EFFECT OF SLUDGE CONTENT ON DIFFERENT TYPES OF FOOD WASTE DEGRADATION IN ANAEROBIC DIGESTER

by

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2021

ACKNOWLEDGMENT

Thanks to Almighty Allah for His graciousness, unlimited kindness that has enabled the completion of this thesis.

I would like to express my deepest sincere gratitude to my academic advisor and thesis supervisor Dr. Sahadat Hossain, for giving me a unique opportunity to work on such an important topic. His continuous guidance, invaluable suggestions, affectionate encouragement, generous help, and invaluable acumen are greatly acknowledged. His keen interest in the topic and enthusiastic support for my effort were a source of inspiration to carry out the study. I consider myself fortunate to work under his supervision.

I sincerely acknowledge UTA Compost Center for their co-operation and assistance in sample collection. I also wish to acknowledge Village Creek Water Reclamation Facility, Texas for providing me with sludge for this study.

I take this opportunity to express our deep sense of gratitude to Nur Basit Zaman for his valuable guidance laced with suggestions and help. Special thanks go to Sakib, Sehneela, Ganga, Tanzim, Alinda, Niloy, Aziz, and all my lab mates for their support and active cooperation through the research.

Finally, I would like to express a very special indebtedness to my parents, brother, and husband whose encouragement and support were a continuous source of inspiration for this work. Everything I am today; I owe it to them.

ABSTRACT

EFFECT OF SLUDGE CONTENT ON DIFFERENT TYPES OF FOOD WASTE DEGRADATION IN ANAEROBIC DIGESTER

Food waste (FW) is the second-largest component in landfills which impacts environments adversely by generating excessive leachate and greenhouse gas. Generally, conventional anaerobic digester and composting can be used for FW disposal. However, the former is highly expensive while the latter is energy inefficient. In contrast, household or community level underground anaerobic digester offers a cost-efficient solution as well as retrieves valuable energy from FW. The addition of nutrients such as sludge to organic waste especially FW accelerates the production of energy by limiting volatile fatty acid (VFA) accumulation. The objective of the current study is to find out the potential of sludge addition on separate components of FW decomposition and gas generation in lanaerobic digester. This research was conducted by preparing laboratory simulated FW anaerobic digester with four combinations: two pairs of reactors containing meat and grain in addition to the sludge of 20% (MGR1 & MGR2) and 30% (MGR5 & MGR6) respectively as inoculum. Another two pairs of reactors containing fruits and vegetables with the sludge of 20% (FVR3 & FVR4) and 30% (FVR7 & FVR8) respectively. Over the operation period, pH, volume, COD, and VFA tests were conducted for leachate while composition and volume measurements were done for the generated gas. Based on the experimental results, it was found that all the bioreactors showed an extended lag period (> 60 days) before methane generation. Due to decreasing rate of VFA accumulation, FVR3, FVR4, FVR7, and FVR8 presented much better results compared to MGR1, MGR2, MGR5, and MGR6 reactors. However, the lag period for FVR7, FVR8, and FVR3, FVR4 reactors were 75 days and 96 days respectively while MGR1, MGR2, MGR5, and MGR6 were still in lag period.

During about 160 days of operation, the average peak methane generation rate for FVR3 and FVR4 was 345 mL/wet-lb./day and 307 mL/wet-lb./day respectively while the cumulative methane generation was 6.8 liters/wet-lb. and 4 liter/wet-lb. respectively. Similarly, the average peak methane generation rate for FVR7 and FVR8 was 182 mL/wet-lb./day and 163 mL/wet-lb./day respectively while the cumulative methane generation was 3.5 liters/wet-lb. and 3.6 liter/wet-lb. respectively. All these reactors FVR3, FVR4, FVR7, and FVR8 were still at the rising stage of the methane generation phase. The percentage of methane found in FVR3, FVR4, FVR7, and FVR8 reactors was 72.5%, 68%, 51%, and 52.1% respectively. However, methane generation from other reactors was found to be negligible; in fact, most of the reactors were still in the initial lag phase. Based on the preliminary results, it is found that the addition of more sludge accelerated the decomposition of fruit and vegetable waste more than the meat and grain waste. Besides, the amount of methane generation was satisfactory for building 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 part of the produced consumables that instead of being consumed either gets discarded, lost, degraded, or affected by pests. In 2011, FAO estimated that around 1/3 of the world's food was lost or wasted every year. Food waste is reported to be the second-largest component (14%-21%) of the waste stream in the USA (USEPA, 2013). According to FDA, food waste is estimated at between 30–40 percent of the food supply in the United States. Globally around one-third of the food produced goes to waste even before reaching the consumer. 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).

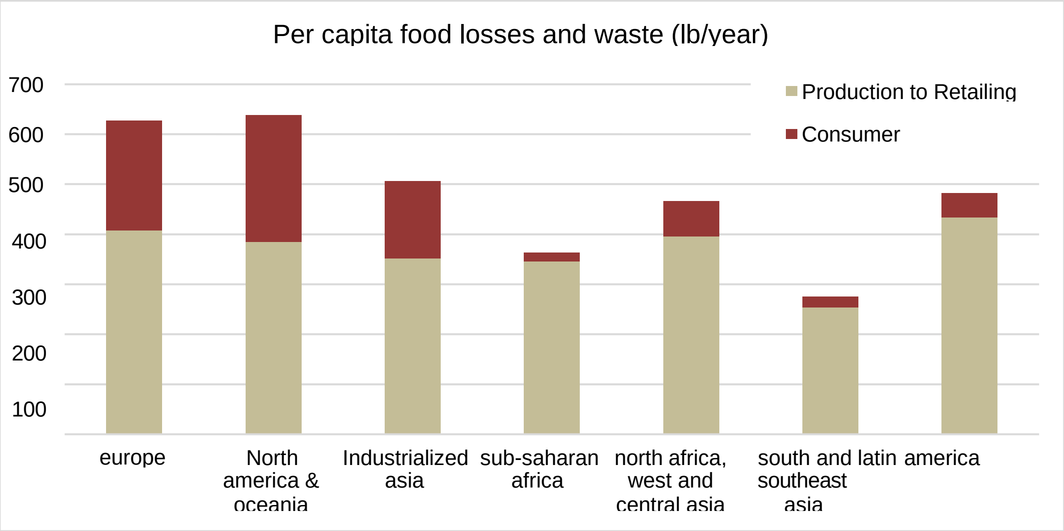


Figure 1.1 Per capita food losses and waste, at consumption and pre-consumptions stages, in different regions (FAO, 2011)

Throughout the entire process of the 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.

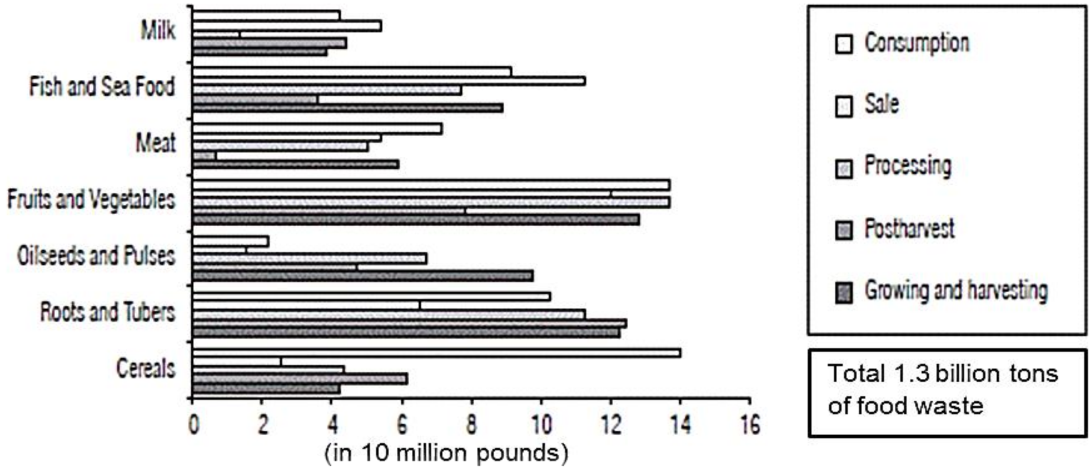


Figure 1. 2 Comparison between food waste components in a different phase of the food supply chain (source: Gustavsson, 2011)

In medium and high-income countries food is to a great extent wasted, meaning that it is thrown away even if it is still suitable for human consumption. Significant food loss and waste do, however, also occur early in the food supply chain. In low-income countries food is mainly lost during the early and middle stages of the food supply chain; much less food is wasted at the consumer level. 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 harms the environment through excessive methane generation and leachate production. Besides, 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 the anaerobic digester (AD) for energy production. Since food waste is one of the largest components in MSW if all food waste is diverted from the landfill a lot more anaerobic digester will be required.

Anaerobic digestion (AD) is a microbiological process whereby organic matter is decomposed in the absence of oxygen via enzymatic and bacterial activities producing biogas that could be used as a renewable energy source (Liu et al., 2009, Vögeli et al., 2014). This process is common to many natural environments such as swamps or stomachs of ruminants. Using an engineered approach and controlled design, the AD process is applied to process organic biodegradable matter in airproof reactor tanks, commonly named digesters, to produce biogas. Various groups of microorganisms are involved in the anaerobic degradation process which generates two main products: energy-rich biogas and a nutritious digestate.

Anaerobic digestion of the food waste transforms this organic waste material into valuable energy resources while at the same time reduce solid waste volumes and thus waste disposal costs. Biogas as a renewable energy source not only improves the energy balance of a country but also contributes to the preservation of natural resources and environmental protection by reducing pollution from waste and the use of fossil fuels (Al Seadi, 2008).

1.2 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 a well-built infrastructure for proper collection and disposal of waste. Most of this food waste ends up in the open dumps due to a lack of proper collection and disposal of waste. This uncontrolled dumping of food waste leads to contamination of water sources and contributes to the greenhouse gas emission having high methane generation potential.

Being the wettest portion of the waste stream as well as having high amount of volatile solids, this food waste can be utilized as a potential energy source and reduce the consumption of non-renewable energy sources. Moreover, anaerobic digestion of this food waste can reduce extreme environmental hazards related to landfilling which is the least preferred option. Thus, it can be said that anaerobic digestion of food waste has substantial potential to be exploited as a sustainable waste management technique alongside be a considerable replacement of fossil fuel as an energy resource.

Approximately 90% of rural households in developing countries are still dependent on natural biomass fuels for cooking and heating (wood, dung and crop residues) (World Bank, 1998) which are typically burnt in ineffectively functioning stoves or open fires in indoors. This combustion process is fragmented in most of the cases which results in significant emissions in the presence of poor ventilation and produce very high levels of indoor pollution (WHO, 2000).

Women's exposure to emission is much higher than men's as cooking customarily has become a primary involvement for women in developing countries (Behera et al., 1988). The effects start appearing with the symptoms of runny eyes, nose, and sore throat irritation. It gradually starts to affect the respiratory system. Very common syndromes to respiratory illness are asthma, dyspnea and intense palpitation (USEPA, 1997). The exposure to benzo[a]pyrene that emits from stoves for cooking around three hours a day can be compared to smoking two packets of cigarettes daily (Bruce et al., 2000). Moreover, mothers carry young children on their backs while cooking that exposes them to breathe smokes (Albalak, 1997).

Thus, biogas produced from anaerobic digester designed to fulfill the cooking demand of a household can significantly eliminate these adverse effects on the environment and human health. Besides, it can be a great source of renewable energy and can reduce dependency on fossil fuel and the related expenditure. However, one of the major problems of organic waste is the high C:N ratio. (Bujoczek, et al., 2002) as well as they are very acidic in nature. That is why mono digestion of food waste can lead to inhibition of microbial activities and thus impede biogas production. Furthermore, finding the acceptable, economical and readily available inoculum in developing countries is also a vital step. Though human feces have significant potential to use as inoculum, usage of biogas produced from it was refused in Dar es Salaam, Tanzania (Vögeli et al., 2014). Moreover, some enzymes have the exclusive ability to break down lignin, but it can never be used because of its high expense. The anaerobic co-digestion of sewage sludge and other organic waste is an attractive method for both waste treatment and biogas production. (Yongtae, et al., 2019).

The goal of the current research was to determine the effect of sludge on different compositions of food waste in the anaerobic digester for developing countries in south and southeast Asia. From figure 1.3 below it is observed that most grains are produced in this region. Then fruits and vegetables are also produced in significant amount followed by dairy products, meats and fishes. Considering this production scenario two combinations of food waste have been decided for bioreactor: grain-meat and fruit-vegetables. An extensive experimental program was prepared to evaluate the results collected from gas and leachate generation data.

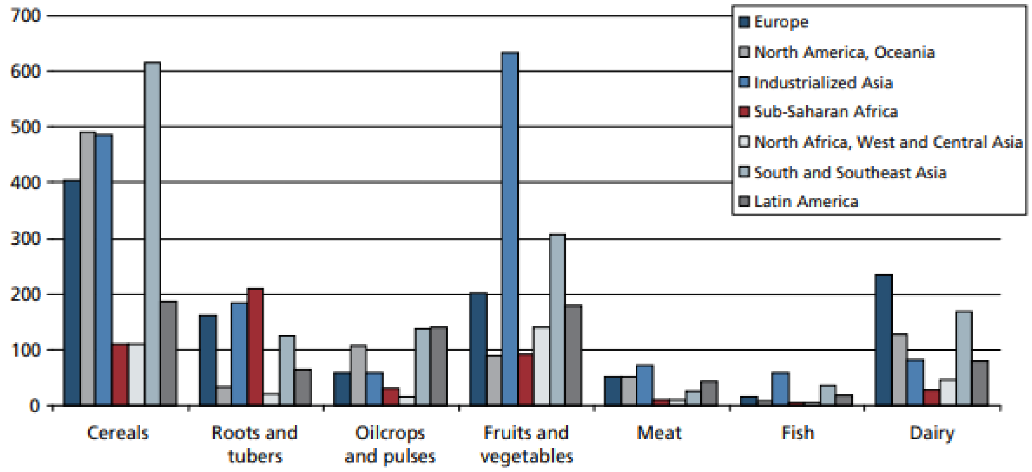


Figure 1. 3 Production volumes of each commodity group per region (million tons), (FAO, 2011)

. Successful design of a household or community level anaerobic digester will help to significantly reduce the harmful effect on human health and environment as well as will ensure a renewable energy source and curtail the need for fossil fuel. Besides, our goal is to build underground AD which will be cost efficient as well.

1.3 Research Objective

The primary objective of the current study is to determine the best possible combination for household level AD for developing countries using food waste. The specific tasks to accomplish the objective of the study include:

1. Determination of Waste Composition of Developing Countries
2. Laboratory Scale Batch Anaerobic Digester will be built to determine the effect of sludge on food waste degradation and gas generation
3. Determination of the best possible combination for maximum gas generation from food waste.

1.4 Thesis Outline

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

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

Chapter 2 presents a 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, sludge as a source of inoculum, and a promising concept for food waste processing alternative to conventional landfill – Anaerobic Digester.

Chapter 3 describes the experimental procedure followed to collect food waste samples and inoculum to build laboratory-scale AD, experimental setups, and laboratory test methodologies to address the research goals.

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 a conclusion based on the results found from the current study, and provides recommendations for future work.

Chapter 2

Literature Review

2.1 Background

Food waste is has become a greatly important issue which increased with the world’s growing population (FAO, 2011). According to US Environment Food Loss refers to food that gets spilled, spoilt, or otherwise lost, or incurs reduction of quality and value during its process in the food supply chain before it reaches its final product stage. Food loss typically takes place at production, post-harvest, processing, and distribution stages in the food supply chain. On the other hand, Food waste refers to food that completes the food supply chain up to a final product, of good quality and fit for consumption, but still doesn't get consumed because it is discarded, whether or not after it is left to spoil or expire. Food waste typically (but not exclusively) takes place at retail and consumption stages in the food supply chain.

Globally around one-third of the edible parts of food produced for human consumption, gets lost or wasted, which makes it 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 that 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 finds its way into landfills 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. The presence of excessive moisture demands higher energy for incineration.

2.2 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. The 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

  i) Cereals
  ii) Roots & tubes
  iii) Oil crops & pulses
  iv) Fruits & vegetables

b. Animal origin

  i) Meat
  ii) Fish & seafood
  iii) Dairy

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 the agricultural and consumption stage where consumer-level wastage is the dominating one (Gustavsson et al., 2011). Figure 2.1 shows a global scenario of ranges of different components of food waste.

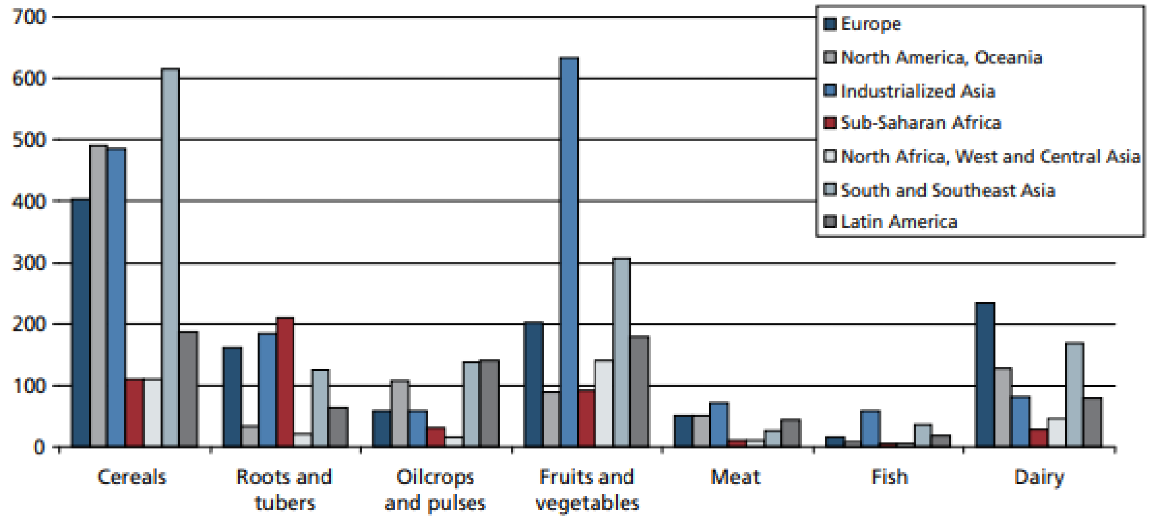


Figure 2. 1 Ranges of different components in food waste: global scenario

According to the 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. A pie chart in Figure 2.2 shows a simple representation composition of food waste in the USA. USDA divided the food waste into nine groups as shown in the same Figure 2.2, while FAO simplified that into five groups: fruits and vegetables, grain products, meat, seafood, and dairy products.

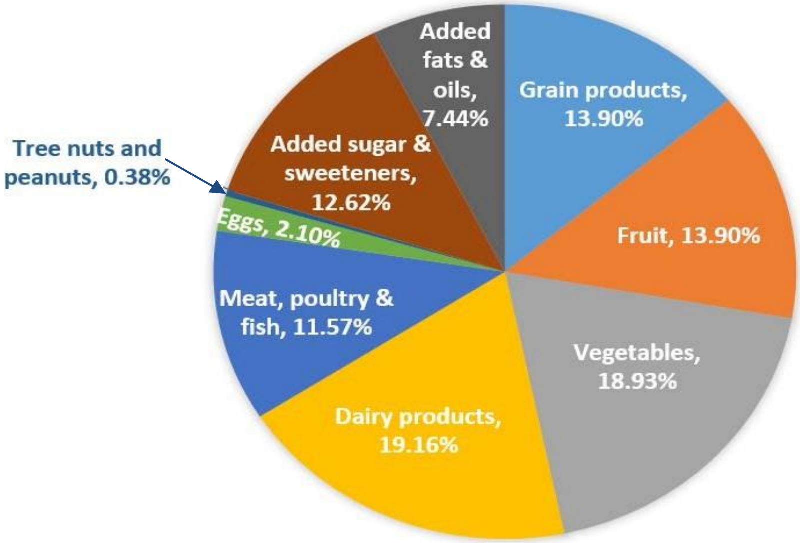


Figure 2. 2 Food waste composition of USA (Buzby et al., 2013)

According to a waste database of Bangladesh (Waste Concern, 2009), food and vegetable residues are the major portion of the solid waste stream, approximately 68%. Figure 2.3 shows the average physical composition of solid waste in urban areas in Bangladesh.

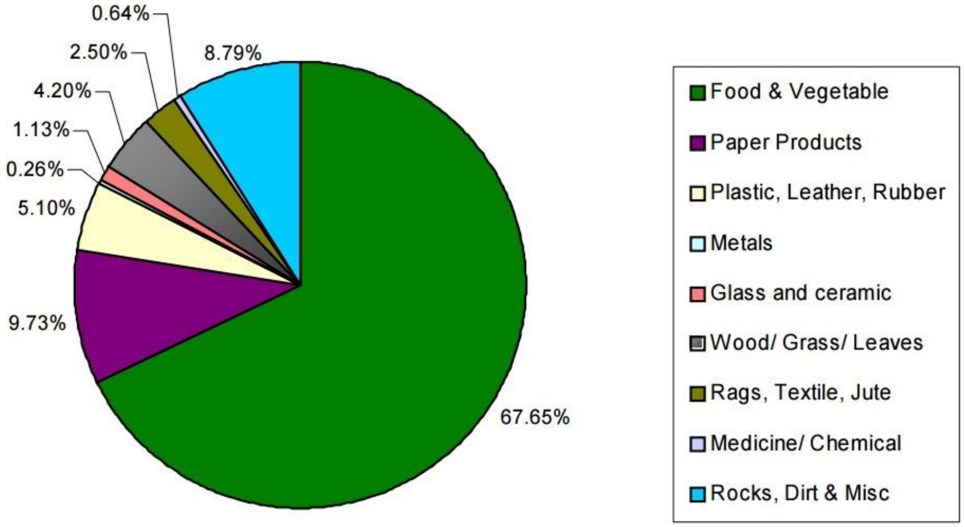


Figure 2. 3 Average physical composition of Urban Solid Waste in Bangladesh (Waste Concern, 2009)

2.3 Global Extent of Food Waste

Food plays the most important role in the survival of human beings. From production to the supply of food occur through several stages which are commonly known as the "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 the market system, and consumption (FAO, 2011; Galanakis, 2012; Islam et al. 2021). Figure 2.4 shows different stages involved in producing food waste.

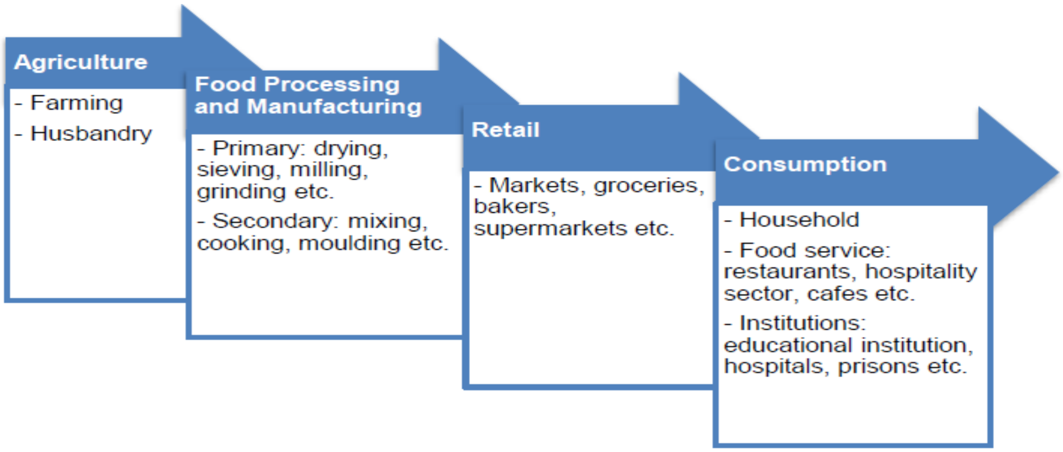


Figure 2. 4 Activities giving rise to food losses and waste in the food supply chain (Parfitt et al., 2010; Smil 2004; Papagyropoulou et al., 2014)

The 2011 Swedish Institute for Food and Biotechnology (SIK) study estimated the total of global food loss and waste to around one-third of the edible parts of food produced for human consumption, amounting to about 1.3 billion tons per year. As the following table shows, industrialized and developing countries differ substantially. In developing countries, it is estimated that 400–500 calories per day per person are going to waste, while in developed countries 1,500 calories per day per person are wasted. In the former, more than 40% of losses occur at the postharvest and processing stages, while in the latter, more than 40% of losses occur at the retail and consumer levels. The total food waste by consumers in industrialized countries (222 million tons) is almost equal to the entire food production in sub-Saharan Africa (230 million tons). Table 2.1 show per capita food loss each year in different regions of the world.

Table 2. 1 Per capita food loss each year in different regions of the world (FAO, 2011)

Food loss and waste per person per year	**Total**	**At the production and retail stages**	**By consumers**
Europe	280 kg (617 lb)	190 kg (419 lb)	90 kg (198 lb)
North America and Oceania	295 kg (650 lb)	185 kg (408 lb)	110 kg (243 lb)
Industrialized Asia	240 kg (529 lb)	160 kg (353 lb)	80 kg (176 lb)
sub-Saharan Africa	160 kg (353 lb)	155 kg (342 lb)	5 kg (11 lb)
North Africa, West and Central Asia	215 kg (474 lb)	180 kg (397 lb)	35 kg (77 lb)
South and Southeast Asia	125 kg (276 lb)	110 kg (243 lb)	15 kg (33 lb)
Latin America	225 kg (496 lb)	200 kg (441 lb)	25 kg (55 lb)

A statistic by FAO (2011) reported that fruits and vegetables have the highest percentage of waste (about 52%). According to the source, the 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 2.5.

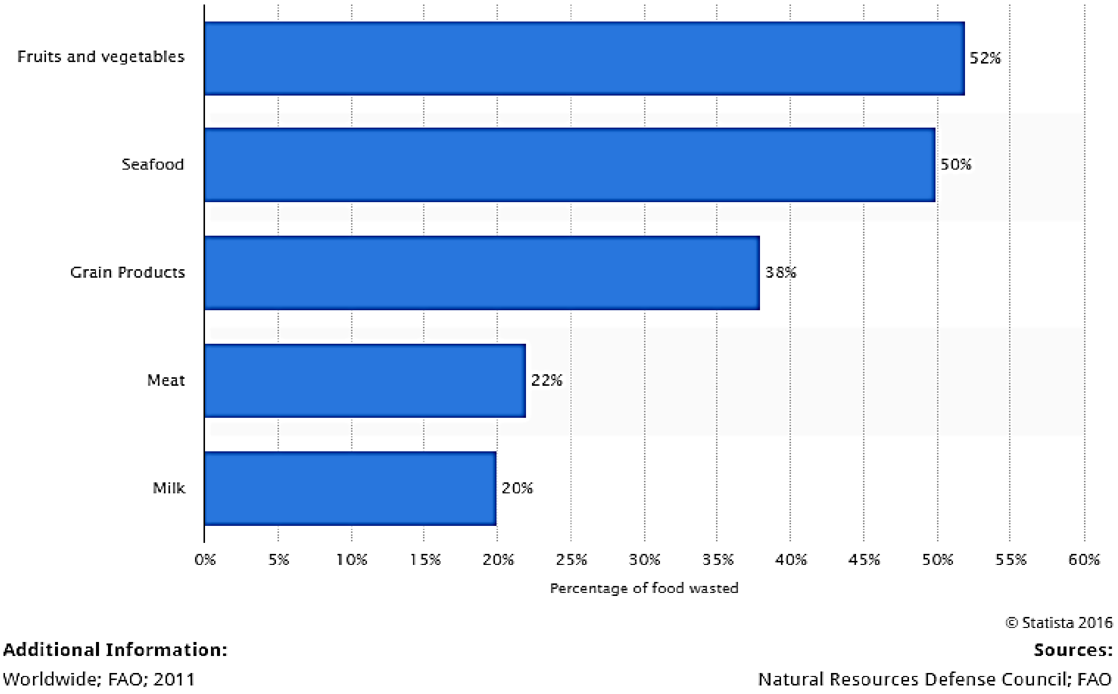


Figure 2. 5 Food waste in United States, Canada, Australia and New Zealand by category (FAO,2011)

2.4 Landfill

A landfill is a place for the disposal of refuse and other waste material. Wastes are buried and covered with soil in the landfill, which is a method of filling in or extending usable land.

2.4.1 Background of Landfill:

In past, wastes were disposed of in open dumps. With the idea of integrated waste management techniques, sanitary landfills were introduced, and it was followed by landfill bioreactors and then sustainable biocell to reduce the effect of environmental pollution and health-related risks (Hettiaratchi, 2007; Islam et al. 2021).

2.4.2 Evolution of Bioreactor Landfill

To confirm faster waste degradation and to reduce the post-closure monitoring period, the idea of bioreactor landfill was familiarized. (Pohland, 1975). Quick degradation of waste is achieved by precise leachate recirculation to ensure nutrients and bacterial circulation (Reinhart and Townsend, 1997). It also helps to stabilize the waste in a short time, faster methane generation, and monitoring period reduction. Bioreactor landfills complete stabilization within 5-10 years. Although, the frequent requirement of new space is not solved by bioreactor landfills.

2.4.3 Food Waste in Landfill

Food waste is the second-largest component in the landfill. It has been en 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. According to the **U.S.** Environmental Protection Agency (EPA, 2014), 20% of MSW contains food waste which goes into landfill.

2.5 Food Recovery Hierarchy - 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 components 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 is deemed as the ideal situation at all points in the food supply chains followed by feeding hungry people. Food that does not reach the consumer can still be utilized as food for livestock as the second-best choice. Recycling food waste for industrial purposes can be another solution (EPA). Anaerobic digester plants and composting are the most preferred options these days to reduce 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 2.6 shows the food recovery hierarchy according to EPA.

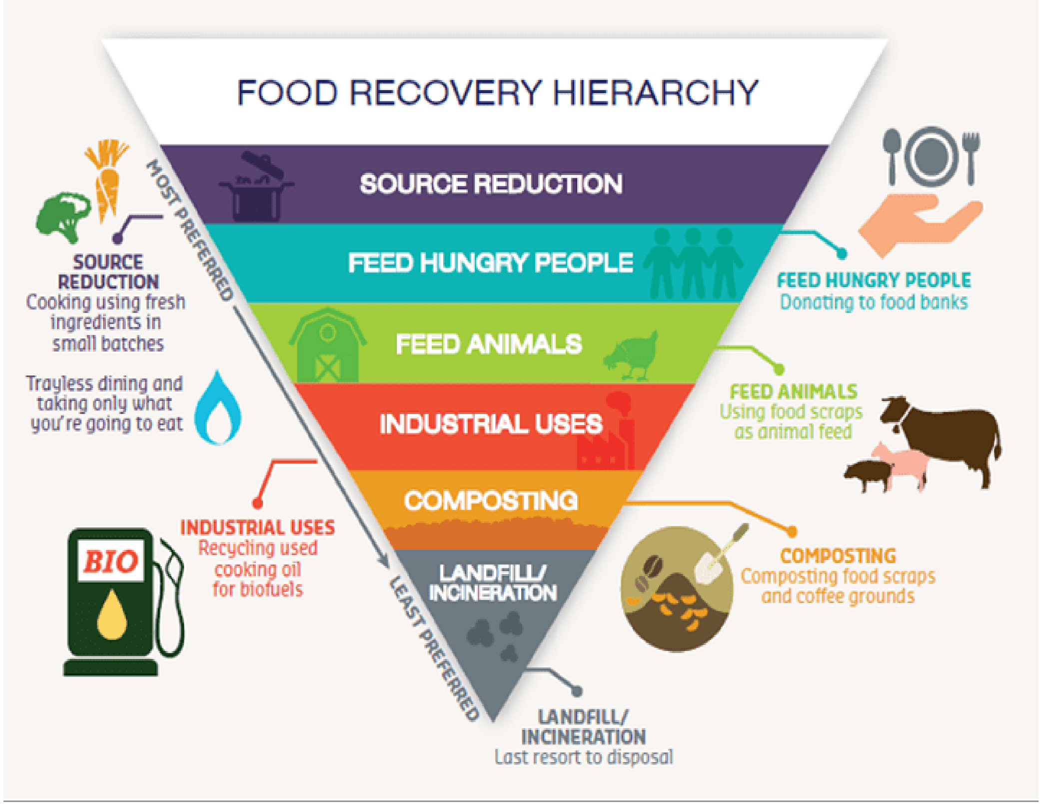


Figure 2. 6 EPA Food recovery hierarchy

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

2.6 Anaerobic Digesters with 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 at least 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 (CH4) 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. Anaerobic digester can be an alternate option to solve all these.

2.6.1 Anaerobic Digestion:

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.

2.6.2 Composition of Gas in Anaerobic Digester:

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 liter/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).

2.6.3 Stages of anaerobic digestion process:

The four key stages of anaerobic digestion involve hydrolysis, acidogenesis,acetogenesis and methanogenesis. The overall process can be described by the chemical reaction, where organic material such as glucose is biochemically digested into carbon dioxide (CO2) and methane (CH4) by the anaerobic microorganisms.

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

- **Hydrolysis**

In most cases, biomass is made up of large organic polymers. For the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts, or monomers, such as sugars, are readily available to other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore, hydrolysis of these high-molecular-weight polymeric components is the necessary first step in anaerobic digestion. Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and fatty acid.

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules, such as volatile fatty acids (VFAs) with a chain length greater than that of acetate must first be catabolized into compounds that can be directly used by methanogens.

- **Acidogenesis**

The biological process of acidogenesis results in further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, VFAs are created, along with ammonia, carbon dioxide, and hydrogen sulfide, as well as other byproducts. The process of acidogenesis is similar to the way milk sours.

- **Acetogenesis**

The third stage of anaerobic digestion is acetogenesis. Here, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen.

- **Methanogenesis**

The terminal stage of anaerobic digestion is the biological process of methanogenesis. Here, methanogens use the intermediate products of the preceding stages and convert them into methane, carbon dioxide, and water. These components make up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and pH 8. The remaining, indigestible material the microbes cannot use, and any dead bacterial remains constitute the digestate. Figure 2.7 shows stages of anaerobic digestion process.

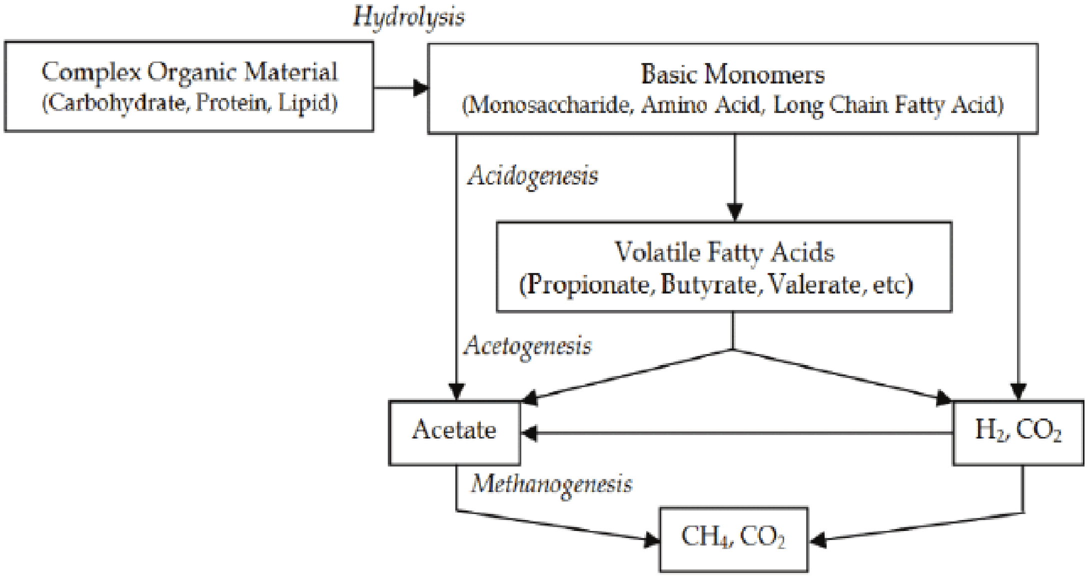


Figure 2. 7 Stages of anaerobic digestion process (Mustafa et. al., 2011)

2.6.4 Configuration

Anaerobic digesters can be designed and engineered to operate using a number of different configurations and can be categorized into

- Batch vs. continuous process mode,
- Mesophilic vs. thermophilic temperature conditions,
- High vs. low portion of solids, and
- Single stage vs. multistage processes.

Continuous process requires more complex design, but still, it may be more economical than batch process, because batch process requires more initial building money and a larger volume of the digesters (spread across several batches) to handle the same amount of waste as a continuous process digester. Higher heat energy is required in a thermophilic system compared to a mesophilic system, but the thermophilic system requires much less time and has a larger gas output capacity and higher methane gas content, so one has to consider that trade-off carefully. For solids content, low will handle up to 15% solid content. Above this level is considered high solids content and can also be known as dry digestion. In a single stage process, one reactor houses the four anaerobic digestion steps. A multistage process utilizes two or more reactors for digestion to separate the methanogenesis and hydrolysis phases.

2.6.5 Gas generation:

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 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 2.8 and 2.9 respectively.

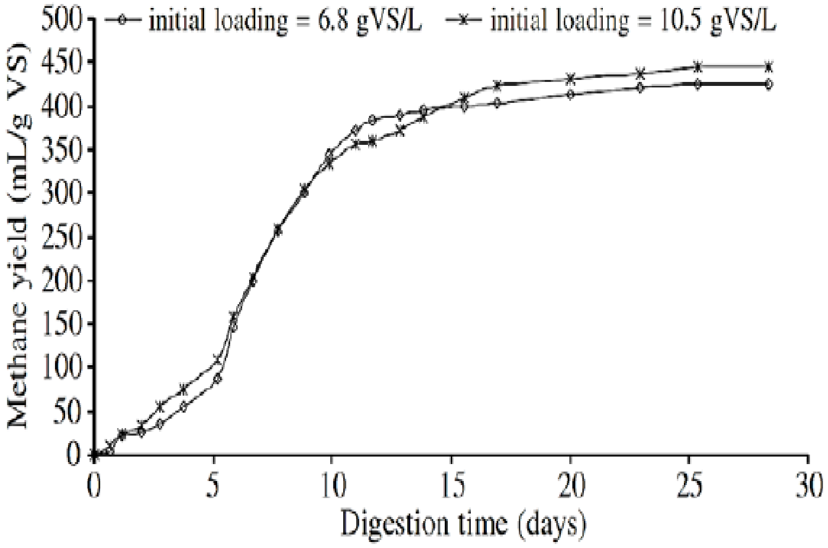


Figure 2. 8 Cumulative methane yield of food waste during anaerobic digestion at 50 °C at two different initial loadings (6.8 and 10.5 g VS/L). (Zhang et. al., 2007)

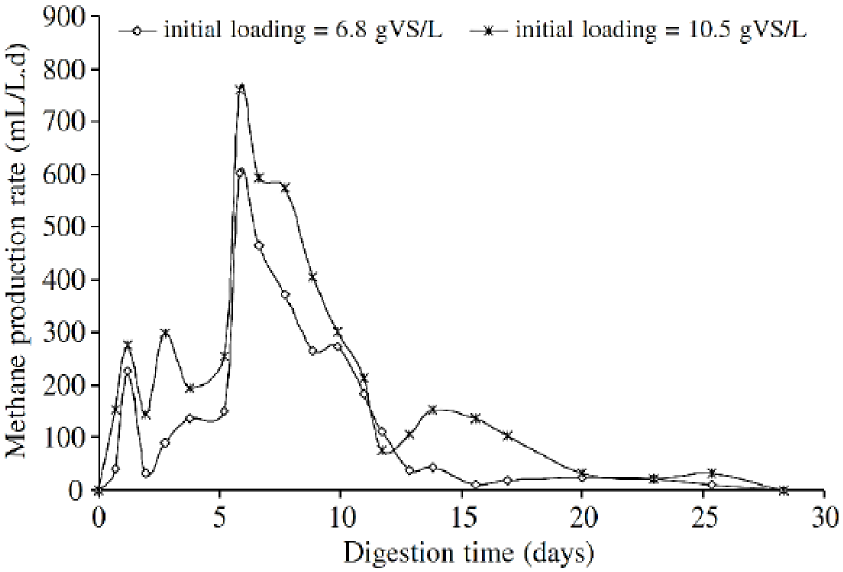
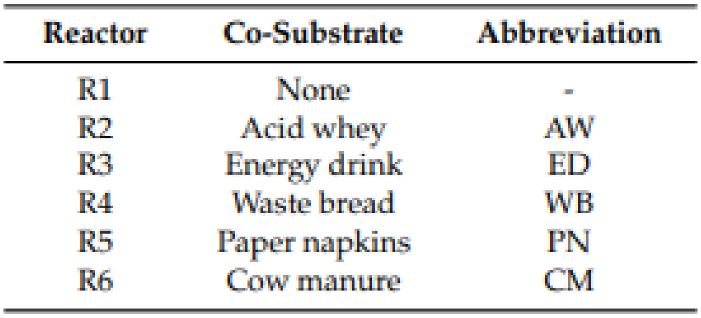


Figure 2. 9 Daily methane generation rate during digestion of food waste at two different initial loadings (6.8 and 10.5 g VS/L) (Zhang et al., 2007)

Another study conducted by Swati and Thomas (2019) investigated the stability of anaerobic digestion with mixed cafeteria food waste (CFW) as the main substrate, combined in a semi-continuous mode with acid whey, waste bread, waste energy drinks, and soiled paper napkins as co-substrates. During digestion of CFW without any co-substrates, the maximum specific methane yield (SMY) was 363 mL gVS^{-1}d^{-1} at organic loading rate (OLR) of 2.8 gVSL^{-1}d^{-1}, and reactor failure occurred at OLR of 3.5 gVSL^{-1}d^{-1}. Co-substrates of acid whey, waste energy drinks, and waste bread resulted in maximum SMY of 455, 453, and 479 mL gVS^{-1}d^{-1}, respectively, and it was possible to achieve stable digestion at OLR as high as 4.4 gVSL^{-1}d $^{-1}$. Table 2.2 shows co-substrates used in each reactor, with cafeteria food waste (CFW) as the primary substrate.

Table 2. 2 Co-substrates used in each reactor, with cafeteria food waste (CFW) as the primary substrate. (Swati et. al., 2019)



Reactor	Co-Substrate	Abbreviation
R1	None	-
R2	Acid whey	AW
R3	Energy drink	ED
R4	Waste bread	WB
R5	Paper napkins	PN
R6	Cow manure	CM

Biogas properties and average methane production rate found in the study are shown in figure 2.10 and figure 2.11 respectively.

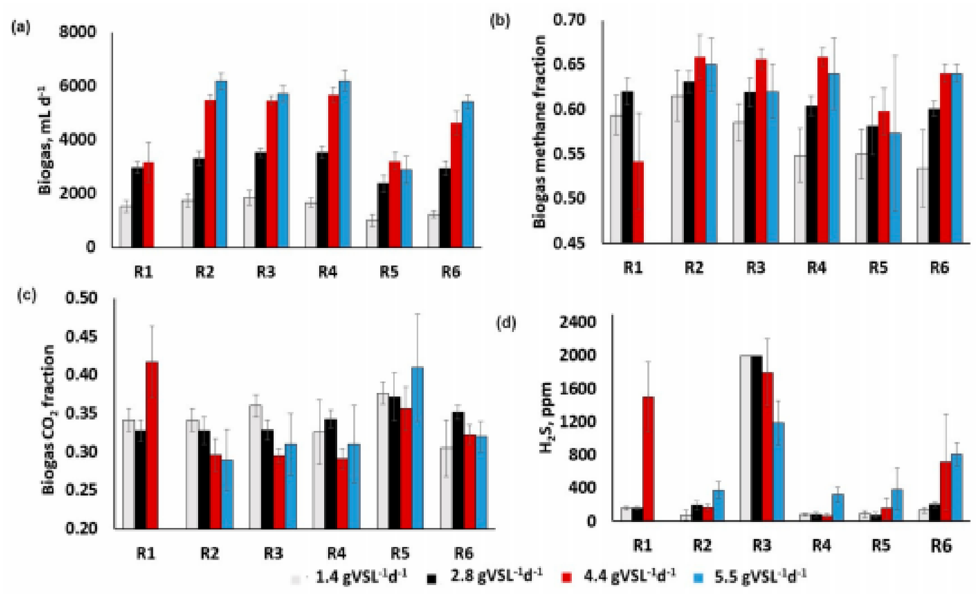


Figure 2.10 Biogas properties: (a) average daily biogas production rate; (b) methane fraction; (c) CO2 fraction; (d) H2S concentration [ppm]. Co-substrates: R1—none; R2—AW (acid whey); R3—ED (energy drinks); R4—WB (wasted bread); R5—PN (paper napkins); R6—CM (cow manure). (Swati et. al., 2019)

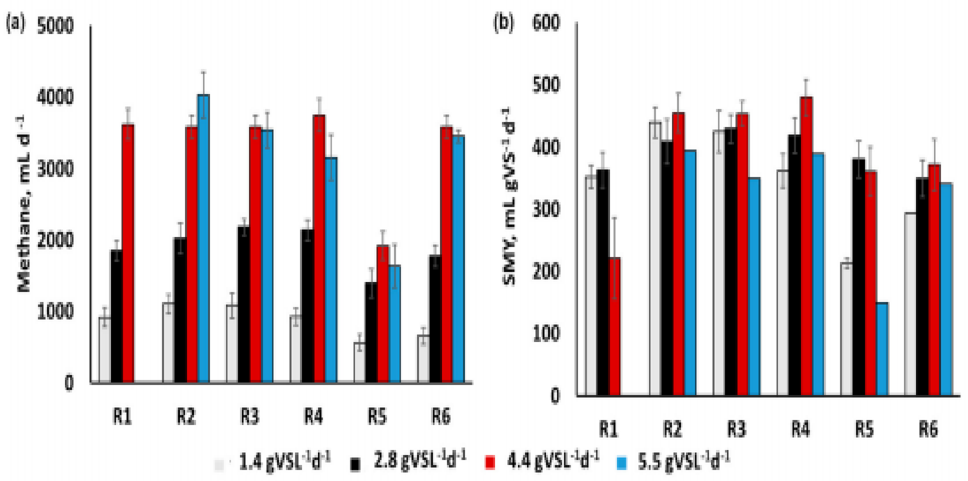
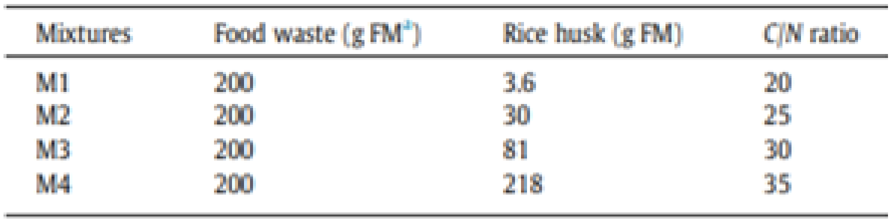


Figure 2. 11 (a) Daily average methane production rate [mL d^{-1}]; (b) Specific methane yield (SMY) [mL gVS^{-1}d^{-1}]. Co-substrates: R1—none; R2—AW (acid whey); R3—ED (energy drinks); R4—WB (wasted bread); R5—PN (paper napkins); R6—CM (cow manure). (Swati et. al., 2019)

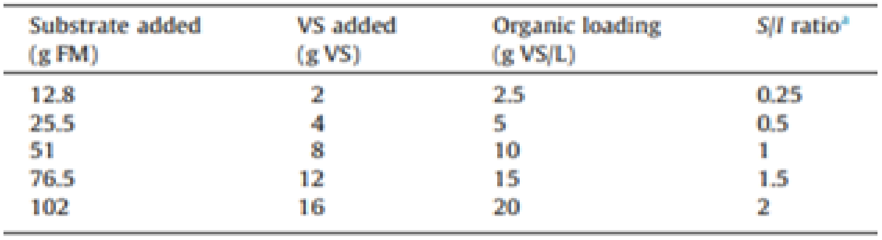
Another study by Haider et al. (2015) was conducted to find out suitable mixing ratio of food waste and rice husk for their co-digestion in order to overcome VFA accumulation in digestion of food waste alone. Four mixing ratios of food waste and rice husk with *C*/*N* ratios of 20, 25, 30 and 35 were subjected to a lab scale anaerobic batch experiment under mesophilic conditions. Highest specific biogas yield of 584 L/kg VS was obtained from feedstock with *C*/*N* ratio of 20. Biogas yield decreased with decrease in food waste proportion. Further, fresh cow dung was used as inoculum to investigate optimum *S*/*I* ratio with the selected feedstock. In experiment 2, feedstock with *C*/*N* ratio 20 was subjected to anaerobic digestion at five *S*/*I* ratios of 0.25, 0.5, 1.0, 1.5 and 2.0. Specific biogas yield of 557 L/kg VS was obtained at *S*/*I* ratio of 0.25. However, VFA accumulation occurred at higher *S*/*I* ratios due to higher organic loadings. Composition of reactors for both experiments are shown in table 2.3 and table 2.4. The results found from the study are shown in figure 2.12 and figure 2.13.

Table 2. 3 Composition of substrate mixtures used in experiment 1 (Haider et. al., 2015)



Mixtures	Food waste (g FM[a])	Rice husk (g FM)	C/N ratio
M1	200	3.6	20
M2	200	30	25
M3	200	81	30
M4	200	218	35

Table 2. 4 Composition of reactors in experiment 2 (Haider et. al., 2015)



Substrate added (g FM)	VS added (g VS)	Organic loading (g VS/L)	S/I ratio[a]
12.8	2	2.5	0.25
25.5	4	5	0.5
51	8	10	1
76.5	12	15	1.5
102	16	20	2

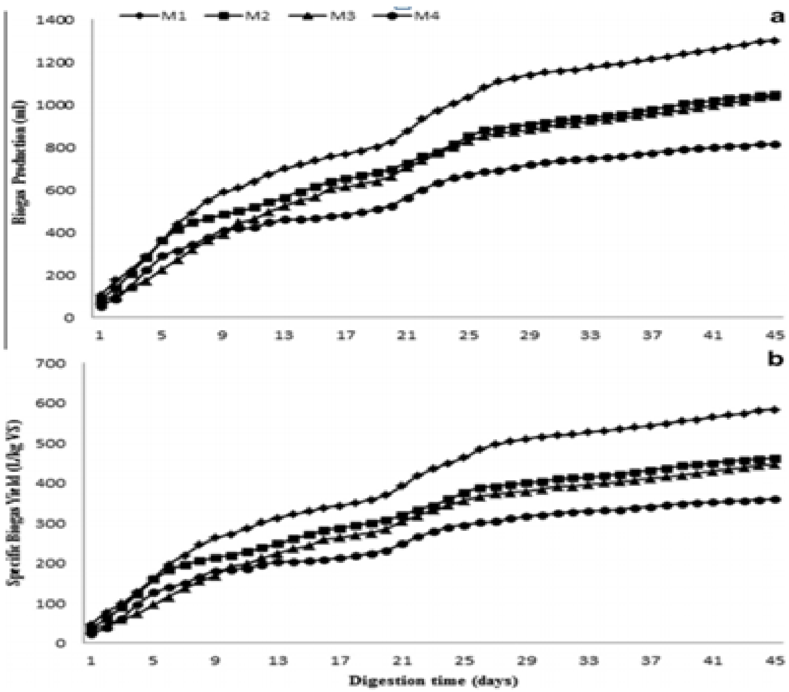


Figure 2. 12 a) Cumulative biogas yield, b) Specific biogas yield of substrate mixtures at different mixing ratio (Haider et. al., 2015)

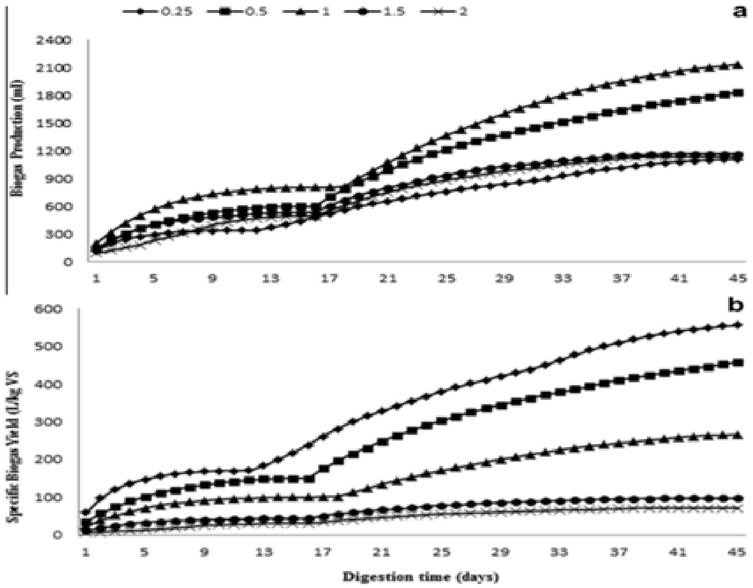


Figure 2. 13 a) Cumulative biogas yield, b) Specific biogas yield of substrate mixtures at different S/I ratio (Haider et. al., 2015)

Another study by Liu et. al., (2013) in which batch experiments were conducted to produce hydrogen and methane from waste activated sludge and food waste by two-stage mesophilic fermentation. Hydrogen and methane production, energy yield, soluble organic matters, volatile solid removal efficiency and carbon footprint were investigated during two stage digestion at various food waste proportions. The highest energy yield reached 14.0 kJ/g-VS at the food waste proportion of 85%, with hydrogen and methane yields of 106.4 ml-H2/g-VS and 353.5 ml-CH4/g-VS respectively. The dominant VFA composition was butyrate for co-digestion and sole food waste fermentation, whereas acetate was dominate in VFA for sole waste activated sludge fermentation. The VS removal efficiencies of co-digestion were 10–77% higher than that of waste activated sludge fermentation. Only 0.1 3.2% of the COD in feedstock was converted into hydrogen, and 14.1–40.9% to methane, with the highest value of 40.9% in methane achieved at food waste proportion of 85%. The result found from their study is shown in figure 2.14.

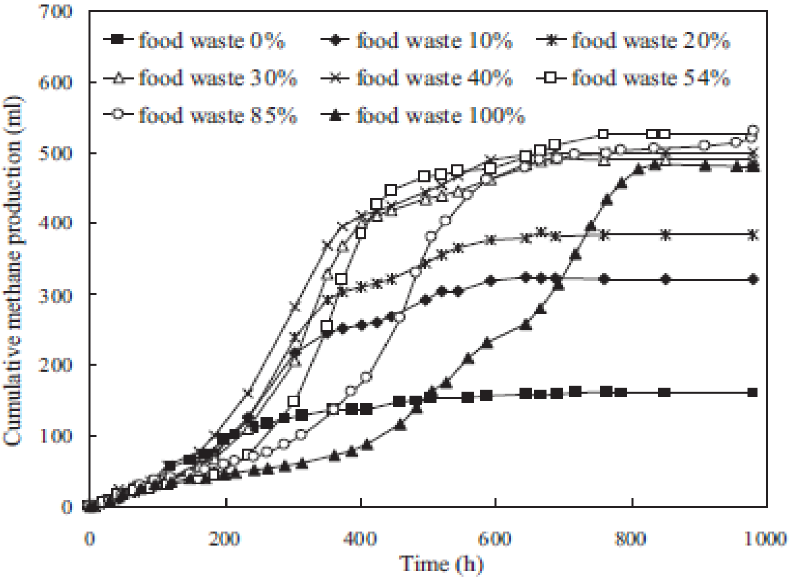
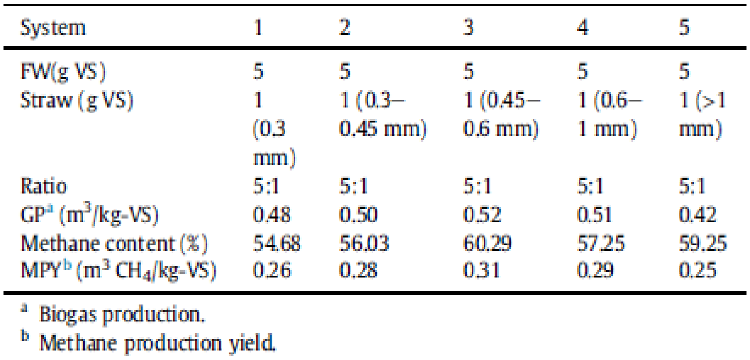


Figure 2. 14 Cumulative CH_4 production at various food waste proportions (Liu et. al., 2013)

Another study by Yong et. al., (2015) was conducted in which food waste, straw and anaerobic granular sludge as inoculum were used. 10 control groups were designed, in which the ratios of FW to straw were 5:0, 0:5, 1:4, 1:1, 3:2, 4:1, 5:1, 6:1, 7:1 and 8:1. Five groups were designed with total organic load of 6 g VS/L, of which the straw sizes were 0.3 mm, 0.3-0.45 mm, 0.45-0.6 mm, 0.6-1 mm and >1 mm. The optimum mixing ratio of FW to straw appears to be close to 5:1, and the methane production yield (MPY) reached 0.392 m3/kg-VS, i.e., increased by 39.5% and 149.7% compared with individual digestion results, respectively. Moreover, the gas production (GP) and methane content was reaching 0.58 m3/kg-VS and 67.62%, respectively. Further study about the optimal straw particle size was explored, and the recommended size range of straw was 0.3-1 mm for the economical and energy-saving consideration.

Table 2. 5 Optimization experiment for the straw particle size (Yong et. al., 2015)

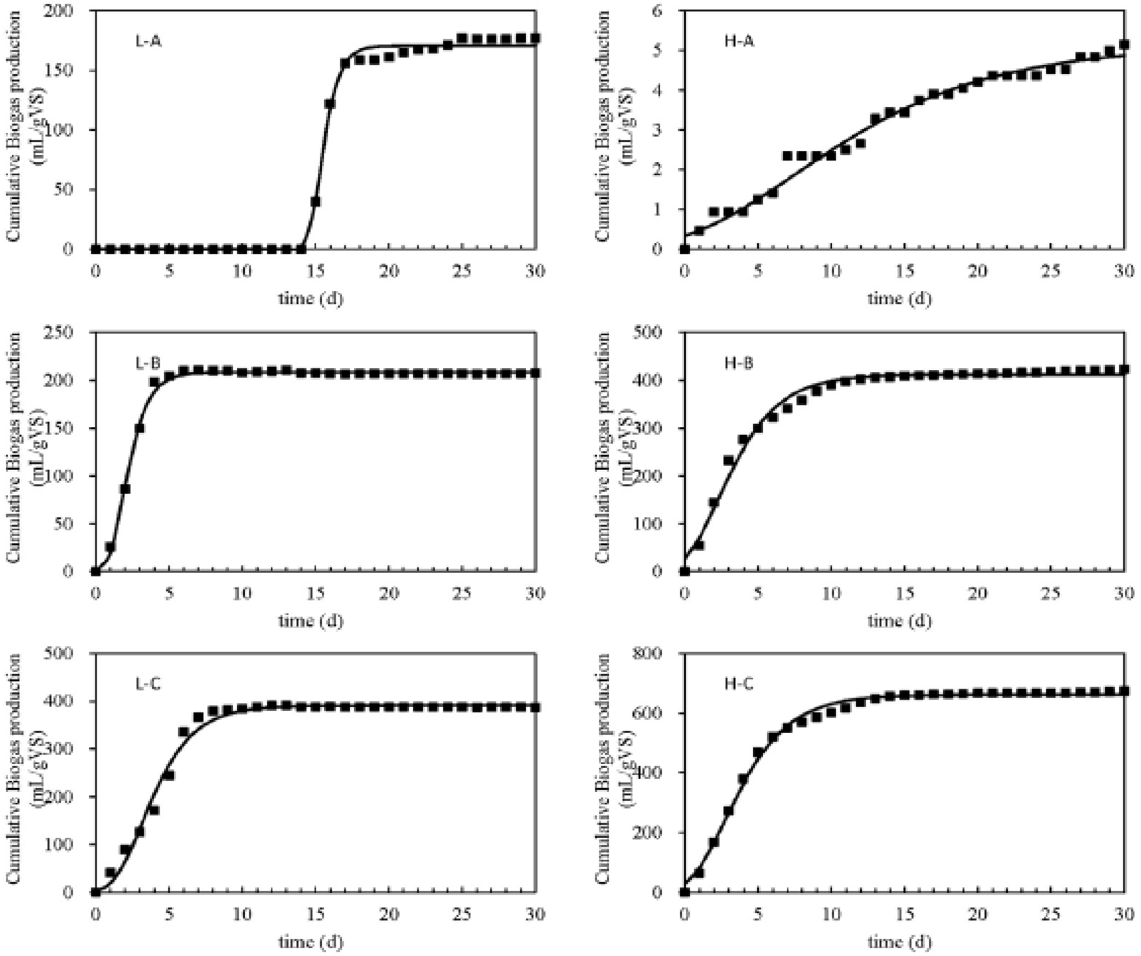


System	1	2	3	4	5
FW(g VS)	5	5	5	5	5
Straw (g VS)	1 (0.3 mm)	1 (0.3–0.45 mm)	1 (0.45–0.6 mm)	1 (0.6–1 mm)	1 (>1 mm)
Ratio	5:1	5:1	5:1	5:1	5:1
GP[a] (m^3/kg-VS)	0.48	0.50	0.52	0.51	0.42
Methane content (%)	54.68	56.03	60.29	57.25	59.25
MPY[b] (m^3 CH$_4$/kg-VS)	0.26	0.28	0.31	0.29	0.25

[a] Biogas production.

[b] Methane production yield.

Another study by Liu et. al., (2016) in which Anaerobic co-digestion of sewage sludge and food waste was tested at two different total solid (TS) concentrations. In the low-solids group with TS 4.8%, the biogas production increased linearly as the ratio of food waste in substrate increased from 0 to 100%, but no synergetic effect was found between the two substrates. Moreover, the additive food waste resulted in the accumulation of volatile fatty acids and decelerated biogas production. Thus, the blend ratio of food waste should be lower than 50%. While in the high-solids group with TS 14%, the weak alkaline environment with pH 7.5, 8.5 avoided excessive acidification but high concentration of free ammonia was a potential risk. However, good synergetic effect was found between the two substrates because the added food waste improved mass transfer in sludge cake. Thus, 50% was recommended as the optimum ratio of food waste in substrate because of the best synergetic effect.



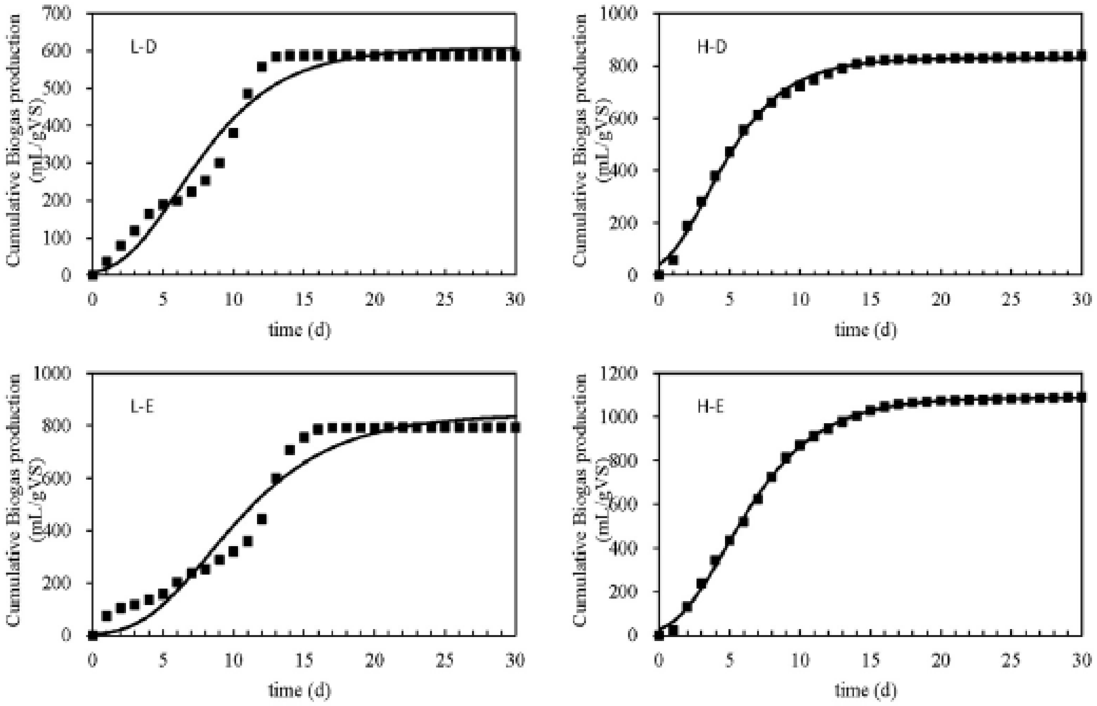
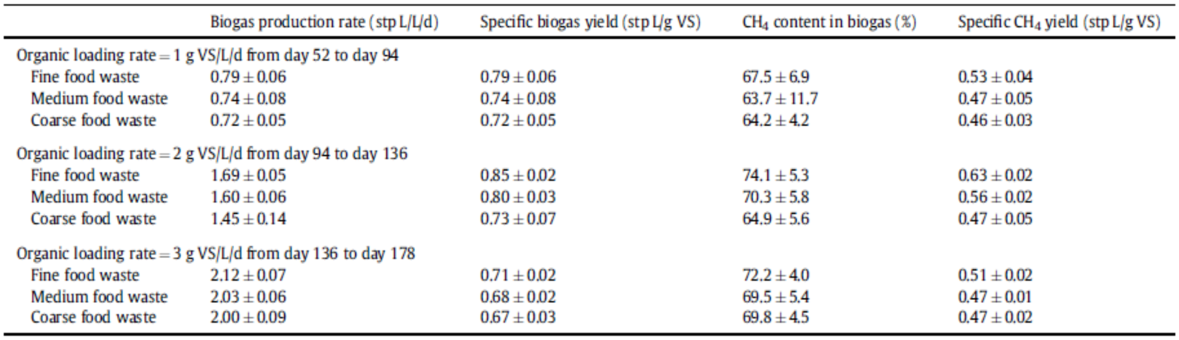


Figure 2. 15 Simulation of biogas production (L means low-solid group and H means high-solids group, blend ratios of sludge and food waste in A–E are 4:0, 3:1, 2:2, 1:3 and 0:4 based on their VS contents, respectively). (Liu et. al., 2016)

Agyeman et. al., (2014) conducted a study to comprehensively evaluate the effects of food waste particle size on co-digestion of food waste and dairy manure at organic loading rates increased stepwise from 0.67 to 3 g/L/d of volatile solids (VS). Three anaerobic digesters were fed semi continuously with equal VS amounts of food waste and dairy manure. Food waste was ground to 2.5 mm (fine), 4 mm (medium), and 8 mm (coarse) for the three digesters, respectively. Methane production rate and specific methane yield were significantly higher in the digester with fine food waste. Digestate dewaterability was improved significantly by reducing food waste particle size. Specific methane yield was highest at the organic loading rate of 2 g VS/L/d, being 0.63, 0.56, and 0.47 L CH4/g VS with fine, medium, and coarse food waste, respectively. Methane production rate was highest (1.40e1.53 L CH4/L/d) at the organic loading rate of 3 g VS/L/d. The energy used to grind food waste was minor compared with the heating value of the methane produced. Table 2.6 shows the biogas production found from the study.

Table 2. 6 Biogas production in co-digestion of dairy manure with different particle sizes of food waste during stable operation periods at increasing organic loading rates (Agyeman et. al., 2014)



	Biogas production rate (stp L/L/d)	Specific biogas yield (stp L/g VS)	CH_4 content in biogas (%)	Specific CH_4 yield (stp L/g VS)
Organic loading rate = 1 g VS/L/d from day 52 to day 94				
Fine food waste	0.79 ± 0.06	0.79 ± 0.06	67.5 ± 6.9	0.53 ± 0.04
Medium food waste	0.74 ± 0.08	0.74 ± 0.08	63.7 ± 11.7	0.47 ± 0.05
Coarse food waste	0.72 ± 0.05	0.72 ± 0.05	64.2 ± 4.2	0.46 ± 0.03
Organic loading rate = 2 g VS/L/d from day 94 to day 136				
Fine food waste	1.69 ± 0.05	0.85 ± 0.02	74.1 ± 5.3	0.63 ± 0.02
Medium food waste	1.60 ± 0.06	0.80 ± 0.03	70.3 ± 5.8	0.56 ± 0.02
Coarse food waste	1.45 ± 0.14	0.73 ± 0.07	64.9 ± 5.6	0.47 ± 0.05
Organic loading rate = 3 g VS/L/d from day 136 to day 178				
Fine food waste	2.12 ± 0.07	0.71 ± 0.02	72.2 ± 4.0	0.51 ± 0.02
Medium food waste	2.03 ± 0.06	0.68 ± 0.02	69.5 ± 5.4	0.47 ± 0.01
Coarse food waste	2.00 ± 0.09	0.67 ± 0.03	69.8 ± 4.5	0.47 ± 0.02

2.7 Factors Affecting Gas Generation

The gas production rate and volume in a landfill depend 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, the temperature of the waste, oxygen availability nutrients, etc. (Barlaz et al., 1989; El-Fadel et al., 1996a; Wraith, 2003; and Wraith et al., 2005; Badhon et al. 2021)

2.7.1 Composition

The composition of waste is a dominating factor as the 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, the presence of chemicals leads to volatilization or chemical reaction that most likely generate NMOCs and other gases. The 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 the 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 Figure 2.16. Another study by Karanjekar (2013) showed a similar result for a reactor with 100% food waste, operated at 37°C (Figure 2.17).

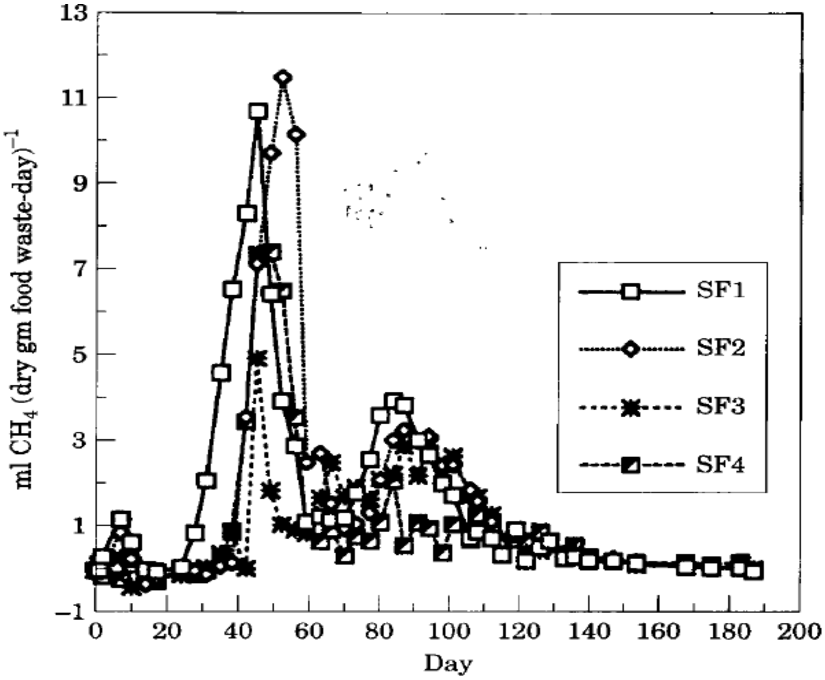


Figure 2. 16 Methane generation rates in reactors with food waste (Wang et al., 1997)

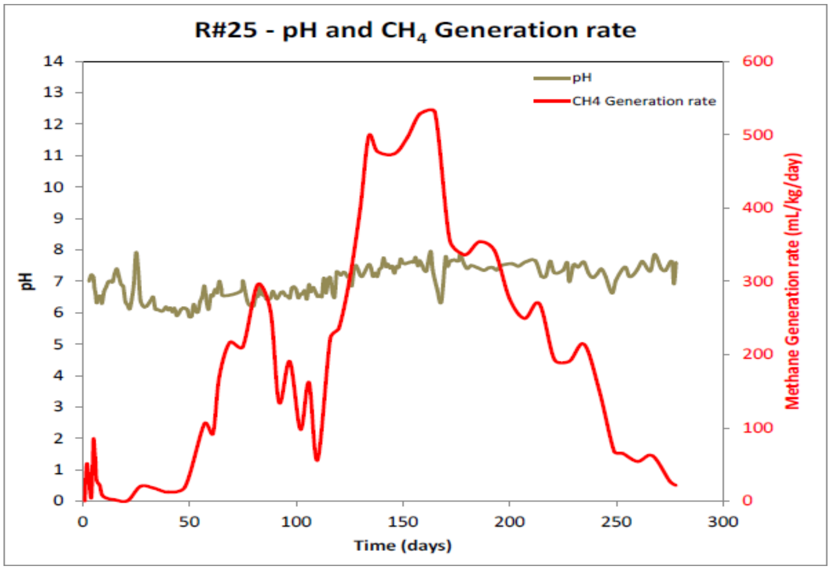


Figure 2. 17 Methane generation rate and pH at 37^{o}C from 100% food waste reactor (Karanjekar, 2013)

2.7.2 Particle Size

Waste particle size affects the gas generation rate. If waste is being shredded it increases the 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 a long 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). According to Liotta et. al., (2014) due to lack of water, volatile fatty acid accumulation occurs during the first step of the process at semi-dry and dry conditions, which is responsible for the reduction of process kinetic rates. 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 2.18 and Figure 2.19.

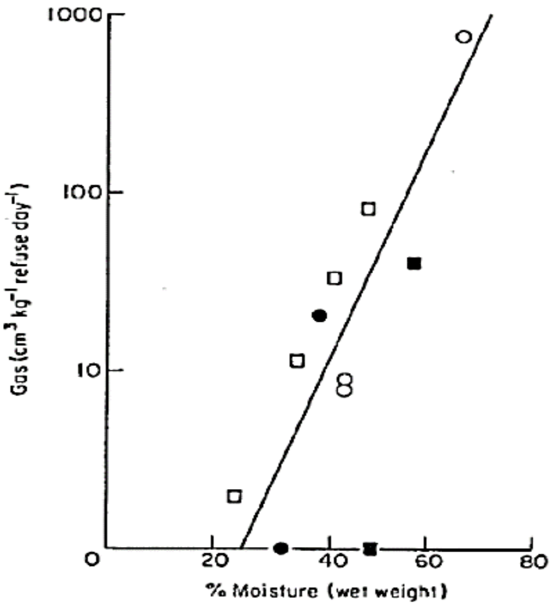


Figure 2. 18 Effect of moisture content on gas generation rate (Rees, 1980)

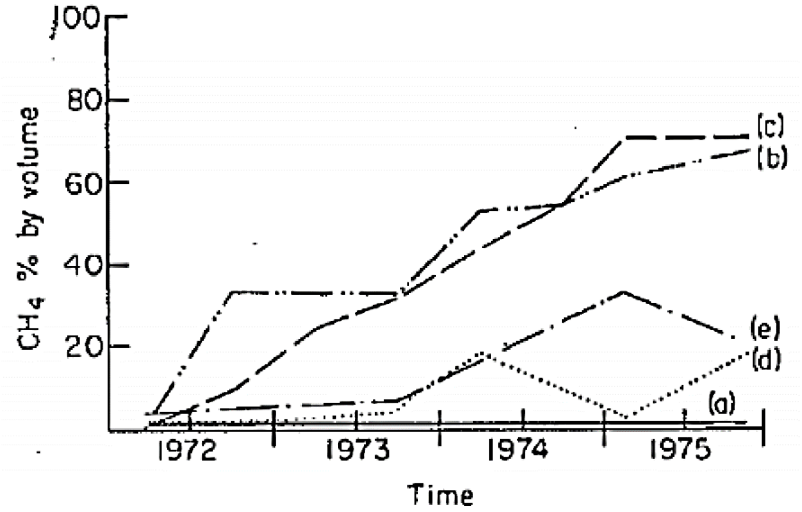


Figure 2. 19 Effect of moisture content on methane generation a) Dry condition; b) & c) Everyday liquid application; d) & e) Initially saturation (Rees, 1980)

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 an increase in moisture content as shown in Figure 2.20.

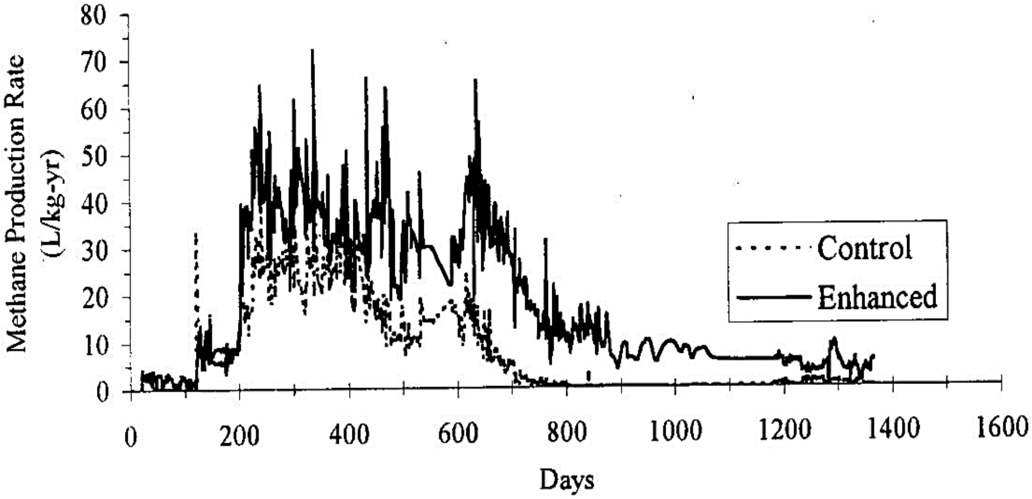


Figure 2. 20 Comparison of methane production rate between cells without moisture addition (control) and with moisture addition (Enhanced) (Mehta et al., 2002)

2.7.4 pH

pH is an influencing factor for biodegradation and gas generation. For optimum bacterial activity, pH should be in the range of 6.8 to 7.4 (Warith, 2003; Warith et al., 2005). Acidogenic bacteria have a higher range of pH. A 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, the intensity of rainfall, type of waste (food waste produces the 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 landfills and maintaining the desired moisture content. Direct application of moisture to waste during landfilling, spray irrigation on the surface of the landfill, surface application, sub-surface application is some of the methods of recirculation (Warith, 2003). It increases the biodegradation as well as the rate of methane recovery from landfills (Samir, 2014). As an added advantage it helps reducing treatment costs 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 2.21.

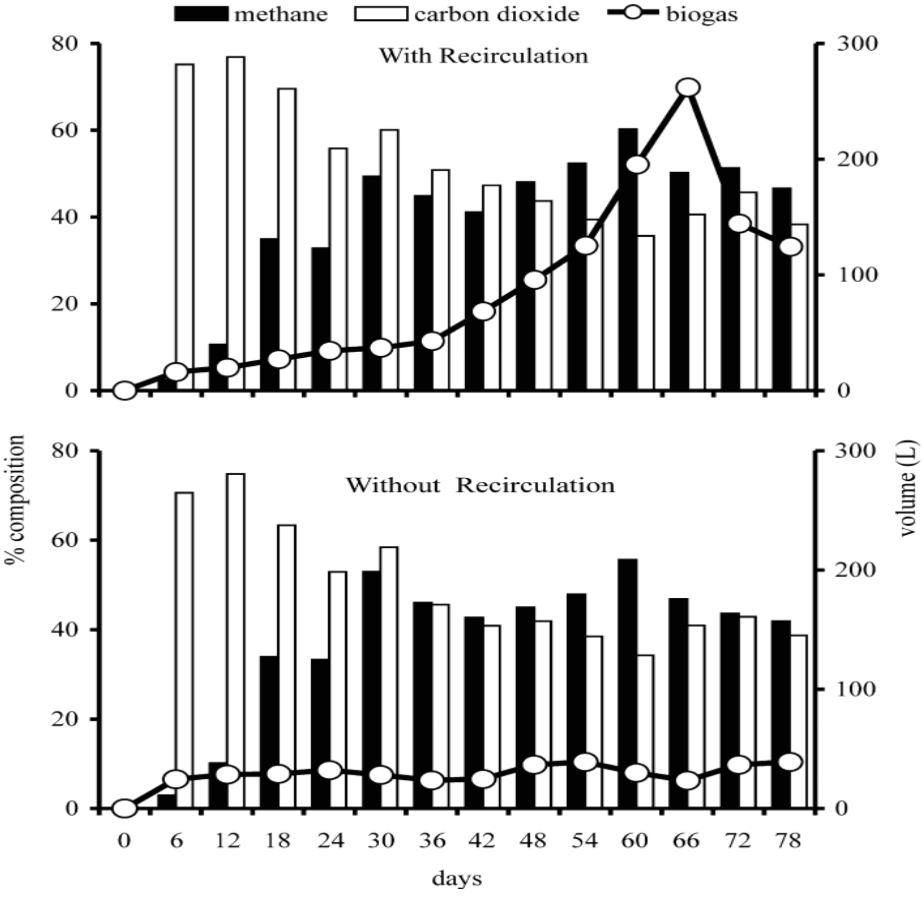


Figure 2. 21 Impact of leachate circulation on gas generation (Chan et al., 2002)

A study by Barlaz et al. (2002) in the 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 the conventional cell. Figure 2.22 shows the results obtained from their research.

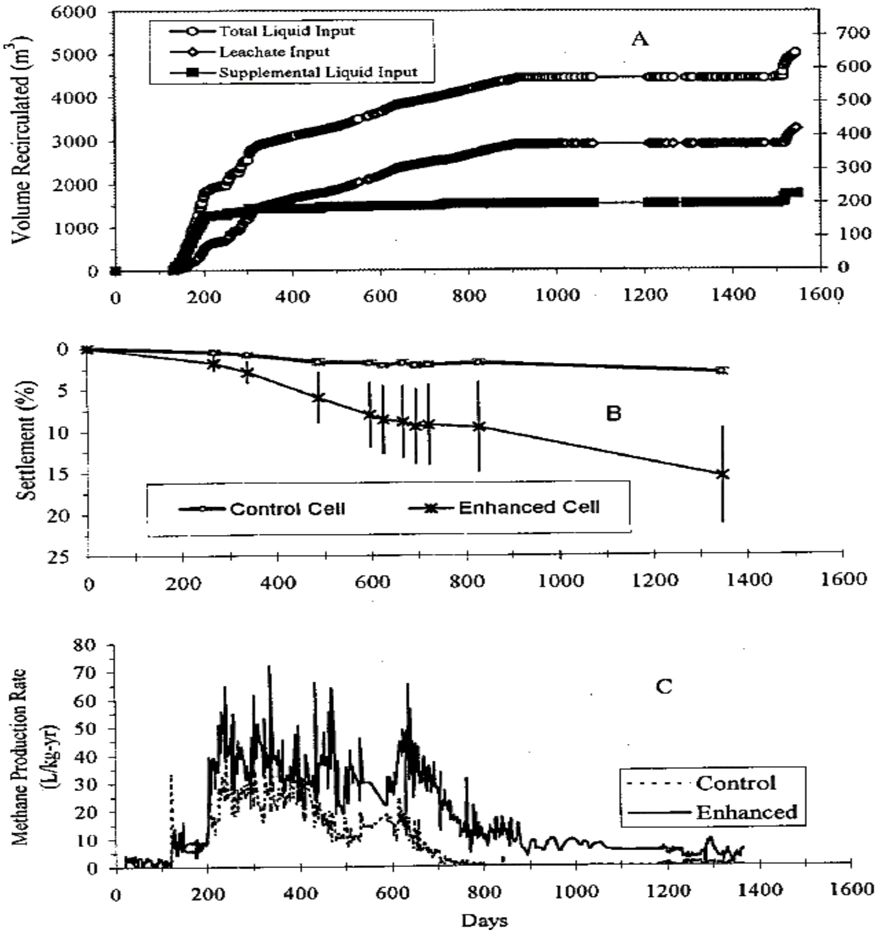


Figure 2. 22 (a) Cumulative liquid input for leachate recirculation and supplemental liquids; (b) refuse settlement over time; and (c) methane production rate in enhanced and control cells (Mehta et al., 2002)

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 cells showed more degradation compared to waste samples from the 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 2.23). The authors stated that moisture addition accelerates landfill gas production compared to conventional landfill operation.

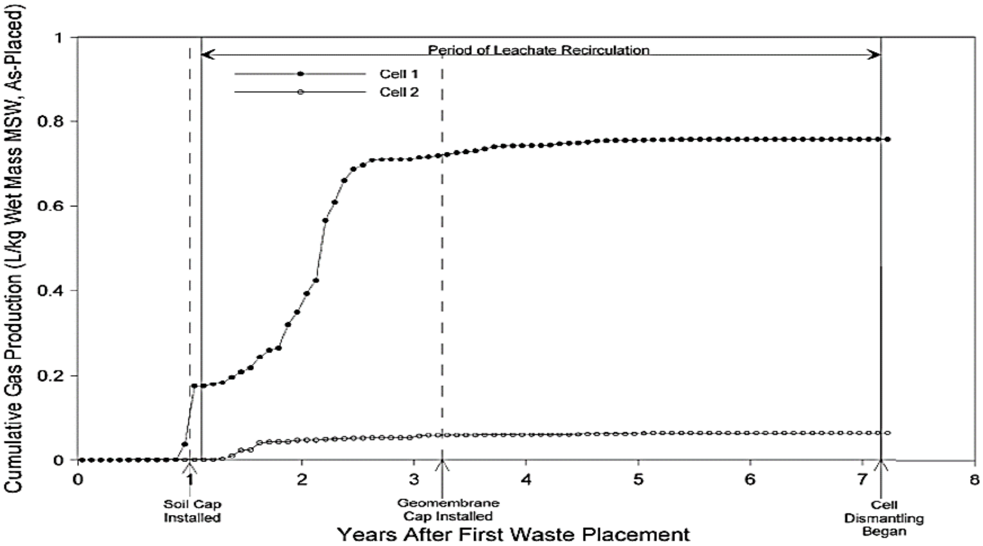


Figure 2. 23 Cumulative Gas Productions in the Test Cells. Cell 1: With Addition of Moisture; Cell 2: Without Moisture Addition, Conventional Cell (Morris et al., 2003)

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 year 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 extend up to 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, the significant gas generation period will vary. Landfill gas generation has two major time-dependent variables: (i) lag time and (ii) conversion time.

Time from waste deposition till the beginning of methane generation is the lag time (Figure 2.24, the start of Phase III); whereas conversion time is the time from waste deposition till the end of methane generation (Figure 2.24, end of Phase V). Lag time and conversion time vary with the type of waste. For example, lag & conversion time for yard waste is very short, while leather & plastic have a long lag & conversion time; for food waste, lag time is very long, however, it has a shorter conversion time.

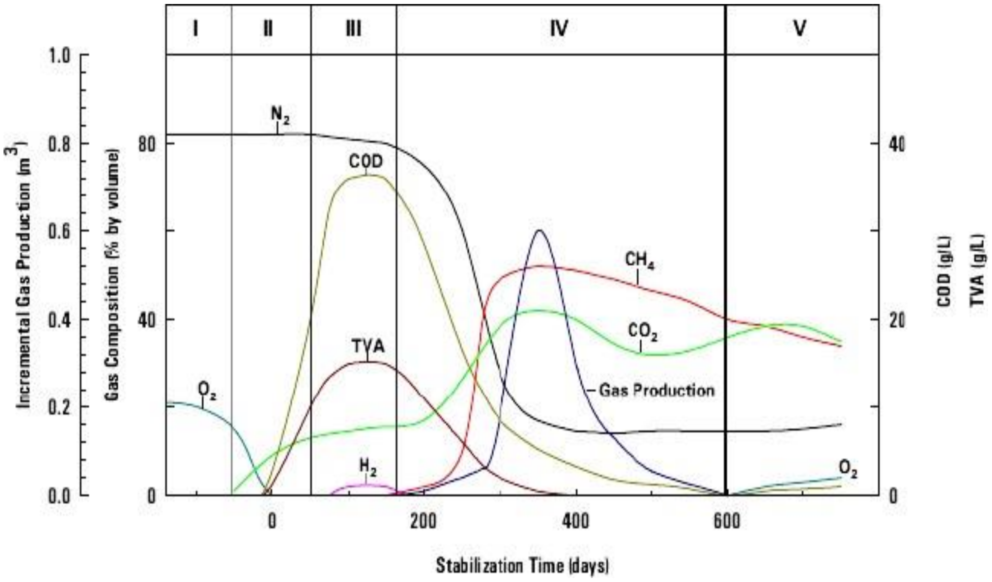


Figure 2. 24 Phases of waste degradation in a typical landfill (Pohland and Harper, 1986)

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 The 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, the 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 Content

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

2.7.9 Total Solid (TS)

The experimental results show a reduction of the specific final methane yield of 4.3% and 40.8% in semi-dry and dry conditions compared with wet conditions (**Liotta**

et. al., (2014)). Kylefors and Lagerkvist (1977) reported the concentration of TS decrease when the leachate transfers from acidogenic to methanogenic phase. S.T.S. Yuen (1999) stated the same results for total solids. From the study of Mali et, al., 2010, Figure 2.25 shows the solid measurement for anaerobic reactors and it varies from 53800 mg/L to 17520 mg/L. Decreasing value of concentration indicates the consumption of organic matter in leachate by bacteria to produce new cells and carbon dioxide. Leachate recirculation is also responsible for the degradation of solids in leachate.

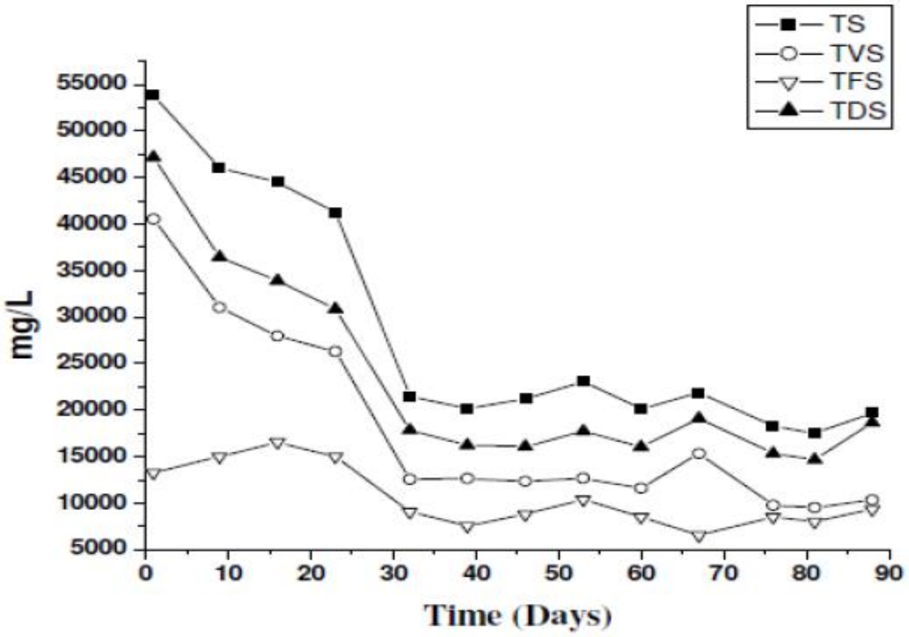


Figure 2. 25 Total Solids change with time (Mali et.al., 2010)

Forster-Carneiro et.al., (2008) studied the effect of various TS percentages on the biogas production of reactors made with Food Waste (FW). In Figure 2.26, the variation of TS with time is shown. It indicates the bioprocess conversion of organic matter. The concentration of TS in the reactor STR20-30 (Stirred Tank Reactor) started from 20g/L. These values remained almost constant and decreased slowly with time.

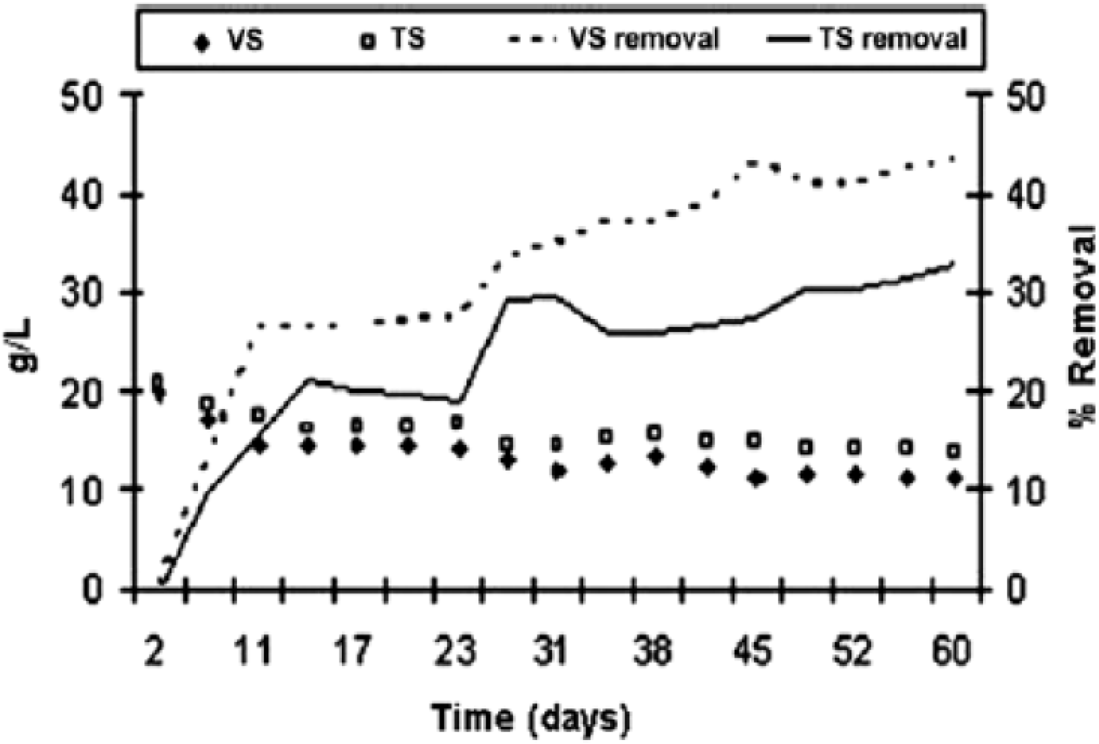


Figure 2. 26 Variation of Total Solids with Time (Forster-Carneiro et.al., 2008)

2.7.10 Volatile Fatty Acid (VFA)

Volatile fatty acids (VFAs) are intermediates in the methane formation pathway of anaerobic digestion. Chao Ji et. al., (2017) reported that the key factor in inhibiting the production of methane is the high concentration of short-chain fatty acids (SCFAs), such as acetic acid, propionic acid, and butyric acid, which are generated during the hydrolytic process. Hydrolyzation facilitates not only altering the pH value of the fermentation broth but also changing the formation of fatty acids. Ziang et. al., (2018) studied that High VFA concentration was the main inhibition factor on methane production, and the threshold VFA inhibition concentrations ranged from 16.5–18.0 g/L.

2.8 Anaerobic Digestion Enhancement:

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). If this accumulation of VFA can be reduced, the lag phase will reduce too which will result in earlier methane production.

2.8.1 Addition of inoculum:

Inoculum addition can be very helpful when dealing with pure organic waste. 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.

2.8.1.1 Sludge as inoculum

The addition of sludge can have both positive and negative effects on the 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, the addition of sewage sludge produces three times more methane than the 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).

Sewage sludge helps to degrade waste faster due to its prolific microorganism activity. Leuschner (1982), Pacey (1989), and Warith (2002) studied the effect of sludge addition on the degradation of MSW. Wraith, 2002 stated that in the reactors with added sludge pH increase and BOD reduction were found. Warith 2005 showed that a positive effect was found on waste degradation by adding anaerobically digested sludge, a seed to microorganisms by providing moisture, a source of nitrogen, phosphorous, and other nutrients.

Buivid et. Al., (1981) performed a test by mixing MSW with 10% of anaerobically digested wastewater sludge & after 90 days more than 3 times of CH4 production was found.

Sludge addition acts as the buffer and increases alkalinity. Due to the rapid degradation of organic matter, higher sludge to waste ratio yielded a higher methane production rate. 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 2.27 shows the results found in their studies.

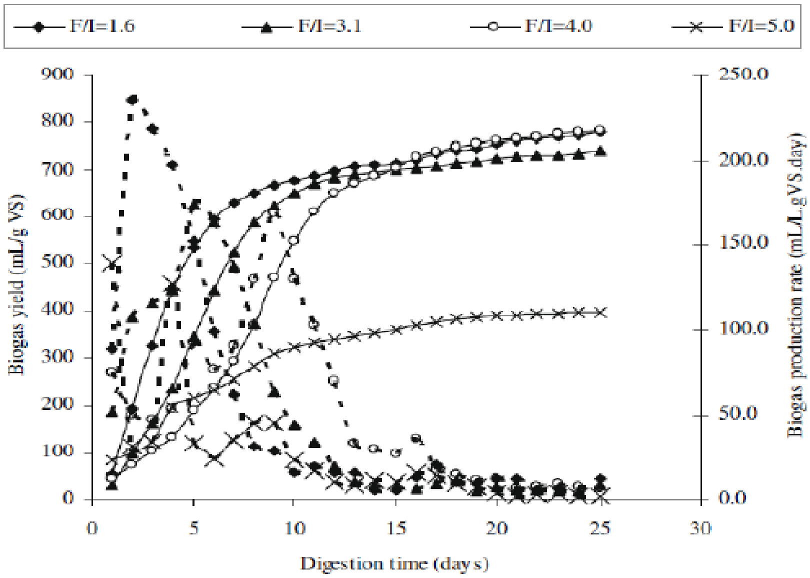


Figure 2. 27 Biogas generation from food waste at four different F/I (Liu et al., 2009)

2.8.1.2 Manure as Inoculum

Manure is 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 to enhancement of gas generation from waste. 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. 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 2.28 shows the result of digestion of food waste with and without manure.

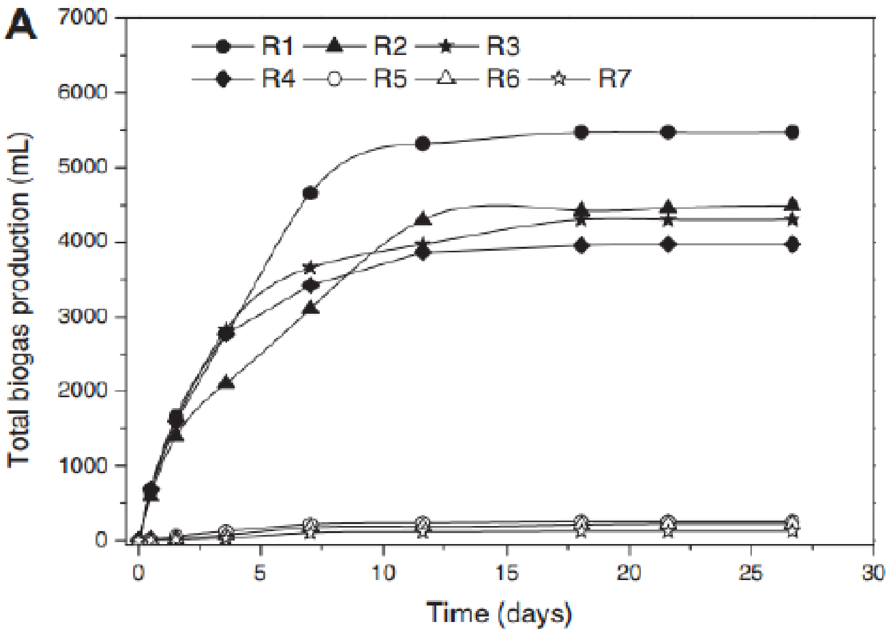


Figure 2. 28 Digestion of food waste with manure (R1, R2, R3) and without manure (R4 through R7) (Zhang et al., 2013)

2.8.2 Addition of Trace Elements:

Zhang et. al., (2015) conducted a study that aimed at investigating the effects of trace metals on methane production from food waste and examining the feasibility of reducing metals dosage by ethylenediamine-N, N'-disuccinic acid (EDDS) via improving metals bioavailability. The results indicated that the effects of metal elements highly depended on the supplemental concentrations.

Trace metals supplemented under moderate concentrations greatly enhanced the methane yield. However, the excessive supplementation of Fe (1000 mg/L) and Ni (50 mg/L) exhibited the obvious toxicity to methanogens. The combinations of trace metals exhibited remarkable synergistic effects. The supplementation of Fe (100 mg/L) + Co (1 mg/L) + Mo (5 mg/L) + Ni (5 mg/L) obtained the greatest methane yield of 504 mL/g VS added and the highest increment of 35.5% compared to the reactor without metals supplementation (372 mL/g VS added). The changes of metals speciation showed the reduction of metals bioavailability during anaerobic digestion, which might weaken the stimulative effects of trace metals. However, the addition of EDDS improved metals bioavailability for microbial uptake and stimulated the activity of methanogens, and therefore, strengthened the stimulative effects of metals on anaerobic digestion of food waste. The batch and semicontinuous experiments confirmed that the addition of EDDS (20 mg/L) bonded to trace metals prior to their supplementation could obtain a 50% reduction of optimal metals dosage. This study provided a feasible method to reduce trace metals dosage without the degeneration of process performance of anaerobic digestion. Figure 2.29 and 2.30 shows the results found in their studies.

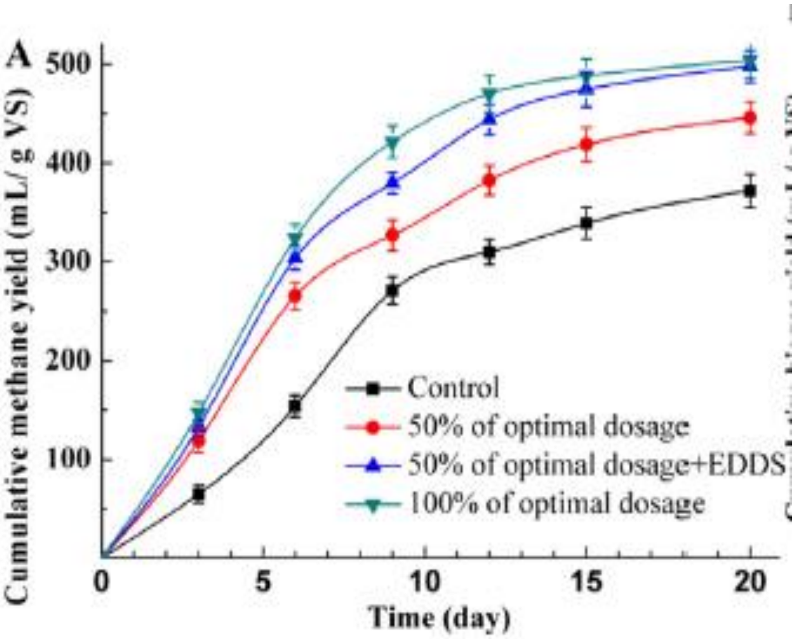


Figure 2. 29 Methane yield of semi-continuous anaerobic digestion of food waste with varying metals supplementation strategies under different OLR and HRT conditions

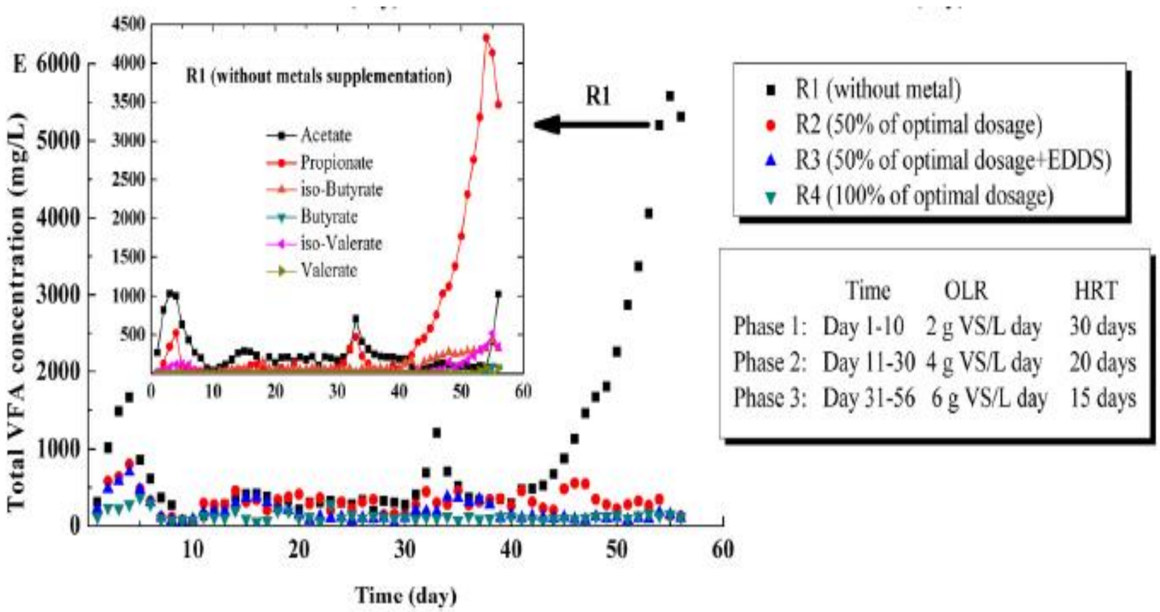


Figure 2. 30 Total VFA concentration and the specific VFA concentration of R1 of semi-continuous anaerobic digestion of food waste with varying metals supplementation strategies under different OLR and HRT conditions.

2.9 WWTPs and sludge treatment in the US

In the United States as of 2014, the number of municipal wastewater treatment facilities is 14,780 in operation. These facilities are treating 32,345 million gallons and an average of wastewater per day (MGD, 1 MGD¼3785 m3/day) (USEPA 2010). According to EPRI 2013, Copeland 2014, municipal wastewater treatment consumes 3–4% of the entire nation’s electrical demand, equal to 30.2 billion kW h every year, and accumulates 21 million metric tons of greenhouse gas (GHG) emission yearly (USWPA). The highest cost for operation of WWTPs is electric power consumption, amount to over 30% of the total maintenance and operation cost (USEPA 2008, USEPA 2010) and up to 80% of the greenhouse gas emission at WWTPs (WEREF 2010). Sewage sludge of the wastewater treatment process needs treatment before final disposal, and costs almost 30% of a WWTP’s operating costs (WEREF 2008). Sewage sludge can also be stabilized and turned into biosolids. Biosolids are energy and nutrient-rich materials, which can be used for land application as a soil conditioner and/or fertilizer substitute for carbon sequestration (Moller 2009) as well as a fuel for renewable energy production. At US WWTPs, around 6.5 million metric tons (dry weight) of sewage sludge are produced yearly, and the volume increases with a rising population (WEREF 2008). Anaerobic digestion (AD) is a commonly used technique for sludge treatment at US WWTPs. The USEPA accounts that 1484 WWTPs dissolve sludge to generate biogas (USEPA 2011). About 48 percent of the total wastewater generated in the US is treated with AD before dumping (WEF 2013). Normally biogas composition of sludge is carbon dioxide (CO2, 30–50%) and methane (CH4, 50–70%). However, to lessen the cost of energy consumption less than 10% of those plants exploit biogas for heating and/or electricity generation (USEPA 2011). Most WWTPs with AD use merely combust biogas in flare biogas and/or boilers but without collective heat and power (CHP) technologies. In 2012 wastewater treatment was the 8th largest man-made source of CH4 discharges (the equivalent of 12.8 million metric tons of CO2) in the US (USEPA 2014). Methane is a greenhouse that has more than 20 to 200 times the radiative forcing per gram of CO_2 depending on the assessment emission time horizon (Edwards 2014). Biogas production can one of the main sources of greenhouse gas production from WWTPs when it is not managed appropriately. So, efficient biogas utilization and production at WWTPs can meaningfully decrease the carbon footprint for WWTPs.

2.10 The potential of biogas production from WWTP Sludge

If managed efficiently, sludge produced at WWTPs could give considerable energy in the form of biogas, possibly turning WWTP into a net energy creator rather than a consumer (McCarty 2014). AD of sludge is not only significant to make the most of the energy production, but also to diminish the overall treatment costs at WWTPs. Benefits of biogas production from sewage sludge:

- Boost **biogas** volume by up to 20%
- Increased power generated from **biogas**.
- Reduced soluble phosphate in the final waste stream.
- Less corrosion in generators and heat exchangers.

The use of biogas for fuel and power as natural gas has numerous environmental benefits since it can be a replacement for fossil fuels to generate electricity and vehicle fuel, dropping the carbon footprint of WWTP operation.

Chapter 3

Methodology

3.1 Introduction

The main objective of this study was to investigate the effect of different percentages of sludge content on the degradation of different types of food waste by laboratory simulation of anaerobic digester operation and determine the most suitable combination for maximum gas generation from food waste AD.

An experimental program was prepared to simulate eight laboratory-scale food waste AD with two different percentages of sludge and four types of food waste. The reactors were monitored daily and the leachate and gas generated from the reactors were collected and tested periodically. The volatile solids, total solids, Volatile Fatty Acid, and COD tests were also conducted to observe the stage of biodegradation in the laboratory. The following subsections discuss the experimental design and test procedure for the reactor operations.

3.2 Experimental Design

3.2.1 Inoculum Percentage

Sludge was chosen as inoculum. Two different percentages of sludge were used for four pairs of the reactor. For the first two pairs, sludge was 20% and for the last two pairs of the reactor, sludge percentage was 30%. This percentage was chosen based on availability and applicability in both developed and developing countries to determine the effect on gas generation from food waste.

3.2.2 Waste Composition

Observing the food waste scenario of south Asian countries, the waste composition was determined. Generally, Grain, meat, fruits, and vegetables are mostly consumed all over the south Asian countries. So, it was decided that 2 pairs of reactors will contain fruits and vegetables as they have similar characteristics while the other two pairs will have meat and grain.

3.2.3 Experimental Design

Laboratory-scale simulated food waste AD were built to analyze the effect of sludge on food waste decomposition and gas generation. Sludge was added to all sets of AD as a 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 bioreactors

Reactors	Food Waste	Sludge
MGR1, MGR2	40% Meat+ 40% Grain	20%
FVR3, FVR4	40% Fruit+ 40%Vegetable	20%
MGR5, MGR6	35% Meat+ 35% Grain	30%
FVR7, FVR8	35% Fruit+ 35%Vegetable	30%

It was necessary to operate the reactors in anaerobic environmental conditions 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 3.1 shows the designed reactor setup.

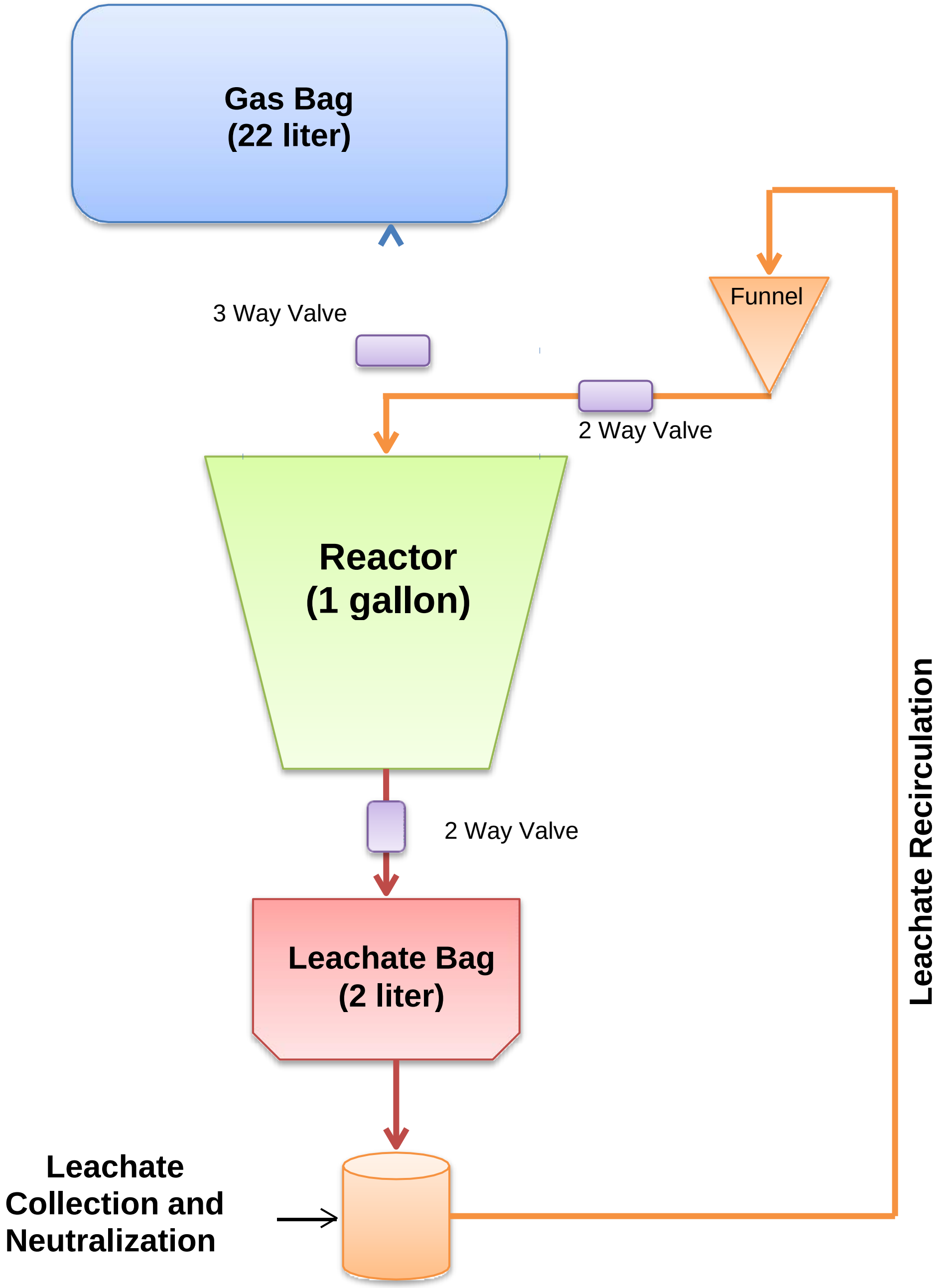


Figure 3.1 Design of Laboratory simulated AD setup

AD 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, VFA, Chemical Oxygen Demand (COD) was measured on a regular basis. Depending on the gas generation, gas composition and gas volume was measured. A summary of the experimental workflow is presented in Figure 3.2.

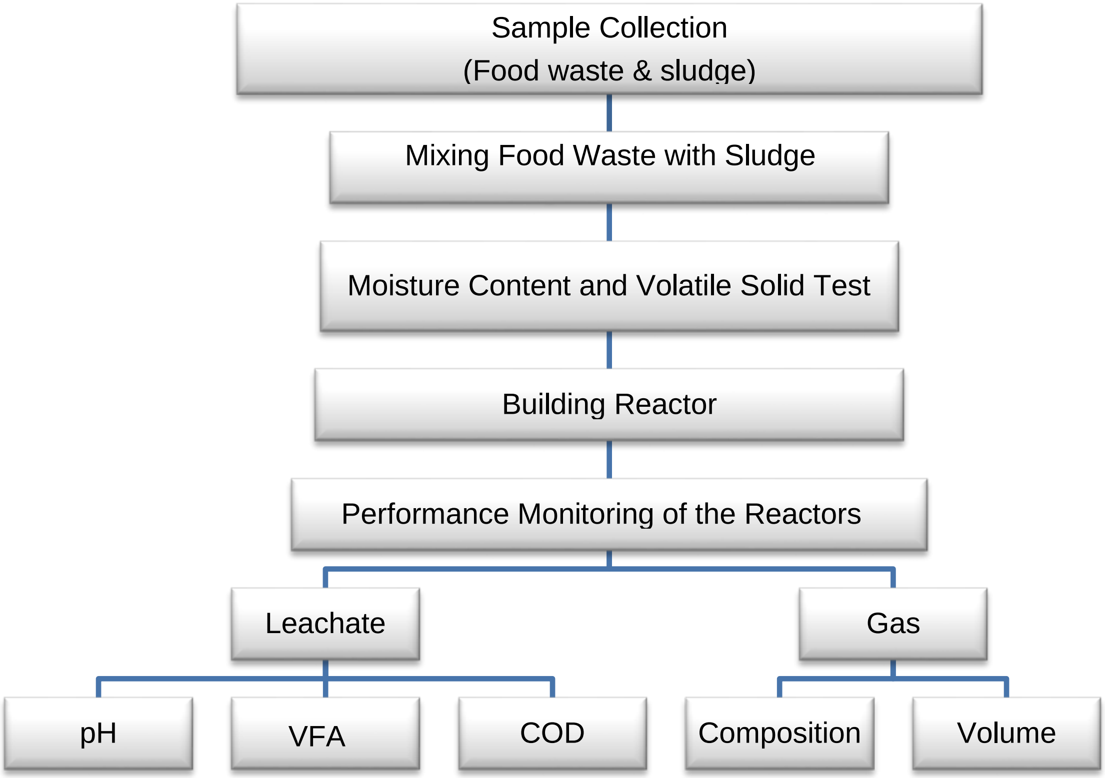


Figure 3. 2 Flow chart of the experimental work program

3.3 Sample Collection & Storage

3.3.1 Food Waste Collection

Food waste was collected from two sources:

i. Fruits and vegetables were collected from the UTA Compost Center.

ii. The meat and grains from the lunch buffet in the University Center dining (Connection Café) at the University of Texas at Arlington (UTA). Approximately 20 pounds of food waste was collected from the café, which contained meat and grain products (rice, noodles, pasta, bread, etc.). 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.


(a) (b)

(c) (d) (e)

Figure 3. 3 (a), (b) Collection of fruits and vegetable waste and collected sample; (c), (d) Collected meat and grain waste from UTA; (c) Environmental control chamber.

3.3.2 Collection of Sludge

Sludge was collected from Village Creek Water Reclamation Facility, Texas in a 5-gallon bucket as shown in Figure 3.4 which was added to the reactors as micro-organism source.

(a) (b)

Figure 3. 4 (a) Collection of Sludge; (b) Collected Sludge.

3.4 Laboratory Scale Simulated AD Setup & Monitoring

3.4.1 Preparation of Laboratory Scale AD

Laboratory scale AD 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 (R1 through R8) were prepared with pairs of four combinations as shown in Table 3.1. First two pairs (MGR1 & MGR2; FVR3 & FVR4) were with only 20 percent of sludge as inoculum and remaining two pairs (MGR5 & MGR6; FVR7 & FVR8) were considered for 30% sludge to investigate the effect of these sludge percentage on food waste degradation individually.

Building each AD required a certain set of materials and equipment as shown in Figure 3.5.

(a)

(b)

Figure 3. 5 (a) Materials and (b) equipment used for reactor building AD AD building operation is shown in Figure 3.8 through Figure 3.14.

Figure 3. 6 Drilling reactor bucket and lid

Figure 3. 7 Connecting tube and hose fitting.

Figure 3. 8 Tubing and valves connected using clamps and silicon sealant.

Figure 3. 9 Pea gravel and geo-composite inside the reactor bucket

Leak tests were conducted to make sure that there were no leaks present in the AD. The lids were sealed with silicon sealant and filled with water from the overhead tank through the base of the AD. All valves at the top plate were kept closed. The pressure was developed inside the bucket due to the head difference of water from the overhead container as shown in Figure 3.10. The leak tests confirmed there were no leaks on the AD since the water level in the manometer showed no significant changes.

Figure 3. 10 Leak test of reactors

Once the AD passed the leak test, the reactors were filled with food waste. Sludge was added with the waste as nutrients. No extra water was added since the original moisture of the waste and sludge was very high (more than 70%).

Waste was filled up to a level to facilitate sufficient space (1.5 inches from the 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 silicone sealant to make it airtight and leakproof. Once the sealing was done, the gas collection bags and leachate collection bags were connected to each AD and placed in the environmental growth chamber at 37°C (99° F). Figure 3.14 shows AD inside the environmental growth chamber.

Figure 3. 11 (a) Four types of food waste, (b) Mixing waste; (c), (d) filling reactors (e) weighing sludge and (f) mixing sludge

Figure 3. 12 AD 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 a wet weight basis. Approximately 2 lbs. of samples were collected from each pair of AD. 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 temperatures (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, the 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 at 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 3.13. The volatile organic content was determined from the percentage of weight loss.

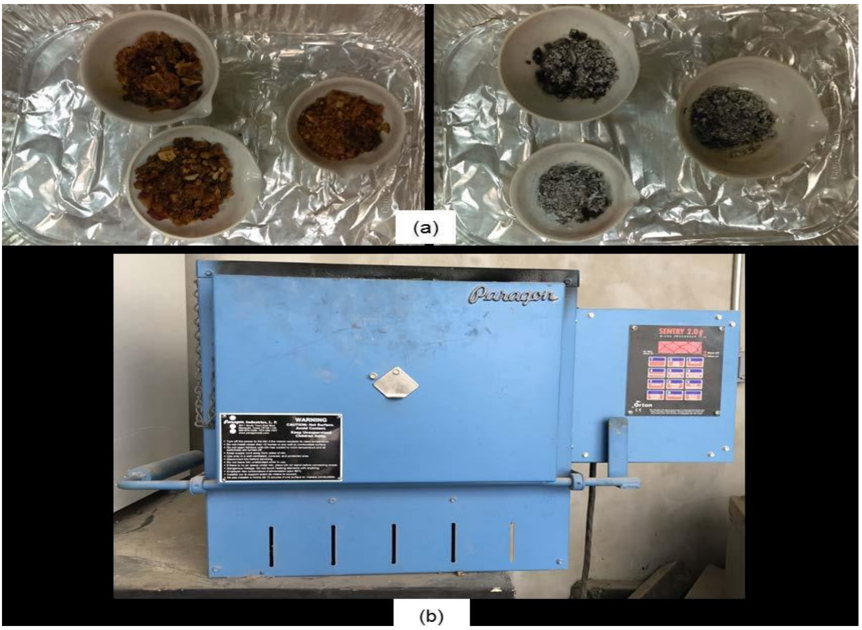


Figure 3. 13 Volatile solids determination (a) samples before & after burning, (b) muffle furnace

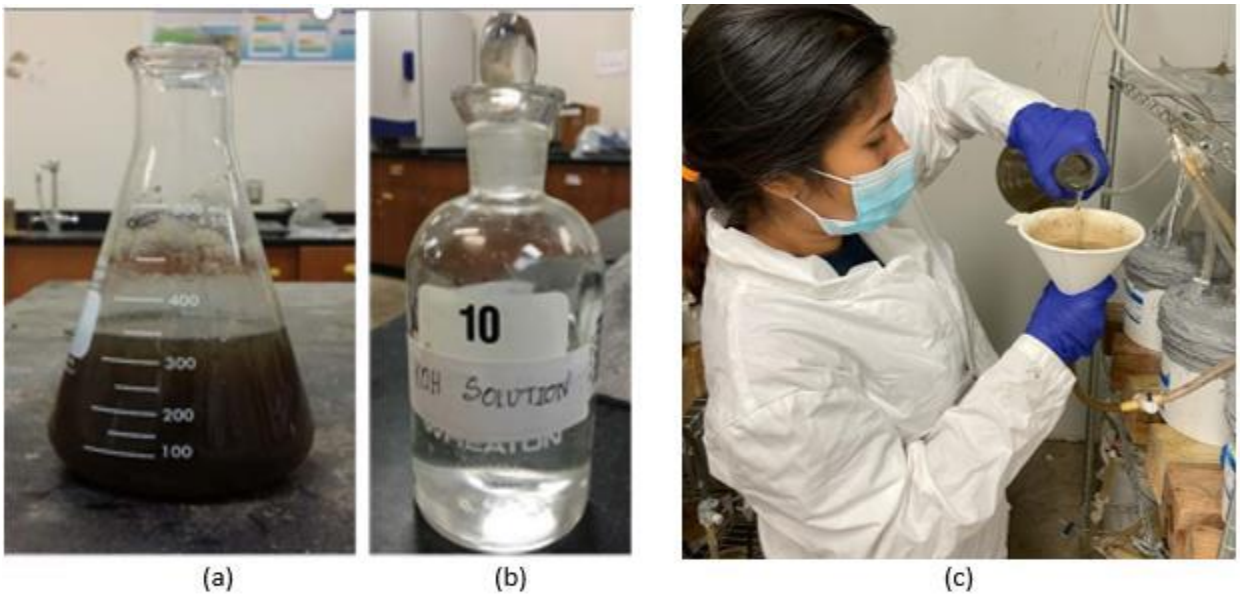
3.4.3 Operation & Monitoring of Reactors

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

3.4.3.1 Leachate Collection and Recirculation

Food waste has a high moisture content (almost 70 percent or more). Hence, after setting up the AD no moisture was added for a couple of days instead the digesters were allowed to drain excess moisture as leachate. During operation collected leachate was recirculated in the respective reactors every day in the beginning. Before recirculation, the volume of leachate was measured using a graduated conical flask. 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 3.14 and Figure 3.15.

Figure 3. 14 Leachate Collection



(a) (b) (c)

Figure 3. 15 Recirculation: (a) Leachate; (b) KOH buffer solution for leachate neutralization; (c) Leachate recirculation

3.4.3.2 Gas Collection and Measurement

During the AD operation, generated gas was collected in Cali-5-BondTM 22-liter gasbags. Gas was collected and measured on a regular basis whenever a considerable amount of gas accumulated in the bag. Landtec GEM 2000 PLUS with infrared analyzer was used for measuring the concentration of methane (%CH4), carbon dioxide (%CO2), oxygen (%O2) and other gases (%BAL) in the gasbags. To measure volume, gas was pumped out of the bag using a 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 the total volume was found. Figure 3.16 shows the gas composition and volume measurement.

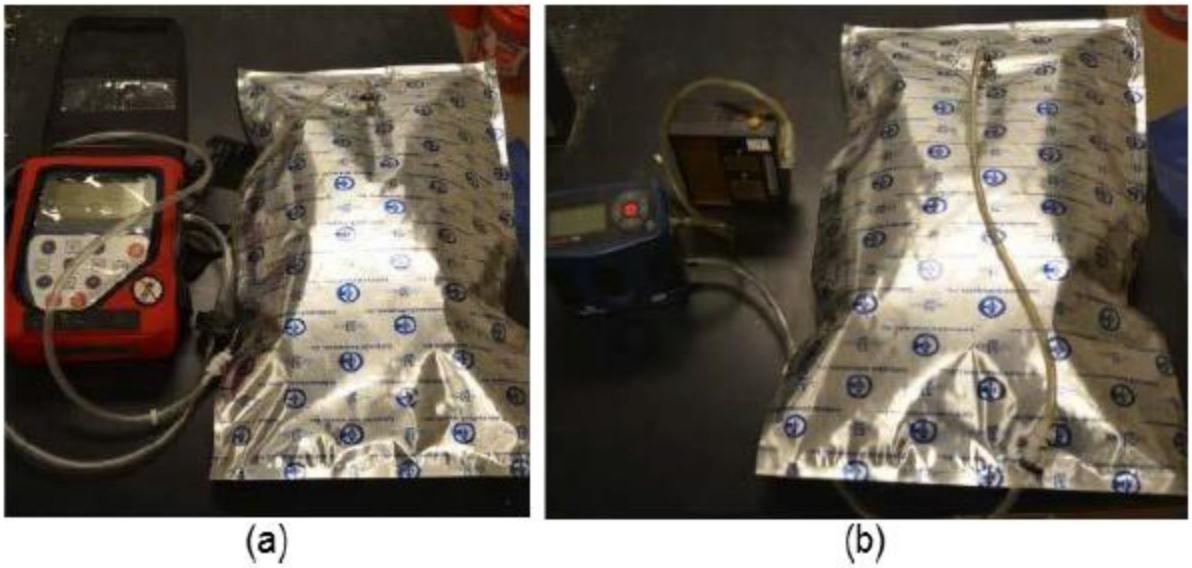


Figure 3. 16 (a) Determination of gas composition by Landtec GEM 2000, (b) Gas volume determination with SKC grab air sampler and Defender 510.

3.4.4 Monitoring Leachate Quality

3.4.4.1 pH

The pH of the leachate generated was measured with the help of a bench-top Oakton pH meter as shown in Figure 3.17. To ensure precise pH reading, the pH probe was calibrated by a 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. 17 pH measurement

3.4.4.2 Chemical Oxygen Demand (COD)

Chemical Oxygen Demand (COD) tests were performed monthly basis. For each reactor, two tests were conducted by diluting the leachate in 1:100 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 room temperature. The vials were then placed inside a spectrophotometer (Spectronic 200+) which determines the absorbance of light and displays an absorbance value. Figure 3.18 represents the procedure of COD measurement.

Figure 3. 18 Chemical oxygen demand (COD) determination: (from top left) COD vials, heating in the digester, vials after heating; (from bottom left) putting vials in the spectrophotometer, 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 3.19, 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.

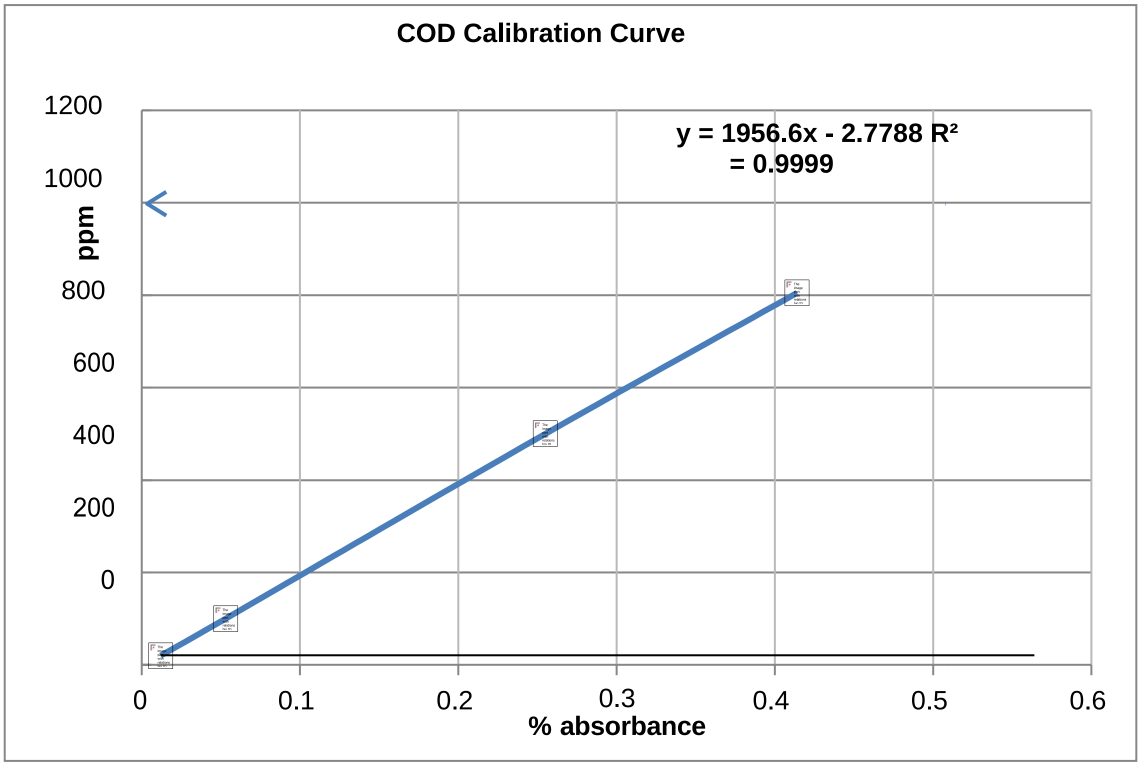


Figure 3. 19 COD calibration curve

3.4.4.3 Volatile Fatty Acid (VFA)

Volatile Fatty Acid (VFA) tests were performed monthly basis. For each reactor, tests were conducted by diluting the leachate in a 1:100 ratio. Titration method on basis of pH (DiLallo and Albertson, 1961) was used to measure VFA.

Initially, pH of the 50 ml filtered sample was measured. Then the pH of the sample was made 3.3-3.5 using H2SO4. Then the sample was allowed to boil for 3 minutes. After cooling, the pH of the sample was adjusted to 4 and the amount of NaOH consumed for making the pH 7 is measured. Figure 3.20 represents the procedure of VFA measurement.

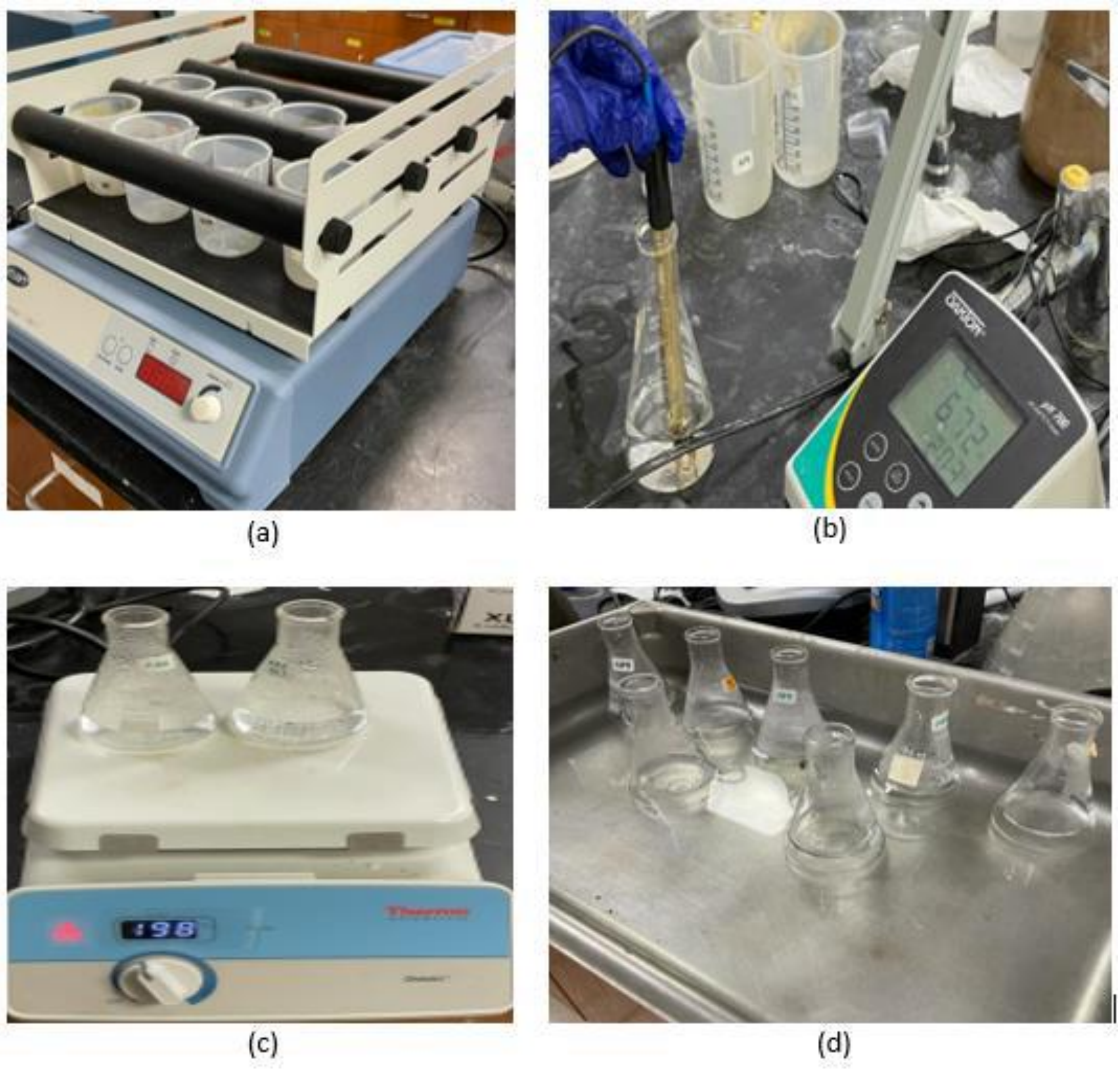


Figure 3. 20 VFA measurement: (a) Sample preparation in a mechanical shaker, (b) pH adjustment, (c) Boiling the sample, (d) Cooling the sample

The equation used for the measurement of VFA is:

VFA (mg/L) = (50000 x ml of NaOH consumed x Dilution Factor x N of Hydroxide)/ Volume of the sample (ml)

If VFA was observed to be greater than 180 mg/l, then it was multiplied by 1.5.

Chapter 4

Results and Discussion

4.1 Introduction

The results obtained from the laboratory simulated food waste bioreactors are evaluated to understand the effect of sludge 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 similar reactors as identical as possible. A total of eight (8) reactors were built with two pairs of reactors of meat and grain with two different combinations of nutrients and two pairs of reactors of fruit and vegetable with two different combinations 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, food waste was collected from two sources, one for fruits and vegetables another for meat and grain. The following subsections discuss the moisture content & volatile solids of the collected waste.

4.2.1 Initial Moisture Content of Food Waste for Reactors

Moisture content tests for both of the collected samples (UTA café and compost center) were conducted in triplicate. Food waste collected from the compost center had high moisture content compared to food waste from UC connection café. This was because fruits and vegetables were collected from compost center that usually contains a 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, had a high amount of rice which has an extremely low moisture content.

As discussed in chapter 3, sub-section 3.4.1, the experimental design was followed while filling the AD with different food waste. Food waste in itself does not have a considerable amount of microorganisms in it. Hence, to ensure microbial population, 20% and 30% sludge was added to the food waste mixture. A total of four pairs of AD were built of which 2 pairs were made of meat and grain with sludge content of 20% and 30% respectively. Another two pairs were of fruits and vegetables with 20% and 30% of sludge respectively. All the AD were filled with about three and a half pounds of food waste mixture. Since food waste had high moisture (78.35 % moisture content), rather than adding water at the beginning of operation, they were allowed to drain excess moisture for first couple of days.

For each pair of AD, food waste samples were collected after mixing with sludge for determining the characteristics of the waste inside the AD at the beginning of the operation. Therefore, the moisture content found will be referred to as the initial moisture content of the waste inside the reactor. Table 4.1 shows the initial moisture content of waste for each pair of reactors which was almost the same for eight reactors.

Table 4. 1 Moisture content of food waste inside the reactors

Reactor		Moisture Content(%) (wet weight Basis)
MGR1	(Meat+Grain+20% Sludge)	68.9
MGR2	(Meat+Grain+20% Sludge)	72.8
FVR3	(Fruit+Veg+20% Sludge)	88.7
FVR4	(Fruit+Veg+20% Sludge)	88.6
MGR5	(Meat+Grain+30% Sludge)	64.6
MGR6	(Meat+Grain+30% Sludge)	68.3
FVR7	(Fruit+Veg+30% Sludge)	90.1
FVR8	(Fruit+Veg+30% Sludge)	91.6

Moisture content found for the mixed food waste in this study was compared to the reported values found in the literature as shown in Table 4.2. The moisture content value found in this study was found to be comparable with the previous studies as shown in the bar chart (Figure4.1)

Table 4. 2 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)	64.6 ~ 91.6
Food Waste	82.86	Karanjekar (2013)	
Food Waste (Manure & sludge)	75.73 ~ 77.66	Zaman (2016)	

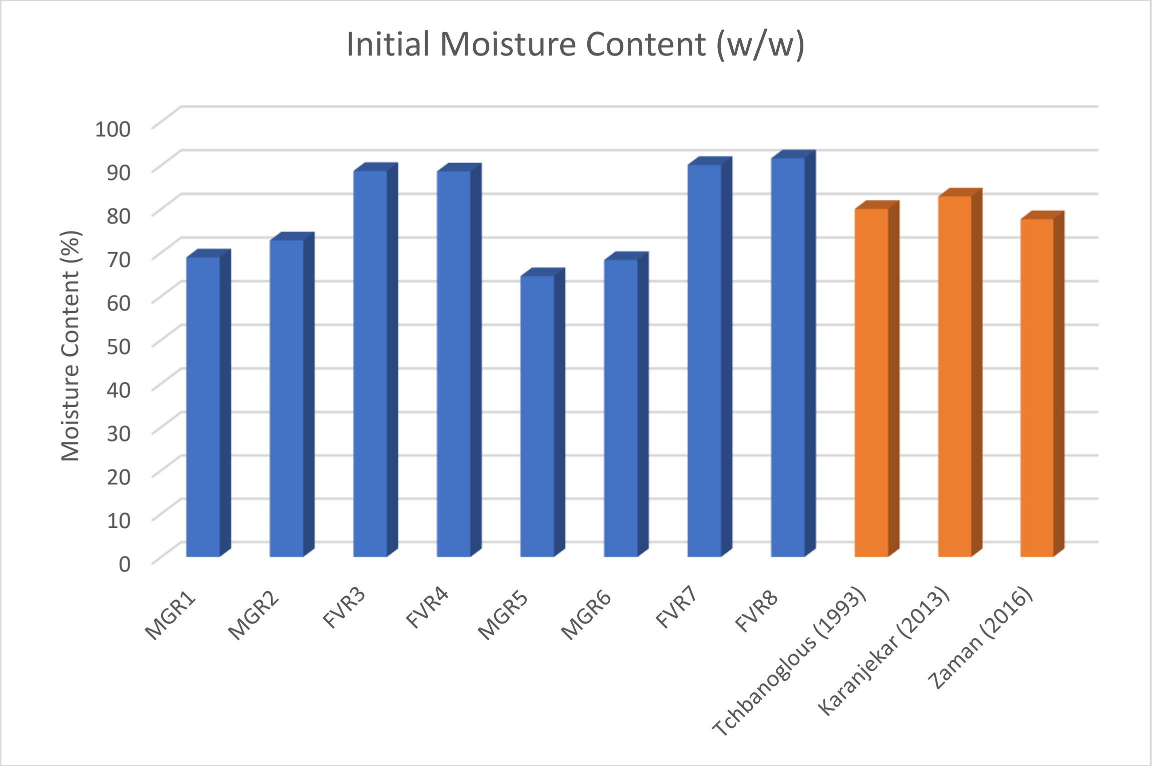


Figure 4. 1 Comparison of food waste moisture content found with previous studies

4.2.2 Initial Volatile Solids

Volatile solids (VS) are one of the determining factors 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. Table 4.3 shows the average volatile solids content for different reactors. Significant variation in volatile solids was observed, due to variation and non-uniformity of waste properties.

Table 4. 3 Volatile solids result for food waste in different set of reactors

Reactor	Volatile Solid (%)
MGR1 (Meat+Grain+20% Sludge)	85.2
MGR2 (Meat+Grain+20% Sludge)	83.4
FVR3 (Fruit+Veg+20% Sludge)	91.5
FVR4 (Fruit+Veg+20% Sludge)	89.7
MGR5 (Meat+Grain+30% Sludge)	86.8
MGR6 (Meat+Grain+30% Sludge)	85.2
FVR7 (Fruit+Veg+30% Sludge)	84.3
FVR8 (Fruit+Veg+30% Sludge)	86.1

Volatile solid results were compared to the VS from literature as shown in Table 4.4. The volatile solids determined for the current research were 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. 4 Comparison of volatile solids (VS) of the current study with previous studies.

	Volatile solids (%)	Author	Volatile solids(%) found in current study
Mixed food waste	88.34	Abu-Qudias (2000)	83.4 ~ 91.5
Food Waste	90.16	Karanjekar (2013)	
Food Waste (Manure & sludge mix)	91.66 ~ 92.96	Zaman (2016)	
Fresh Waste (MSW& sludge mix)	70.4 ~ 74.8	Hossain et al. (2014)	

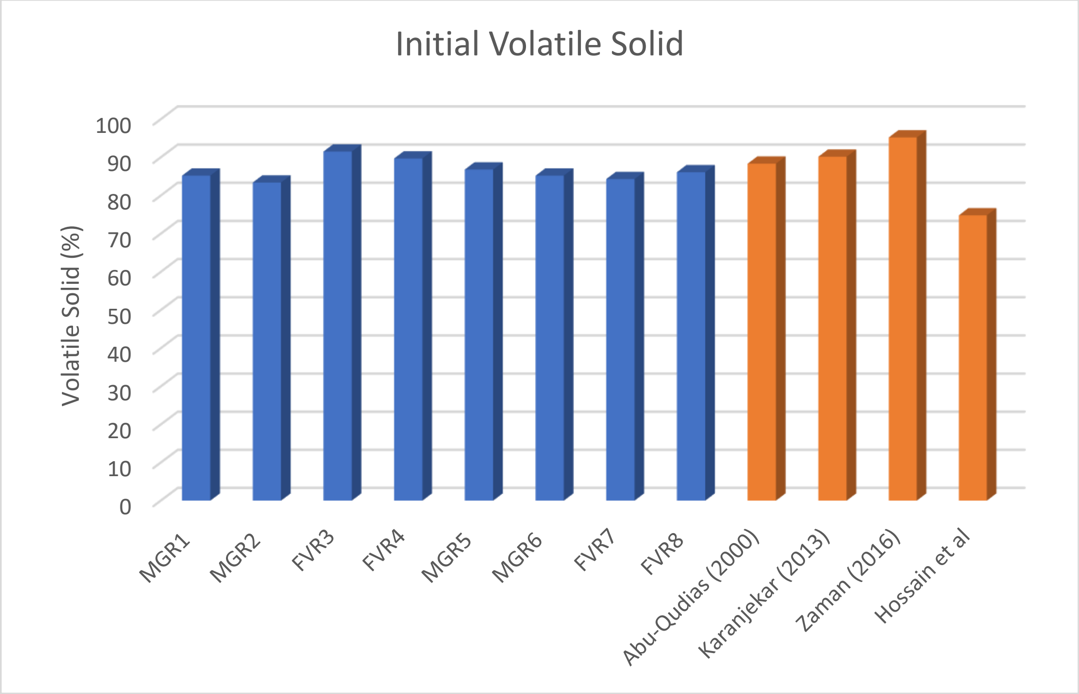


Figure 4. 2 Comparison of volatile solid found for food waste with previous studies

4.3 Characteristics of Inoculum

Microorganism helps the waste decompose faster. Especially in food waste or organic waste the microbial population is very low and requires inoculum from an external source to facilitate the decomposition of waste and gas generation as a byproduct. An increase in inoculum percentage increases gas production. Previous studies found some successful results by adding sludge from 20% to 80% (Liu et al., 2009; Wang et al., 1997; Karanjekar, 2013). However, for field applications, this high percentage is not feasible. In different studies of food waste digestion by anaerobic digester, manure was used as inoculum. In this study, sludge as inoculum was added to the different combinations of food waste to observe the effect of sludge on individual food waste components.

As mentioned earlier in chapter 3, sub-section 3.3.2 sludge was collected from the Village Creek Water Reclamation Facility, Texas, to be used as inoculum in the food waste reactors. Typically, sludge contains a high microbial population and as sludge is being digested anaerobically so it has a good amount of anaerobic bacteria in it. Sludge usually has high pH because of being digested anaerobically which might help to dilute the initial acidic environment generated in the food waste. The pH, moisture content, and volatile solid content were tested for the sludge collected before mixing it with food waste. The test results are shown in Table 4.5.

Table 4. 5 Test results for sludge

Name of the test	Result
pH	7.21
Moisture Content	98.36%
Volatile Solid	86.2%

4.4 Leachate Monitoring

Leachate monitoring included monitoring of pH, volume, chemical oxygen demand (COD) and volatile fatty acid (VFA) is discussed in the following subsection.

4.4.1 pH

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

Meat and grain AD were the first to show a stable increase rather than high fluctuation noticed at the beginning of the operation, followed by AD of fruit and vegetable reactors. For the first 90 days, pH was measured more frequently compared to the rest of the operational time of the AD. pH variation with time for all the reactors is graphically presented in Figure 4.3.

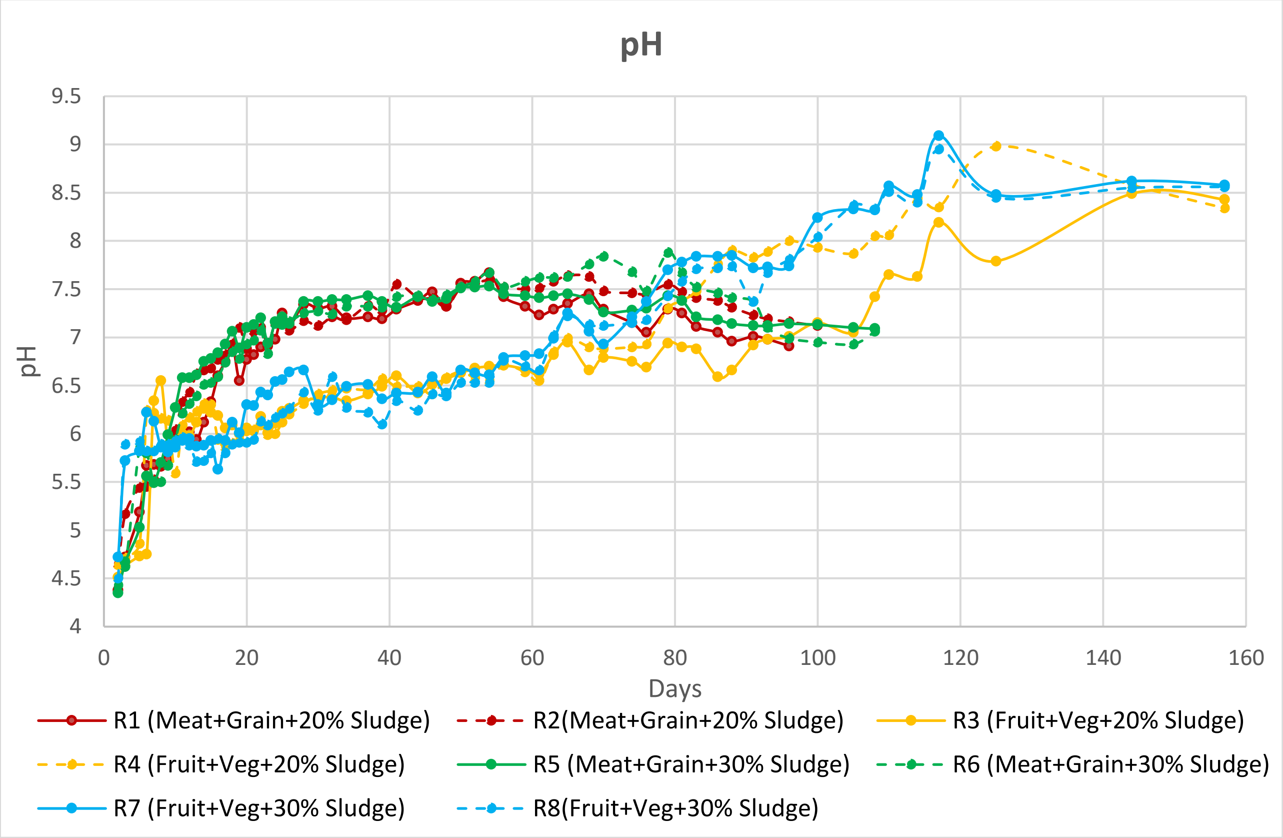


Figure 4. 3 Change in pH over the time of the leachate collected.

At the beginning of the operation, the pH of the reactors dropped rapidly due to the acidogenic phase and excessive volatile fatty acid (VFA) accumulation in food waste (Shao et al., 2005) which might be responsible for lower pH for a 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 was acidic (pH 5 or below). Leachate was recirculated on regular basis for pH neutralization with the addition of KOH whenever the pH of the leachate falls below 7.0. pH gradually became stable between 6 and 7 after 20 days (about 3 weeks) of recirculation for reactors with meat and grain (MGR1, MGR2, MGR5 & MGR6) and 60 days (about 2 months) after recirculation for fruit and vegetable reactors (FVR3, FVR4, FVR7 & FVR8). After that, the pH of the leachate gradually started increasing. KOH neutralization was done whenever pH tends to decrease.

pH started increasing faster for reactor MGR1, MGR2, MGR5 & MGR6 which has meat and grain. All these reactors crossed pH 7.0 before 20 days (about 3 weeks). It is because protein degradation releases ammonia which increases the pH faster (Sabrina et al., 2012). As MGR1, MGR2, MGR5 & MGR6 contain meat and meat is a source of a high amount of protein which leads to the faster increment of pH. But after crossing pH 7.0, the pH did not increase that much. For MGR1 and MGR2 the pH increased up to 7.67 and 7.76 respectively and then it started decreasing. For MGR5 and MGR6 the peak of pH was 7.67 and 7.84 respectively and then the pH started decreasing gradually. Once the pH started decreasing, Reactor operation in MGR1 and MGR2 was stopped after 96 days and 100 days of operation, respectively. The same happened to reactor MGR5 and MGR6 after 108 days of operation.

Again, it took time to increase pH for reactor FVR3, FVR4, FVR7 & FVR8 which contains fruit and vegetable. They were in an acidic phase (>60 days) for a longer period than meat and grain reactor. It is because fruit and vegetable wastes are hydrolyzed quickly due to low TS and high VS which leads to acidification and a rapid decrease in the pH (Chao, 2017). That is why it took time to increase pH for FVR3, FVR4, FVR7 & FVR8.

In the case of reactor FVR7 and FVR8 which had 30% sludge mixed with fruit and vegetable, pH was below 7.0 up to 63 days. After 63 days of lag period pH in reactor FVR7 and FVR8 started going above 7.0 and increased up to 9.09 and 8.95 for reactor FVR7 and FVR8, respectively. The gas generation from reactor R7 and R8 also significantly increased during this period due to reaching the methanogenic phase of degradation.

For reactor FVR3 and FVR4 which were having fruit, vegetable, and 20% sludge, the lag phase was a bit longer than reactor FVR7 and FVR8 which had fruit, vegetable, and 30% sludge. For reactor FVR4 pH was below 7.0 for 76 days and it was 93 days for reactor FVR4 which is a duplicate of reactor FVR3 as well. After 76 days of lag phase, the pH increased up to 8.55 and 8.98 for reactor FVR3 and FVR4, respectively. The gas generation significantly increased during this period as well due to the optimum environment for methanogenic bacteria.

A study was done by Wang et al. (1997) on food waste reactors which showed a similar trend in pH variation except the initial pH was higher than the current study and also the lag phase was shorter as shown in Figure 4.4. This was because the authors used a high percentage of inoculum (up to 70%) as the lower percentage (30%) failed in their case. The use of higher inoculum diluted the acidic environment and helped reducing lag time.

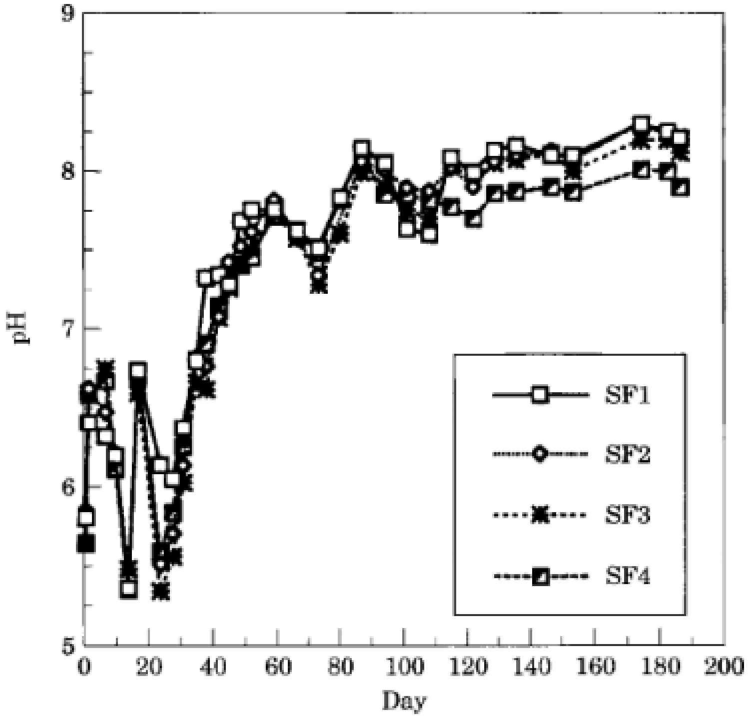


Figure 4. 4 Change in pH of the reactors with time (Wang et al., 1997)

4.4.2 Leachate Volume

The purpose of leachate recirculation in landfills is to maintain the 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 extremely acidic environment created by the acid accumulation in the 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 30, then it was done every alternate day, and afterward, the frequency of recirculation was reduced. Generated leachate volume measurement data are shown in Figure 4.5.

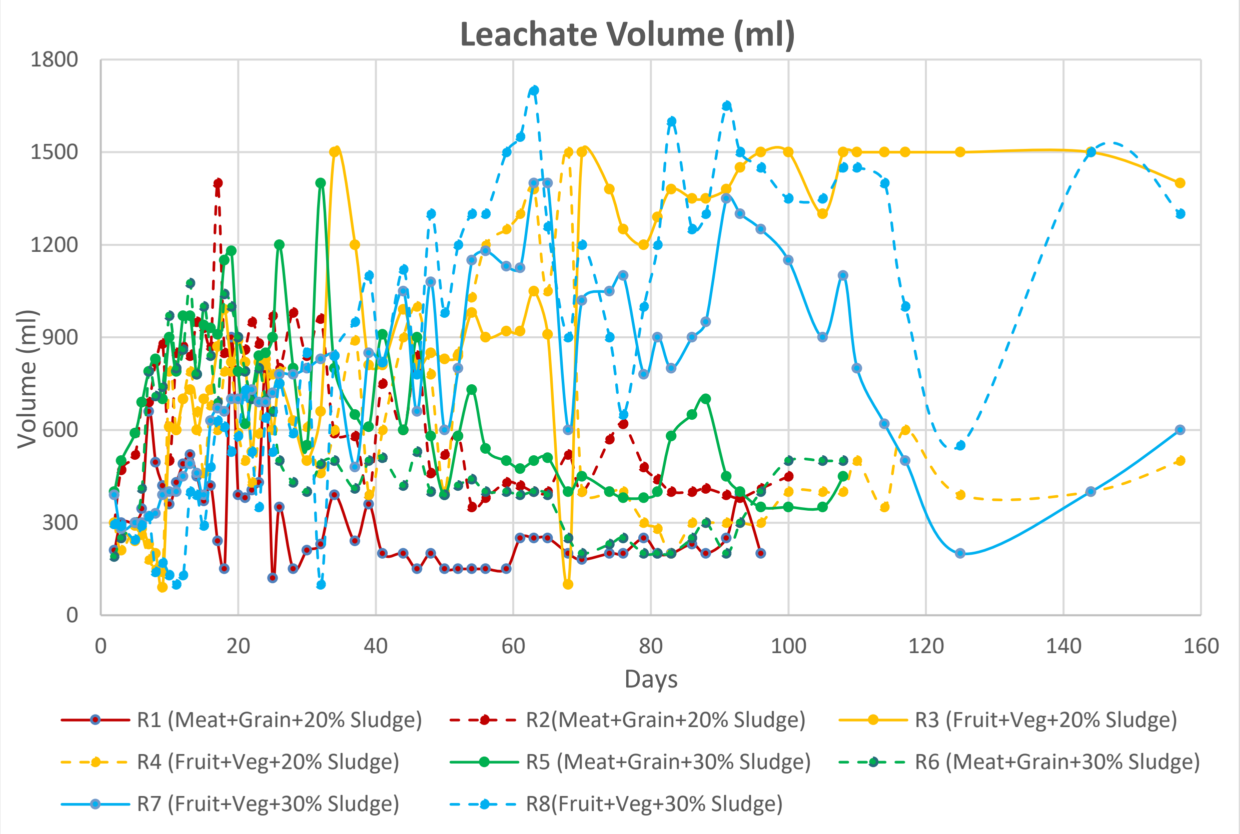


Figure 4. 5 Volume of leachate generated from the reactors

From the leachate generation data, it was observed that in the initial stage the generation of leachate was almost the same for all the reactors and the volume was increasing. Gradually, the volume of leachate started decreasing for reactors with meat and grain that is MGR1, MGR2, MGR5, and MGR6 after 20 days. On the other hand, the leachate volume for the reactor with fruit and vegetable was increasing day by day. It can be observed that when the leachate volume was the highest, the generation of gas and methane were also at the peak for those reactors because moisture accelerates the degradation process.

4.4.3 Chemical Oxygen Demand (COD)

Variation in chemical oxygen demand (COD) for the reactors is shown in Table 4.6 andalso Figure 4.6 shows the graphical representation. The test for COD was done monthly on the leachate collected. In this study, all the reactors have 100% different components of food waste and for all ofthe reactors, a high value of COD was observed.

Table 4. 6 Monthly COD test data

Age (month)	**Chemical Oxygen Demand (COD) (mg/L)**							
	MGR1 (Meat+Grain+20 % Sludge)	**MGR2 (Meat+Grain+20 % Sludge)**	**FVR3 (Fruit+Veg+20% Sludge)**	**FVR4 (Fruit+ Veg+20 % Sludge)**	**MGR5 (Meat+ Grain+ 30% Sludge)**	**MGR6 (Meat+ Grain+ 30% Sludge)**	**FVR7 (Fruit+ Veg+30 % Sludge)**	**FVR8 (Fruit+ Veg+30 % Sludge)**
1	206904.7	211034.9	177381.4	165739.6	219839.6	200273.6	174544.3	167696.2
2	213969.8	239405.6	176011.8	170435.5	236697.3	206419.6	152798.8	160456.8
3	217163.3	248417.7	160807.7	156900.9	240604.1	211303.1	147719.9	144301.5
4	223303.1	291392.5	153012.4	130725.4	242557.5	234514.1	119102.6	120958.4
5			131995.1	118614.3			113144.8	113437.8

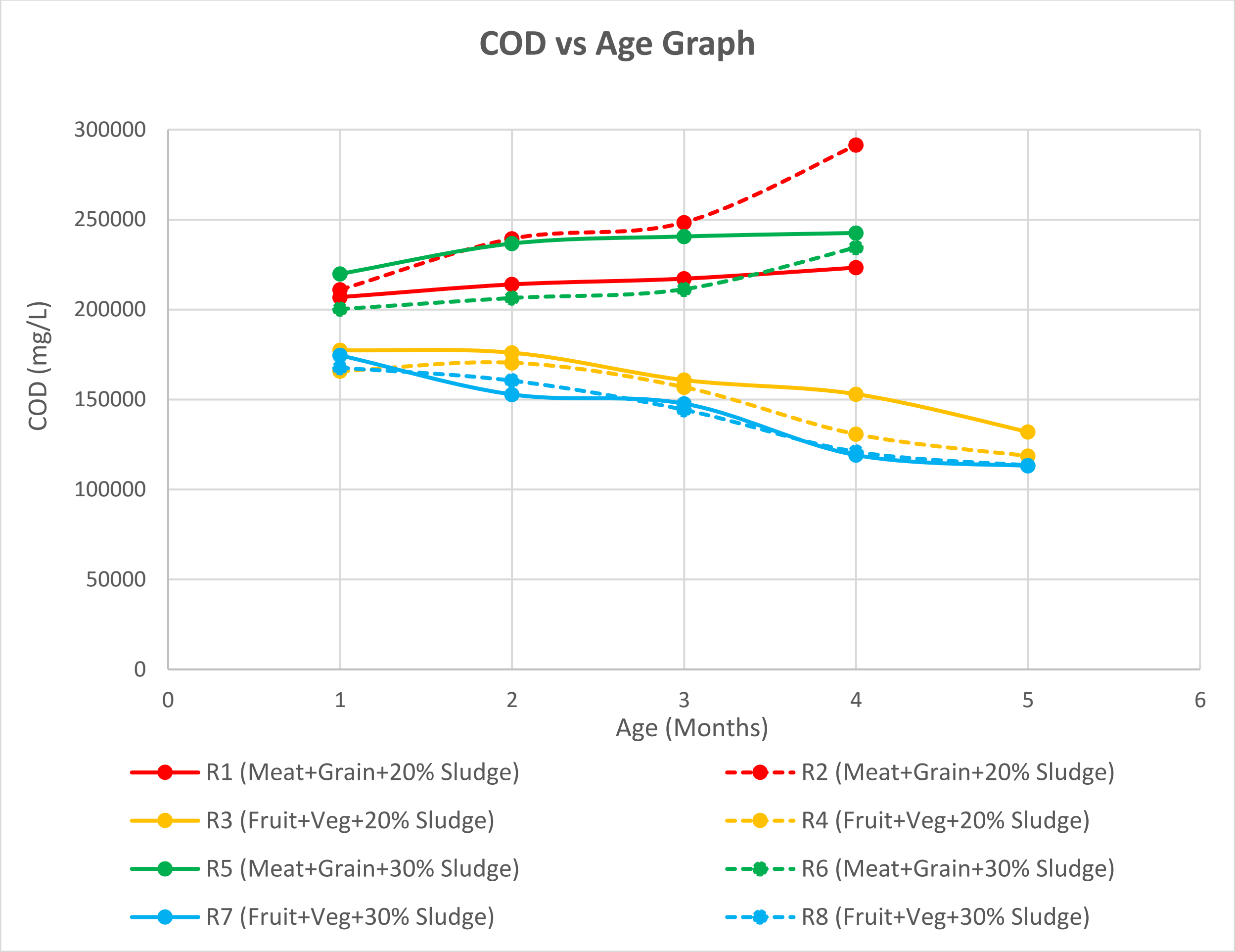


Figure 4. 6 Change in COD with time for the reactors

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 COD values for reactors with meat and grain were comparatively higher than the reactors with fruit and vegetable. Because the reactors were in lag phase which is the acidogenic phase and almost no degradation occurred.

In the case of reactor MGR1, MGR2, MGR5, and MGR6, the COD value was increasing from the beginning. The initial values of COD of reactor MGR1 and MGR2 were

206904.7 mg/L and 211034.9 mg/L respectively which gradually increased to 223303.1 mg/L and 291392.5 mg/L respectively at the end of the fourth month. The increasing value of COD indicates that the degradation did not take place properly in reactors with meat and grain due to VFA accumulation which stopped the operation in the reactors as well.

In the case of reactor FVR3, FVR4, FVR7, and FVR8, as soon as the acidogenic phase ended and the degradation took place and started to go into the methanogenic phase COD started dropping. Initial COD for reactor FVR3 and FVR4 were 177381.4 mg/L and 165739.6 mg/L respectively which reduced to 131995.1 mg/L and 118614.3 mg/L respectively at the end of the fifth month. Similarly, the COD values for reactor R7 and R8 reduced to 113144.8 mg/L and 113437.8 mg/L respectively from 174544.3 mg/L and 167696.2 mg/L.

Figure 4.7 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 vary 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 20% and 30%. As a result, their lag phase was significantly reduced and reached the methanogenic phase rapidly compared to the current study.

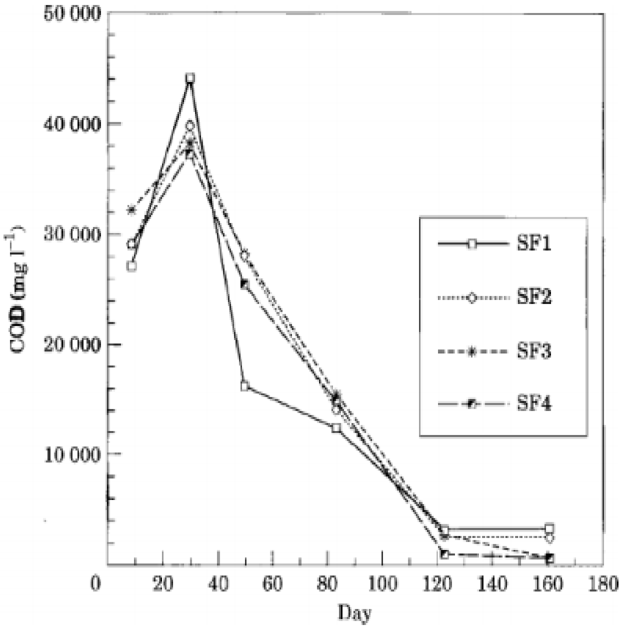


Figure 4. 7 Variation of COD over time in the reactors (Wang et al., 1997)

4.4.4 Volatile Fatty Acid (VFA)

Variation in VFA for the reactors is shown in Table 4.7 andalso Figure 4.8 shows the graphical representation. The test for VFA was done monthly on the leachate collected. In this study, a high value of VFA accumulation was observed for all the AD.

Table 4. 7 Monthly VFA test data

Age (month)	**Volatile Fatty Acid (VFA) (g/L)**							
	MGR1	**MGR2**	**FVR3**	**FVR4**	**MGR5**	**MGR6**	**FVR7**	**FVR8**
1	44.55	44.7	21.6	24.75	51.75	42.75	20.7	25.5
2	46.65	52.35	26.4	41.4	61.2	45.75	34.5	26.1
3	52.5	73.5	21	36	75	84	24.3	24.45
4	62.5	79.125	12.5	12.8	82.5	90	8.1	11.2
5			7	8.5			7.3	9.8

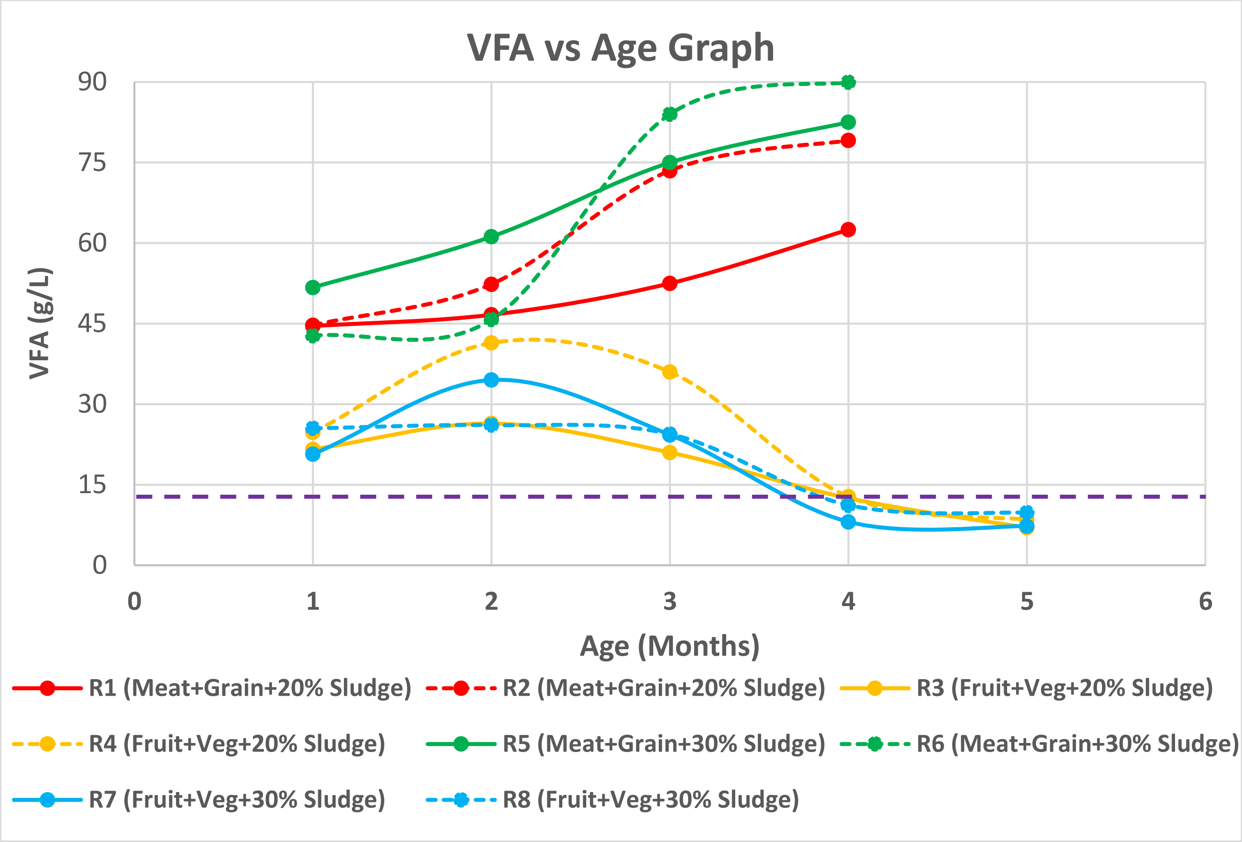


Figure 4. 8 Change in VFA with time for the reactors

It is observed that VFA accumulation was comparatively high for reactors MGR1, MGR2, MGR5, and MGR6 at the beginning which contain meat and grain. On the other hand, VFA accumulation was a bit less in the beginning for reactors with fruit and vegetable compared to reactors with meat and grain. Then the VFA accumulation started to increase for all the reactors in the second month. After the second-month VFA accumulation for reactors with fruit and vegetable started decreasing gradually while the VFA accumulation for reactors with meat and grain was still increasing.

In the case of reactor MGR1 and MGR2, the VFA accumulation was 44.55 g/L and 44.7 g/L respectively on the first month. Then the VFA accumulation was increasing for these two reactors every month and it became 62.5 g/L and 79.125 g/L respectively on the fourth month when the operation was stopped. Similarly, for reactor MGR5 and MGR6 VFA accumulation was 51.75 g/L and 42.75 g/L at the beginning which gradually increased to 82.5 g/L and 90 g/L in the fourth month. Because of the continuous increase of VFA in these reactors, their methane generation was negligible and their operation was stopped early.

Again, for reactor FVR3 and FVR4 VFA accumulation was 21.6 g/L and 24.75 g/L respectively at the first month. Then it was increased to 26.4 g/L and 41.4 g/L respectively in the second month. After the second month, VFA accumulation started decreasing and it became 7.3 g/L and 9.8 g/L respectively in the fifth month. From a study done by Viéitez et. al. (1999), it has been found that if VFA accumulation is greater than 13 g/L it will create an inhibitory environment for methane production. The VFA accumulation for reactor FVR3 and FVR4 went below 13 g/L in the fourth month and then they started showing a great amount of methane production throughout the fifth month.

For reactor FVR7 and FVR8, the VFA was 20.7 g/L and 25.5 g/L in the first month and then it increased in the second month. Finally, the VFA accumulation reduced to 7.3 g/L and 9.8 g/L respectively in the fifth month. For reactor FVR7, VFA accumulation crossed 13 g/L after almost three and half months and the same happened for reactor FVR8 just before four months. When their VFA accumulation was less than 13 mg/L, they were showing a good percentage and volume of methane generation like reactor FVR3 and FVR4.

Figure 4.9 shows a result found by Jiang et. al. (2013), which shows VFAs were produced in the acidogenesis and acetogenesis steps. Figure 4.9 shows the variation in VFAs concentration in the reactor at different pH conditions. Under all pH conditions, the concentration increased rapidly at first and then was relatively stable and changed little. The maximum VFAs concentrations at pH uncontrolled, 5.0, 6.0, and 7.0 were 3.94, 17.08, 39.46, and 37.09 g/L, respectively, indicating that the greatest VFAs production was occurred at pH 6.0. The same happened for reactors with fruit and vegetables. Their VFA accumulation was at its peak when pH the pH was around 7.0 and it started decreasing as soon as the pH was around 7.0.

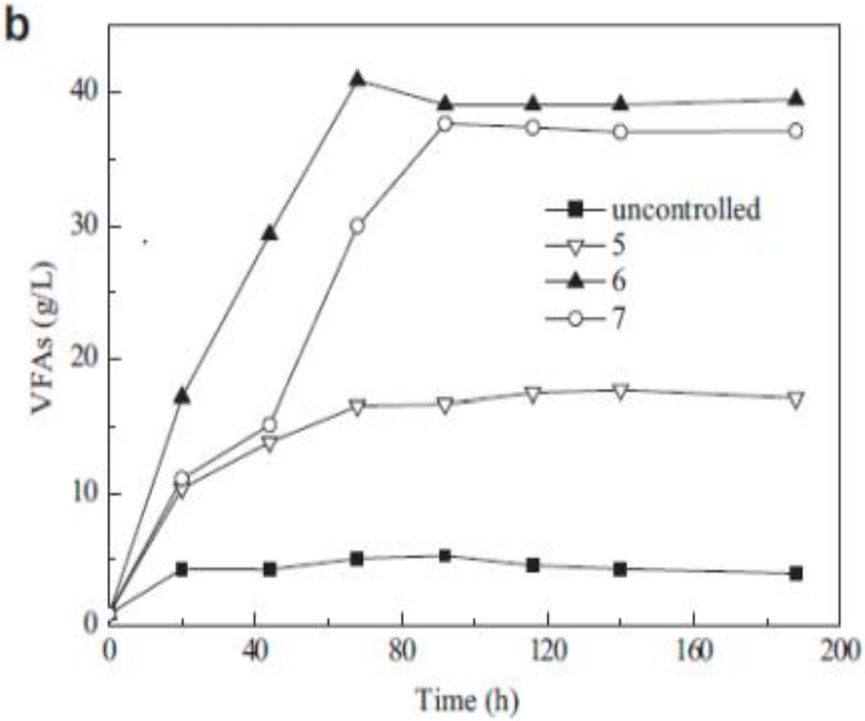


Figure 4. 9 VFA concentration of food waste at different pH values

4.5 Reactor Gas Data

4.5.1 Gas Composition

The reactors were operated at 37°C inside an environmental growth chamber. Gas data were collected whenever there was gas inside the gasbags. Figure 4.10 shows a 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 4.10) it can be seen that the initial percentage of oxygen in the reactors was a bit high which depleted rapidly. This was the aerobic phase where gas mainly consisted of carbon dioxide in high percentage and other gases (e.g. H2S, nitrogen compounds, etc.). In this stage, all the reactors had a 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 a high percentage of food waste, a sudden drop in pH occurs due to the accumulation of excessive volatile fatty acid. Reactors in the current study had pure organic waste which was different types of food waste. As a result, the environment inside the reactors kept getting acidic which was neutralized frequently through the addition of KOH with leachate. The excessive acid accumulation tends to inhibit bacterial activity which in turn affects the gas production, creating a lag phase before the decomposition enters the 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 Figure 4.10, with time percentage of gas component went down due to little to no gas production. Apart from reactors FVR3, FVR4, FVR7 and FVR8 (which had fruit and vegetable in addition to sludge), all the other reactors containing meat and grain were still in lag phase. Reactors FVR7 and FVR8 entered the methanogenic phase earlier than reactor FVR3 and FVR4.

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 five months and till that time reactor FVR3, FVR4, FVR7, and FVR8 were found to have reached the methanogenic phase. The pH of these reactors went as high as 8.55, 8.98, 8.95, and 9.09 respectively while methane content showed a much higher value than previous studies. Methane content for the reactors FVR3 and FVR4 were found to be stabilized around 68~72%. The remaining 20~28% were found to be composed of mainly carbon dioxide and a negligible amount of other gases. Similarly, methane content for reactors FVR7 and FVR8 were stabilized between 51~52%. Oxygen content in these reactors was near to zero during this time as the reactors were operated in anaerobic conditions.

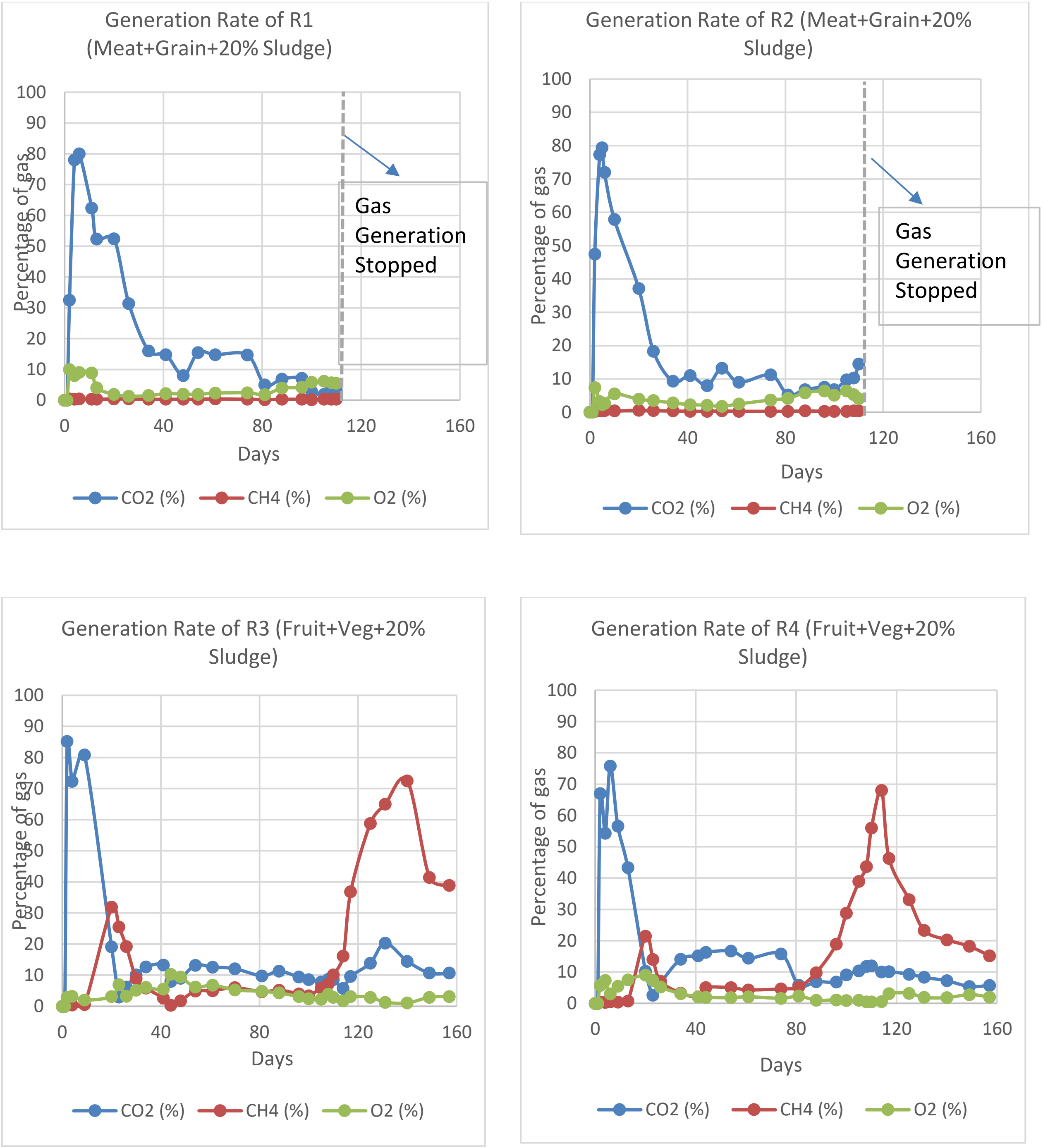


Figure 4.10 Gas composition data for all AD

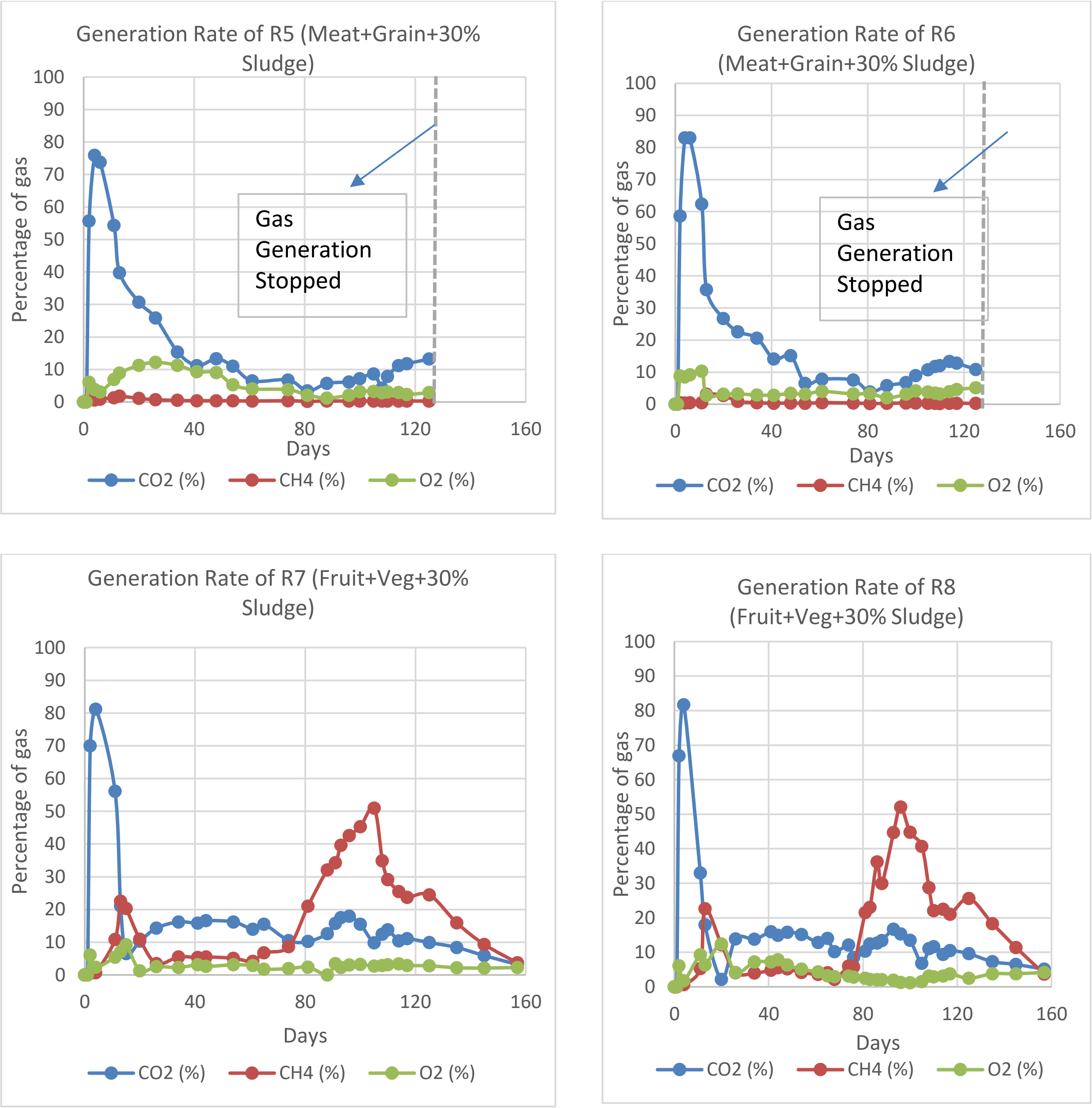


Figure 4. 10 Gas composition data for all AD (Contd.)

The initial increase in carbon dioxide was due to the breakdown of organics into simpler compounds and carbon dioxide generation as a by-product. Over time carbon dioxide percentage decreased and the methane percentage increased. Till the reactors reached the methanogenic phase methane to carbon dioxide ratio was below 1.0. The scenario of increasing methane and decreasing carbon dioxide can be shown by CH4:CO2 vs the time graph in Figure 4.11. For reactors FVR3 and FVR4 the ratio increased to as high as 8.5 and 6.6 respectively and for FVR7 and FVR8 it increased to 5 and 5.9, respectively. For the remaining reactors they were still in lag phase and no gas was produced during the time.

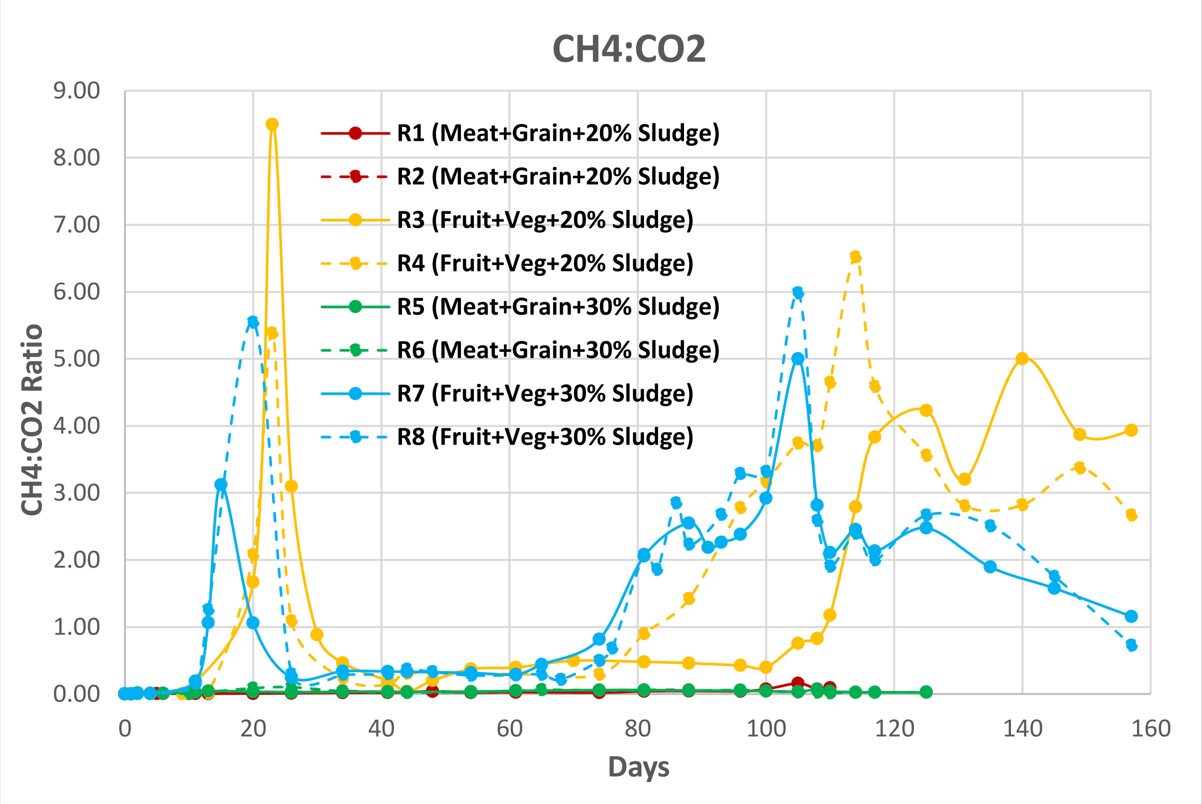


Figure 4. 11 Variation in methane to carbon dioxide ratio over time (days)

4.5.2 Gas Volume

Total gas generated from all the AD with time is shown in Figure 4.12. It was observed that reactor MGR1, MGR2, MGR5, and MGR6 were producing the highest amount of gas from the beginning and the gas generation rate was a bit less for reactors FVR3, FVR4, FVR7, and FVR8. That means the reactors with meat, grain, and sludge were producing more gas in the beginning than the reactors with fruit, vegetable, and sludge. But after around 20 days the gas generation rate started decreasing for reactors with meat, grain, and sludge. It was because meat and grain reactors were producing a huge amount of CO2 during the acidic phase which bumped up the gas generation in the beginning. On the other hand, though the reactors with fruit and vegetable were producing less gas at the beginning, after 60 days when their pH was near 7, the gas generation rate increased significantly. Again, when the VFA went below the inhibitory amount that is 13 g/L, the gas generation rate increased exponentially for reactors with fruit, vegetables, and sludge.

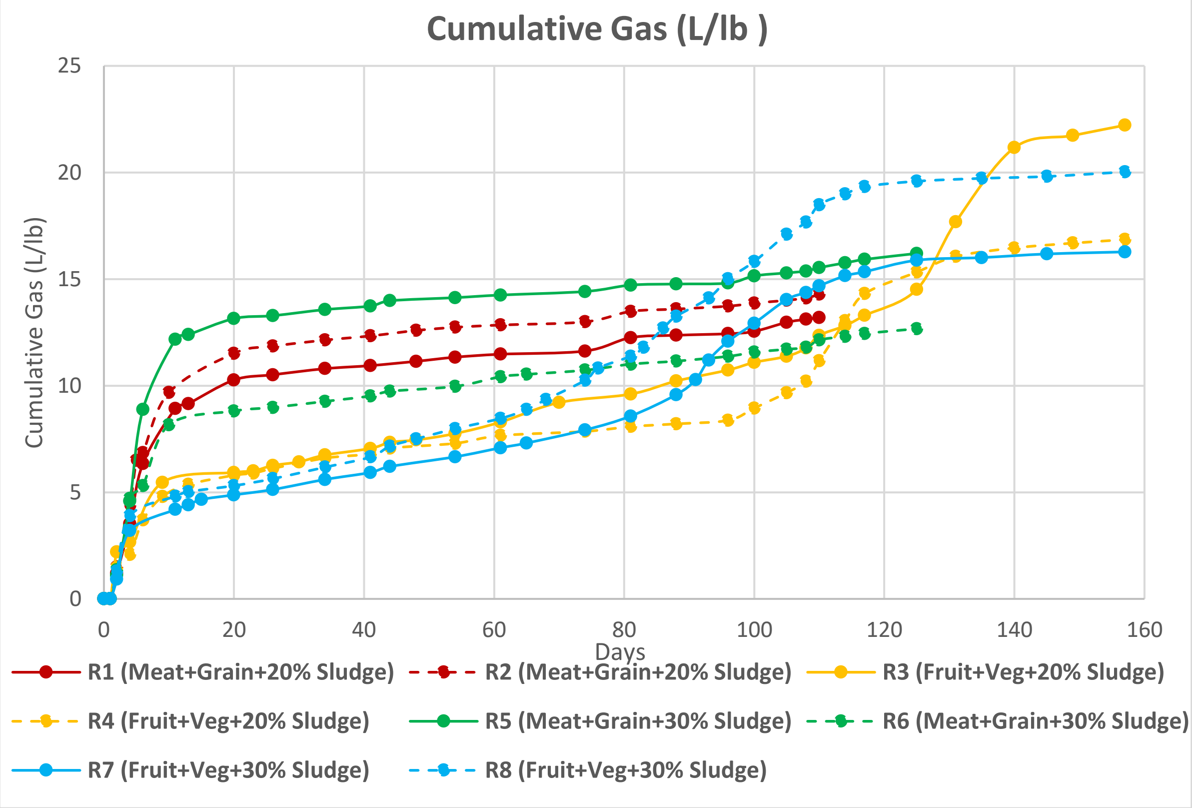


Figure 4. 12 Cumulative gas generated by reactor over the time

By observing the scenario of cumulative methane generation, methane generated in the initial phase was almost negligible. Due to 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 4.13 shows the cumulative methane generation with time. It can be seen that all the reactors containing meat, grain, and sludge produced a negligible amount of methane until they stopped gas production. In the case of reactor FVR7 and FVR8, they started producing a considerable amount of methane after around 75 days of lag period and rapidly went into the methanogenic phase. Similarly, reactor FVR3 and FVR4 started producing a good amount of methane after around 100 days as their methanogenic phase started. Reactor FVR3 produced a total of about 6.7 liters of methane per pound of food waste on a wet weight basis till 160 days of the observation period and it was still producing a considerable amount.

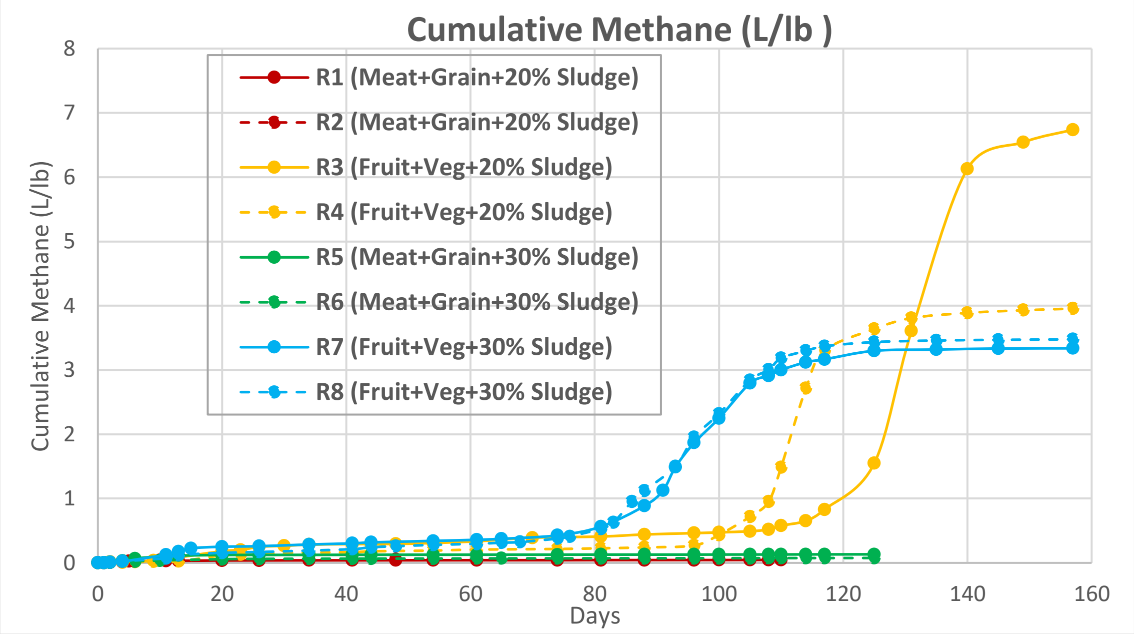


Figure 4. 13 Comparison of cumulative methane generation with time

In the case of reactor FVR4 which had the same configuration as reactor FVR3, the cumulative methane generation curve showed a similar trend. Except there was a bit long lag period of 88 days compared to reactor FVR3. Reactor FVR4 produced a total of about 4 liters of methane per pound of food waste on a wet weight basis till 160 days of observation period and it was just introduced into the methanogenic phase.

The acidogenic phase continued to be longer for reactors with meat and grain even after 160 days of the operation and the amount of methane generation was almost negligible. Therefore, it can be said that sludge was found to be a better source of inoculum for fruit and vegetable waste decomposition and methane generation compared to meat and grain waste.

All the reactors were monitored for around 160 days. In Figure 4.14, methane percentages for all reactors are shown. For the first 8-10 days, the CH4 percentage was very low for all reactors. Then methane production started for reactors FVR3, FVR4, FVR7, and FVR8 which contain fruit and vegetable and their methane percentage started increasing. But for reactors MGR1, MGR2, MGR5, and MGR6 there was no significant percentage of methane and it was almost negligible. The highest methane percentage was found from reactors FVR3 and FVR4 which were 72.5% and 68% respectively. Then the second-highest percentage of methane was found in reactor FVR7 and FVR8 which were 52.1% and 51% respectively.

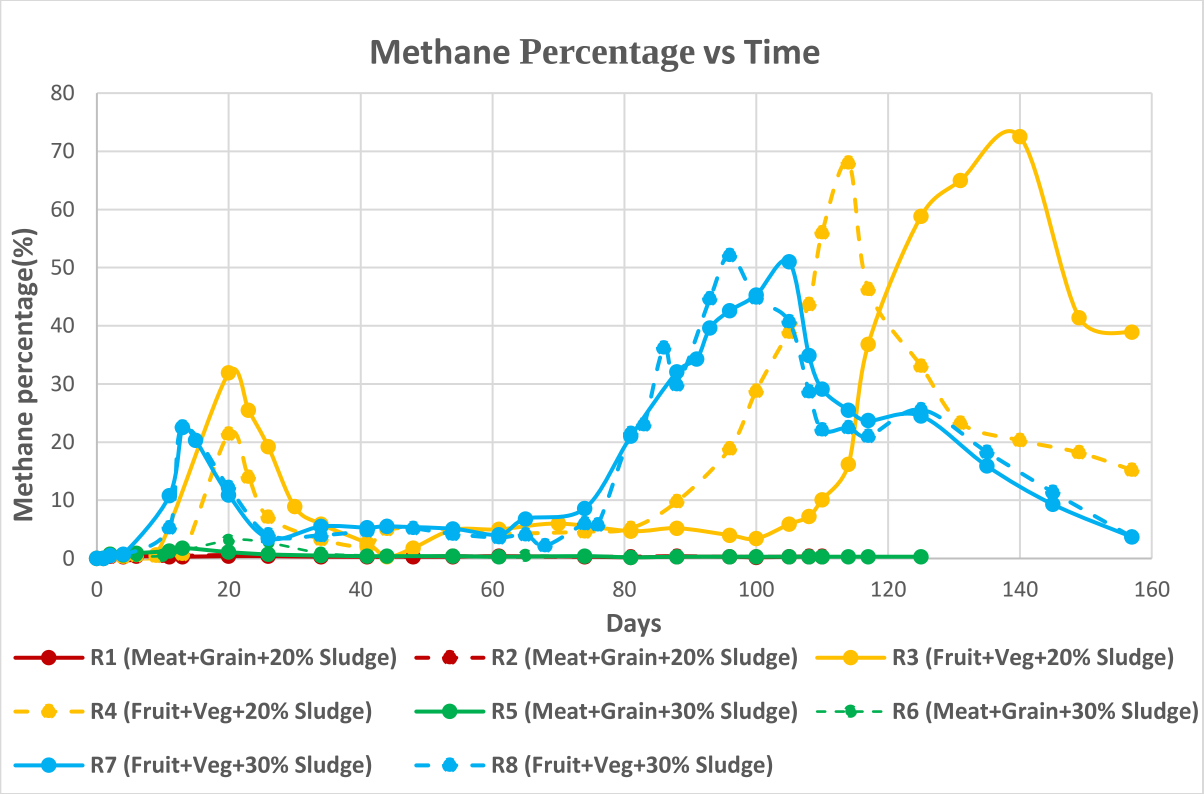


Figure 4. 14 Methane Percentage vs. Age for all reactors

The total daily gas generation rate or gas yield graph and methane yield graph for the reactors show a similar trend (Figure 4.15 and 4.16) 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 a greater gas yield followed by a lag phase. In the beginning, the reactors with meat, grain, and sludge were producing a huge amount of gas every day. Reactor FVR3, FVR4, FVR7, and FVR8 produced a good amount of gas in the beginning, then the lag phase was introduced. The lag period continued for 40 ~ 60 days for reactor FVR3, FVR4, FVR7, and FVR8 which then started producing gas and gradually entered the methanogenic phase (Figure 4.16).

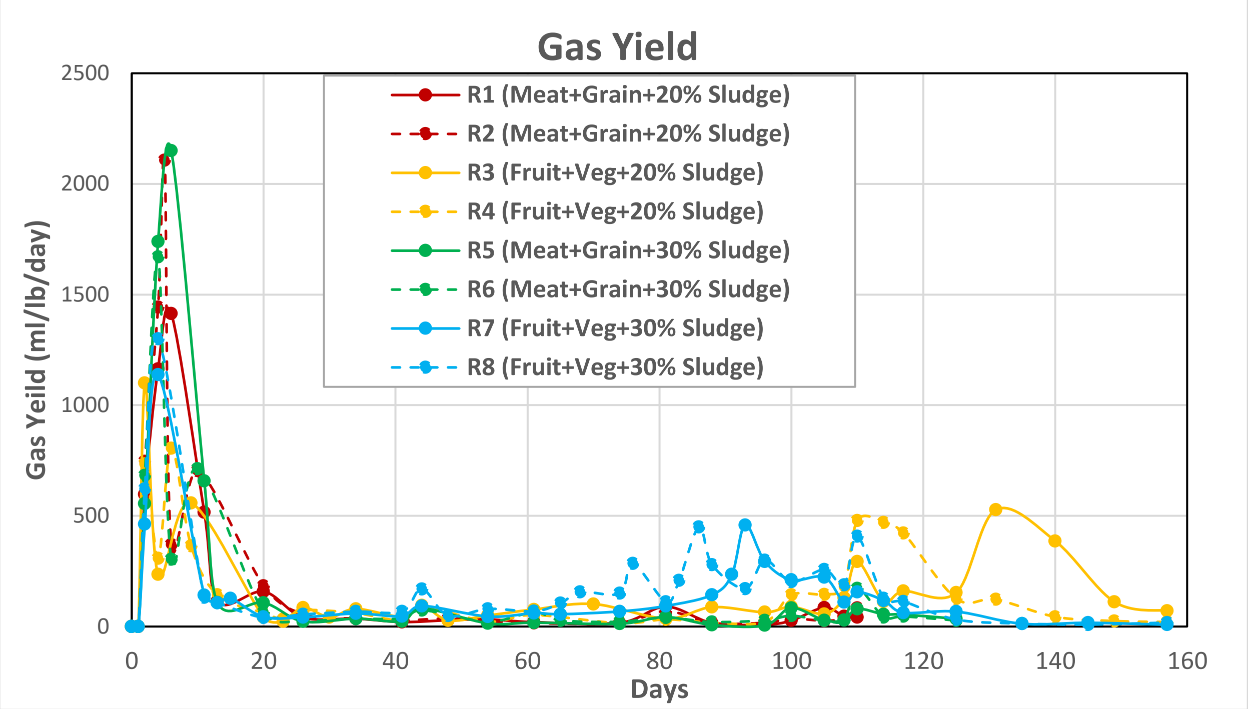


Figure 4. 15 Comparison of total gas generation rate with time for the reactors

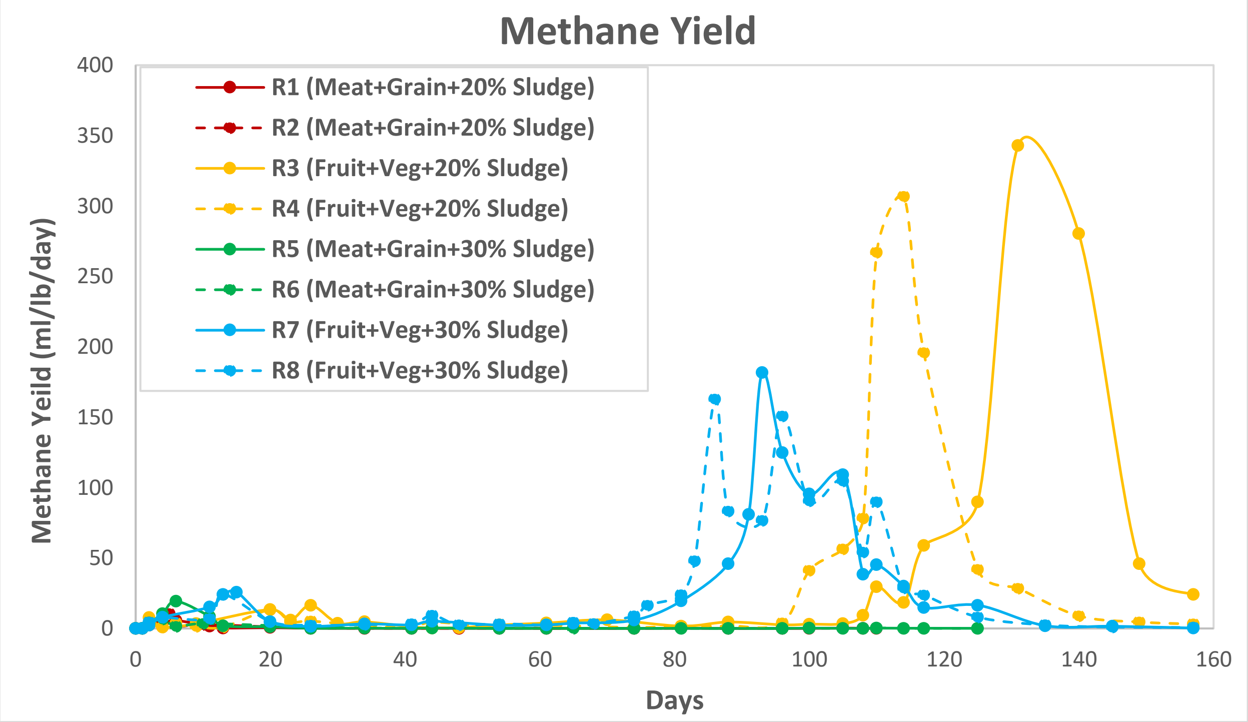


Figure 4. 16 Comparison of methane generation rate with time for the reactors

In the methanogenic phase, methane yield was found to be as high as 343 mL per pound per day for reactor FVR3, and for reactor FVR4 the value was 307 mL per pound per day on a wet weight basis. The gas yield graph, as well as the methane yield graph, shows multiple peaks because of the non-homogeneity of waste and all the waste components did not start decomposing at the same time.

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 observations were reported in a study done by Wang et al. (1997) where the 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 20% and 30%. Although the percentage was low compared to the previous study it was successful for a pair of reactors where seed included sludge. In another study by Karanjekar (2013) showed an addition of 20% sludge as the seed to the food waste reactor produced a 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 4.17 the black curve shows the result of 100% food waste found by Karanjekar (2013).

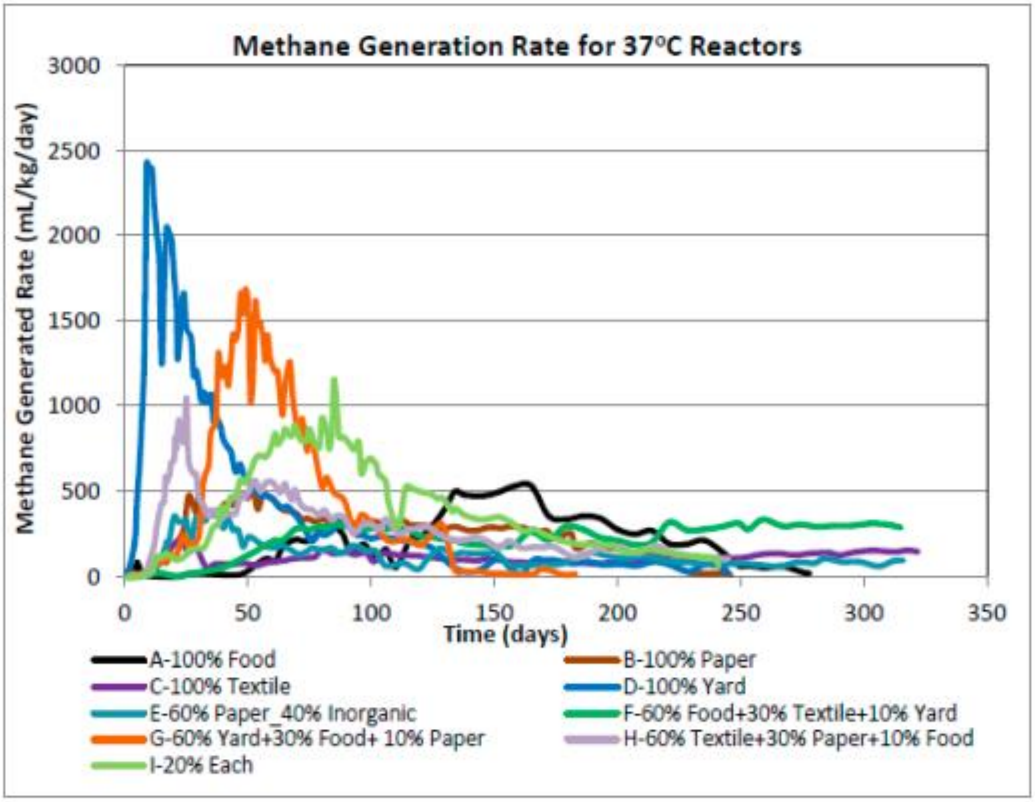


Figure 4. 17 Methane yield with time (Karanjekar, 2013)

Chapter 5

Summary and Recommendations

The prime focus of this research is to the sustainable management of organic waste as well as energy retrieve from organic waste as it poses several problems in the traditional landfill. The anaerobic digester can handle all the problems associated with organic waste in a conventional landfill such as excessive leachate generation & gas production, ground & surface water contamination, and requirement of additional space as well as energy can be retrieved. AD also permits the addition of nutrients required for accelerated degradation of food waste which has been seeking a place to be disposed of after being diverted from conventional landfills. Handling waste with a high percentage of organics especially food waste has always been a challenge for the solid waste industry.

Through the addition of sludge, the main concern of this research was to find out the most possible choice for the accelerated decomposition of several types of food waste as well as energy recovery (methane generation) in the AD. To satisfy this goal, several types of food waste (meat, grain, fruit, and vegetable) were collected. A set of eight (8) laboratory simulated AD were constructed with four combinations with several types of food waste and inoculum ratio (20% and 30% sludge). Physical properties such as moisture content, volatile solid content of the food waste was figured out 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 VFA 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 section.

5.1 Summary and Conclusions

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

1. Different fresh food waste samples were collected from two sources :

   i) Fruits and vegetables waste from the UTA Compost Center,

   ii) Meat and grain waste from the university center connection café of the UTA.

2. Inoculum which is sludge was collected from Village Creek Water Reclamation Facility, Texas. The pH of sludge is 7.21, the moisture content is 98.36% and volatile solid is 86.2%

3. Eight laboratory-scale AD were built with two different combinations of food waste (Meat-Grain and Fruit-Vegetable). Sludge 20% and 30% was added to the reactors and it was added by weight. The inoculum was added for accelerated degradation of food waste in bioreactor operation.

4. Moisture content and volatile solid content of the waste were figured out before filling the AD. The moisture content of the reactors was found to be a little bit more in AD with fruits and vegetables compared to the AD with meat and grain. But less variation was observed in volatile solid content of all the AD.

5. The reactors were constructed with one (1) gallon bucket, modified as per the necessity, and filled with food waste of 3.5 pounds (wet weight basis) after passing the leak test. The AD were sealed to make them airtight and operated at a temperature of 37°C (99°F) in an environmental growth chamber.

6. Leachate was monitored frequently for the pH. The initial pH level of the AD was below 5.0 and kept becoming acidic although the leachate was neutralized by mixing KOH before recirculation. The pH of AD with meat and grain increased faster because protein degradation releases ammonia and it increased the pH faster. On the other hand, it took time for r

AD with fruit and vegetable for increasing because fruit and vegetable wastes are hydrolyzed quickly due to low TS and high VS which leads to acidification and a rapid decrease in the pH.

7. Initial COD values for all the reactors were as the reactors were in the lag phase which is the acidogenic phase and almost no degradation occurred. In the case of reactor MGR1, MGR2, MGR5, and MGR6, the COD value was increasing every month. On the other hand, for reactor FVR3, FVR4, FVR7, and FVR8, as soon as the acidogenic phase ended and the degradation took place and started to go into the methanogenic phase COD started dropping.

8. VFA accumulation was comparatively high for AD that contain meat and grain. On the other hand, VFA accumulation was a bit less in the beginning for AD with fruit and vegetable compared to reactors with meat and grain. Then the VFA accumulation started to increase for all the reactors in the second month. After the second month VFA accumulation for AD with fruit and vegetable started decreasing gradually while the VFA accumulation for AD with meat and grain was still increasing. Reactor FVR7 and FVR8 started showing a good amount of methane generation from the fourth month as well as reactor FVR3 and FVR4 did the same throughout the fifth month because their VFA reduced below 13 g/L. VFA more than 13 g/L starts creating an inhibitory environment for methane production.

9. Initially the concentration of carbon dioxide in the gas composition was higher in all the AD. The scenario changed for reactors with fruits and vegetables as methane concentration started increasing the carbon dioxide started decreasing. For AD FVR3 and FVR4 the ratio increased to as high as 8.5 and 6.6 respectively and for FVR7 and FVR8 it increased to 5 and 5.9, respectively. For the other reactors, the CH4:CO2 ratio did not increase as they were in the lag phase. On the other hand, concentration of oxygen-depleted rapidly and remained negligible as the AD were operated in anaerobic conditions.

10. Total gas generation rate and methane generation rate followed the same trend except at the beginning there was a negligible amount of methane in the gas composition. The initial gas generation rate was high for all the reactors before they went into the lag phase. Only reactor FVR3, FVR4, FVR7, and FVR8 crossed the lag phase and started producing a considerable amount of methane, as high as 72.5%, 68%, 52.1%, and 51% by composition, respectively.

11. Reactor MGR1, MGR2, MGR5, and MGR6 were producing the highest amount of gas from the beginning and the gas generation rate was a bit less for reactors FVR3, FVR4, FVR7, and FVR8. But after around 20 days the gas generation rate started decreasing for AD with meat, grain, and sludge. On the other hand, though the AD with fruit and vegetable were producing less gas at the beginning, but after 60 days when their pH was near 7, the gas generation rate increased significantly.

12. Based on the cumulative methane production results, it was found that reactor FVR3 produced a total of about 6.7 liters and FVR4 produced a total of about 4 liters of methane per pound of food waste on a wet weight basis till 160 days of the observation period and it was just introduced into the methanogenic phase (wet weight basis). Reactor FVR7 and FVR8 also produced a significant amount of methane as well. The gas generation for these AD was still at its prime and was producing more gas, so it was decided to monitor further. The rest of the reactors were still not producing any gas and were kept under observation.

13. Methane generation curves did not follow a typical first-order degradation curve and showed multiple peaks for reactor FVR3 and reactor FVR4.

14. The main difference between reactors FVR3, FVR4, FVR7, and FVR8 with other reactors was the type of food waste. Based on the results obtained so far, fruit and vegetable showed faster decomposition compared to meat and grain and they were producing a

considerable amount of gas. Therefore, it can be reported that the use of sludge with fruit and vegetable waste might be advantageous compared to meat and grain waste for accelerated decomposition. Besides sludge is necessary to dilute the initial acidic environment created during the initial phase of decomposition of food waste through excessive VFA accumulation.

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

16. AD can also retrieve energy from food waste which can be used to solve cooking gas problem in south Asian countries. Besides, our plan is to build underground household or community level AD with the best possible feedstock inoculum ratio found from this study which will be cost efficient as well.

5.2 Recommendations for Future Studies

Based on the earlier literature review and the current study results some recommendations are proposed for future studies:

1. Crystalline potassium hydroxide (KOH) or something similar may be added to see the effect on first 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 by varying their percentages and analyze the effect.

3. Further studies can be done by using sludge having more pH value and observe whether it affects the VFA accumulation.

4. Additional research is necessary to reduce the lag period by increasing the percentage

of inoculum or addition of enzymes, manure, or trace elements.

5. Further studies can be done by building an AD with only meat and only grain to observe which component was creating access VFA accumulation and lag period for AD with meat and grain.

6. Further study is necessary to reduce the VFA accumulation soon after the operation of the AD starts as it creates an inhibitory environment for methane production.

7. Further study is necessary by mixing other types of waste such as yard waste because it contains a good amount of methanogens. Therefore, mixing yard waste might reduce the required percentage of inoculum. Mixing MSW with several types of food waste can be observed as well in further studies.

8. It would give a good perspective about the environmental impact of organic waste AD operation if Life Cycle Analysis (LCA) can be performed, and the results can be compared with other food waste processing alternatives.

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