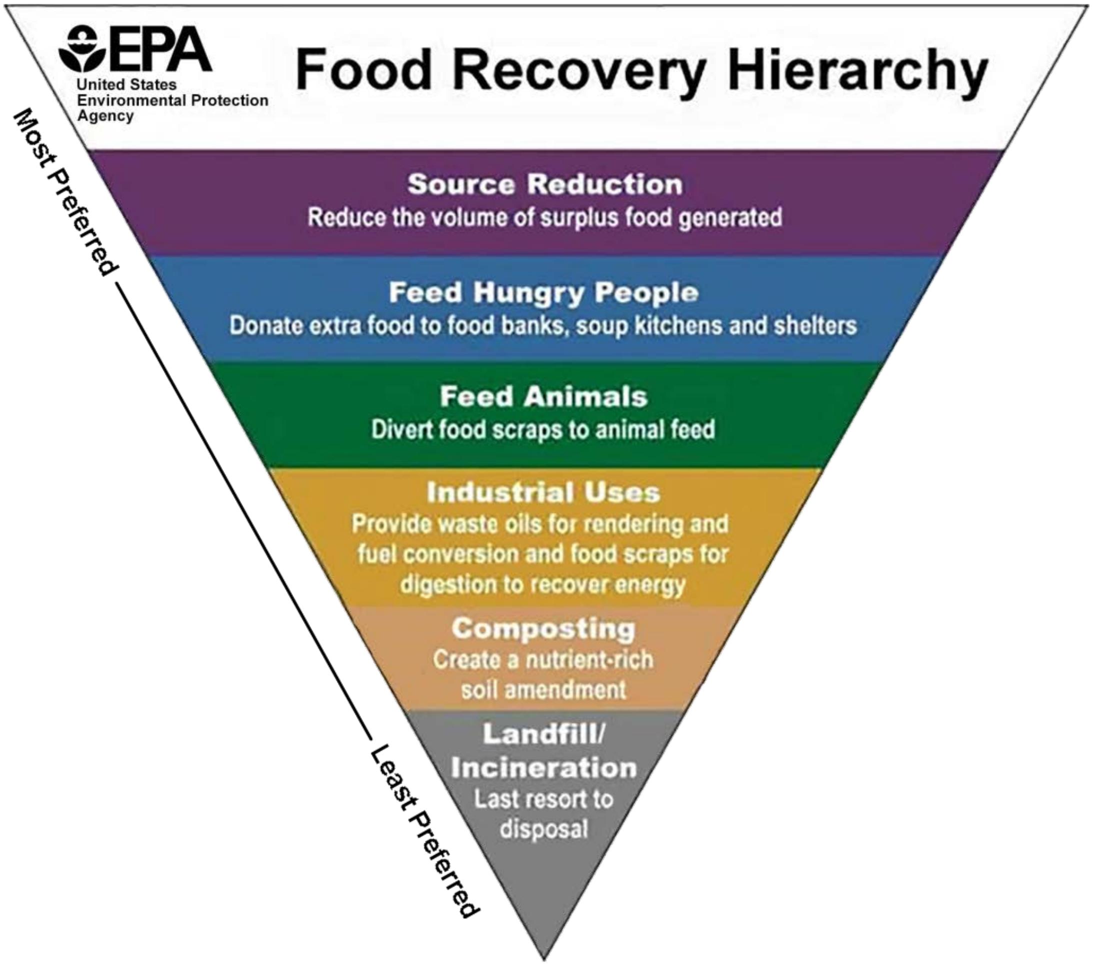


Figure 2.8 EPA Food recovery hierarchy

However, landfills are still by far the most widely used option for waste management because of its low capital, operational and maintenance cost instead of being avoided due to being placed at the bottom of waste management hierarchy. As per EPA (2008), 97 percent of food waste finds their way into landfill. However, the most concerning is due to problems associated with food waste in landfill some states in USA started banning food waste from landfill, among them Connecticut was the first state to ban commercial food waste from landfills in 2011 (AR News, 2014). The latest state to declare ban of commercial food waste from landfills is Massachusetts. On the contrary, banning the food waste disposal from traditional landfill will only cause future problems if feasible diversions are not provided.

2.5 Anaerobic Digesters with Food Waste

Biological treatment with Anaerobic Digester (AD) can be an alternative for the waste diversion from landfill (Levis et al., 2010). A biological process of molecular breakdown of biodegradables by the use of microorganisms under a controlled environment in absence of oxygen with a goal to generate biogas from organic substances is known as anaerobic digestion. This process takes place in a sealed airtight oxygen free tank commonly known as anaerobic digester. According to American biogas council (2014), there are over 191 anaerobic digesters operating on farms, 1500 at wastewater treatment plants and nearly 645 at food waste to biogas plants. According to US EPA, the biogas produced from anaerobic digester consist of 60 – 70 percent of methane, 30 – 40 percent of carbon dioxide and other gases e.g. ammonia, carbon monoxide, hydrogen, sulfur gases etc. According to Weiland (2010), food waste anaerobic digester has a biogas yield of 240 m^3 gas/t substrate or 120 litre/lb. Anaerobic digester of organics has the advantage of energy gain by methane production, in addition the residues formed can be utilized as fertilizer (Edelmann et al, 2000). Figure 2.9 shows the reaction stages of a typical anaerobic digester.

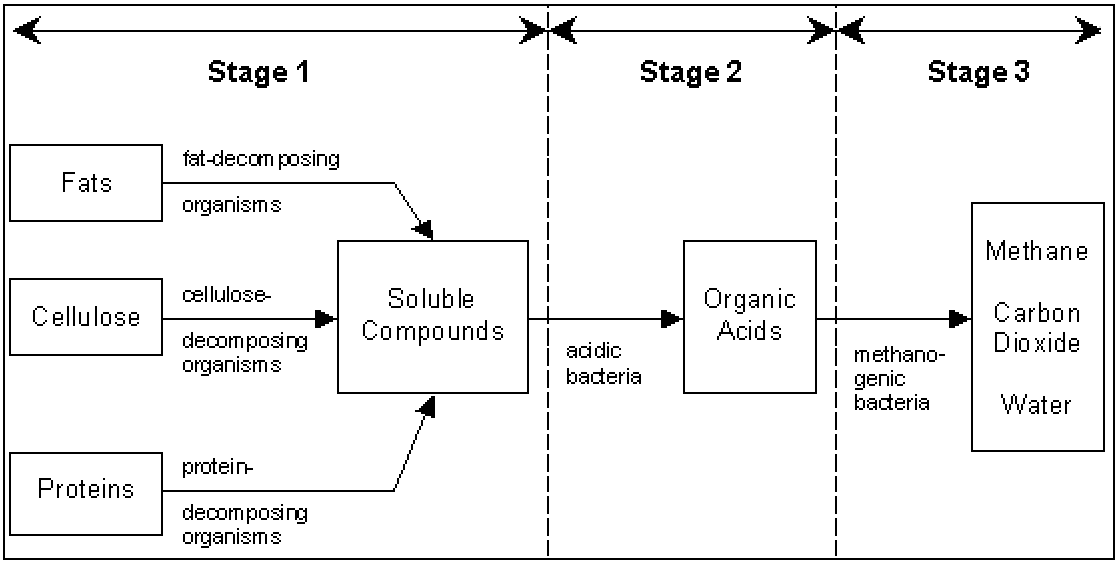


Figure 2.9 Stages of anaerobic digestion process (Source: http://energyfromwasteandwood.weebly.com/technologies.html)

For maintaining proper seed to feed ratio sludge and/or manure is added as inoculum with the food waste in the AD. Inoculum addition is necessary for food waste as in food waste presence microorganism is negligible and in addition as shown in Figure 2.9 during digestion process in stage two organic acids start accumulating which is both advantageous and disadvantageous at the same time. Some amount of organic acids or volatile fatty acid (VFA) is required as food for methanogenic bacteria to start producing gas but if the concentration of VFA is high it inhibits the microbial activity creating a lag phase (Shao et al., 2005).

Different studies have been conducted on liquid state digester (when solid presence is less than 15 percent) and solid state digester (when solid presence is higher than 15 percent) to see the gas generation potential. Almost all the previous studies with food waste digester showed satisfactory result by producing considerable amount of methane. A study conducted by Cho and Park (1995) on Korean food waste. They tested on the individual items such as cooked meat, boiled rice, fresh cabbage and also mixed food waste. As component-wise food waste is never homogeneous so for mixed food waste the authors tested on *Bibimbab* a Korean food made of boiled rice mixed with vegetables, cooked meat and eggs. The study was conducted at 37°C and a digestion time of 28 days. Table 2.4 shows the summary of the results found by Cho and Park (1995) and graphical representation is shown in Figure 2.10.

Table 2.4 Methane yield from different component & mixed food waste of Korea (Cho & Park, 1995)

Food waste components	**Methane yield(mL/g VS)**
Cooked meat	482
Boiled rice	294
Fresh cabbage	277
Mixed food wastes	472

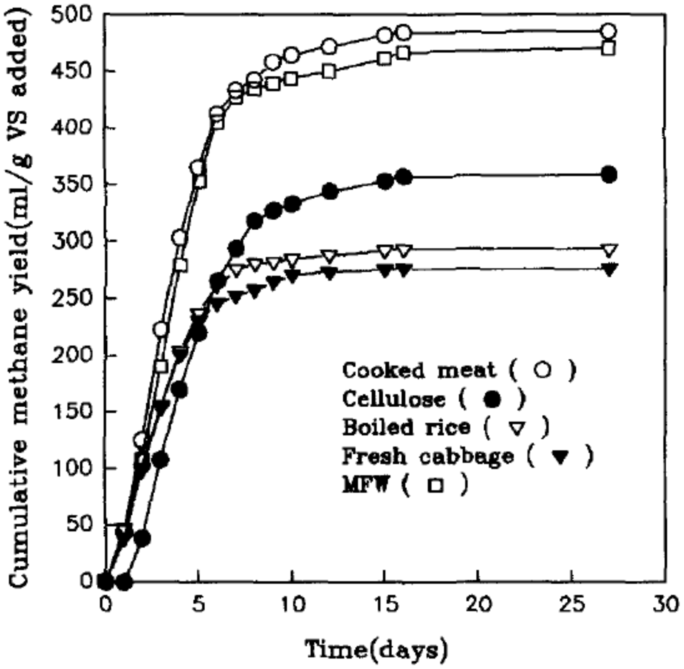


Figure 2.10 Cumulative methane generation of various food waste components (Cho & Park, 1995)

Another study by Heo et al. (2004) on mixed food waste (65% – Vegetables, 10% – 15% boiled rice, 15% – 20% eggs) with a temperature of 35°C and digestion time of 40 days showed a methane yield of about 489 ml/g VS. Zhang et al. (2007) tested on US food waste at 50 ± 2°C with a digestion time of 28 days and found methane yield of 435 ml/g VS. Average moisture content reported by the authors was 74 percent. Cumulative and daily methane yield found by Zhang et al. (2007) is shown in Figure 2.11 and 2.12 respectively.

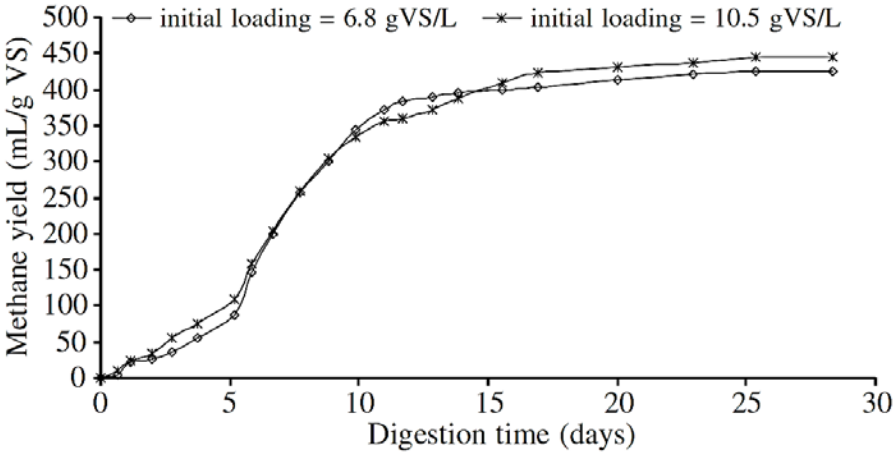


Figure 2.11 Cumulative methane yield of food waste during anaerobic digestion at 50 °C at two different initial loadings (6.8 and 10.5 g VS/L). (Zhang et. al., 2007)

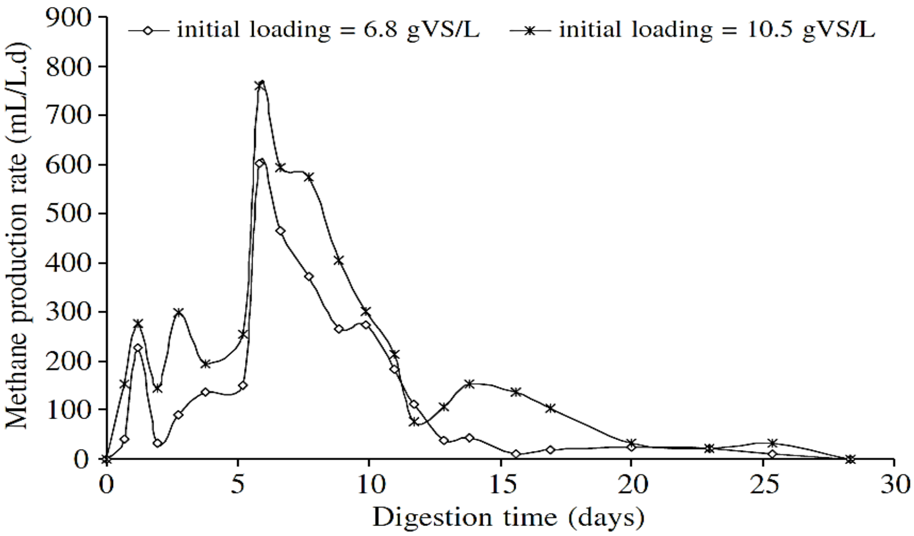


Figure 2.12 Daily methane generation rate during digestion of food waste at two different initial loadings (6.8 and 10.5 g VS/L) (Zhang et al., 2007)

Studies on food waste anaerobic digesters showed considerable methane yield. All the previous studies reported that food waste was digested by addition of inoculum in different ratio, and the higher the percentage the greater is the methane yield (Heo et. al., 2004). In Korea most of the landfills are about to reach its capacity and it was determined from the study that anaerobic digester could be a possible alternative to divert organics specially food waste from landfills.

However, the main drawbacks with the ADs are they require high capital investment and operational/maintenance cost. A 5000 tons per year capacity AD set up costs around 2.5 million USD as shown in table 2.5.

Table 2.5 Conceptual AD plant estimate (5,000 TPY capacity) (Rogoff et al., 2014)

Item	**Cost (USD $)**
Digester components (Leachate collection slab, gas collection bag, heating element, gas piping etc.)	1,000,000
Building superstructure	575,000
Engine generator set	200,000
Improved base for foundation	200,000
Mixing platform	100,000
Biofilters	100,000
Food storage pad	50,000
Electrical interconnection	75,000
Design, permitting support and fees	50,000
Contingency	100,000
Total	2,450,000

2.6 Waste Decomposition & Landfill Gas Generation

Landfill gas, the byproduct of waste decomposition, is a mixture of different types of gases. Primary constituents of landfill gas are methane and carbon dioxide. Table 2.6 shows the typical landfill gases’ percentage by volume.

Table 2.6 Typical landfill gas components

Components	**Percent Range by Volume (%)**
Methane	45 – 60
Carbon dioxide	40 – 60
Nitrogen	2 – 5
Oxygen	0.1 – 1.0
Ammonia	0.1 – 1.0
NMOC (Non-methane organic compounds)	0.01 – 0.60
Sulfides	0 – 1
Hydrogen	0 – 0.2
Carbon monoxide	0 – 0.2

(Source: Tchobanoglous, Theisen, and Vigil 1993; EPA 1995)

Landfill gas generation is the byproduct of natural or enhanced decomposition of the organics (e.g. food waste etc.) by microbial activities. The whole process is the integration of five different phases:

Phase I is also known as aerobic phase which has no methane generation. In this phase aerobic bacteria plays dominant role in breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. Depending on the oxygen availability this phase can last days to even months.

Phase II is acidogenic phase where organics start being fermented by bacterial activity and produces acids e.g. acetic, lactic, formic acids etc. which starts dissolving nutrients and produces carbon dioxide and hydrogen. More the organics higher will be the acid accumulation.

Phase III starts when certain kinds of anaerobic bacteria (e.g. methanogens) begin consuming organic acids and make the environment in landfill more neutral. At the same time starts producing methane and carbon dioxide.

Phase IV is the stage where methanogenic bacteria is dominant. It has almost equal amount of methane and carbon dioxide generation by volume. Methane production is highest in this stage. This stage is called methanogenic phase.

Phase V is the stage when most of the organics are done decomposing leaving air in the landfill and landfills starts being stable.

Figure 2.13 shows the five phases of gas generation in landfill.

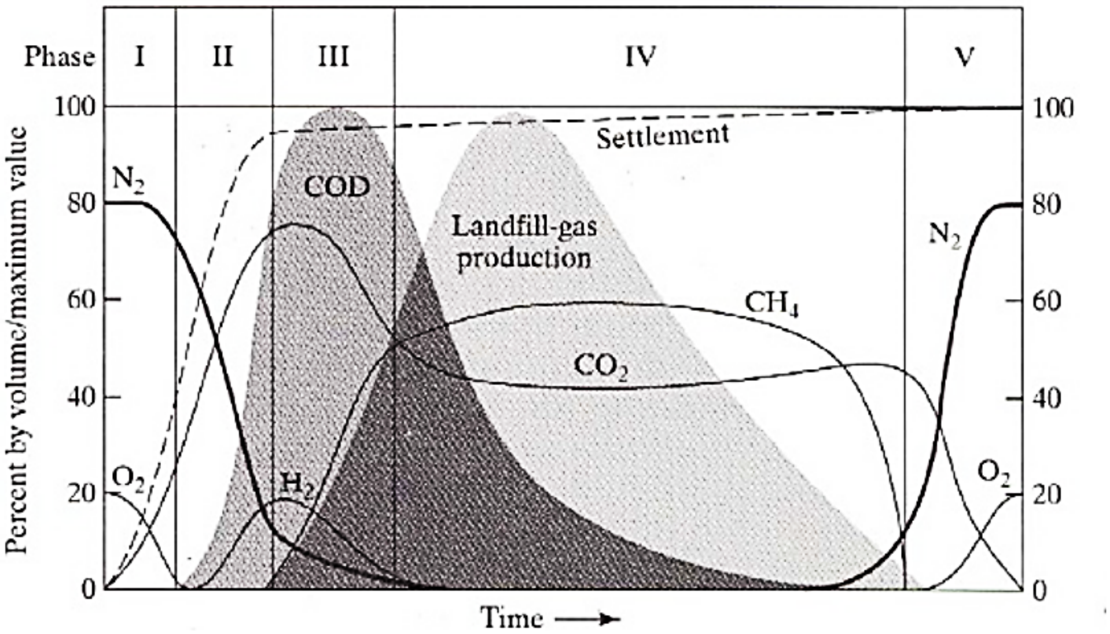


Figure 2.13 Five phases of landfill gas generation (UKDOE, 1993)

Landfill gas generation is extremely variable as wastes are never homogeneous (even for pure organics like food waste), operational conditions of site (waste density, moisture, placement, cover materials) and site-specific climatological conditions (i.e. atmospheric pressure, temperature, humidity, precipitation and seasonal variation of waste composition) (Yesiller et al., 2008).

2.7 Factors Affecting Gas Generation

The gas production rate and volume in a landfill depends on the biodegradation of waste. Therefore, factors that control biodegradation at any specific site condition also directly or indirectly affect gas generation. Some of the factors are waste composition, particle size, moisture content, pH, leachate recirculation, age of the refuse, temperature of the waste, oxygen availability nutrients etc. (Barlaz et al., 1989; El-Fadel et al., 1996a; wraith, 2003; and wraith et al., 2005)

2.7.1 Composition

Composition of waste is a dominating factor as more the organics percentage is quicker the decomposition will be, resulting in higher landfill gas (e.g. methane, carbon dioxide, nitrogen, hydrogen sulfide) generation. Also presence of chemicals leads to volatilization or chemical reaction that most likely generate NMOCs and other gases. Composition is geographic location, economic condition, lifestyle, waste management techniques etc. dependent. Guermond et al. (2009) published a compiled information on country wise waste composition as presented in Table 2.7.

Table 2.7 Waste composition in different countries (Source: Guermond et al., 2009)

Country	City	Organics (%)	Cardboard (%)	Plastic (%)	Metal (%)	Glass (%)
Morocco	Agadir	65 – 70	18.0	2 – 3	5.6	0.5 – 1.0
Guinea	Labe	69.0	4.1	22.8 (incl. textile)	1.4	0.3
Tunisia	Tunis	68.0	11.0	7.0	4.0	2.0
Jordan	Amman	63.0	11.0	16.0	2.0	2.0
Mauritania	Nouakchott	48.0	6.3	20.0	4.2	4.0
Turkey	Istanbul	36.1	11.2	3.1	4.6	1.2
Portugal		35.5	25.9	11.5	2.6	5.4
Greece	Palermo	31.7	23.1	11.8	2.7	8.3
Canada	Toronto	30.2	29.6	20.3	2.1	2.0
France	Paris	28.8	25.3	11.1	4.1	13.1

From Table 2.7 it can be deduced that due to higher percentage of organic content in developing countries, the gas generation potential might also be higher. Methane generation potential for food waste should be excessive as food contents tend to decompose rapidly in presence of moisture. Wang et al. (1997) conducted a study to see the methane generation potential of food waste by setting four reactors, gas generation started increasing after 40 days of operation and varied over time as shown in the Figure 2.14. Another study by Karanjekar (2013) showed similar result for a reactor with 100% food waste, operated at 37°C (Figure 2.15).

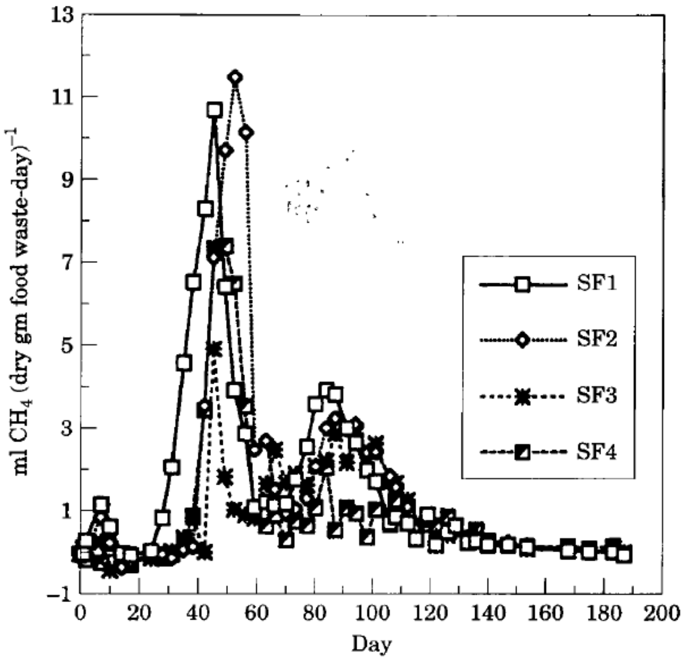


Figure 2.14 Methane generation rates in reactors with food waste (Wang et al., 1997)

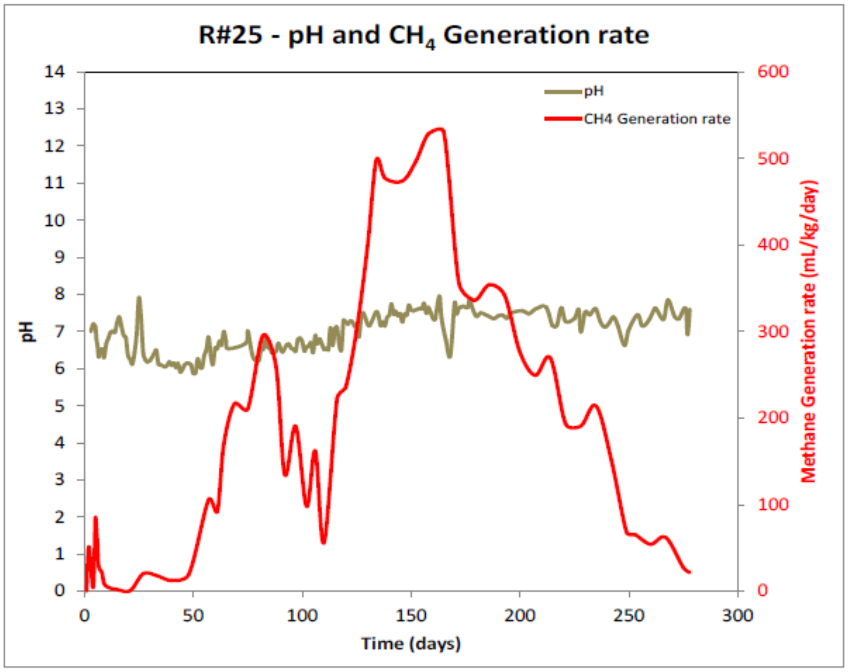


Figure 2.15 Methane generation rate and pH at 37C from 100% food waste reactor (Karanjekar, 2013)

2.7.2 Particle Size

Waste particle size affects the gas generation rate. If waste is being shredded it increases rate of decomposition by increasing surface area for microbial contact (Ress et al. 1998; Barlaz, 2006). A lysimeter test by Ham and Bookter (1982) showed that methane generation i.e. landfill gas generation spiked after shredding the waste.

2.7.3 Moisture Content

Moisture plays a critical role by supporting microbial activities. Dry waste takes longer time to decompose compared to moist waste (EPA). With an increase in moisture content microbial activities accelerate and a moisture content of 40 percent is most feasible for maximum gas production. It also limits the oxygen transport from the atmosphere while facilitating nutrient exchange and microbial exchange (Warith et al., 2005). A study done by Rees (1980) showed that gas production as well as methane percentage can be significantly increased by increasing moisture content from 25 to 60 percent as shown in Figure 2.16 and Figure 2.17.

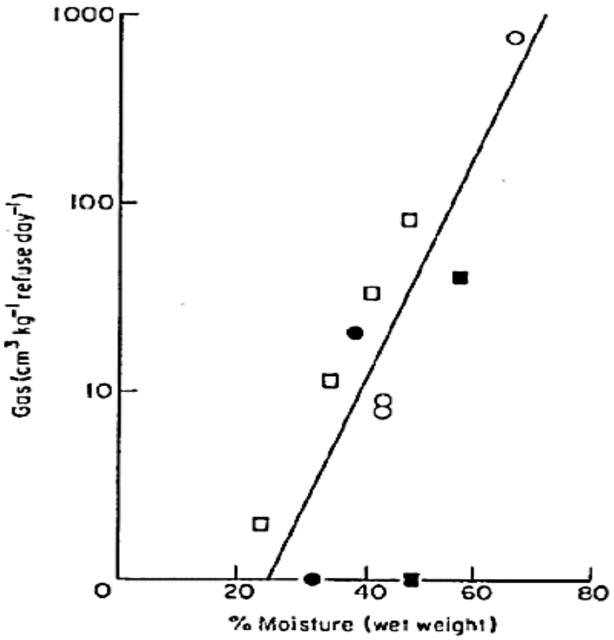


Figure 2.16 Effect of moisture content on gas generation rate (Rees, 1980)

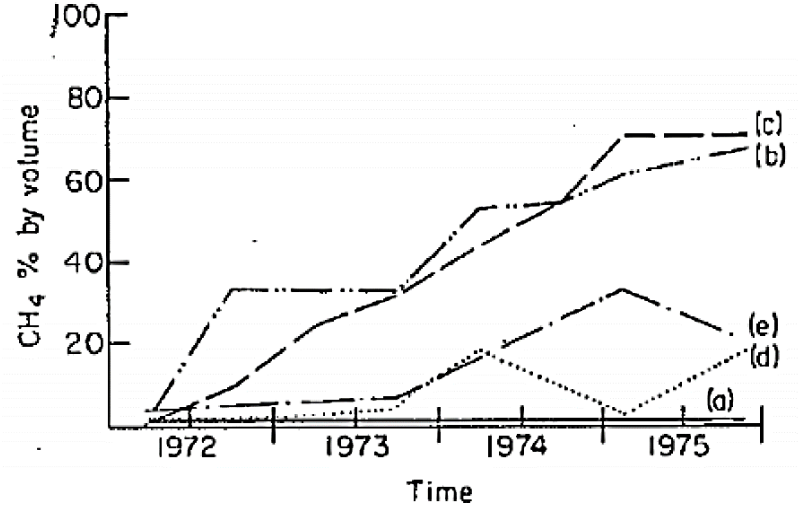


Figure 2.17 Effect of moisture content on methane generation a) Dry condition; b) & c) Every day liquid application; d) & e) Initially saturation (Rees, 1980)

Mehta et al (2002) conducted a study on two cells with and without controlled moisture addition, the result found was quite satisfactory and it supports the theoretical explanation of gas generation being spiked with increase in moisture content as shown in Figure 2.18.

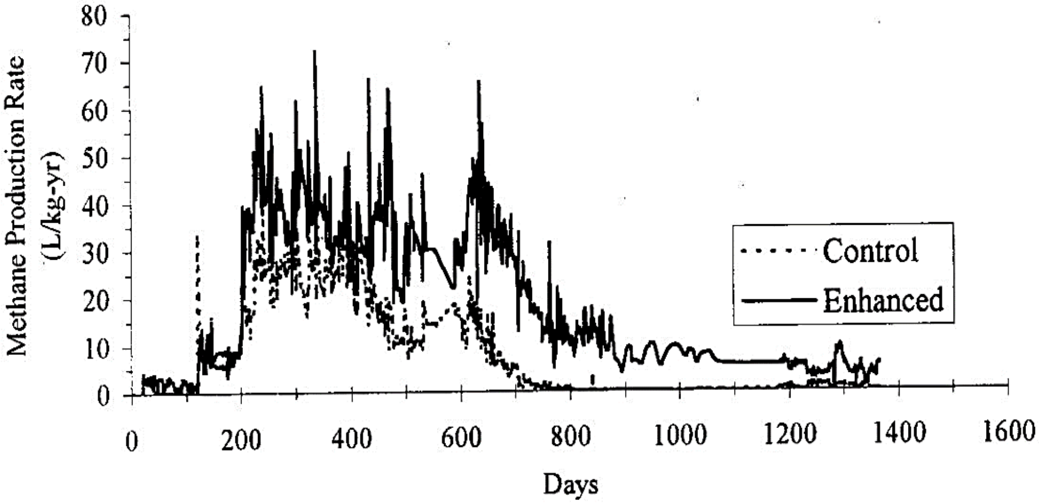


Figure 2.18 Comparison of methane production rate between cells without moisture addition (control) and with moisture addition (Enhanced) (Mehta et al., 2002)

2.7.4 pH

pH is an influencing factor for biodegradation and gas generation. For optimum bacterial activity pH should be in range of 6.8 to 7.4 (Warith, 2003; Warith et al., 2005). Acidogenic bacteria have a higher range of pH. Lower range of pH (below 5.0) or acidic environment causes inhibition of microbial activities thus affects methane generation.

2.7.5 Leachate Recirculation/ Bioreactor Landfill Operation

Leachate generation is a common scenario with waste, it depends on initial moisture in waste, seasonal variation, intensity of rainfall, type of waste (food waste produces highest amount) etc. As waste generates leachate moisture content in it reduces. Leachate circulation is a process to help waste degrade faster by injecting leachate collected from landfill and maintaining the desired moisture content. Direct application of moisture to waste during landfilling, spray irrigation on the surface of landfill, surface application, sub-surface application are some of the methods of recirculation (Warith, 2003). It increases the biodegradation as well as rate of methane recovery from landfill (Samir, 2014). As added advantage it helps reducing treatment cost for leachate, enhance settlement rate and reducing post closure maintenance cost. Chan et al. (2002) proved through a study that leachate recirculation significantly increases gas generation as shown in Figure 2.19.

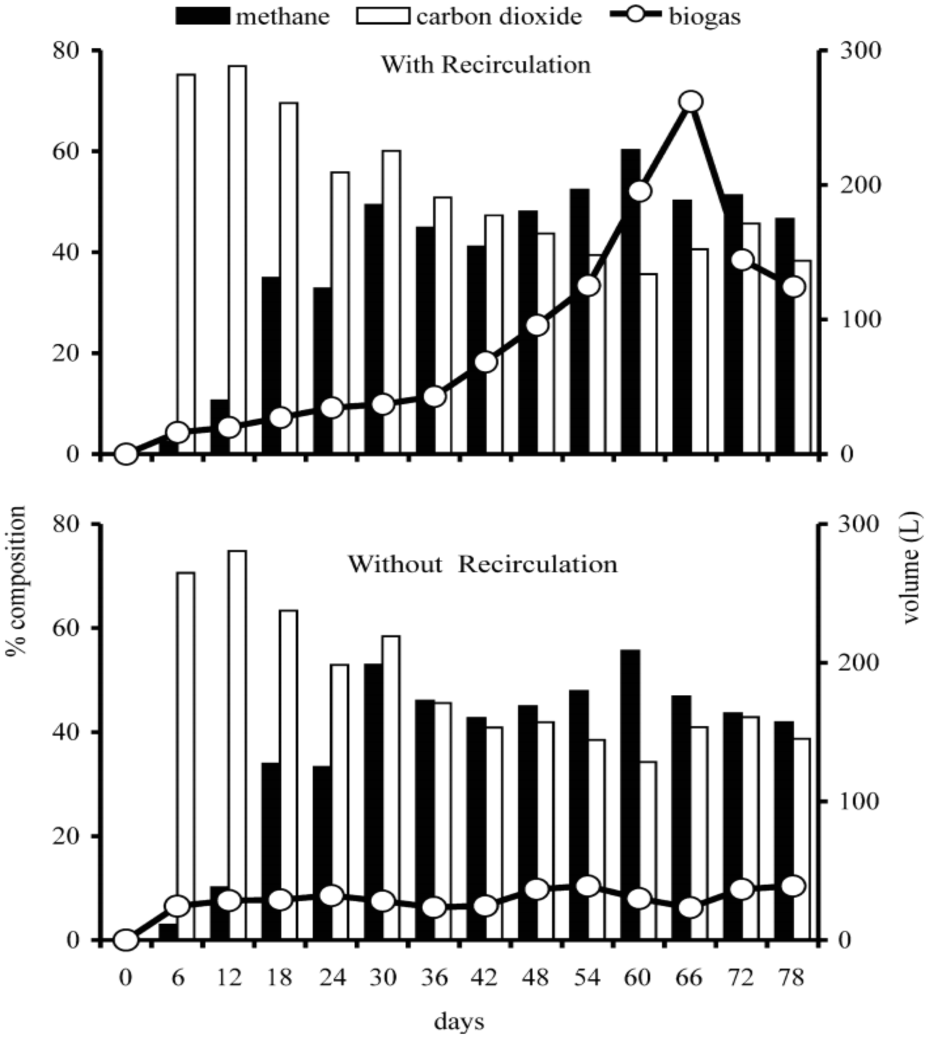


Figure 2.19 Impact of leachate circulation on gas generation (Chan et al., 2002)

A study by Barlaz et al. (2002) in Yolo County landfill project reported that gas generation from conventional landfill cell was half of that generated from leachate recirculated cell. A parallel study was conducted by Mehta et al. (2002) in Yolo County landfill on waste degradation with and without recirculation. A noticeable rise in methane production was observed in the study when leachate was circulated compared to conventional cell. Figure 2.20 shows the results obtained from their research.

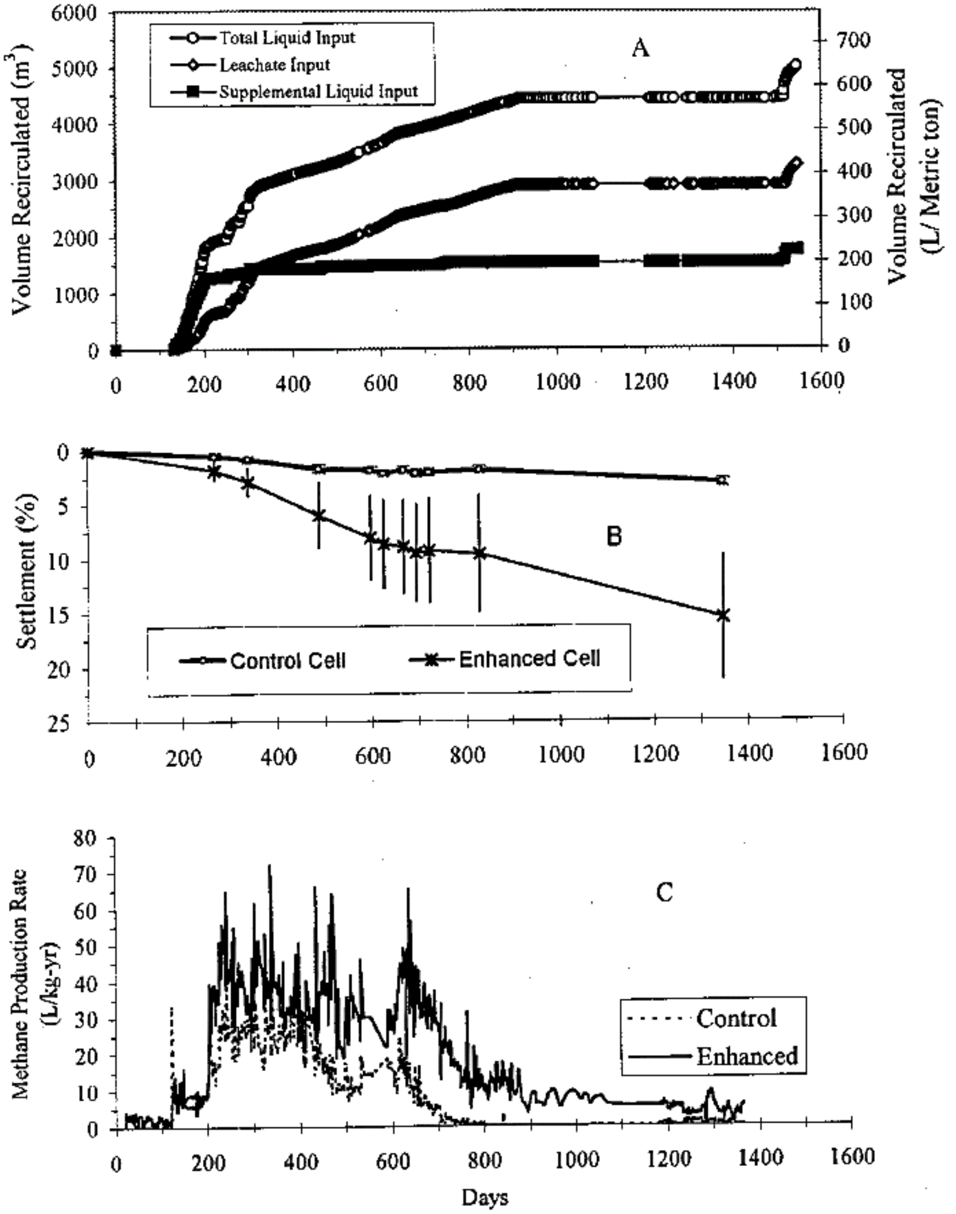


Figure 2.20 (a) Cumulative liquid input for leachate recirculation and supplemental liquids; (b) refuse settlement over time; and (c) methane production rate in enhanced and control cells (Mehta et al., 2002)

Another field scale study was conducted by Morris et al. (2003) by preparing two cells; one with leachate recirculation and another without recirculation. The authors reported that after the operation, waste sampling from recirculated cell showed more degradation compared to waste sample from cell without recirculation. Moreover, their research showed that gas generation from the cell with no recirculation produced only 10% of the gas produced from cell with recirculation (Figure 2.21). The authors stated that moisture addition accelerates landfill gas production compared to conventional landfill operation.

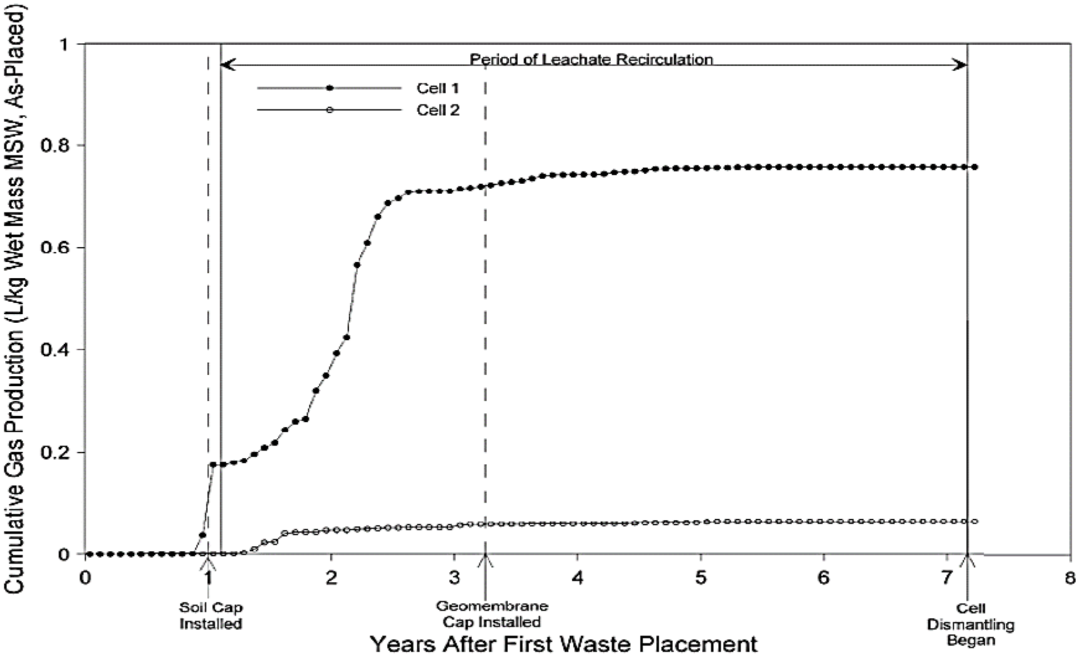


Figure 2.21 Cumulative Gas Productions in the Test Cells. Cell 1: With Addition of Moisture. Cell 2: Without Moisture Addition, Conventional Cell (Morris et al., 2003)

2.7.6 Age of Refuse

Landfill gas generation starts immediately after the waste has been deposited. However, methane generation takes place only after the depletion of all available oxygen. Usually peak landfill gas generation occurs after about a years of waste burial and thereafter slowly reduces. Generally the major portion of gas generation takes place approximately within the initial 20 years of deposition. However, this is site dependent; the time frame of significant gas generation might extent upto 40 or 50 years where gas generation is slow.

Gas generation for an entire site also depends on the components of waste; as gas generation stage for some components of the waste starts faster compared to others. As a result, significant gas generation period will vary.

Landfill gas generation has two major time-dependent variable: (i) lag time and (ii) conversion time.

Time from waste deposition till the beginning of methane generation is the lag time (Figure 2.22, start of Phase III); whereas conversion time is the time from waste deposition till the end of methane generation (Figure 2.22, end of Phase V). Lag time and conversion time varies with type of waste. For example, lag & conversion time for yard waste is very short, while leather & plastic have long lag & conversion time; for food waste lag time is very long, however it has shorter conversion time.

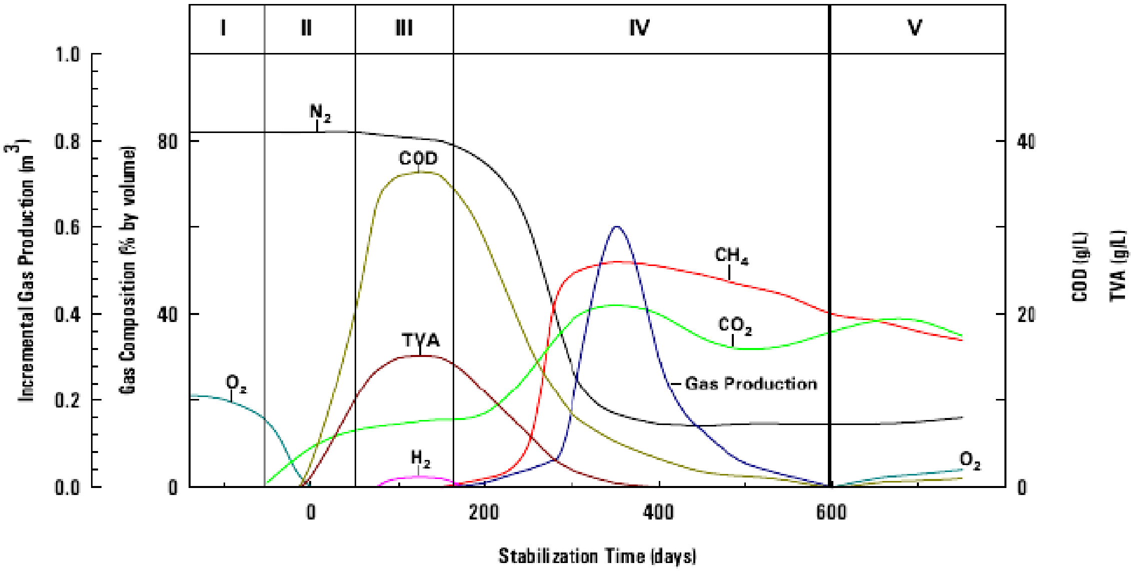


Figure 2.22 Phases of waste degradation in a typical landfill (Pohland and Harper, 1986)

Biochemical Methane Potential (BMP) is an indicator of waste decomposition. Wang et al (1994) observed that BMP reduces as the age increases for waste. Francois et al. (2006) also discovered that for new waste BMP is higher compared to old waste.

2.7.7 Temperature of the Waste

Temperature plays an influencing role in gas generation by controlling bacterial activity. Gas production as well as bacterial activity increases under mesophilic and thermophilic conditions with temperature increase (El-Fadel et al., 1996). Laboratory scale studies by Christensen and Kjeldsen (1989) showed that as the temperature increases from 20 to 30 and 40°C, rate of methane production increases. Tchobanoglous et al. (1993) noticed through experiments that below 20°C and above 70°C methane generation decreases significantly. Effect of temperature on waste decomposition in laboratory grade simulated reactors by choosing 25°C, 37°C and 60°C was conducted by Buivid et al. (1981) and reported that for enhanced methane generation the most favorable temperature is 37°C.

2.7.8 Oxygen Availability

Presence of oxygen in the landfill indicates phase I decomposition of landfill waste in aerobic phase. Once the oxygen are all used by aerobic bacteria methanogens will start shifting the phase and produce methane. If waste in landfill is loosely placed availability of oxygen becomes higher and aerobic phase lasts longer producing more carbon dioxide thus slows down the methane generation. Optimum compaction ensures minimum air intrusion into landfill thus lessen oxygen availability which helps earlier replacement of aerobic bacteria by anaerobic bacteria and introduction of methane generation.

2.7.9 Inoculum Addition

Addition of inoculum accelerates the biodegradation and gas generation in landfill. The inoculum can be old decomposed waste, sludge, manure or any other source that has high amount of bacteria to help enhancing degradation. Addition of sludge can have both positive and negative effect on biodegradation of waste (Rees 1980; Barlaz et al., 1990; Christensen et al., 1992; Komilis et al., 1999 and Wraith et al., 2002). Anaerobically digested sewage sludge addition into fresh waste initially decreases the pH due to accumulation of acid and resulting in reduced microbial activity (Barlaz et al., 1990), however, addition of sewage sludge produces three times more methane than addition of primary sludge (Komilis et al., 1999). Sewage sludge has the advantage of being the source of nutrients & methanogenic bacteria, in addition it helps increasing moisture content (Christensen et al., 1992).

Inoculum addition can be very helpful when dealing with pure organic waste. Since in food waste, excessive volatile fatty acid (VFA) accumulation takes place at the early stages of decomposition by bacterial activity which creates a lag phase before methanogens can start produce gas (Shao et al., 2005). Wang et al. (1997) also showed that for pure food waste high percentage of inoculum reduces the lag phase. The researchers used well decomposed refuse as source of inoculum. Other source of inoculum e.g. sludge or manure can reduce the percentage to be used and at the same time may reduce the lag phase before methane generation. Liu et al. (2009) did a test on four food waste reactors with different feed to inoculum (F/I) ratio (i.e. 1.6, 3.1, 4.0, and 5.0) and found the biogas yield to be 778, 742, 784 and 396 ml/g VS respectively, which indicates the significance of inoculum addition. Figure 2.23 shows the results found in their studies.

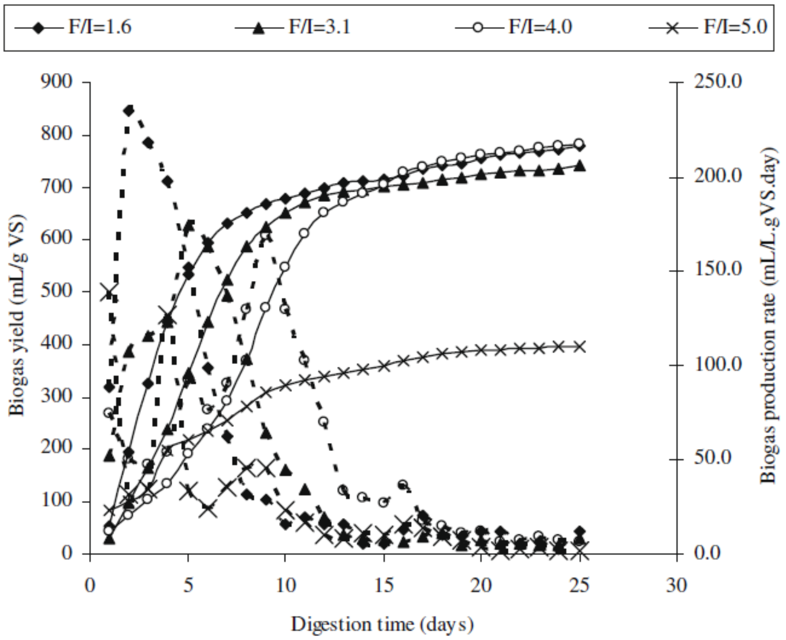


Figure 2.23 Biogas generation from food waste at four different F/I (Liu et al., 2009)

2.8 Use of Manure as Inoculum

Livestock manure have been used as an excellent source of fertilizer in improving agricultural lands for centuries. Manure are considered as good source of nutrient (Carbon, nitrogen, phosphorus etc.) and microorganism necessary for plant growth. Having large amount of organic carbon and a good source of bacteria such as methanogens, manure can prove to be an important source of inoculum when mixed with landfill waste and may enhance the methane generation to some extent. Gas generation largely dependents on type and quantity of inoculum added to the waste.

Gas generation rate from waste significantly depends on the inoculum added. Especially for pure organics i.e. food waste addition of inoculum is mandatory due to lack of adequate amount of microorganism. Manure being a potential source of microorganism can contribute greatly in enhancement of gas generation from waste. Addition of chemicals might also be a possible solution for enhanced degradation and gas generation. However, use of chemical might be expensive and have potential adverse effects. Animal manure can be added to food waste as an alternative to get desirable result (Chen et al, 2010). Major problem with organic waste is accumulation of volatile fatty acid (VFA) during acidogenic phase which inhibits bacterial activity. Therefore adding manure is advantageous since it enhances the buffer capacity creating an environment to neutralize the pH to some extent and reduces the inhibition time (Zhang et al., 2013). The authors used food waste to manure ratio of 2 and found that the methane generation increased by 41.1% and the total methane yield was 388 mL/g VS. They also tested for methane generation from food waste with and without manure and the results were quite interesting as shown in Figure 2.24. Without the addition of manure total methane found compared to the other case was almost negligible. Another study done by Li et al. (2009), showed that kitchen waste when mixed with cattle manure produces 44% more methane than if kitchen waste digested alone.

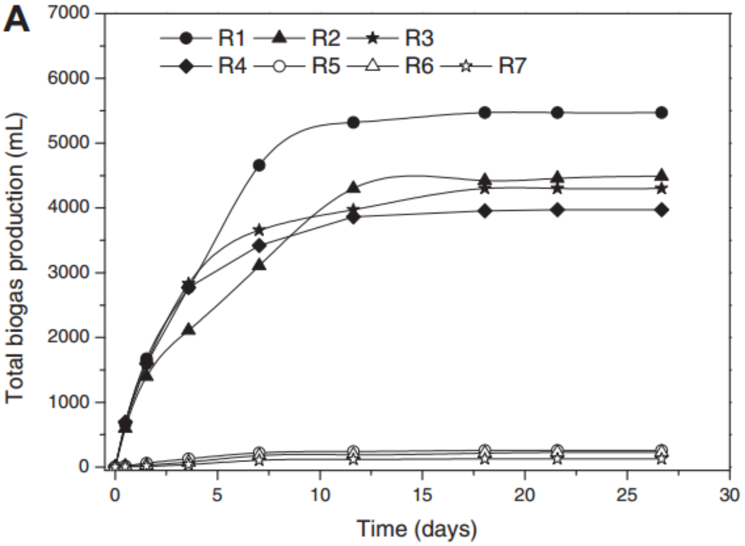


Figure 2.24 Digestion of food waste with manure (R1, R2, R3) and without manure (R4 through R7) (Zhang et al., 2013)

2.9 Biocell and Food Waste

Landfills are considered to be the principal waste management in North America. Over the past few decades landfills becoming less popular due to four primary operational problems (Hettiaratchi, 2007):

i. Aesthetics of operation
ii. Ground/surface water contamination due to landfill leachate
iii. Greenhouse gas emission
iv. Additional space requirement

Therefore waste management professionals are leaning towards designing sanitary landfill that eliminates atleast the first three issues. However, the fourth problem remains unresolved over the years and further studies are required to eliminate the space issues which apparently is becoming the major issue for waste management. In addition when the organics portion increases in waste it imposes additional problems with higher greenhouse gas (CH_4) emission. Which is more severe with developing countries as they have mostly open dumps and non-engineered landfills with waste having more than 60 percent food waste. Food waste as we know have higher moisture content (70 percent or more) leading to more leachate generation and the rate of degradation is faster compared to other components which balloon the generation of methane. Hence, as an alternative, improved and sustainable solution for waste management, “Biocell” can be a holistic approach to solve all four problems (Hettiaratchi et al., 2010).

Biocell is an advanced form of a bioreactor landfill, which can be considered as a diversion technique for waste from a traditional sanitary landfill. The main difference between bioreactor landfill and biocell is that the biocell has the ability to handle higher moisture and permits use of nutrients for accelerated decomposition. Unlike traditional landfills, rather than being a waste storage facility, biocell acts as a waste processing facility where organic contents of MSW is processed after diverting them from recycling facility. In short *Biocell* is a waste processing facility where waste degradation & stabilization is followed by mining and ultimately reusing the same space without requiring the need for new land acquisition. Energy recovery, greenhouse gas (GHG) emission control, groundwater contamination control, resource recovery as compost like material and space recovery are the main advantages of biocell landfill operation (Hettiaratchi et al., 2010). Also as an added benefit apart from leachate recirculation for enhanced degradation, nutrients (inoculum source) e.g. sludge or manure can be added to accelerate the degradation even further, therefore, shortening the time interval for reusing the same space over and over again. At the same time faster degradation increases methane generation which can be collected efficiently in biocell as energy recovery.

Being a third generation landfill, *Biocell* can be adopted as an attractive alternative to conventional landfilling system. Researchers conducted several studies with MSW in biocell. However, no studies were conducted on 100% food waste biocell; moreover the effect of different types of manure on food waste degradation have never been tested. Hence, the aim of current study was to focus on evaluating the effect of different manure on food waste decomposition and gas generation in biocell.

Chapter 3

Methodology

3.1 Introduction

The main objective of this study was to investigate the effect of different types of manures on degradation of food waste by laboratory simulation of biocell landfill operation and determine the most suitable manure for maximum gas generation from food waste biocell.

An experimental program was prepared to simulate eight laboratory scale waste reactors with three different types of manures and control reactors. The reactors were monitored daily and the leachate and gas generated from the reactors were collected and tested periodically. The volatile solids, BOD_5 and COD tests were also conducted to observe the stage of biodegradation in laboratory. The following subsections discusses the experimental design and test procedure for the reactor operations.

3.2 Experimental Design

3.2.1 Inoculum Percentage

A mixture of sludge (10 percent) and manure (6 percent) was used for this study based on previous studies. Three (3) different types of manure– cow, pig and horse manure were chosen based on availability and applicability in both developed and developing countries to determine the effect on gas generation from the food waste.

3.2.2 Waste Composition

The composition of food waste was decided based on the national food waste composition as shown in Figure 3.1.

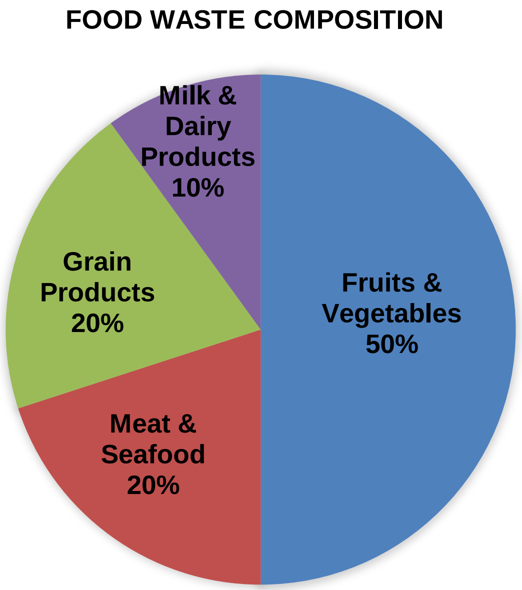


Figure 3.1 Reactor food waste composition

3.2.3 Experimental Design

Laboratory scale simulated food waste reactors were built with the goal to analyze the effect of manures on food waste decomposition and gas generation in biocell landfill. Sludge (for control reactor) and mixture of sludge & manure (cow, pig and horse) was added in different set of reactors as source of microorganisms. Four combinations with their duplicates, a total of eight reactors were built. Table 3.1 shows the combinations of the reactors.

Table 3.1 Waste combinations in laboratory scale simulated biocell reactors

Reactors	**Organic Waste (Food Waste*)**	**Sludge**	**Manure**
B1, B2 (Control)	90%	10%	-
B3, B4	84%	10%	6% Cow Manure
B5, B6	84%	10%	6% Pig Manure
B7, B8	84%	10%	6% Horse

*50% fruits &vegetables, 20% grain products, 20% meat & seafood and 10% milk & dairy

It was necessary to operate the reactors in anaerobic environmental condition as in landfill and at the same time provide a proper leachate collection & recirculation system and gas collection system. For this reason an appropriate reactor setup design was required. Figure 3.2 shows the designed reactor setup.

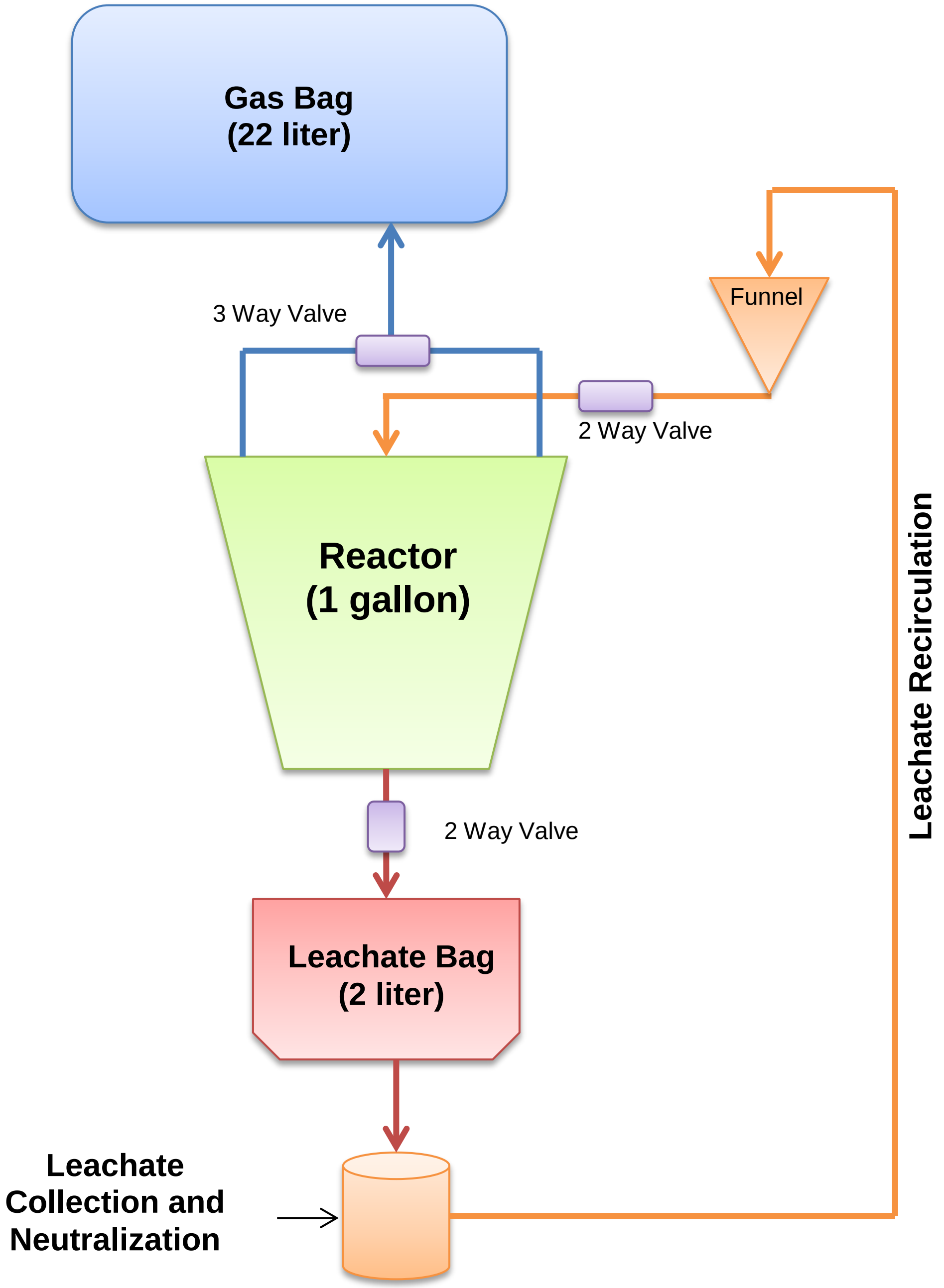


Figure 3.2 Laboratory scale simulated biocell reactor setup design

Reactors were kept in an environmental control chamber at a constant temperature of 37°C for faster degradation of the food waste. For leachate quality pH, Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were measured in a regular basis. Depending on the gas generation, gas composition and gas volume were measured. A summary of experimental work flow is presented in Figure 3.3.

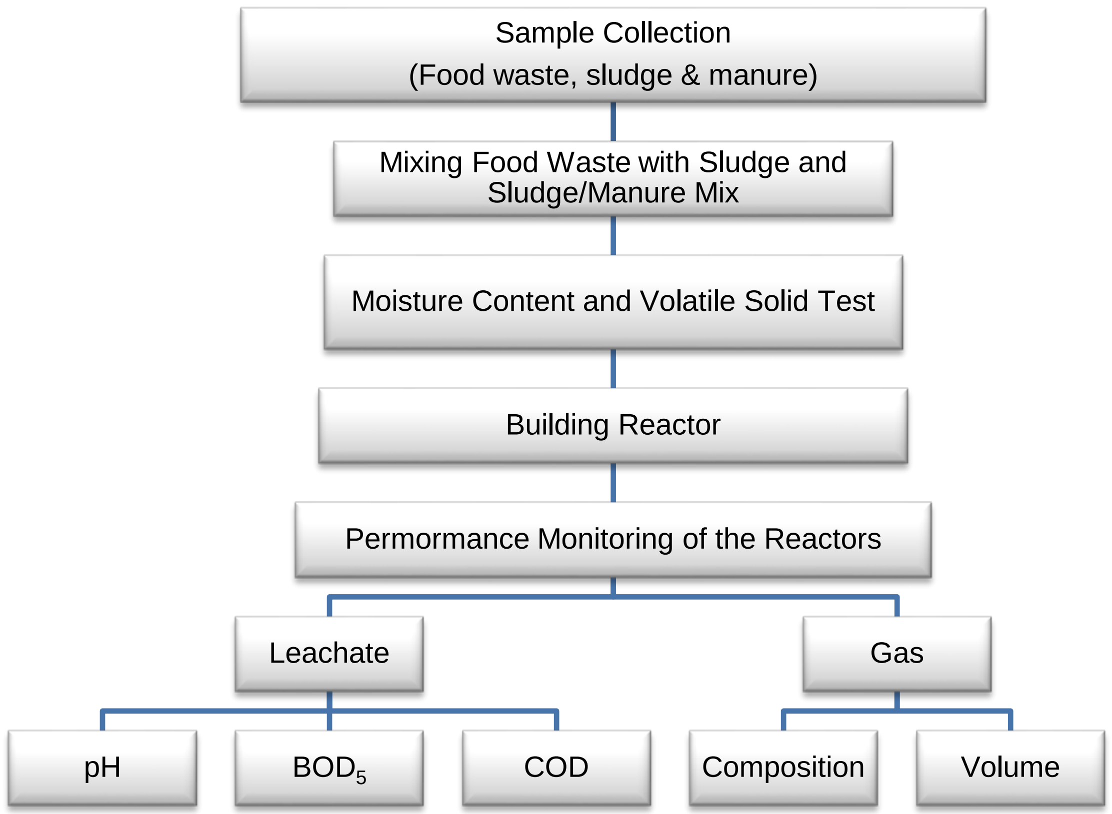


Figure 3.3 Flow chart of experimental work program

3.3 Sample Collection & Storage

3.3.1 Food Waste Collection

Food waste was collected from two sources, one for fruits and vegetables another for meat, seafood, grains and dairy products. Fruits and vegetables were collected from Walmart, Denton, Texas in two (2) five gallon buckets, each weighed approximately 15 to 20 pounds. The second source was the food scrapings from lunch buffet in the University Center dining (Connection Café) at the University of Texas at Arlington (UTA). Approximately 60 pounds of food waste was collected from the café, which contained meat, seafood, grain products (rice, bread etc.), and a small amount of fruits & vegetables. The collected samples were brought to the laboratory and stored at 4°C (38°F) in the environmental growth chamber for preserving its original properties before building the reactors. Figure 3.4 shows the food waste collection and storage.

(a)

(b)

(c)

Figure 3.4 (a) Collection of fruits and vegetable waste and collected sample; (b) Collected food waste from UTA; (c) Environmental control chamber

3.3.2 *Collection of Sludge*

Sludge was collected from the City of Denton Landfill, Texas in a 5 gallon bucket as shown in Figure 3.5 which was added to the reactors as micro-organism source.

Figure 3.5 Collected sludge in container

3.3.3 *Collection of Manure*

Three types of manures (cow manure, pig manure and horse manure) were collected from different sources. Aged manure was collected since aging reduces the acidic bacteria and increases hydraulic retention time; in addition, carbon to nitrogen ratio increases with age. Therefore, it was suggested to collect manure of at least a year old (Yazdani, 2010).

Cow manure was collected from a nursery which was approximately 9 to 12 months old. Pig manure was collected from a farm (Maypiggen) that was approximately 6 to 12 months old. Horse manure was also collected from a farm. However, it was very difficult to obtain aged horse manure and the oldest one that was collected was a week old. Figure 3.6 shows collected cow, pig and horse manure.

(b)

(a) (c)

Figure 3.6 Collected manure: (a) Cow manure, (b) Pig manure, (c) Horse manure

3.4 Laboratory Scale Simulated Reactor Setup & Monitoring

3.4.1 Preparation of Laboratory Scale Biocell Reactors

Laboratory scale reactors were built in one (1) gallon smart seal leak tight HDPE buckets (United States Plastic Corporation, OH), modified (according to design) for gas and leachate collection and leachate recirculation. Eight (8) reactors (B1 through B8) were prepared with pairs of four combinations as shown in Table 3.1. First pair (B1 & B2) was considered as controls with only 10 percent of sludge as inoculum. Remaining three pairs have additional 6 percent of cow, pig and horse manure respectively to investigate the effect of these three types of manure on food waste degradation individually.

Building each reactors required a certain set of materials and equipment as shown in Figure 3.7.

(a) (b)

Figure 3.7 (a) Materials and (b) equipment used for reactor building

Reactors building operation is shown in Figure 3.8 through Figure 3.14.

Figure 3.8 Drilling reactor bucket and lid

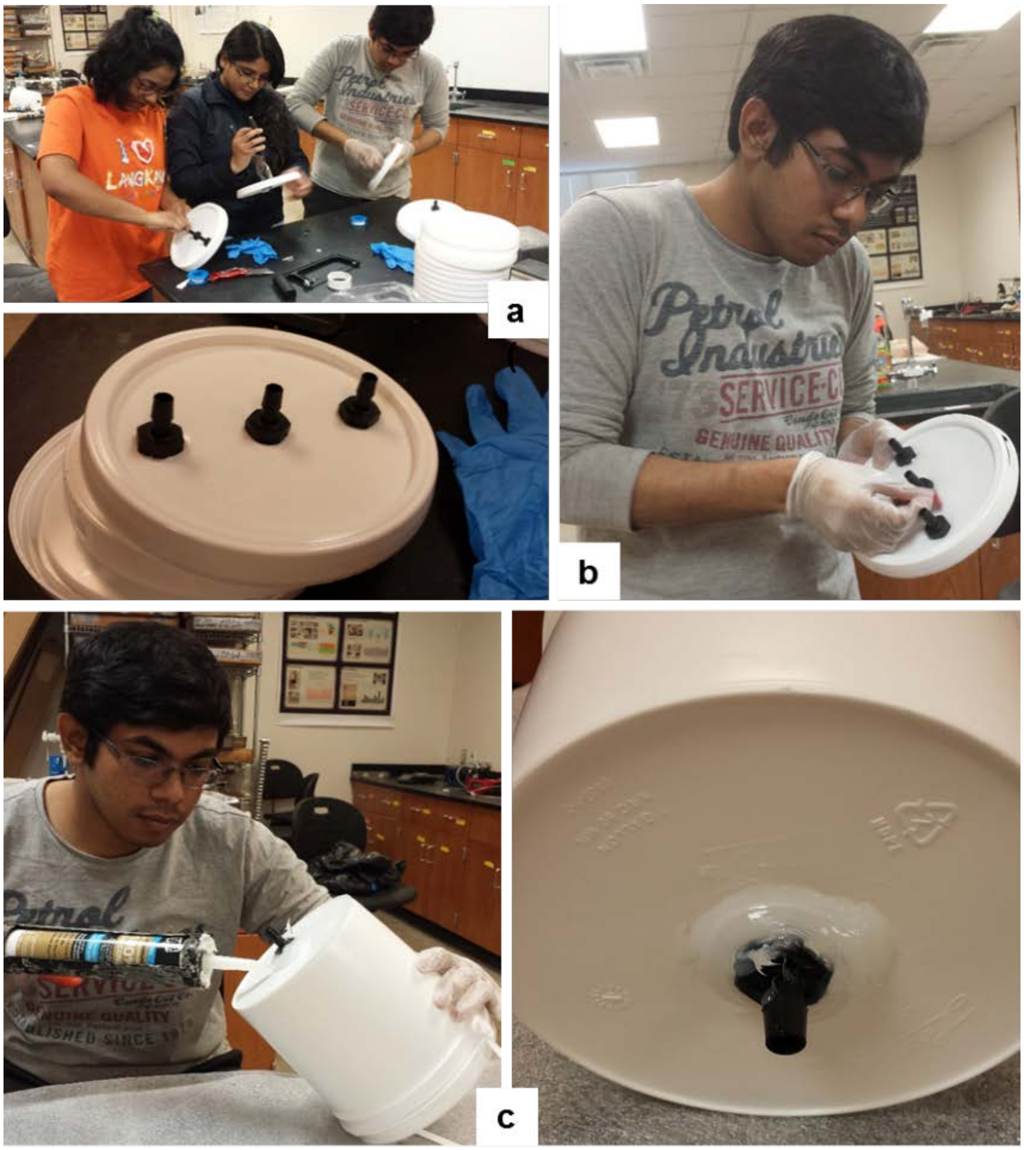


Figure 3.9 Connecting tube and hose fitting

Figure 3.10 Tubing and valves connected using clamps and silicon sealant

Figure 3.11 Pea gravel and geo-composite inside the reactor bucket

Leak tests were conducted to make sure that there were no leaks present in the reactors. The lids were sealed with silicon sealant and filled with water from overhead tank through the base of the reactor. All valves at the top plate were kept closed. Pressure was developed inside the bucket due to head difference of water from the overhead container as shown in the Figure 3.12. The leak tests confirmed there were no leaks on the reactors since the water level in the manometer showed no significant changes.

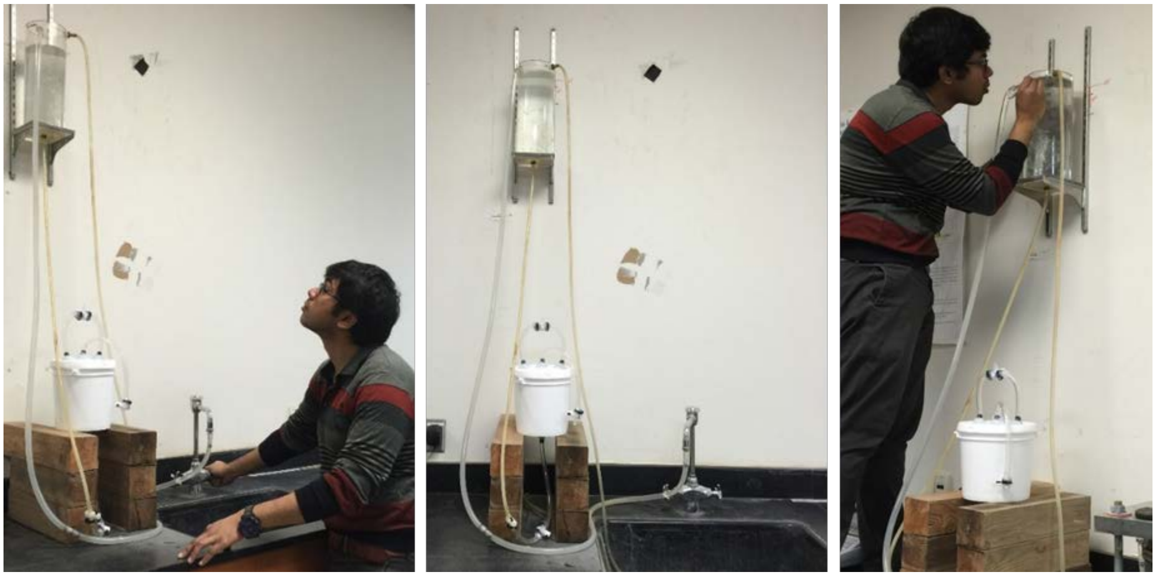


Figure 3.12 Leak test of reactors

Once the reactors passed the leak test, the reactors were filled with food waste (composition shown in Figure 3.1). Manure and sludge mixture was added with the waste as nutrients. No extra water was added since the original moisture of the waste was very high (more than 70%).

Figure 3.13 (i) Mixing waste; (ii, iii) weighing and mixing nutrient; (iv, v, vi) filling reactors

Waste was filled up to a level to facilitate sufficient space (1.5 inches from top) for gas to freely escape to the gas bag through the gas outlets. After filling with food waste, reactors' lids were closed and sealed with silicon sealant to make it air tight and leak proof. Once the sealing was done, the gas collection bags and leachate collection bags were connected to each reactors and placed in the environmental growth chamber at 37°C (99° F). Figure 3.14 shows reactors inside the environmental growth chamber.

Figure 3.14 Reactors inside the environmental growth chamber

3.4.2 Properties of Food Waste

3.4.2.1 Moisture Content

The moisture content of the food waste samples was measured on wet weight basis. Approximately 2 lbs of samples were collected from each pair of reactors. The samples were dried for 5 to 7 days until a constant weight was achieved at 65°C (±5°C) in the oven and measured for moisture loss. Extra care was required to find the moisture content of the waste (food waste) as it was reported that organic matter from food waste volatilizes at high temperature (105°C for MSW) (Angelidaki et al., 2009).

3.4.2.2 Volatile Solids Determination

The volatile solids measurement followed a modified version of Standard Methods APHA Method 2440-E. For VS determination, first samples were oven dried at 65°C (±5°C) temperature. Dried samples were then cut into smaller pieces. About 50 grams of sample were measured in a porcelain crucibles weight of which was known. The sample was placed in the muffle furnace at

550 ± 10°C (1022°F) for about two hours and burnt completely to ashes. Test samples and equipment setup are presented in Figure 3.15. The volatile organic content was determined from the percentage of weight loss. Equation 3.1 was used for volatile solids determination.

$$Volatile\ Solids\ (VS), \% = \frac{Weight\ loss\ after\ burning}{Dry\ weight\ of\ sample\ before\ burning}\ x\ 100 \tag{3.1}$$

Figure 3.15 Volatile solids determination (a) samples before & after burning, (b) muffle furnace

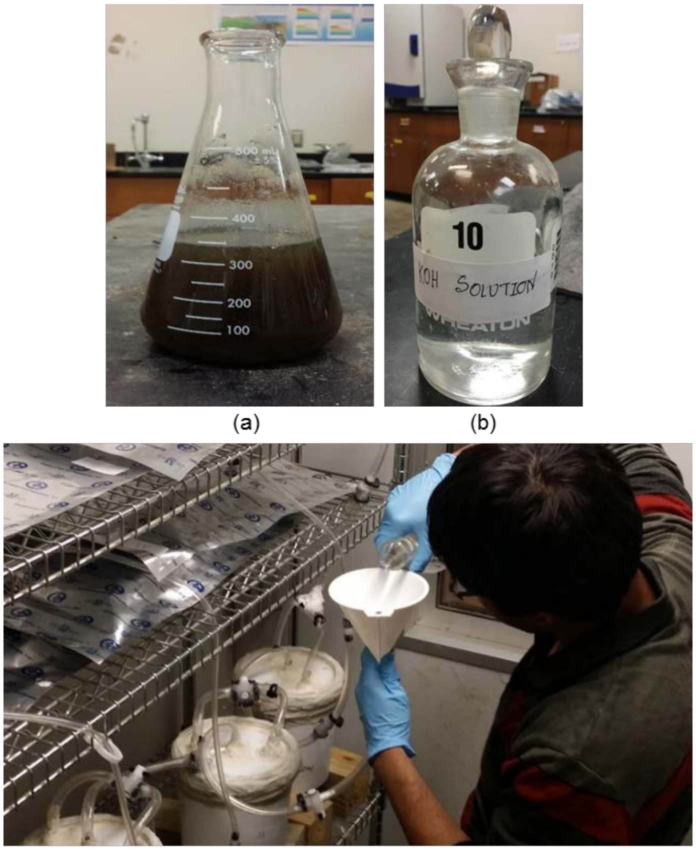
3.4.3 *Operation & Monitoring of Reactors*

A routine operation and monitoring of the reactors included collection & recirculation of leachate and collection and measurement of the gas generated.

3.4.3.1 Leachate Collection and Recirculation

Food waste has high moisture content (almost 70 percent or more). Hence, after setting up the reactors no moisture was added for a couple of days instead the reactors were allowed to drain excess moisture as leachate. During operation 400 mL of leachate was recirculated in the respective reactors every day at the beginning. Before recirculation, volume of leachate was measured using a graduated conical flask. If the generated leachate was less than 400 mL, water was added to make the recirculation volume equal to 400 mL. The leachate to be recycled was neutralized (pH≈7) with KOH buffer as necessary. Different steps involved in leachate collection and recirculation are presented in Figure 3.16 and Figure 3.17.

Figure 3.16 Leachate Collection



(a) (b)

(c)

Figure 3.17 Recirculation: (a) Leachate; (b) KOH buffer solution for leachate neutralization; (c) Leachate recirculation

3.4.3.2 Gas Collection and Measurement

During the reactor operation, generated gas was collected in Cali-5-BondTM 22 liter gas bags. Gas was collected and measured on regular basis whenever considerable amount of gas accumulated in the bag. Landtec GEM 2000 PLUS with infrared analyzer was used for measuring the concentration of methane (%CH_4), carbon dioxide (%CO_2), oxygen (%O_2) and other gases (%BAL) in the gas bags. To measure volume, gas was pumped out of the bag using standard SKC grab air sampler (SKC Aircheck sampler model 224-44XR) connected to a calibrator (Bios Defender 510) which gives a fixed flow rate. Using a stopwatch, time for emptying the gas bag was measured and total volume was found. Figure 3.18 shows gas composition and volume measurement.

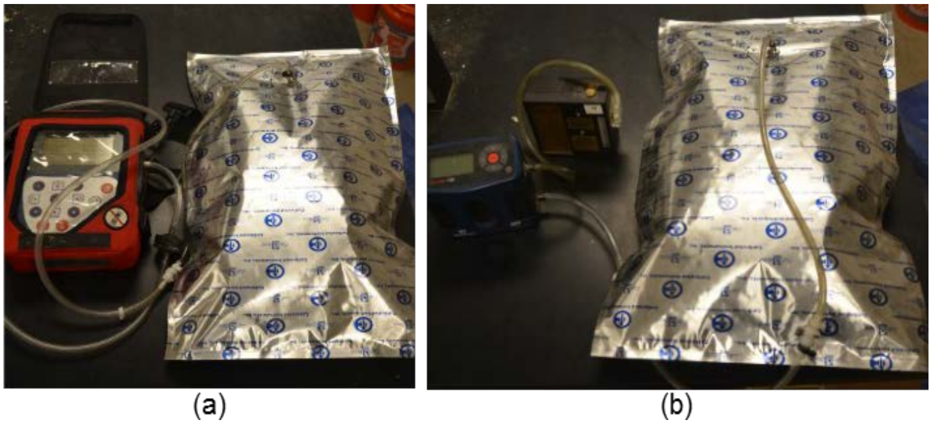

(a) (b)

Figure 3.18 (a) Determination of gas composition by Landtec GEM 2000, (b) Gas volume determination with SKC grab air sampler and Defender 510

3.4.4 Monitoring Leachate Quality

3.4.4.1 pH

pH of the leachate generated was measured with the help of a bench-top Oakton pH meter as shown in Figure 3.19. To ensure precise pH reading, pH probe was calibrated by three point calibration method (pH 4.00±0.01, 7.00±0.01 and 10.00±0.01) using buffer solution. In between taking pH readings, the probe was washed under flowing water and rinsed with deionized water. It was necessary to keep the probe always dipped in a buffer solution of pH 7.0. Leachate was neutralized to pH 7.0 before recirculation using KOH buffer solution.

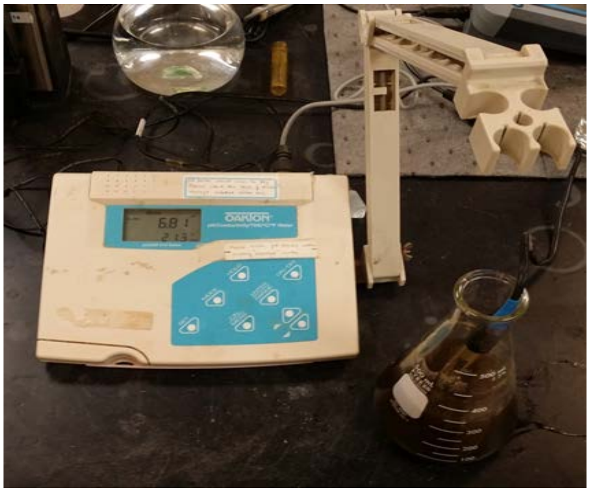


Figure 3.19 pH measurement

3.4.4.2 Chemical oxygen demand (COD)

Chemical Oxygen Demand (COD) tests were performed monthly basis. For each reactors two tests were conducted by diluting the leachate in 1:200 ratio. Samples were prepared by pouring 2.5 ml of diluted leachate into COD vials and placing them in the digester previously heated to a temperature of 150°C and keeping them in the digester for two hours. After digestion, the vials were kept outside the digester to cool them down to the room temperature. The vials were then placed inside a spectrophotometer (Spectronic 200+) which determines the absorbance of light and displays an absorbance value.

Figure 3.20 Chemical oxygen demand (COD) determination: (from left) COD vials, heating in digester, absorbance measurement by spectrophotometer

To determine the COD value from the absorbance value a calibration curve was generated using potassium hydrogen phthalate solution of known COD values. Using the calibration graph shown in Figure 3.21, COD values were determined from corresponding absorbance values. Then the COD values were adjusted to get the actual value according to the dilution factor of the samples.

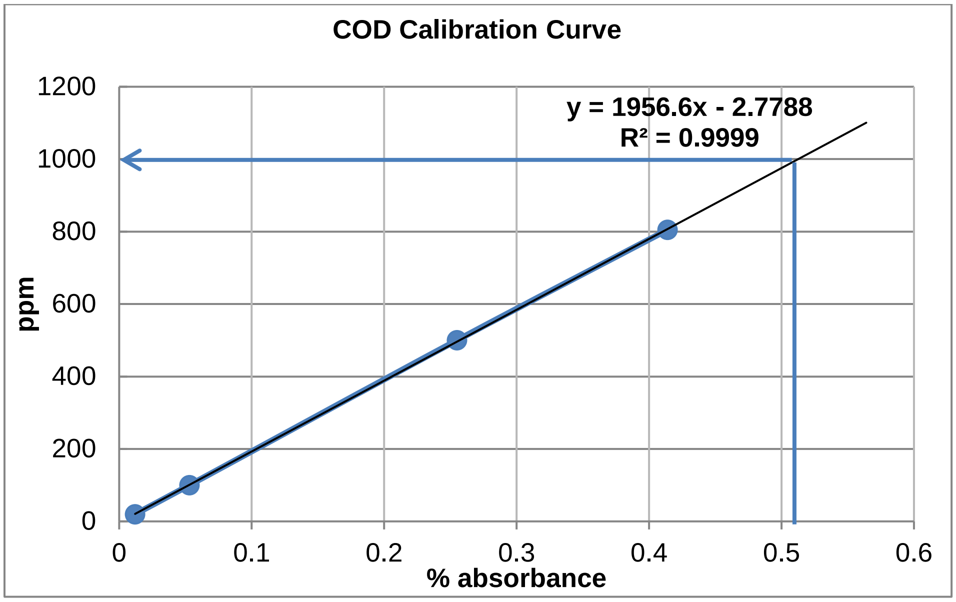


Figure 3.21 COD calibration curve

3.4.4.3 Biochemical oxygen demand (BOD)

The amount of oxygen required for the biodegradation of organic matter in the waste during 5 days of incubation at 20°C is called BOD_5. The Biochemical Oxygen Demand (BOD) was determined following the standard BOD procedure 8043. Tests were conducted using HACH HQ 440d benchtop dissolved oxygen measuring instrument. A dilution factor of 200 was used and each test was performed in triplicates. Dilution water was prepared by adding buffer pillow (one pillow for 4 liter deionized water) and aerating for two hours. Seed was prepared by adding one seed capsule in 500ml of dilution water. The BOD probe was calibrated using distilled water. Initial dissolved oxygen (DO) for each sample was measured. The samples were then capped and kept in a constant room temperature of 20°C by placing them in a water bath. After five days, dissolved oxygen in each sample was again measured and the five day BOD_5 was calculated for the samples. Figure 3.22 shows the BOD_5 measuring process.

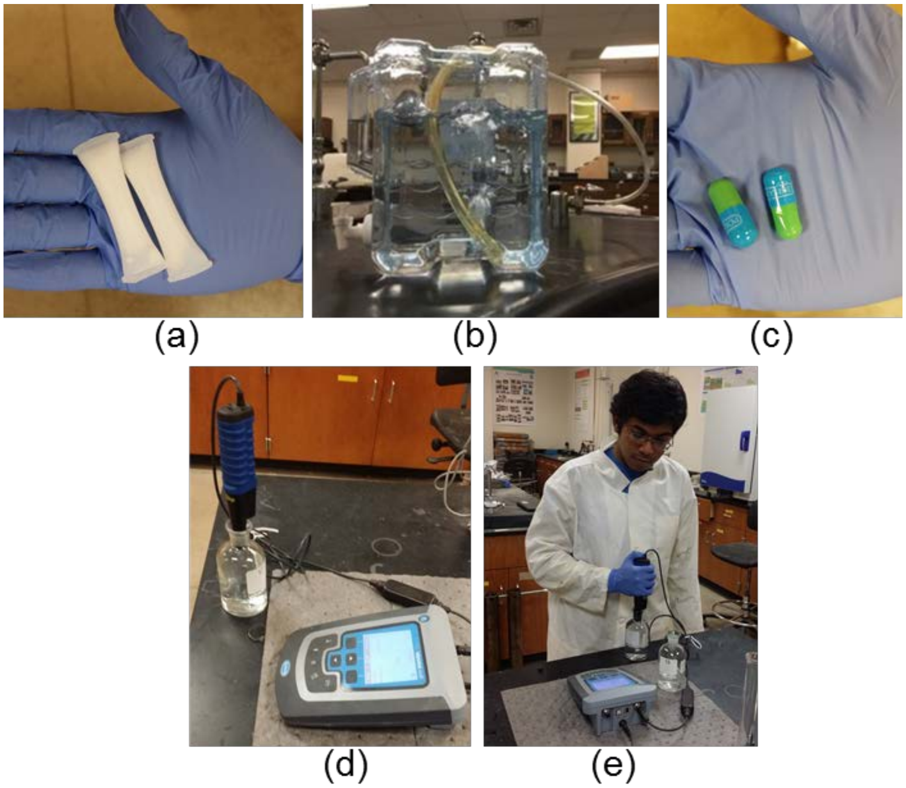


Figure 3.22 (a) Buffer pillow for dilution water preparation; (b) aeration of dilution water; (c) seed capsule; (d) calibration of DO probe; (e) dissolved oxygen (DO) measurement

Chapter 4

Results and Discussion

4.1 Introduction

The results obtained from the laboratory scale biocell experiments with food waste are evaluated to understand the effect of manure on food waste decomposition and gas generation are presented and discussed in this chapter. Fresh food waste samples were collected from different sources and mixed to a synthetic ratio to keep the combination inside the reactors as identical as possible. A total of eight (8) reactors were built to simulate the food waste scenario of biocell in laboratory with two control reactors and six reactors with three different combination of nutrients.

The results of initial waste characteristics (moisture content, composition and volatile solids), inoculum properties, leachate and gas volume and composition during monitoring are discussed in the following sub-sections.

4.2 Characteristics of Food Waste

As discussed in chapter 3, sub-section 3.3.1.1, food waste were collected from two sources, one for fruits and vegetables another for mixed food waste. The following subsections discusses the physical composition, moisture content & volatile solids of the collected waste.

4.2.1 Waste Composition

Collected food waste sample were sorted in four categories: fruits & vegetables, meat & seafood, grains and dairy products. Physical composition of the waste sample collected from the UTA café was determined by weight basis as shown in Table 4.1 along with the synthetic food waste composition used for reactor building. Food waste collected from Walmart was composed of only fruits and vegetables, therefore, no sorting was necessary.

Table 4.1 Physical composition of food waste

Food waste components	UTA café food waste composition	Synthetic composition used for building the reactors
Fruits & Vegetables	49.85	50
Grain Products	30.15	20
Meat & Seafood	9.98	20
Dairy Product	2.02	10

Synthetic composition was decided based on national average as described in section 2.3.3 and rounded for ease of sample preparation. Based on the experimental result it was found that fruits and vegetables was the largest component by weight (49.85%) which was similar as national percentage. Fluid milk consists of a good percentage of national food waste which was not included in the synthetic composition and other components were adjusted accordingly.

4.2.2 Initial Moisture Content of Food Waste for Reactors

Moisture content test for both of the collected samples (UTA café and Walmart waste) were conducted in triplicate. Food waste collected from Walmart had high moisture content (83.45%) compared to food waste from UC connection café (51.38%). This was because Walmart food waste had fruits and vegetables that usually contains very high amount of water in them (e.g. water content in pineapple, orange, apricot, apple etc. 84 ~ 87 %, strawberry, grapefruit contains >90%, banana 81%; cucumber, lettuce, eggplant etc. >90%, green peas, potato 79% and so on). However, in the food waste from connection café, as part of grain products, it had high amount of breads which has extremely low moisture content (approximately 30%) and tend to absorb moisture from surroundings, also during sorting paper napkins were found and removed that might have in addition absorbed a little amount of moisture.

As discussed in chapter 3, sub-section 3.3.2, the experimental design was followed while filling the reactors with food waste. Food waste sample for the reactors were prepared according to the synthetic proportions shown in Table 4.1. Food waste in itself does not have considerable amount of microorganism in it. Hence, to ensure microbial population, 10 percent sludge was added to the food waste mixture. A total of four pair of reactors were built of which first pair was considered as control as nothing other than sludge was added. For remaining three pair of reactors, in addition to sludge 6 percent manure, cow, pig and horse manure respectively (as source of inoculum), was also added to observe the effect of different kind of manure on food waste degradation. For proper mixture of sludge and manure with food waste very little amount of water was sprayed during mixture. All the reactors were filled with about four pounds of food waste mixture. Since food waste had high moisture (78.35 % moisture content), rather than adding water at the beginning of reactor operation, reactors were allowed to drain excess moisture for first couple of days.

For each pair of reactors, food waste samples were collected after mixing with sludge and manure for determining the characteristics of the waste inside the reactor at the beginning of the operation. Therefore, the moisture content found will be referred to as initial moisture content of the waste inside the reactor. Table 4.2 shows the initial moisture content of waste for each pair of reactors which was almost same for all eight reactors.

Table 4.2 Moisture content of food waste inside the reactors

Reactor	**Weight of moist waste (lb)**	**Weight of Dry Waste (lb)**	**Moisture Content (%) (wet weight Basis)**
B1 & B2 (Control)	2.345	0.547	76.67
B3 & B4 (Cow manure)	2.147	0.521	75.73
B5 & B6 (Pig manure)	2.225	0.497	77.66
B7 & B8 (Horse manure)	2.017	0.481	76.15

Moisture content found for the mixed food waste in this study were compared to the reported values found in the literature as shown in Table 4.3. The moisture content value found in this study was found to be comparable with the previous studies as shown in bar chart (Figure 4.1).

Table 4.3 Comparison of food waste moisture content found with the previous studies

	Moisture content (%) (wet weight Basis)	**Author**	**Moisture content (%) (wet weight Basis) found in current study**
Food waste	50.00 ~ 80.00	Tchbanoglous (1993)	75.73 ~ 77.66
Mixed food waste (Korean)	74.00	Cho et al. (1995)	
Mixed food waste	68.30	Abu-Qudias (2000)	
Food Waste	82.86	Karanjekar (2013)	

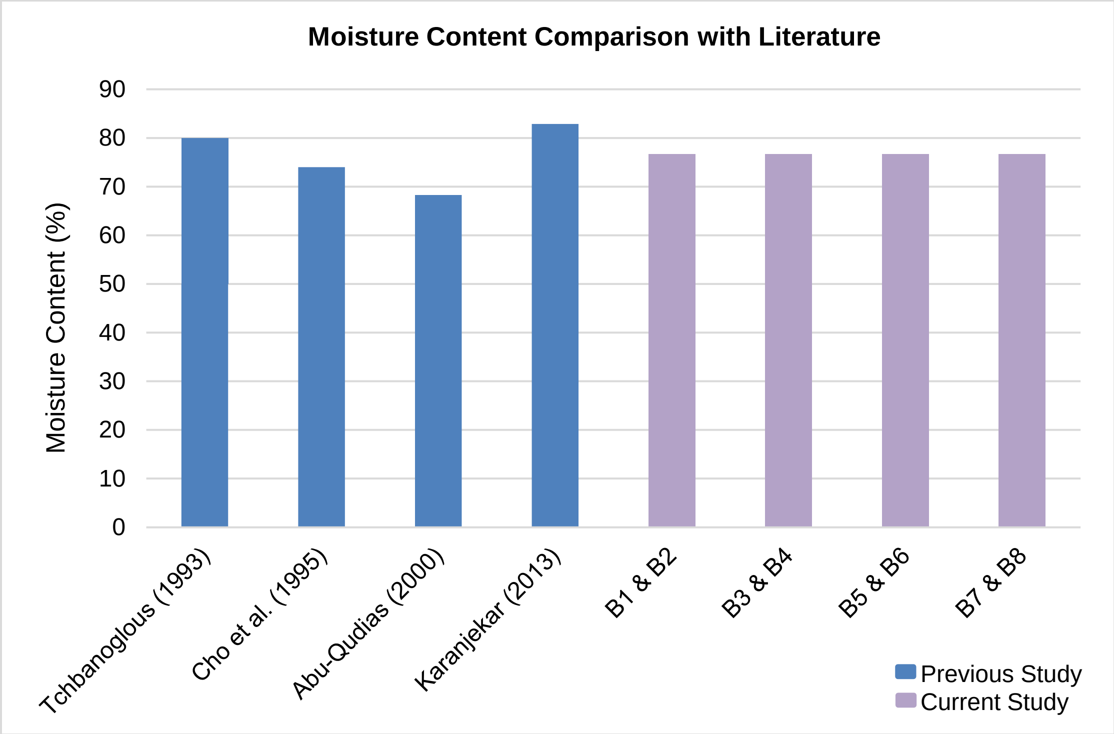


Figure 4.1 Comparison of food waste moisture content found with previous studies

4.2.3 *Initial Volatile Solids*

Volatile solids (VS) are one of the determining factor of waste decomposition and gas production. Before putting the waste inside the reactors, volatile solids for each pair of reactor waste were determined and hereafter will be referred to as initial volatile solids. Volatile solids were almost similar for all the reactors as all the reactors were filled with same food waste mix. Table 4.4 shows average volatile solids content for different set of reactors. Although no significant variation in volatile solids was observed, minimal deviation were found due to non-uniformity of waste properties itself.

Table 4.4 Volatile solids results for food waste in different set of reactors

Reactor	**Volatile Solids (VS) (%)**			**Average VS (%)**
	Sample 1	**Sample 2**	**Sample 3**	
B1 & B2 (Control)	91.73	91.66	91.58	91.66
B3 & B4 (Cow manure)	92.98	92.96	92.94	92.96
B5 & B6 (Pig manure)	91.79	91.78	91.76	91.78
B7 & B8 (Horse manure)	92.22	92.23	92.25	92.23

Volatile solid results were compared to the VS from literature as shown in Table 4.5. The volatile solids determined for the current research was found to be comparable to the results from previous studies as represented in the bar chart in Figure 4.2. VS for food waste compared to fresh waste (MSW) is significantly higher.

Table 4.5 Comparison of volatile solids (VS) found in the current study with previous studies

	Volatile solids (%)	**Author**	**Volatile solids (%) found in current study**
Mixed food waste (Korean)	95.00	Cho et al. (1995)	91.66 ~ 92.96
Food waste	93.80	Eleazer et. al. (1997)	
Mixed food waste	88.34	Abu-Qudias (2000)	
Food Waste	90.16	Karanjekar (2013)	
Fresh Waste (MSW & sludge mix)	70.4 ~ 74.8	Hossain et al. (2014)	

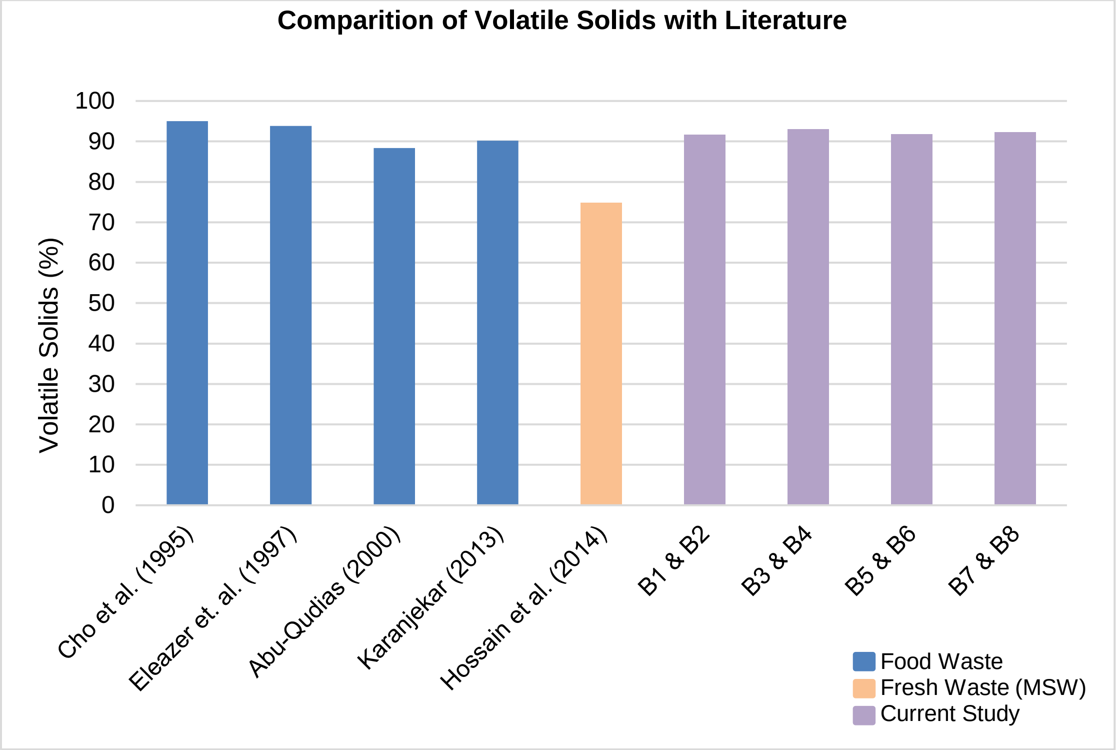


Figure 4.2 Comparison of volatile solid found for food waste with previous studies

4.3 Characteristics of Inoculum

Microorganism aids in faster decomposition of waste. Especially in the food waste or organic waste the microbial population is very low and requires inoculum from an external source to facilitate decomposition of waste and gas generation as byproduct. Increase in inoculum percentage increases gas production. Previous studies found some successful result by adding sludge from 20% to 80% (Liu et at., 2009; Wang et al., 1997; Karanjekar, 2013). However, for field application this high percentage is not feasible. In different studies of food waste digestion by anaerobic digester manure was used as inoculum. However, mixture of sludge and manure was never tested. In this study, as inoculum, sludge and manure was added to the food waste.

As mentioned earlier in chapter 3, sub-section 3.3.1.2 sludge was collected from the city of Denton landfill, Texas, to be used as inoculum in the food waste reactors. Typically sludge contains high microbial population and as sludge is being digested anaerobically so it has a good amount of anaerobic bacteria in it. Sludge usually have high pH (above 8.00) because of being digested anaerobically which might help diluting the initial acidic environment generated in the food waste. The pH was tested for the sludge collected before mixing it with food waste. pH was found to be 8.37. pH test results are shown in Table 4.6.

The prime objective of this study was to add different types of manure with food waste and analyze the effect of manure type on methane generation and food waste degradation. As mentioned in chapter 3 sub-section 3.3.1.3, aged cow manure and pig manure was collected and almost fresh horse manure was collected. Before mixing with food waste each of the manure was tested for pH. The test results are shown in Table 4.6. pH for all the manures was found to be above neutral pH (7.0) and for cow manure pH was the highest, almost 8.95.

Table 4.6 pH test results for sludge and manures

Inoculum Source	**Sample 1**	**Sample 2**	**Sample 3**	**Average pH**
Sludge	8.42	8.33	8.36	8.37
Cow manure	8.89	9.09	8.86	8.95
Pig manure	7.73	7.43	8.26	7.81
Horse manure	7.68	7.59	7.79	7.69

4.4 Leachate Monitoring

Leachate monitoring included monitoring of pH, volume, Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) is discussed in the following subsection.

4.4.1 pH

Variation in pH of the food waste reactors depends on stage of degradation of waste inside the reactors. To monitor pH of the reactors, leachate was collected and pH was measured using Oakton benchtop pH meter. According to previous researchers (Shao et. al., 2005; Karanjekar, 2013), food waste experiences pH drop due to VFA accumulation resulting in frequent recirculation. Similar scenario was observed in the current study. Due to initial low pH, frequent recirculation was necessary by neutralizing the pH.

Reactor B3 and reactor B4 were the first to show stable increase rather than high fluctuation noticed at the beginning of operation, followed by reactors B5 & B6 and then the rest. For first 50 days, pH was measured more frequently (daily) compared to the rest of the operational time of the reactors. pH variation with time for all the reactors are graphically presented in Figure 4.3.

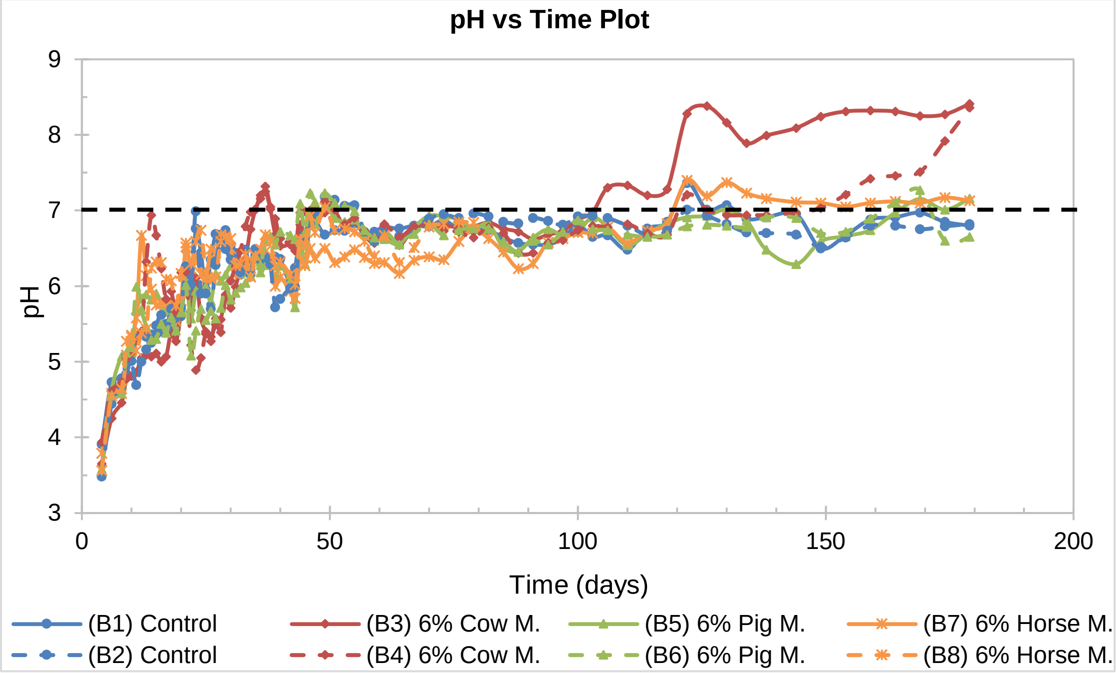


Figure 4.3 Change in pH over time of the leachate collected

At the beginning of operation, pH of the reactors dropped rapidly due to acidogenic phase and excessive volatile fatty acid (VFA) accumulation in food waste (Shao et al., 2005) which might be responsible for lower pH for longer period than typical solid waste reactors. Therefore, to avoid excessive acid accumulation, leachate was collected to monitor the pH level and potassium hydroxide (KOH) was added to neutralize the leachate before recirculation whenever found below 7.0. At the beginning of the operation pH for all the reactors were really acidic (pH 5 or below) until sludge was added to the reactors after 20 days. Leachate was recirculated on regular basis for pH neutralization with an addition of KOH whenever the pH of the leachate fall below 7.0 for almost 50 days. pH gradually became stable between 6 and 7 after 50 days of recirculation and

KOH neutralization was done whenever pH tend to decrease. After that, pH of the leachate gradually started increasing with a few abrupt changes in pH level. Even after around 180 days (six months) of operation, pH for most of the reactors were below 7.0 except for reactor B3 and reactor B4 (food waste reactors with cow manure).

In case of reactor B3 which had 6% cow manure mixed with food waste in addition to 10% sludge, pH was below 7.0 up to 100 days. This prolonged acidic phase might have occurred due to volatile acid accumulation which inhibited bacterial activity and resulted in delayed degradation. After 100 days of lag period pH in reactor B3 started going above 7.0 and increased up to 8.41. The gas generation from reactor B3 also significantly increased during this period due to reaching the methanogenic phase of degradation.

Similar scenario was observed for the reactor B4 which was the duplicate of B3 reactor. However, longer lag period was observed in reactor B4 compared to reactor B3 (around 120 days). This might be due to the non-homogeneity of waste as well as the acid concentration and accumulation rate which was difficult to control even in similar laboratory scale reactors. After 120 days of operation the pH for reactor B4 started increasing and reached up to 8.36 and remained in basic state from that point onward till the end of operation. Similar to reactor B3, higher gas production was observed once the acidic phase of the reactors were over.

Reactor operation in B8 was stopped after 80 days of operation as shown in Figure 4.4. Since, none of the reactors were generating gas for prolonged period, it was suspected that the micro-organisms inside might have died due to excessive acidic condition. However, from the destructive test no proof was found that supported the theory. Due to no gas production and pH being low for too long one of the reactors were dismantled to check on the parameters inside and reactor B8 was chosen for this purpose. Reactor B8 was dismantled after 80 days of operation and pH of the leachate was found to be 6.39 while pH of the waste was 5.27. This indicates the waste inside was in highly acidic condition compared to leachate produced. The rest of the reactors were kept monitoring.

The pH variation with time for the reactors B1 through B8 are shown in Figure 4.4.

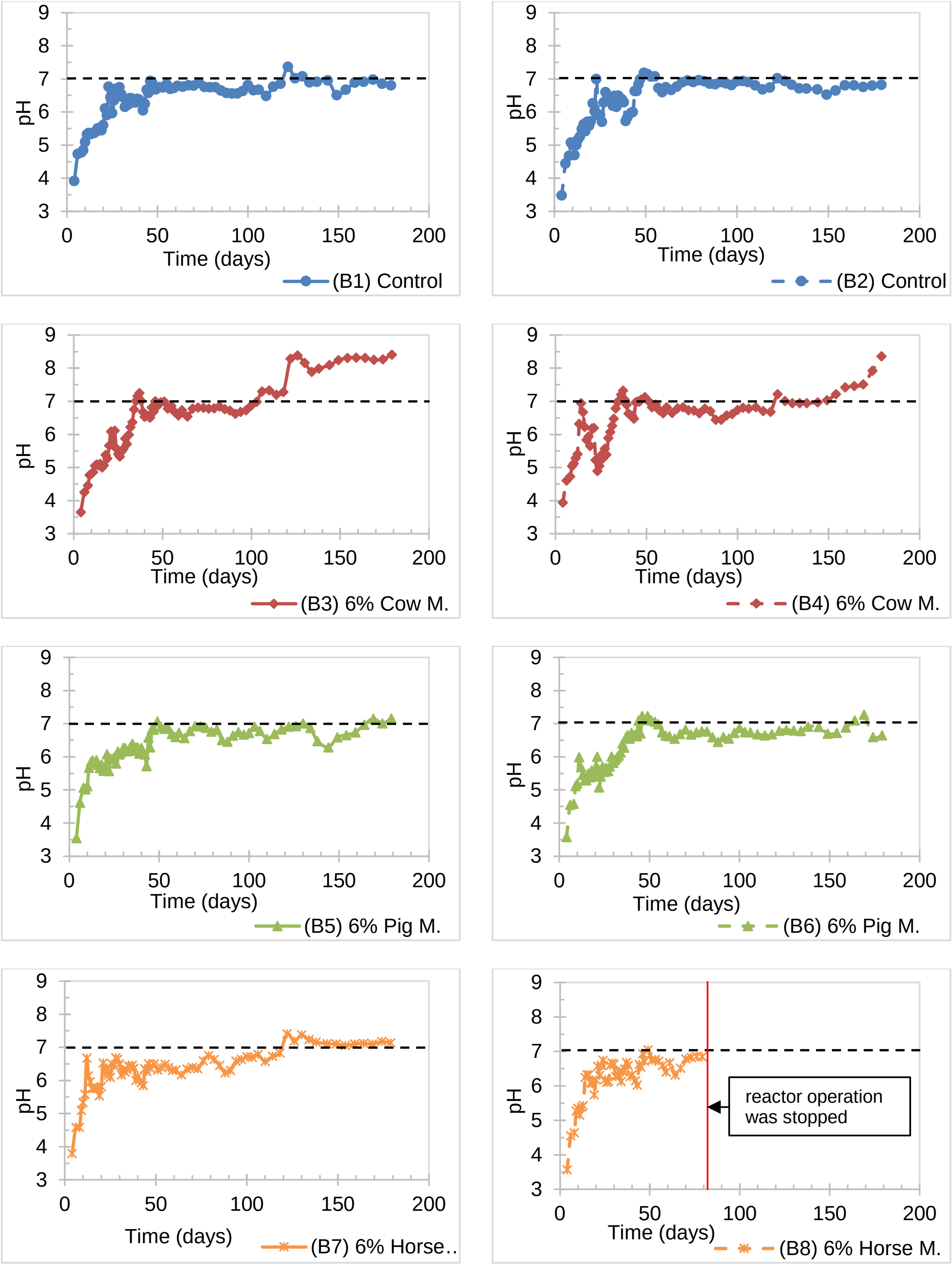


Figure 4.4 Variation of pH with time for leachate of all reactors (individual graphs)

A study done by Wang et al. (1997) on food waste reactors showed a similar trend in pH variation except the initial pH was higher than current study and also the lag phase was shorter as shown in Figure 4.5. This was because the authors used high percentage of inoculum (upto 70%) as the lower percentage (30%) failed in their case. The use of higher inoculum diluted the acidic environment and helped reducing lag time. In the current study, initially only manure of low percentage (6%) was added, as a result pH was really low at the beginning. After 20 days 10% sludge was introduced to the system and the situation improved.

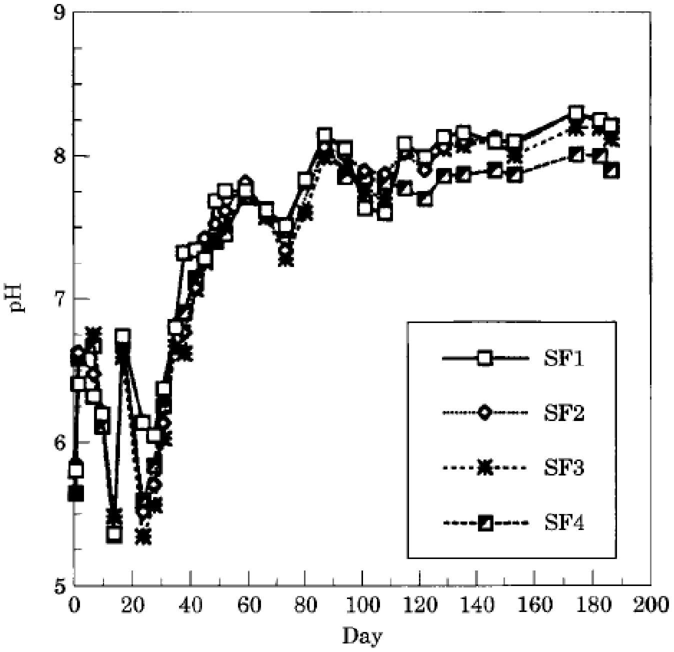


Figure 4.5 Change in pH of the reactors with time (Wang et al., 1997)

4.4.2 Leachate Volume

The purpose of leachate recirculation in landfill is to maintain moisture content of waste to accelerate degradation. However, if the waste is organic or food waste, it contains a very high level of moisture (>70%) and there is no need for maintaining moisture by recirculation of leachate in the initial stage. Instead the recirculation of leachate (mixed with neutralizer i.e. KOH) becomes necessary to neutralize the extreme acidic environment created by the acid accumulation in acidogenic phase. In this research all the reactors contain waste that is 100% food waste. To neutralize the reactor environment, leachate was recirculated everyday up to day 50 and afterwards the frequency of recirculation was reduced. Initially the volume recirculated was about 200 ml which was found to be not sufficient as the pH kept going down rapidly. So, after 20 days in addition to sludge, the recirculation volume increased to 400 ml which showed a promising improvement to the scenario. Generated leachate volume measurement data are shown in Figure 4.6.

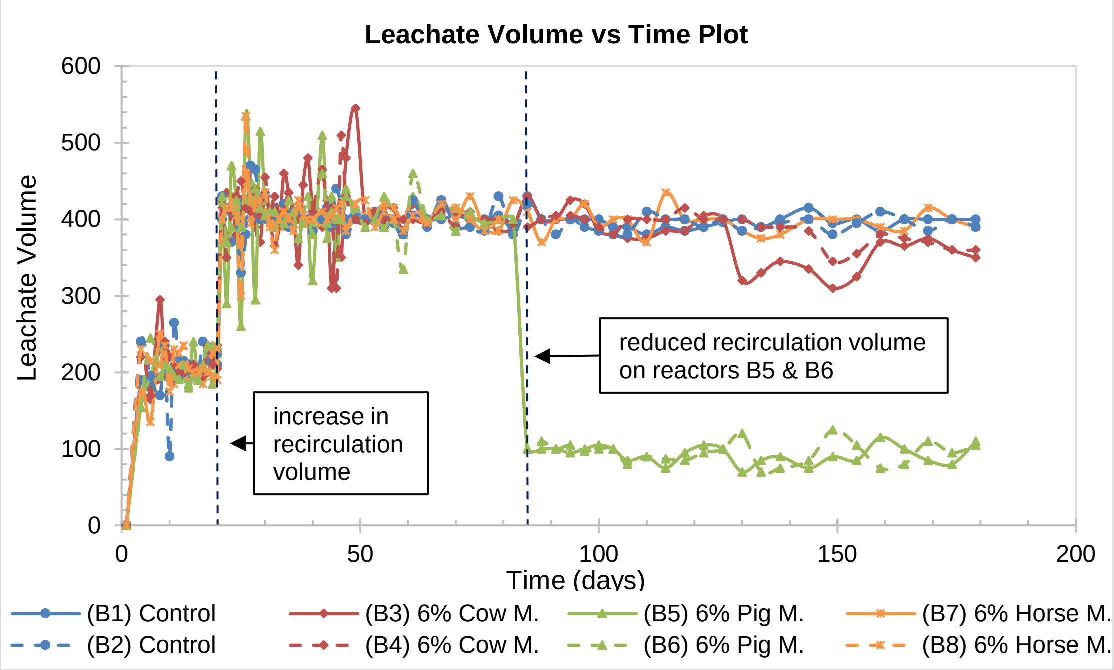


Figure 4.6 Volume of leachate generated from the reactors

From the leachate generation data, it was observed that in the initial stage (till day 50) there was some abrupt changes in leachate generation of the reactors, compared to the recirculation volume. This might be due to the high frequency of recirculation providing not enough time for some of the reactors to drain the total amount of leachate that was recirculated. The sudden fluctuation in leachate volume reduced after increasing the interval between recirculation.

Moisture is necessary for faster degradation of waste, at the same time if the moisture content is too high it might reduce the degradation process. As none of the reactors were producing any gas for almost 80 days it was suspected that high moisture could be one of the reasons along with VFA accumulation. So to observe the effect of moisture, the reactors B5 & B6 were chosen and it was decided to reduce the recirculation volume to the need of only pH neutralization as show in Figure 4.6.

For reactors B3 and B4, after 100 days and 120 days of operation respectively, the generated leachate volume was found to be less than the amount injected. The reason for this behavior might be because, after the lag phase when the reactors started producing gas it started moving towards methanogenic phase and the methanogens uses some amount of moisture for waste degradation and gas production.

4.4.3 Chemical Oxygen Demand (COD)

Variation in chemical oxygen demand (COD) for the reactors are shown in Table 4.7 and also Figure 4.7 shows the graphical representation. The test for COD was done on a monthly basis on the leachate collected. In this study all the reactors have 100% food waste and for all of the reactors a high value of COD observed.

Table 4.7 Monthly COD test data

Age (month)	**Chemical Oxygen Demand (COD) (mg/L)**							
	B1 (Control)	**B2 (Control)**	**B3 (6% Cow Manure)**	**B4 (6% Cow manure)**	**B5 (6% Pig manure)**	**B6 (6% Pig manure)**	**B7 (6% Horse manure)**	**B8 (6% Horse manure)**
1	122,710	133,080	146,385	138,559	142,080	136,798	102,557	95,709
2	116,449	121,536	150,494	158,320	129,754	145,407	126,036	145,015
3	140,731	136,042	144,637	150,888	148,349	157,530	121,392	-
4	144,637	139,949	99,709	127,252	151,865	139,559	121,197	-
5	124,713	120,415	52,632	94,240	138,973	135,456	120,220	-

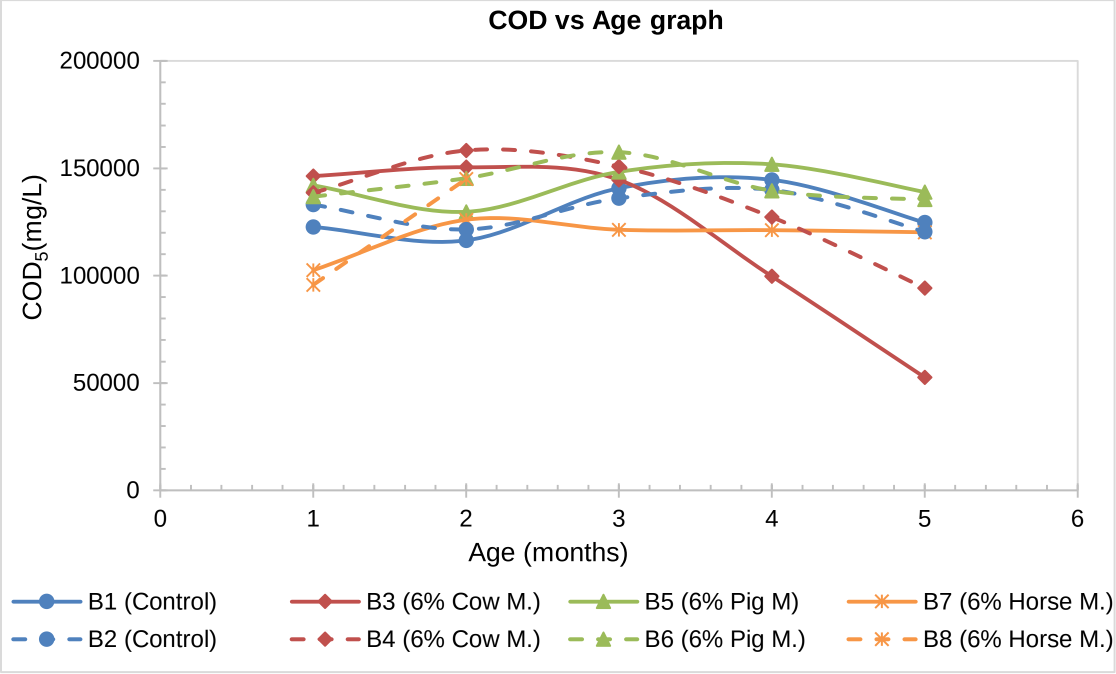


Figure 4.7 Change in COD with time for the reactors

The relation between COD and waste degradation is that COD decreases with time as the waste decomposes. In this study, initial COD values for all the reactors were high and it stayed like that for all the reactors except reactor B3 and B4. Because the reactors were in lag phase which is the acidogenic phase and almost no degradation occurred.

In case of reactor B3 and B4 as soon as the acidogenic phase ended and the degradation took place and started to go into methanogenic phase COD started dropping. Initial COD for reactor B3 and B4 were 146,385 mg/L and 138,559 mg/L respectively which reduced to 52,632 mg/L and 94,240 mg/L respectively at the end of fifth month.

Figure 4.8 shows a result found by Wang et. al. (1997), which shows as the reactor reached the methanogenic phase COD dropped significantly. The values found from their research varies significantly with current research might be because they used around 70% degraded waste as inoculum while in the current study the inoculum percentage was only 16% (10% sludge & 6% cow manure). As a result their lag phase was significantly reduced and reached methanogenic phase rapidly compared to current study.

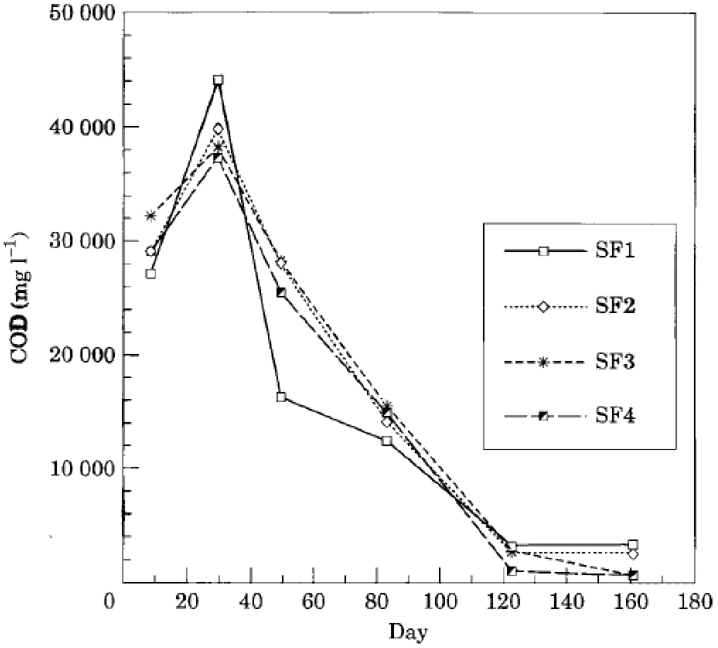


Figure 4.8 Variation of COD over time in the reactors (Wang et al., 1997)

A research by Al-kaabi et al. (2010) showed that, the COD value initially decreases in the aerobic stage as shown in Figure 4.9. Initially COD concentration increased in all the reactors rapidly as the hydrolysis continued. After reaching some maximum values COD started dropping as waste started decomposing in methanogenic phase. Same thing was observed in the current study for reactors B3 and B4 (Figure 4.7), COD value increased to a peak value as the hydrolysis continued during the transition from aerobic to anaerobic phase and after that started decreasing rapidly. The other reactors were still in the lag phase which were under observation for further change.

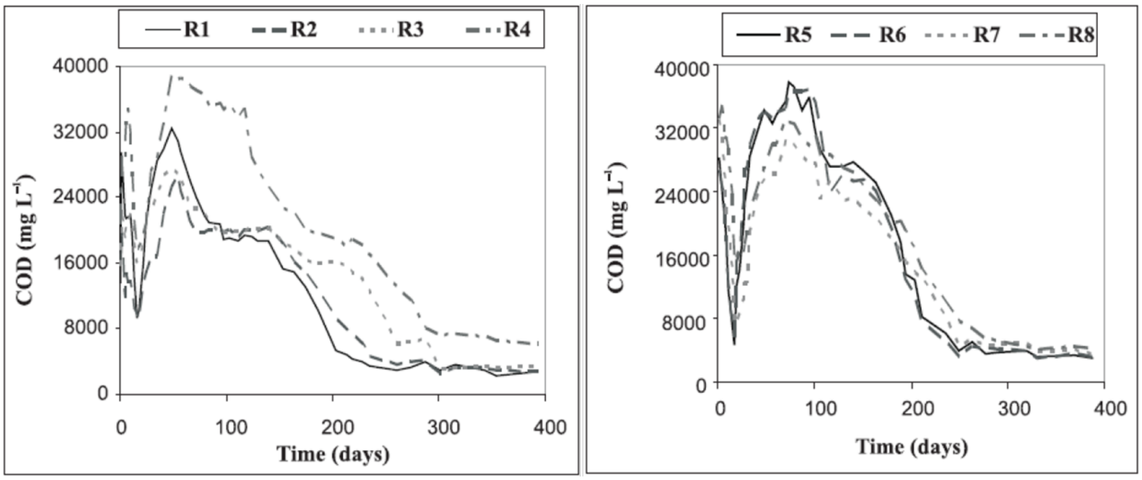


Figure 4.9 Variation in COD contentration (Al-kaabi et. al., 2009)

4.4.4 Biochemical Oxygen Demand (BOD)

Along with COD, Biochemical Oxygen Demand (BOD_5) tests were conducted on monthly basis in order to measure microbial concentration to oxidize carbonaceous and nitrogenous compounds in leachate. The results found are show in Table 4.8, also graphically represented in Figure 4.10.

Table 4.8 Monthly BOD test data

Age (month)	**Biochemical Oxygen Demand (BOD) (mg/L)**							
	B1 (Control)	**B2 (Control)**	**B3 (6% Cow Manure)**	**B4 (6% Cow manure)**	**B5 (6% Pig manure)**	**B6 (6% Pig manure)**	**B7 (6% Horse manure)**	**B8 (6% Horse manure)**
1	91,800	94,500	101,025	95,550	91,350	97,425	75,840	71,280
2	79,700	82,200	93,889	105,600	97,600	106,100	79,556	94,900
3	98,900	97,800	103,600	112,550	99,700	107,000	86,775	-
4	98,033	95,100	65,422	82,911	97,200	87,700	81,244	-
5	89,133	81,689	24,517	49,107	89,867	82,533	78,422	-

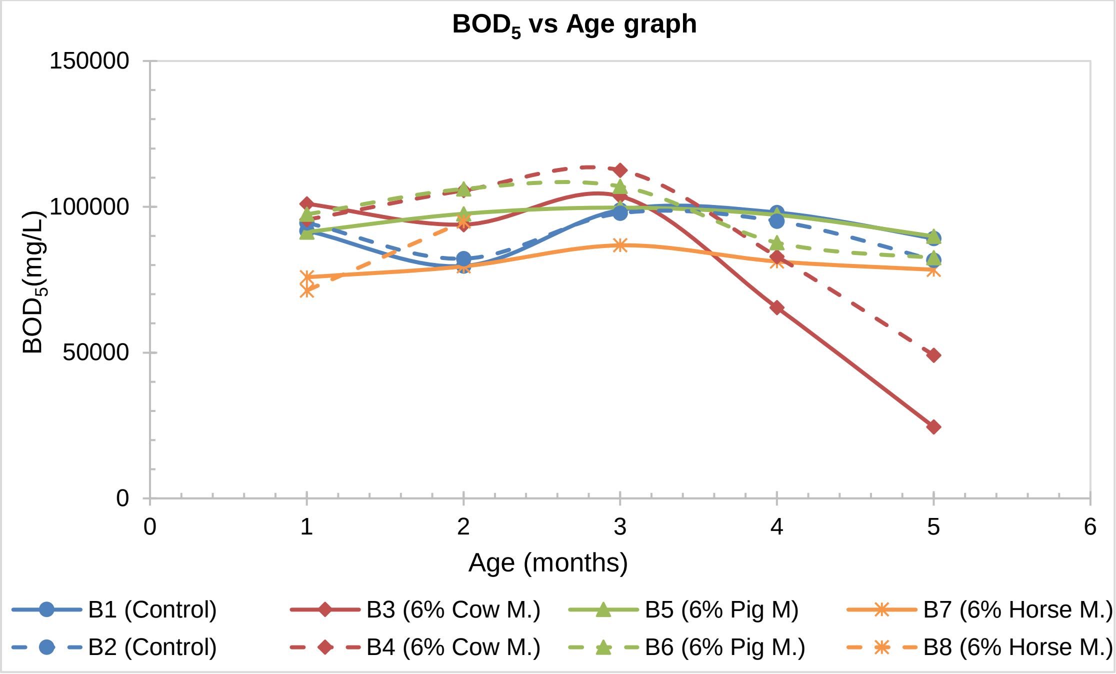


Figure 4.10 Change in BOD with time for the reactors

From the results obtained it was found that with the start of degradation BOD_5 decreased. For reactor B3 and B4 till 100 days and 120 days the reactors were in acidogenic phase and almost no decomposition occurred. After that as the decomposition took place BOD_5 started decreasing. Initial BOD_5 for reactors B3 and B4 were 101025 mg/L & 95550 mg/L which was found 24517 mg/L & 49107 mg/L at the end of fifth month respectively. For the remaining reactors as they were still in acidogenic phase BOD_5 values were found to be high. A study done by Barlaz et at. (1993), reported that highest BOD_5 was found during acidogenic phase.

4.4.5 Variation in BOD_5/COD Ratio

BOD_5/COD ratio is an indicator of waste degradation. The ratio degrades as the waste ages (Reinhart et al., 1996). According to Kjeldsen et al. (2002), in acidic phase BOD_5/COD ratio is around 0.58 and 0.06 for methanogenic phase. For the current study variation of BOD_5/COD values are graphically plotted in Figure 4.11. From the Figure it is evident that the waste inside the reactors were still in the initial degradation stage. Only values for reactor B3 and B4 took a little dive (initial BOD_5/COD 0.69 for both and after 5 months 0.47 & 0.52 respectively). The other reactors were still in the acidic phase. According to Warith (2002), if the ratio is in the range of 0.4-0.8 the leachate is highly biodegradable.

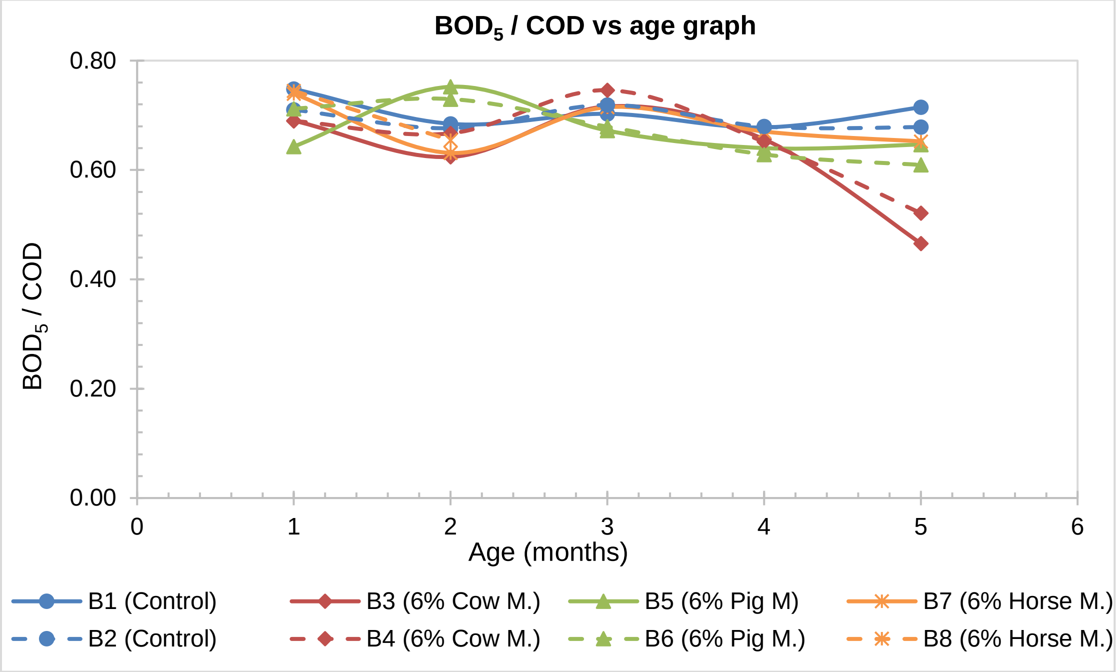


Figure 4.11 Variation of BOD_5/COD with time

4.5 Reactor Gas Data

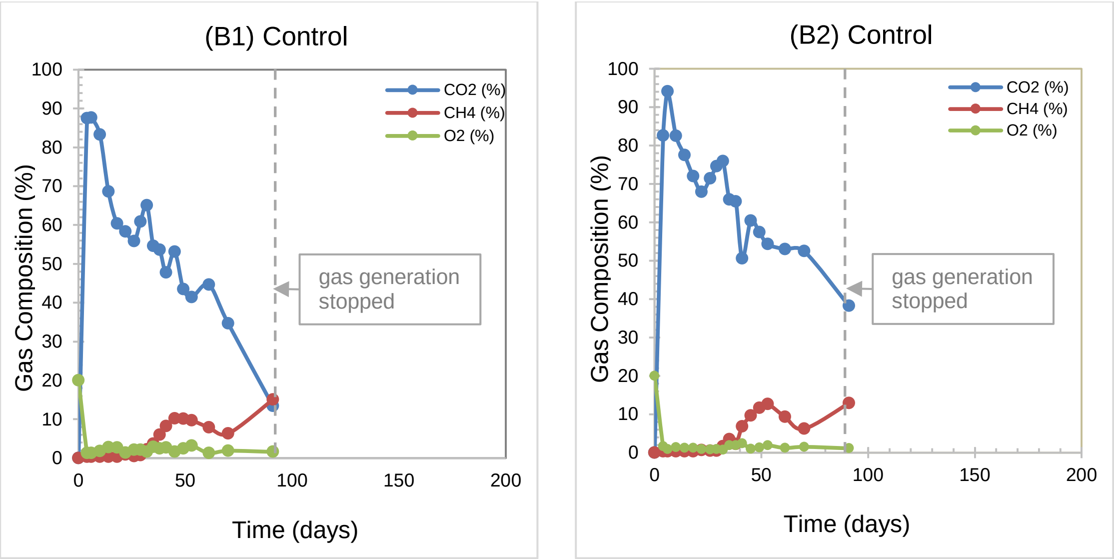
4.5.1 Gas Composition

The reactors were operated at 37°C inside an environmental growth chamber. Gas data was collected whenever there was gas inside the gas bags. Figure 4.12 shows graphical representation of gas composition data for all the reactors. All the compositions are shown in percentages (%). Typically anaerobic decomposition of waste occurs in four phases: i) aerobic phase, ii) acidogenic (acid formation) phase, iii) methanogenic (methane generation) phase, iv) methane depleting phase. From the gas composition data (Figure 4.12) it can be seen that the initial percentage of oxygen in the reactors was high (20%) which depleted rapidly. This was the aerobic phase where gas mainly consisted of carbon dioxide in high percentage and other gases (e.g. H_2S, nitrogen compounds etc.). In this stage all the reactors had negligible amount of methane content.

In the acidogenic phase, the pH started dropping for all the rectors. It was reported by Shao et. al (2005) that if the waste stream has high percentage of food waste, sudden drop in pH occur due to accumulation of excessive volatile fatty acid. Reactors in the current study had pure organic waste which was food waste. As a result the environment inside the reactors kept getting acidic which was neutralized frequently through addition of KOH with leachate. The excessive acid accumulation tend to inhibit bacterial activity which in turn affect the gas production, creating a lag phase before the decomposition enters methanogenic phase. In the current study similar thing occurred due to VFA accumulation and there was a long lag phase found for all the reactors which can be seen in the Figure 4.12, with time percentage of gas component went down due to little to no gas production. Apart from reactors B3 and B4 (which had cow manure as inoculum in addition to sludge) all the other reactors were still in lag phase. Only reactors B3 and B4 entered the methanogenic phase after a long lag period.

In the methanogenic phase, typically the dominating component in the gas is methane and carbon dioxide. In this stage the methane percentage goes as high as 60~65% and the pH of the leachate varies between 6.0 and 8.5 (Karanjekar, 2013). In the current study, the reactors were monitored for about six months and till that time only reactor B3 and reactor B4 was found to have reached the methanogenic phase. pH of these reactors went as high as 8.31 and 7.51 respectively while methane content showed a much higher value than previous studies. Methane content for the reactors B3 and B4 were found to be stabilized around 72 ~ 76%. Remaining 20~28% were found to be composed of mainly carbon dioxide and negligible amount of other gases. Oxygen content in these two reactors were almost zero as the reactors were operated in anaerobic condition.

Reactor B1 & B2: Control reactors (food waste and 10% sludge)



Reactor B3 & B4: (food waste, 10% sludge and 6% cow manure)

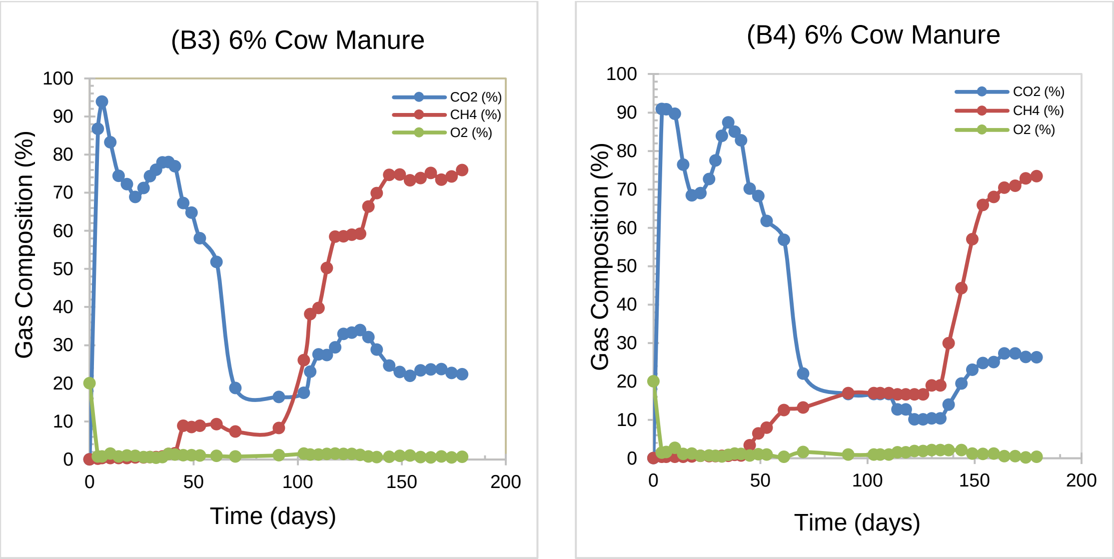
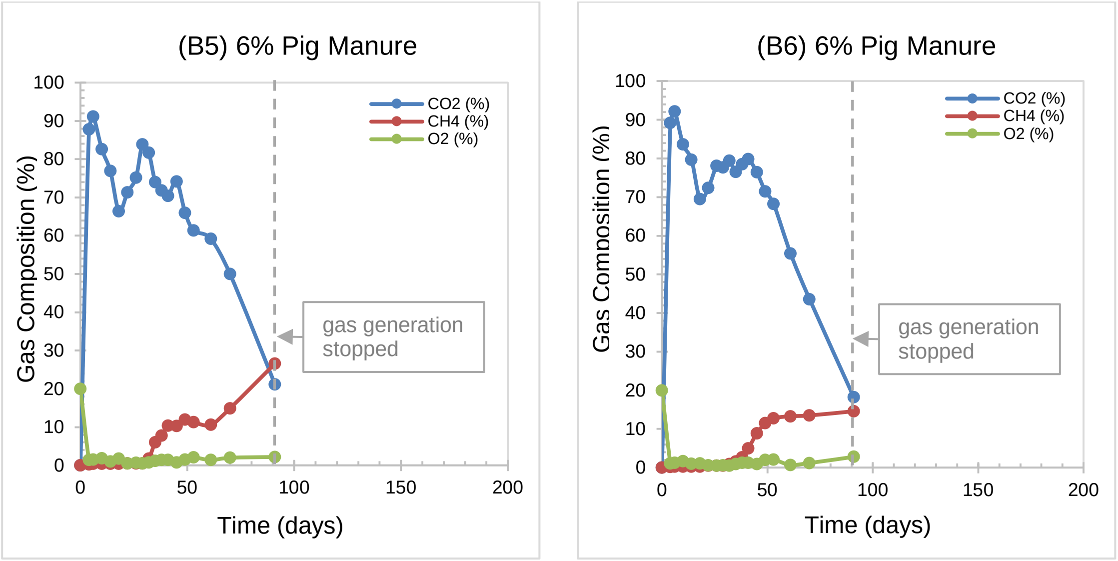


Figure 4.12 Gas composition data for reactors B1 through B8

Reactor B3 & B4: (food waste, 10% sludge and 6% cow manure)



Reactor B3 & B4: (food waste, 10% sludge and 6% cow manure)

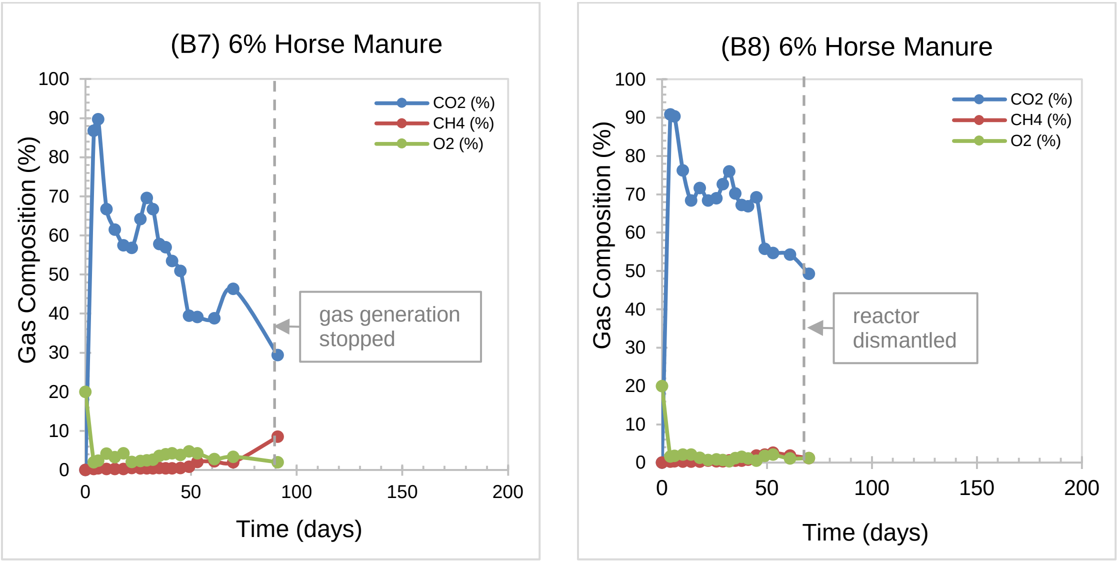


Figure 4.13 Gas composition data for reactors B1 through B8 (contd.)

The initial increase in carbon dioxide was due to the breakdown of organics into simpler compounds and carbon dioxide generation as by product. Over the time carbon dioxide percentage decreased and the methane percentage increased. Till the reactors reached methanogenic phase methane to carbon dioxide ratio was below 1.0. The scenario of increasing methane and decreasing carbon dioxide can be shown by CH_4:CO_2 vs time graph in Figure 4.13. For reactors B3 and B4 the ratio increased to as high as 3.34 and 2.77 respectively. For the remaining reactors they were still in lag phase and no gas was produced during the time.

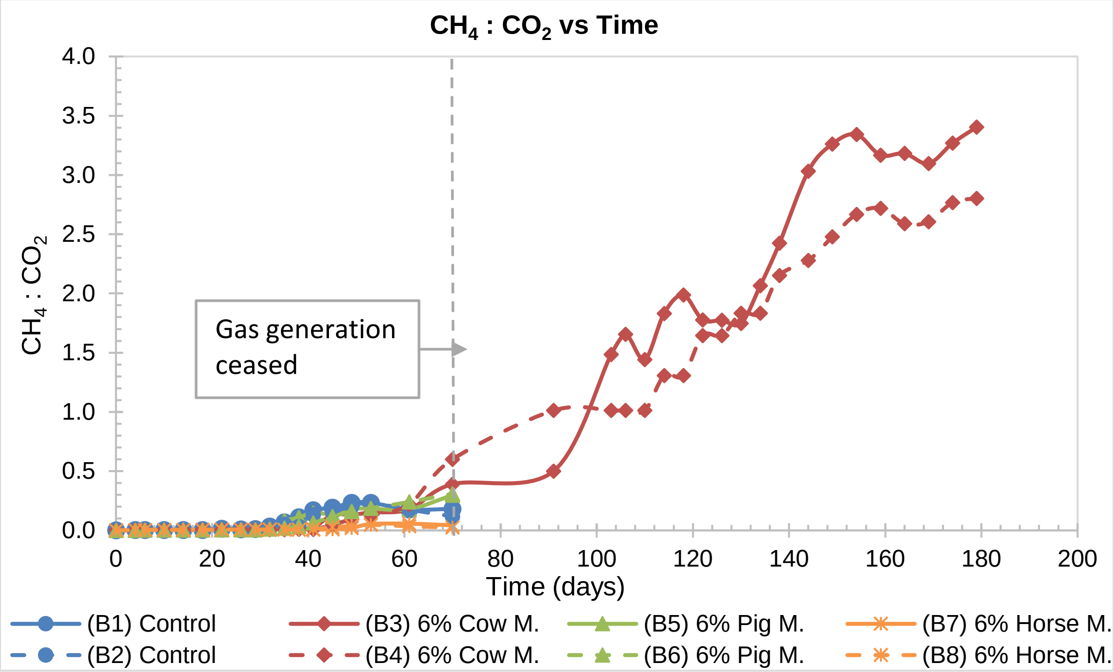


Figure 4.14 Variation in methane to carbon dioxide ratio over time (days)

4.5.2 Gas Volume

Total gas generated from reactors B1 through B8 with time is shown in Figure 4.14. It was observed that reactor B3 and reactor B4 were producing the highest amount of gas from the beginning compared to the other reactors. The only difference between the reactor B3 and B4 compared to the rest was that these two had cow manure in addition to sludge as inoculum while the others had only sludge (B1 & B2), sludge and pig manure (B5 & B6), sludge and horse manure (B7 & B8) as inoculum, which indicated that the cow manure was working better than the others. From the Figure 4.14 it can be seen that there was an initial lag few days after the reactor setup which bumped up after 20 days. This was because initially the reactors were operated without any sludge. After 20 days it was decided that due to low microbial population, sludge addition was necessary. Addition of sludge bumped up the gas production till day 45 and a secondary lag phase was introduced. This might be because initially while the accumulation of VFA started the primary lag phase, sludge somewhat diluted the acidic condition. However, continuous VFA accumulation was so high in case of pure food waste that the long lag phase came into the picture.

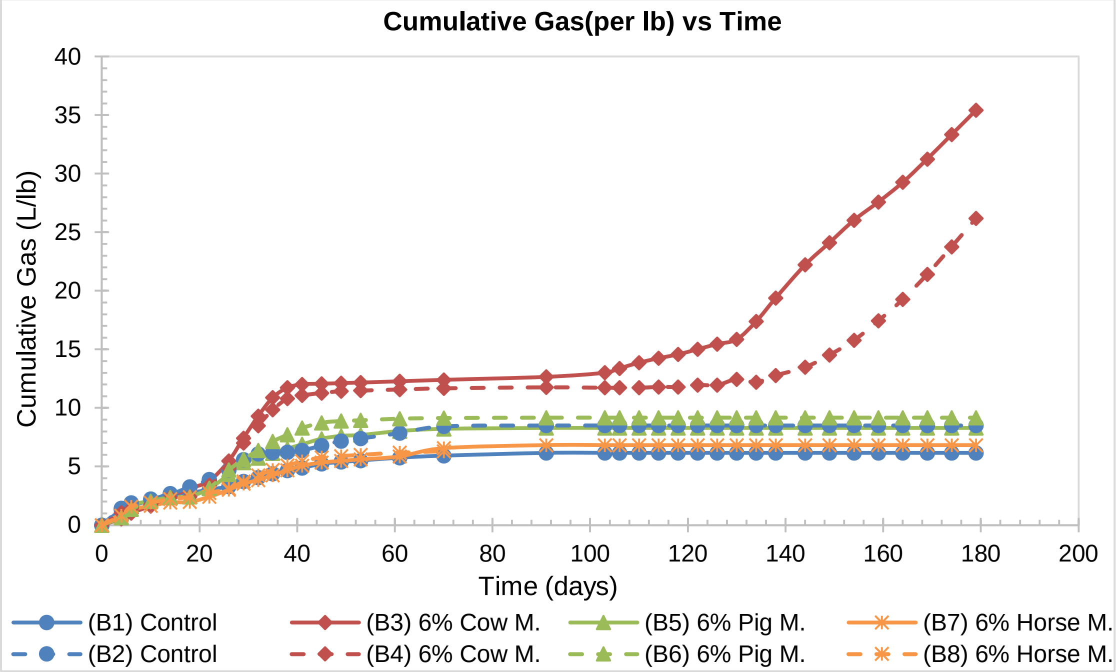


Figure 4.15 Cumulative gas generated by reactor over the time

Looking at the scenario of cumulative methane generation, methane generated in the initial phase was almost zero. Due the excessive VFA accumulation all the reactors were in the acidogenic phase which inhibited bacterial activities resulting in little to no gas production for a long time. Figure 4.15 shows the cumulative methane generation with time. It can be seen that all the reactors but B3 and B4 produced negligible amount of methane.

In case of reactor B3, it started producing considerable amount of methane after around 100 days of lag period and rapidly went into the methanogenic phase. Reactor B3 produced a total of about 16 liter of methane per pound of food waste in wet weight basis till 180 days of observation period and it was still producing considerable amount.

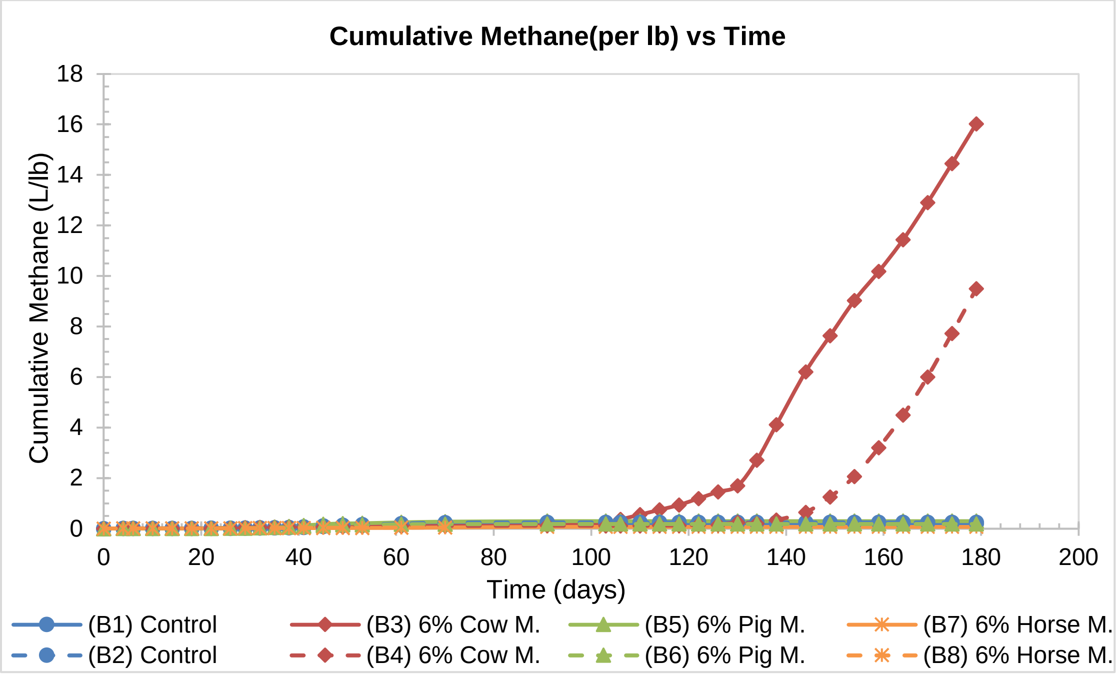


Figure 4.16 Comparison of cumulative methane generation with time

In case of reactor B4 which had the same configuration as reactor B3, the cumulative methane generation curve showed a similar trend. Except there was a longer lag period of 122 days compared to reactor B4. Reactor B4 produced a total of about 9.5 liter of methane per pound of food waste in wet weight basis till 180 days of observation period and it was just introduced into the methanogenic phase.

Acidogenic phase continued to be longer for control reactors, reactors with pig manure and horse manure as inoculum and even after 180 days of operation amount of methane generation was almost negligible. Therefore, it can be said that cow manure was found to be a better source of inoculum compared to other manures for food waste decomposition and methane generation.

Figure 4.16 shows the methane percentage for the reactors B1 through B8 with time. From the methane percentage vs time plot it can be seen that initially all the reactors were started producing some percentage of methane which eventually depleted as waste decomposition went into the lag phase. Only reactor B3 and reactor B4 kept producing methane and at a considerable percentage of as high as 75.9% for B3 and 73.4% for B4.

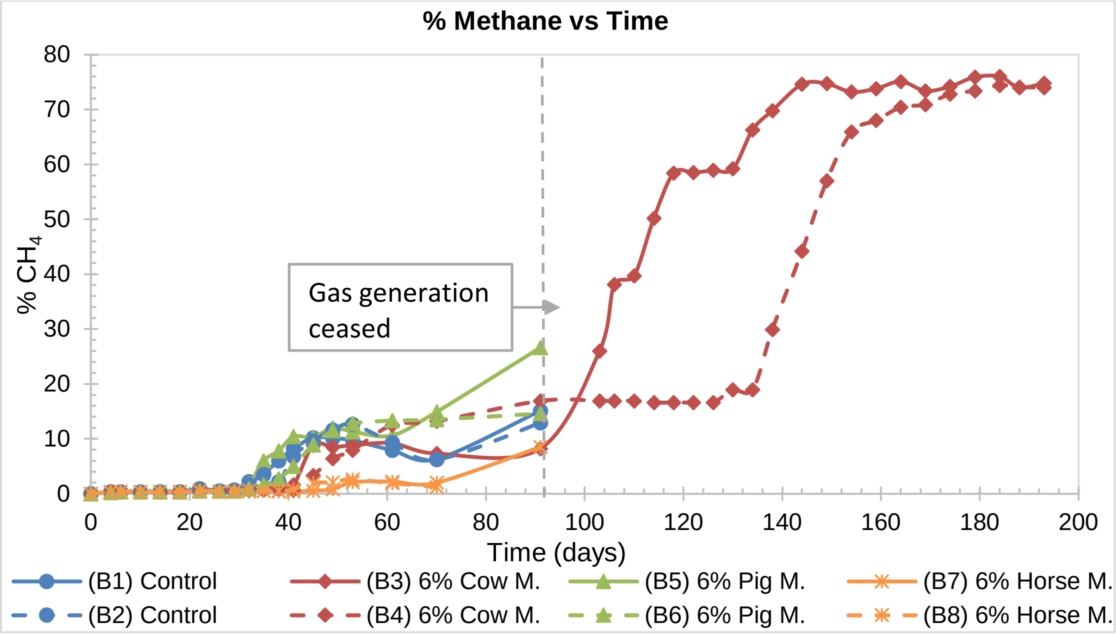


Figure 4.17 Comparison of percent methane with time for the reactors

Total daily gas generation rate or gas yield graph and methane yield graph for the reactors shows similar trend (Figure 4.17 and 4.18) except initially as the methane percentage was extremely low. Therefore, in the methane yield graph the initial values are almost close to zero. From the total gas generation rate plot it can be observed that at the beginning there was greater gas yield followed by a lag phase. The lag period continued for 50 ~ 70 days for reactor B3 and reactor B4 which then started producing gas and gradually entered the methanogenic phase (Figure 4.18).

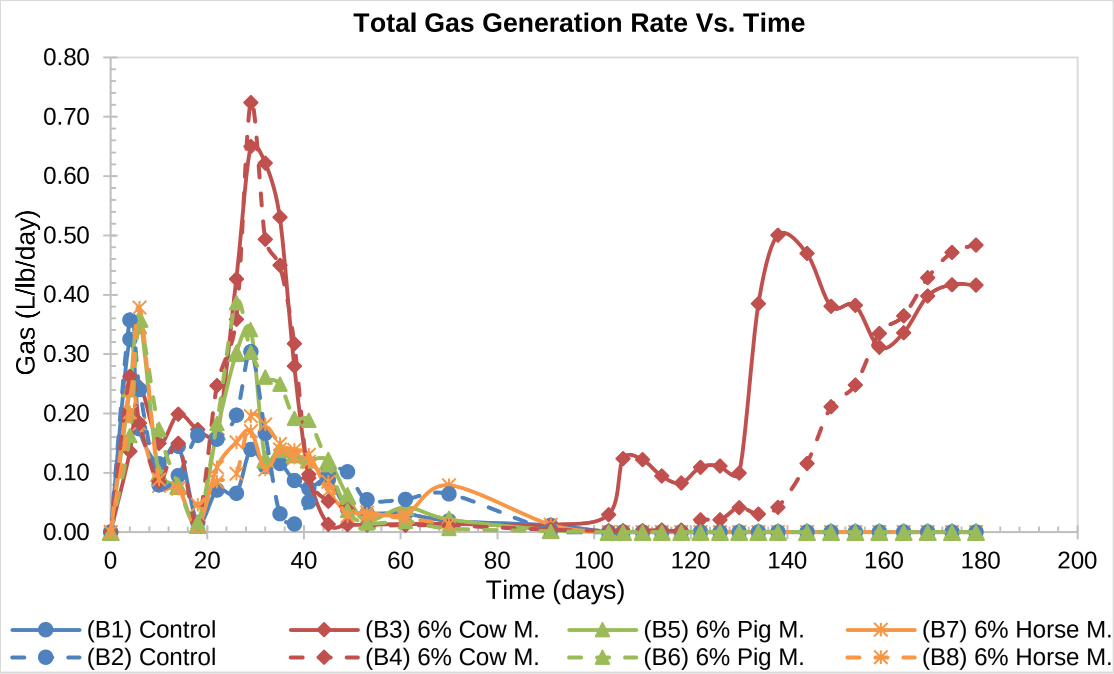


Figure 4.18 Comparison of total gas generation rate with time for the reactors

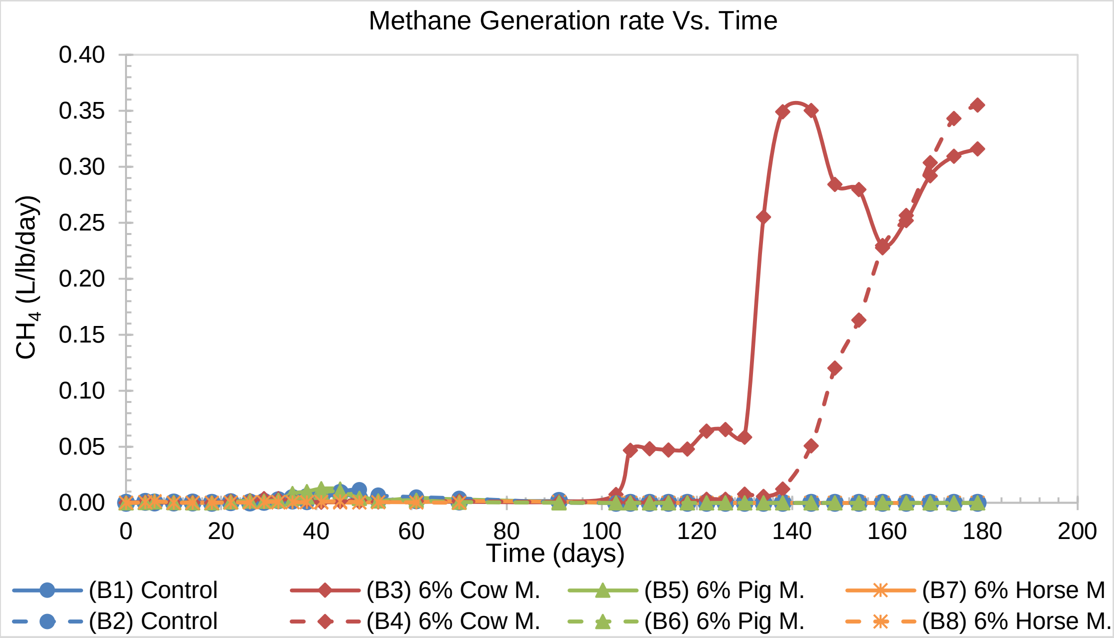


Figure 4.19 Comparison of methane generation rate with time for the reactors

In the methanogenic phase, methane yield was found to be as high as 0.35 liter or 350 mL per pound per day for reactor B3 and for reactor B4 the value was 0.355 liter or 355 mL per pound per day in wet weight basis. The gas yield graph as well as methane yield graph shows multiple peaks because of the non-homogeneity of waste and all the food waste components did not start decomposing at the same time, some components (fruits & vegetables) decomposes earlier than others thus generating varying rate of gas.

4.5.3 Comparison with Previous Studies

Reactors with food waste usually have a long lag phase due to VFA generation as observed so far for the current study. Similar observation were reported in a study done by Wang et al. (1997) where addition of 30% seed in the food waste was not enough and the reactors failed due to excessive acid accumulation. However, when the seed percentage was increased to 70%, due to the dilution effect the reactors became successful. In this study the total amount of seed added was within 16%. Although the percentage was low compared to previous study it was successful for a pair of reactors where seed included cow manure. In another study by Karanjekar (2013) showed an addition of 20% sludge as seed to the food waste reactor produced satisfactory result, however there was a lag period of more than 50 days and the peak methane yield of around 550 mL per kg per day or 250 mL per pound per day. In Figure 4.19 the black curve shows the result of 100% food waste found by Karanjekar (2013).

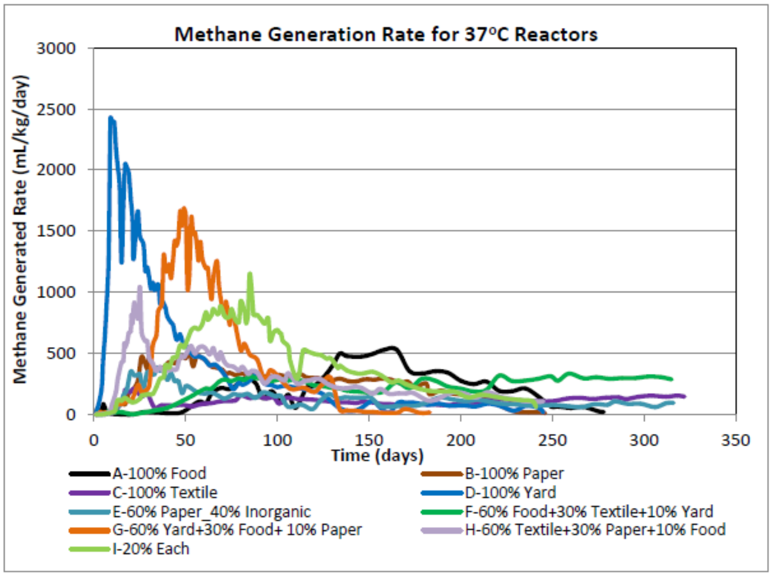


Figure 4.20 Methane yield with time (Karanjekar, 2013)

The methane generation data found from current study was converted into methane generation per gm of volatile solids (VS). Figure 4.20 shows the cumulative methane generation per gram volatile solids.

It can be compared to a study done by Zhang et al. (2007) on food waste in anaerobic digester. The author found the cumulative methane as high as around 450 mL per gm VS as shown in Figure 4.21. While in this study the value found to be almost 160 mL per gm VS. In the current study the methane production just started bumping up and it might go as high as the values found in previous studies. Also the temperature of operation for current study was 37°C while in the study done by Zhang et al. (2007) it was 50°C.

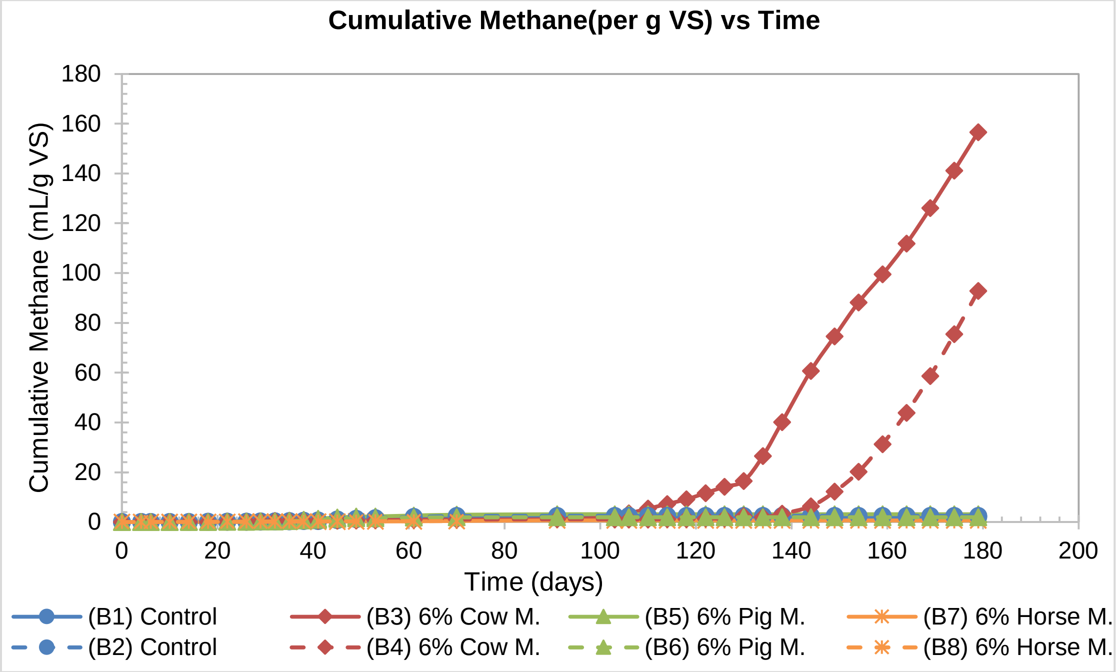


Figure 4.21 Cumulative methane generation with time for the reactors B1 through B8

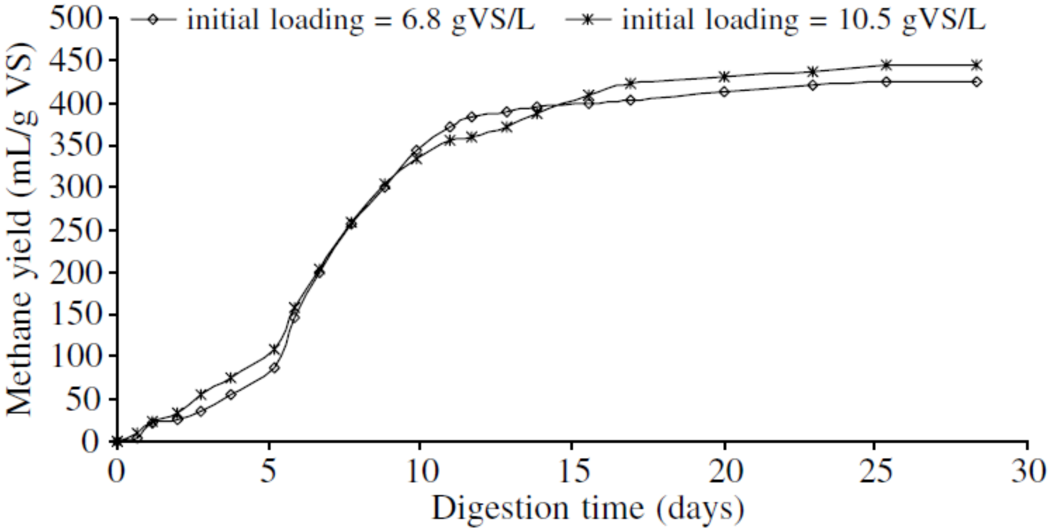


Figure 4.22 Methane generation from food waste digester at 50°C (Zhang et a., 2007)

4.6 Destructive Test on Reactor

Due to the initial long lag period two scenarios were suspected, one was there might be some leak. So the reactor B8 was again tested for leak and no leak was found. Secondly it was suspected that due to excessive VFA accumulation the reactors might have failed. As a result it was decided to destructively sample reactor B8. To sample the waste inside, reactor "B8" was dismantled and the waste was taken out for test. Figure 4.22 shows the waste after dismantling reactor B8. Table 4.9 shows the results of the test done on the waste.

Figure 4.23 Waste inside reactor B8 after dismantling

From the Figure it is evident that the waste was yet to degrade. Also the pH of leachate was found to be 6.39 while the pH of waste inside was 5.27. Which indicated even after neutralizing pH through mixing KOH during leachate recirculation the waste itself was in an acidic environment. This was due to continuous volatile acid accumulation which was really difficult to neutralize. This concluded that for food waste VFA accumulation was the reason behind the extended lag period.

To check the moisture content, the waste was placed in oven at 65 (±5)°C for 5 days and the dry weight of the waste was found to be 0.576 lb. Moisture content was found to be 78.75%. Figure 4.23 shows waste after drying.

Figure 4.24 Dried food waste of reactor B8

Volatile solid (VS) content was determined using muffle furnace. 3 samples (grounded) from the dried waste of around 50 gm was taken and placed inside the furnace for 2 hours at 550°C. VS was found to be 89.91%.

Table 4.9 Test result summary from dismantling reactor B8

Parameters	
Temperature (°C)	34.5
pH (of leachate)	6.39
pH (of Waste)	5.27
Weight of waste (moist) (lb)	2.71
Weight of waste (dry) (lb)	0.576
Moisture Content (%)	78.75
VS (%)	89.91

Chapter 5

Conclusions and Recommendations

Biocell is an evolved form of landfill concept (a third generation landfill) capable of handling all the problems associated with organic waste in conventional landfill such as excessive leachate generation & gas production, ground & surface water contamination and requirement of additional space. As a processing unit, biocell also permits addition of nutrients required for accelerated degradation of food waste which has been seeking a place to be disposed after being diverted from conventional landfills. Handling waste with high percentage of organics especially food waste has always been a challenge for the solid waste industry. Through addition of different types of manures, current study was trying to find out the most feasible option for accelerated decomposition of food waste.

The main objective behind this research was to develop a solution for the growing problems associated with food waste. The goal was to evaluate the potential of different types of manures as inoculum to enhance food waste decomposition and methane generation in biocell. To satisfy this objective, food waste was collected, sorted and mixed to a synthetic composition. A set of eight (8) reactors were constructed with four combinations by varying the inoculum type (cow manure, pig manure, horse manure). Physical properties such as moisture content, volatile solid content of the food waste were determined before filling the reactors. Regular recirculation and monitoring of leachate were done along with measurements of the gas generated from the reactors. For leachate, pH, volume, COD and BOD_5 tests were conducted while composition and volume measurement was done for the gas generated. The results obtained from the current research are summarized in the following subsection.

5.1 Summary and Conclusions

Following summarized results and conclusions are based on the findings from the current study:

1. Fresh food waste samples were collected from two sources, one from Walmart which composed of only fruits and vegetables having extremely high moisture content (83.45%). The other source was university center connection café of the University of Texas at Arlington which had mixed food waste with relatively lower moisture content (51.38%) due to the presence of high amount of grain products (e.g. breads).
2. Inoculum was collected from different places and tested for pH. Sludge (pH 8.37) was collected from the City of Denton Landfill, Texas. Cow manure (pH 8.95) was collected from a nursery, pig manure (pH 7.81) from a farm (Maypiggen) and horse manure (pH 7.69) was also from a farm. All the manures were aged (6 months to a year) except for horse manure which was a week old.
3. A synthetic composition was decided based on national food waste composition. The composition included fruits & vegetables (50%), meat & seafood (20%), grain products (20%) and dairy products (10%). A fixed composition was required for the homogeneity during the research.
4. Eight laboratory scale reactors were built with three different types of manures (cow, pig and horse manure) and control reactors. Sludge (10%) was common for all the reactors and 6% manure was added by weight. Inoculum was added for accelerated degradation of food waste in biocell operation.
5. Moisture content and volatile solid content of the waste was determined before filling the reactors. Moisture content of the reactors were found to be almost close to each other (75~77%), same thing was observed with volatile solid content of all the reactors which was found to be almost same (91.66~92.96%). This was because the waste composition was identical in all the reactors, the only varying factor was the type of manure used.
6. The reactors were constructed with one (1) gallon bucket, modified to the need and filled with food waste of approximately 4 pounds (wet weight basis) after passing the leak test.

The reactors were sealed to make them airtight and operated at a temperature of 37°C (99°F) in an environmental growth chamber.

7. Leachate was monitored frequently for pH. The initial pH level of the reactors were below 5.0 and kept becoming acidic although the leachate was neutralized by mixing KOH before recirculation. Excessive accumulation of acids might be the reason behind the continuous drop in pH which was cross checked by dismantling reactor B8 as no reactor was producing any gas even after 80 days of operation. The waste inside reactor B8 had much lower pH than the pH of leachate generated.
8. Reactor B3 was the first one to break through the acidic phase after a lag period of 100 days followed by reactor B4 (135 days lag period). pH values for these two reactors went above 7 as they progressed towards methanogenic phase. Conversion of fatty acid into methane and carbon dioxide by methanogenic bacterial activities in the methanogenic phase was the prime reason behind the rise in pH. Rest of the reactors were still in the acidic phase and was decided to keep under further observation.
9. Based on the test results for chemical oxygen demand (COD), it was found that the COD values were high in the acidogenic phase due to hydrolysis for all the reactors. For reactor B3 and reactor B4 (reactors with cow manure as inoculum) the COD values started decreasing gradually as the reactors started moving towards the methanogenic phase. The COD values for the other reactors remained high as they were still in the acidogenic phase. The same trend was observed with the biochemical oxygen demand (BOD_5) values, a decreasing trend for reactor B3 and reactor B4 while remained high for the rest of the reactors.
10. BOD_5/COD ratio is an indicator of waste degradation. This ratio decreases along with waste degradation. The initial value of BOD_5/COD for all the reactors were high (around 0.7) which was around the same for all the reactors along the operation except reactor

B3 and reactor B4. As these two reactors passed the lag phase and the waste degradation continued the BOD_5/COD value started decreasing.

11. Initially the concentration of carbon dioxide in the gas composition was higher in all the reactors. The scenario changed for reactor B3 and B4 as methane concentration started increasing the carbon dioxide started decreasing. The CH_4:CO_2 ratio for these two reactors increased as high as 3.34 for reactor B3 and 2.77 for reactor B4. For the other reactors the CH_4:CO_2 ratio did not increase as they were in the lag phase. On the other hand concentration of oxygen depleted pretty rapidly and remained negligible as the reactors were operated in anaerobic condition.
12. Total gas generation rate and methane generation rate followed almost the same trend except at the beginning there were negligible amount of methane in the gas composition. Initial gas generation rate was high for all the reactors before they went into lag phase. Only reactor B3 and reactor B4 crossed the lag phase and started producing considerable amount of methane, as high as 75.9% and 73.4% by composition respectively.
13. Based on the cumulative methane production results, it was found that after about 180 days of operation reactor B3 produced 16 liter per pound (wet weight basis). The gas generation for reactor B3 was still at its prime and was producing more gas, so it was decided to monitor further. Reactor B4 produced 9.5 liter per pound at the same time and was just started bumping up the methane production. Rest of the reactors were still not producing any gas and were kept under observation.
14. Methane generation curves did not follow a typical first-order degradation curve and showed multiple peaks for reactor B3 and reactor B4. The presence of multiple peaks could be due to different types of food waste degrading at different rates.
15. The main difference between reactors B3, B4 with other reactors were the type of inoculum added which was cow manure. Based on the results obtained so far, cow manure found to be a better source of inoculum compared to other manures in

decomposing food waste since it was the only one that was producing gas. Therefore, it can be reported that use of cow manure in food waste might be advantageous compared to other manure for accelerated decomposition, also in addition sludge is necessary to dilute the initial acidic environment created during initial phase of decomposition of food waste through excessive VFA accumulation.

16. The high moisture and potential to generate higher methane & excessive leachate restrict the disposal of food waste into the conventional landfills. As an alternative biocell can be a suitable option which can neutralize all the negative sides associated with food waste disposal in landfill and permits the addition of nutrients for enhanced waste decomposition.

5.2 Recommendations for Future Studies

On the basis of the results obtained from the current study and to improve the reliability some recommendations can be made for future study.

1. Crystalline potassium hydroxide (KOH) or something similar may be added to see the effect on initial VFA accumulation in the food waste during waste mixing and filling for future studies.
2. Further research needs to be done to determine the optimum percentage of sludge or manure by varying their percentages and analyze the individual effect.
3. Further study is necessary to find out the effect of manure age on the decomposition of food waste by using different manure with varying age.
4. Additional research is necessary to reduce the lag period through increasing the percentage of inoculum or addition of enzymes.
5. Further study is necessary by mixing other type of waste such as yard waste or construction and demolition (C&D) waste with food waste to analyze their effect on degradation and to determine the optimum percentage for successful operation. In

addition, as yard waste contains good amount of methanogens, therefore, mixing yard waste might reduce the required percentage of inoculum.

6. Life Cycle Analysis (LCA) can be performed on food waste biocell to ascertain the environmental impact of organic waste biocell operation and compare it with other food waste processing alternatives.

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Biographical Information

Md Nur Basit Zaman completed his Bachelor’s (B.Sc.) degree in Civil Engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in February 2013. His bachelor’s thesis was focused on determining an economic solution for the removal of ammonia from water. After completing his bachelor’s degree, he joined as a faculty member in the department of Civil Engineering at the University of Information Technology and Sciences, Bangladesh. He also worked as a junior engineer at a multinational company named SMEC in Bangladesh on railway projects. He started his graduate studies at The University of Texas at Arlington in Spring’ 2015 as a graduate research assistant under the supervision of Dr. Sahadat Hossain. He was part of the team that competed in the national Solid Waste Design Competition (SWDC) organized by Solid Waste Association of North America (SWANA) in WASTECON 2016 and won the first prize. His research interest includes but not limited to municipal solid waste (MSW), biocell landfill, landfill gas and landfill mining. He is passionate about working in a field where lies the prospect to surpass his latent potentials, creativity and adroitness in order to make significant contribution towards the research field by utilizing skills and ingenuity and also involving a steep learning curve.