Optimization and Performance Evaluation of Household Anaerobic Digester

by

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Abstract

OPTIMIZATION AND PERFORMANCE EVALUATION OF HOUSEHOLD ANAEROBIC DIGESTER

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Globally, one-third of food produced for human consumption is wasted. The waste stream of developing countries constitutes a substantial amount of food waste. In addition to contributing to greenhouse gas emissions, food waste is a significant source of leachate due to its high organic content and moisture content. While food wastes do not pose a threat to the environment in terms of pollution control, their disposal in landfills presents a serious concern for the environment. Food waste, which contains high levels of volatile solids and wettest portion of the waste stream, can be utilized as an energy source to offset the use of non-renewable energy.

The primary objective of this study is to design, operate and performance monitoring of household-scale anaerobic digester based on specific food waste composition for developing countries. There are many benefits of anaerobic digestion, including the cost effectiveness, faster methane production, and a smaller footprint. A laboratory scale study was conducted to investigate the impact of Food/Inoculum ratio and total solid (%) on food waste decomposition and gas production in anaerobic digester. To simulate the digester, laboratory scale reactors were filled with food waste. Cow manure and sludge were used as inoculum. Among the food waste reactors, the highest methane volume, as well as biogas volume, was generated by reactors with F/I=2 and total solid of 11%. Based on the results from the laboratory scale study, two sets (total 4) field scale anaerobic digesters (F/I=2 and 1.5) were installed at the Civil Engineering Laboratory Building in University of Texas, Arlington with food waste feedstock and were monitored for 180 days. Having successfully operated the first one, the second study included inoculum for the whole hydraulic retention period on Day 0, and two anaerobic digesters of F/I=2 were monitored for 120 days to determine the potential for lag phase reduction. The result from the anaerobic digester revealed that continuous flow of biogas can be achieved with average of 42 L/day for one-fifth size of the digesters. For the full-scale size, that will be of 210 liter per day which can be used for 1.25 hours of cooking daily for developing countries. The quality and amount of the biogas and quality of the leachate showed that the initial inclusion of inoculum for the whole hydraulic retention time on Day 0, and then operating the anaerobic digester with F/I ratio 2 decreased the lag phase from 100 days to 2 days and enhanced the food waste degradation in continuous anaerobic digester. Thus, it can be concluded that operating a household scale anaerobic digester is a sustainable food waste management system that results in enhanced methane and biogas production.

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CHAPTER 1: INTRODUCTION

1.1 Background

In underdeveloped nations, food waste accounts for over 70% of municipal solid waste (MSW) (Waste Concern, 2009). In wealthy nations, it is also the second-largest component (14% to 21%). (USEPA, 2008). One-third of the food produced for human consumption, or 1.3 billion tons, according to the Food and Agricultural Organization (FAO, 2011), is wasted globally. Food is lost or thrown away at every stage of the food production and distribution process, starting with agricultural production and ending with domestic consumption (FSC). Even when food waste is still fit for human consumption in middle and high-income countries, it is nevertheless thrown away, increasing the amount of food wasted to a very high level. Significant food waste also occurs at the beginning of the food supply chain. When comparing the stages in the food supply chain, less amount of food is lost at the consumer level than is lost primarily in the early and middle stages for low-income nations.

However, less than 3% of the food waste is separated and handled, largely by composting, and the remaining 80% is disposed of in landfills, according to Chen et al., 2010. Food waste contains the highest moisture content of any municipal solid garbage, ranging from 50 to 80 percent (Tchbanoglous, 1993). The food and green wastes are significant contributors to the emissions of greenhouse gases and generate increased leachate due to their high moisture, organic contents, and biodegradability. Green and food wastes are not dangerous materials by themselves, but when they are dumped in landfills, they cause significant environmental problems (Thassitou and Arvanitoyannis, 2001).

According to figures provided by the EPA (2008), 97 percent of waste from food production is disposed of in landfills, despite the fact that this is the least favoured food recovery option. From the perspectives of environmental preservation and economic development, Liu et al. (2009) state that it is crucial to divert and create values (such as energy production) from organic wastes. Anaerobic digestion facilities and composting are the most popular solutions, according to EPA, to reduce waste and benefit the environment.

In the absence of oxygen, organic matter is broken down by bacterial and enzymatic processes to produce renewable energy source (biogas) in the anaerobic digestion (AD) process (Liu et al., 2009; Vögeli et al., 2014). Swamps and the stomachs of ruminants are two examples of natural settings where this process occurs frequently. The AD process uses an engineered technique and regulated design to process organic biodegradable matter in airproof reactor tanks, also known as digesters, to produce biogas. The anaerobic degradation process, which yields two primary products—nutritious digestate and energy-dense biogas—involves numerous types of bacteria.

By converting this organic waste into useful energy resources through anaerobic digestion of food waste, solid waste quantities as well as disposal costs are reduced. By minimizing waste pollution and the usage of fossil fuels, biogas as a renewable energy source helps a nation's energy balance while simultaneously preserving its natural resources and protecting the environment (Al Seadi, 2008).

1.2 Problem statement

Food waste makes up a sizable portion of the waste stream in developing nations. Due to its high concentration of volatile solids and its position as the waste stream's wettest component, food waste hold great promise as a renewable energy source with the ability to reduce reliance on fossil fuels. The least desirable alternative, landfilling, poses high environmental risks that anaerobic digestion can lessen. Because of this, anaerobic digestion of food waste has a lot of potential as a method of sustainable waste management and as an alternative energy source to fossil fuels.

According to the World Bank, 90% of rural households in developing nations still use open fires or inefficient stoves to cook and heat their homes with natural biomass fuels including dung, wood, and crop wastes. Due to lack of ventilation , fragmented combustion of these stoves results in substantial amount of indoor pollution (WHO, 2000).

While the United States Environmental Protection Agency's 8-hour average carbon monoxide threshold is 9 ppm, values of 10-500 ppm have been recorded during cooking. In poor countries, the mean 24-hour levels of carbon monoxide in houses utilizing biomass fuels are in the range of 2-50 ppm (USEPA, 1997). Additionally, during times of cooking, 24-hour mean PM_{10} levels may rise to as much as 30,000 mg/m^3 higher than usual (Smith et al., 1994). While the 24-hour average PM10 concentration standard set by the US Environmental Protection Agency is 150 mg/m^3 (USEPA, 1997).

Since cooking has become a key activity for women in developing nations, their exposure to emissions is higher than that of men's (Behera et al., 1988). The initial signs include a runny nose, sore throat, and watery eyes. The respiratory system is progressively impacted. Respiratory sickness frequently manifests as asthma, dyspnea, and severe palpitations (USEPA, 1997). Benzo[a]pyrene from cooking stoves for three hours a day can expose someone who smokes two packs of cigarettes every day (Bruce et al., 2000). Children who are held by their moms while they cook are also exposed to smoke (Albalak, 1997). Children are more likely to develop a range of respiratory ailments since they spend proportionally more time indoors because they breathe more air per pound than adults do (Albalak, 1997). Accordingly, there are around 24 million alveoli present at birth, but by the age of four, there are 250 million (World Bank, 1998). Each year, acute lower respiratory infections cause over 2 million fatalities in children under the age of five (Bruce et al., 2000).

By creating biogas from anaerobic digesters made to accommodate their cooking demands, a household can dramatically lessen these consequences on the environment and human health. In addition, it is a fantastic renewable energy source that can lessen reliance on fossil fuels and the costs connected with them. However, because mono-digesting food waste is acidic and hinders microbial activity, it may make it more difficult to produce biogas. Finding an acceptable, affordable, and easily accessible inoculum in poor nations is also a crucial step. Although the use of biogas generated from human waste has been rejected in Dar es Salaam, Tanzania (Vögeli et al., 2014), human waste has a large potential for use as an inoculum. Furthermore, lignin can only be broken down by a few enzymes, but they are too expensive to ever be used.

To successfully construct and operate an anaerobic digester, you must determine the ideal Food/Inoculum ratio and Total Solid (%). According to research by Kawai et al. (2014), the F/I ratio has an inverse relationship with the biogas generation from food waste. Although a very high F/I ratio won't be able to guarantee optimal biogas generation, a very low F/I ratio won't be an affordable or sensible choice either. In addition, Chen et al. (2014) found that high-solids (15%) anaerobic digestion produced larger biogas yields than liquid anaerobic digestion (5–10% TS), but Forster-Carneiro et al. (2008) indicated that biogas production declined when the total solids contents rose from 20% to 30%.

So, this study focuses on determining optimum Food/Inoculum ratio and Total Solid (%) for co-digestion of food waste in lab-scale reactor and utilizing that ratio and percentage to design an anaerobic digester that will have the ability to produce cooking gas for a single household in developing countries. A successful design of a household anaerobic digester will ensure a sustainable energy source and lessen the need for fossil fuels while also greatly reducing the negative effects on human health and the environment.

1.3 Objectives of the Study

The main objective of this research is to design, operate and performance monitoring of household scale anaerobic digester based on specific food waste composition of developing countries. The specific tasks to accomplish the objective of the study include:

1. Evaluation of Different Food/Inoculum Ratio (F/I) in Laboratory Scale Batch Reactor for food waste composition of developing countries.
2. Design of Household Scale Anaerobic Digester based on Household Size and Waste Generation Rate in Developing Countries.
3. Construction of Household Scale Anaerobic Digester.
4. Operation and Performance Monitoring of Household Scale Anaerobic Digester.

1.4 Dissertation Outline

The study is divided into seven chapters that are summarized as follows:

- Chapter 1 offers an introduction and outlines the study's goals and problem statement.
- Chapter 2 presents the concepts of anaerobic digesters, benefits and challenges as well as other previously conducted studies related to these topics.
- Chapter 3 describes the methodology of the work in the laboratory scale and field scale.
- Chapter 4 presents the results and analysis of the laboratory study on anaerobic digesters.
- Chapter 5 depicts the construction, operation, and monitoring techniques of field-scale household anaerobic digesters for performance evaluation.

- Chapter 6 describes the results and analysis of field scale household anaerobic digesters in two different conditions and the feasibility of the biogas as cooking purpose.
- Chapter 7 offers suggestions for future research as well as a summary of the key findings from the present study.

CHAPTER 2: LITERATURE REVIEW

2.1 Solid Waste Scenario

At least 33 percent of the world's municipal solid waste is not managed in an environmentally safe way, according to estimates of 2.01 billion tons per year. There is an average of 740 grams of waste generated per person per day worldwide, but this varies widely, ranging from 110 grams to 4540 grams. Countries having high incomes generate about one-third of the world's waste, or 683 million tons, despite only making up one-sixth of the population.

Over the next three decades, global waste will grow to three billion tons, which is more than double the growth in population during the same time frame. In general, generation of waste increases with increase in income level. The rate of waste creation per capita is projected to increase 19 percent in high-income countries by 2050, compared to an increase of approximately 40% or more in low- and middle-income countries. Households having low-income produce less waste than households having high-income during a period of incremental income change, but it increases faster at high income levels during a period of incremental income change. By 2050, low-income countries will generate more than three times as much waste as high-income countries. There are 23 percent of the world's wastes generated in East Asia and Pacific, while six percent of wastes are produced in Mideast and North Africa. Nevertheless, Sub-Saharan Africa, South Asia, and the Middle East and North Africa will see the fastest growth in waste generation, with the total set to triple, double, and triple respectively by 2050. It is estimated that more than half of all waste is currently dumped openly in these regions, and the trajectory of waste growth will have profound implications for the health, environment and growth. Therefore, immediate action for the situation is required.

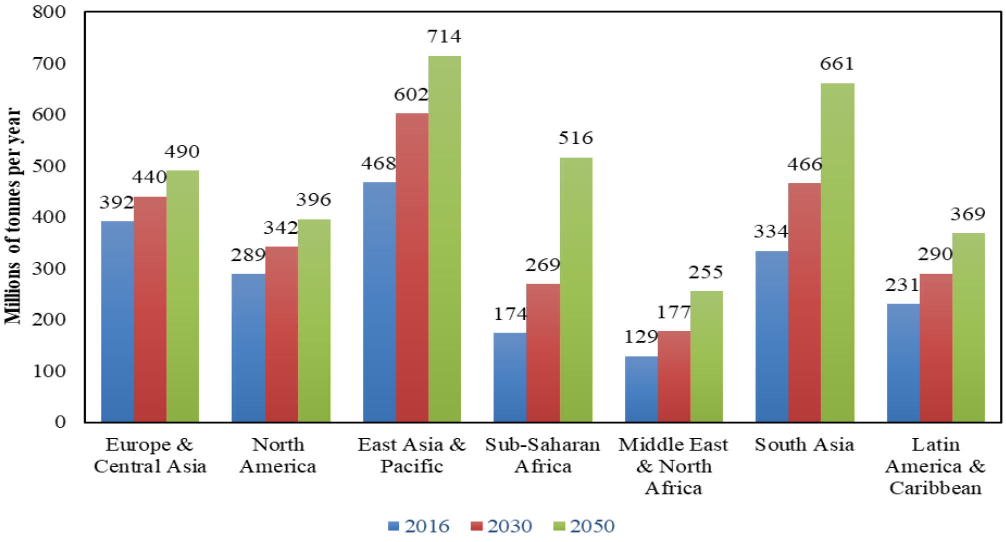


Figure 2-1: Waste generation prediction, by region (millions tons/year) (Reference: World Bank)

Despite the fact that waste collection is an essential part of waste management, rates of waste collection vary widely according to income levels, with high-income and upper-middle-income countries providing nearly universal and similar waste collection system. The proportion of waste collected in cities in low-income countries drops significantly to one-fourth outside cities. In North America and Europe, approximately 90 percent of waste is collected while less than 44 percent of waste is collected in Sub-Saharan Africa.

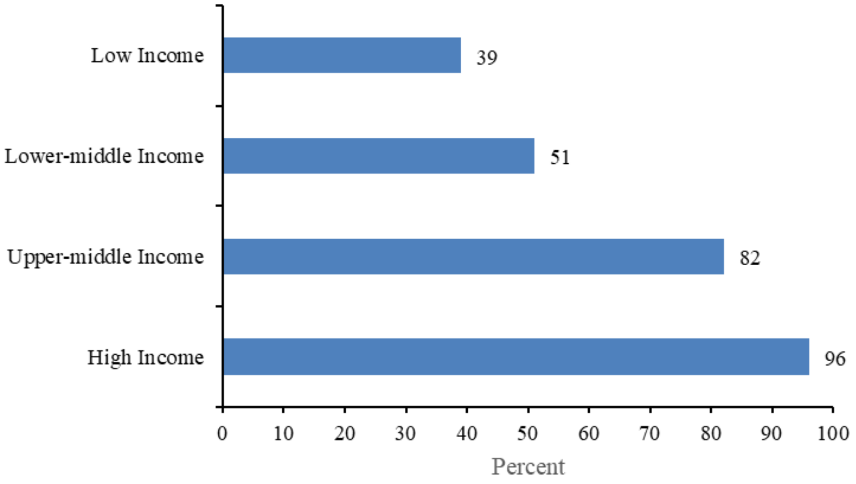


Figure 2-2: Waste collection rates based on income level (percent) (Reference: World Bank)

Consumption patterns vary across income levels, resulting in different waste compositions. It is estimated that countries with high-income generate 32 percent less food and green waste than low-income countries, while generating 51 percent more dry waste which could be recycled, including paper, plastic, cardboard, metal, and glass. According to a study conducted by (Shruti Singh, 2022) Hamburg Test results clearly shows that inclusion of plastic has an added advantage in improving the deformation and moisture resistance of HMA design. This will extend the service life of pavement with improved performance and will help in reducing the legacy plastic waste at the same time. There is a 53 percent of food waste and 57 percent green waste generation rate in middle- and low-income countries, with the percentage of organic waste increasing with a decrease in economic development. It is estimated that only 20 percent of waste in low-income countries can be recycled. Within waste streams, there is little variation across regions beyond those aligned with income. The average amount of organic waste generated is 50 percent or more in all regions, apart from Central Asia, Europe and North America, where dry waste generation is higher.

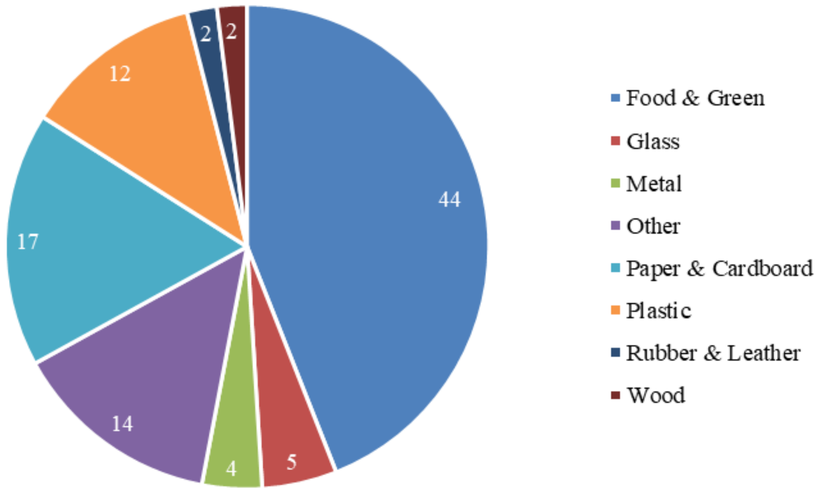


Figure 2-3: Global waste composition (percent) (Reference: World Bank)

The idea that technology will solve the issue of uncontrolled and growing garbage is a common misunderstanding. Technology is not a cure-all and is typically just one aspect to take into account when managing solid waste. When nations choose regionally appropriate solutions, they have a better chance of succeeding than those that continue to use other primitive waste management techniques like open dumping. The majority of waste is currently deposited or disposed of in some type of landfill on a global scale. A landfill is used to dispose of about 37% of waste, and 8% of that waste is dumped in sanitary landfills with landfill gas collection systems. In open areas, about 31% of waste is dumped, while 19% is recycled or composted, and 11% is burned as the last step in the disposal process. Ninety-three percent of the world's trash ends up in nations with low incomes, whereas only two percent of it winds up in high-income countries, which are frequently the poorer of the two categories. South Asia, Sub-Saharan Africa, and Middle East and North Africa are the three regions where open dumping accounts for more than fifty percent of the world's garbage. The majority of waste is dumped in landfills—54 percent—in upper middle-income nations. In high-income nations, this rate drops to39%, with 22% of garbage being diverted to incineration and the remaining 36% going to composting and recycling. Incineration has been adopted by most high-capacity, high-income, and land-constrained nations.

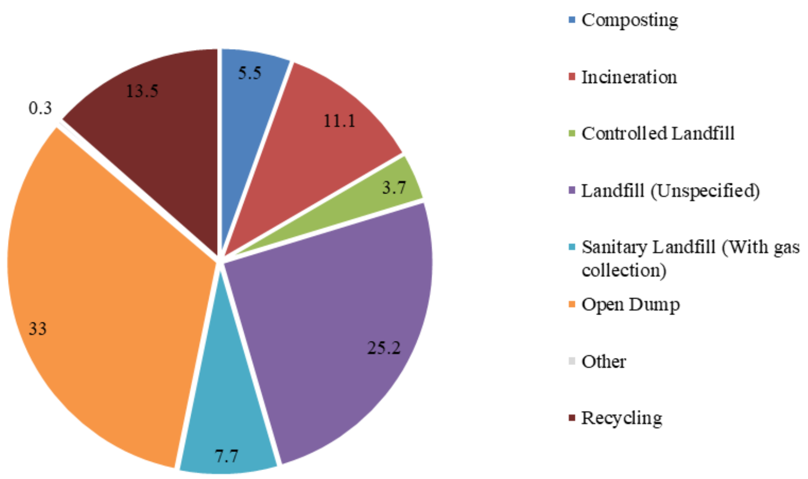


Figure 2-4: Waste treatment and disposal system (percent) (Reference: World Bank)

It is estimated that 1.6 billion tons of carbon dioxide (CO_2) equivalent greenhouse gas emissions, or 5% of world emissions, were produced by the treatment and disposal of solid waste in 2016. This figure is based on the volume of garbage produced, composition, and how the garbage is being managed. Having no proper landfill gas collecting equipment in waste disposal in open dumps and landfills is the main cause of this. Nearly 50% of emissions come from food waste. If no changes are done in the sector by 2050, emissions coming from solid waste are predicted to rise to 2.38 billion tons of CO_2-equivalent year.

Solid waste management operations are primarily local government responsibilities in the majority of nations, and almost 70% of nations have institutions in place to handle policy creation and regulatory monitoring in the waste sector. Though enforcement varies greatly, almost seventy percent of nations have adopted specific legislation and rules for the management of solid waste. About two-third of waste services are directly supervised by local public authorities, with the central government often just participating in regulatory monitoring or monetary transfers. From primary garbage collection to treatment and disposal, at least half of the services are run by public organizations, and around a third include public-private partnerships. However, effective collaborations with the private sector for funding and operations frequently only work under specific circumstances with suitable incentive structures and enforcement systems, so they are not always the best option.

The upfront consideration of operational costs is necessary since financing solid waste management systems is a considerable barrier, more so for ongoing operational costs than for capital investments. Operating expenses for high-income countries typically surpass $100 per ton for integrated waste management which includes collection, transportation, treatment, and disposal. With expenses of roughly $35 per ton and occasionally more, lower-income countries spend less overall on waste management, but they have far more trouble recovering their costs. Waste handling requires a lot of labor, and the expense of transportation alone is between $20 and $50 per ton. Across income levels, cost recovery for garbage services varies greatly. User fees range from an average of $170 in high-income nations to $35 in low-income countries on a yearly basis. This is due to the fact that countries with high incomes are the only ones that typically recoup all or almost all of their costs. Depending on the kind of user being charged, user fee models might vary- either fixed or variable. About half of the investment expenses for waste systems are typically covered by local governments, while the remaining half expenditures primarily come from various private sector and national government subsidies.

2.2 Food Waste Extent

The primary factor in a person's ability to survive is food. The "Food Supply Chain" refers to the several processes that the food goes through from manufacture to supply (FSC). Agriculture production, postharvest handling and storage, processing, distribution, and consumption are the five steps that make up the FSC. Each of these phases results in significant amounts of food waste due to inappropriate handling, mechanical damage while in use, leakage, and deterioration during processing and storage, as well as loss in the market system and consumption (FAO, 2011; Galanakis, 2012). Figure 2-5 depicts the steps used to turn food into garbage.

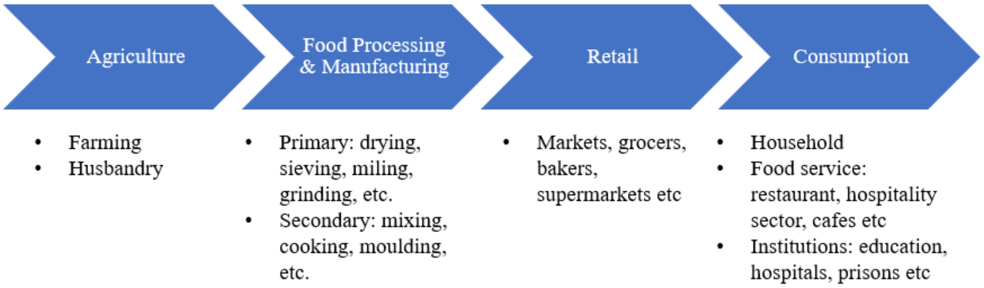


Figure 2-5: Food waste and losses in food supply chain (Papagyropoulou et al., 2014)

According to a 2011 study by the Swedish Institute for Food and Biotechnology (SIK), around 33 percent of the edible portions of food produced for human consumption, or 1.3 billion tons annually, are lost or wasted globally. Figure 2-6 food loss each year per person dividing the world into seven major regions.

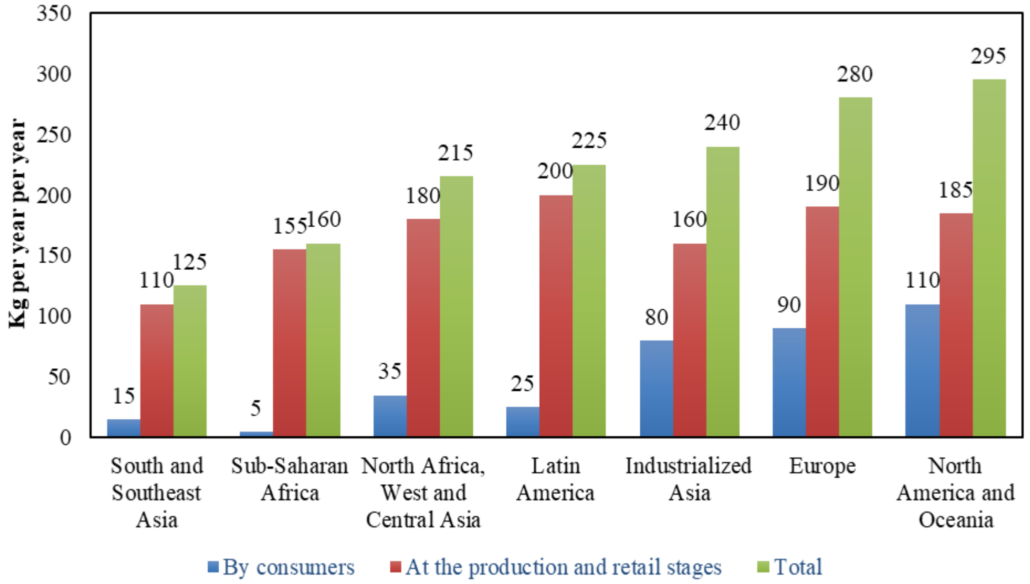


Figure 2-6: Per capita food loss each year in different regions of the world (FAO, 2011)

Fruits and vegetables make for the majority of waste, or around52%, according to FAO statistics from 2011. The proportion of losses for each food category were determined for the US, Canada, Australia, and New Zealand collectively (Statista, 2016), as shown in Figure 2-7.

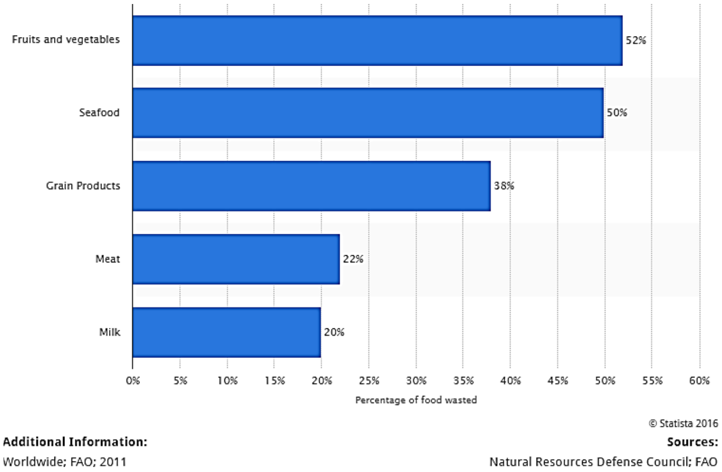


Figure 2-7: Food waste by category (FAO,2011)

2.3 Food Waste Scenario and composition in Developing Countries

Food waste and loss are being made at different levels in developing countries. Figure 2-8 demonstrates the production volume of all commodity groups in their primary form in different regions of the world from FAO,2011 data.

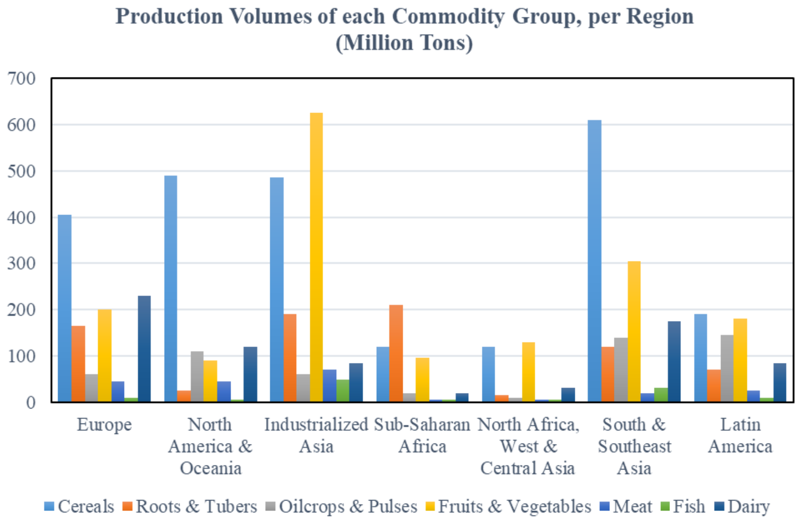


Figure 2-8: Volume of Production in each Group based on Region (FAO, 2011)

Figure 2-9 expresses the waste percentage of the seven commodities based on the production volume per region. From waste percentage perspective in developing countries, the maximum was found to be for fruits and vegetables, followed by food produced from grains, and lastly, meat, fish and dairy products which make sense from economical viewpoint.

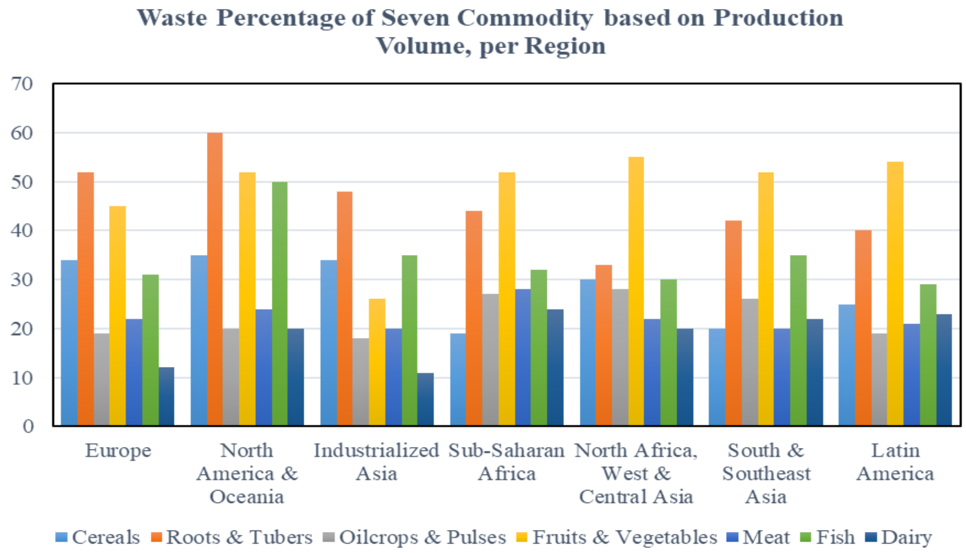
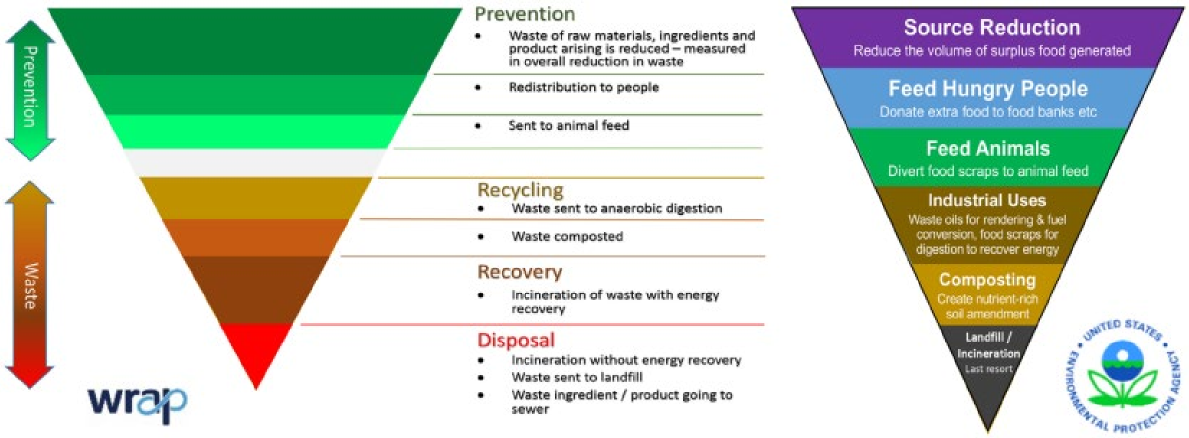


Figure 2-9: Waste Percentage of Commodities based on Production Volume, per Region (FAO, 2011)

2.4 Food Waste Hierarchy - Diversion from Landfill

By far, household consumption accounts for the majority of food waste. Household food waste components can now be classified as either preventable or unavoidable, with the possibility of partially or perhaps avoiding them also being employed in specific circumstances. Generally speaking, residues and by-products from food production, such as inedible peels or seeds, make up the first category of unavoidable or inedible food waste. Unused food, frequently thrown out as a result of overspending or the passing of a "best before" date, or partially consumed foods like leftovers from meals are two types of avoidable food waste. Foods and beverages that are ingested by some people but not others (like the crusts of bread, for instance) or that can be consumed when a food is prepared in a certain manner but not in another are referred to as "specialty foods and beverages" (for example, potato skins) fall within the category of being potentially or partially preventable. (WRAP, 2009).

One of the major degradable components in the waste stream, food waste makes up a sizeable amount of municipal solid trash in both developed and developing countries. With a moisture level of between 50 and 80 percent, food waste is often the fraction of municipal solid garbage that is the wettest (Tchbanoglous, 1993). Because the leachate and gas production from the disposal of this moist, putrescible organic waste is higher, there are additional costs associated with monitoring it and migration difficulties. According to the United States' support for the food recovery hierarchy reduction at source is considered the best method at all points in the hierarchy, followed by feeding the needy, according to the Environmental Protection Agency (EPA). Food can still be used as nourishment even if it does not reach the consumer, livestock is the runner-up option. Another option is to recycle food waste for commercial use (EPA). Composting and anaerobic digestion facilities are currently the most popular methods for reducing waste and improving the environment. The landfill, on the other hand, is the disposal method that the EPA cites as being least desirable for food waste. Figure 2-10 shows the schematics food recovery hierarchy from the UK and USA.



(a) (b)

Figure 2-10: Food Waste Hierarchy. (a) from WRAP (2017), (b) from US EPA

However, landfills remain by far the most popular method for disposing of waste, rather than being avoided because of their less investment, operating, and maintenance costs being positioned at the base of the hierarchy of waste management. EPA (2008) reports that 97 percentage of food waste ends up in landfills. However, the most worrying is that certain US states have started prohibiting food waste from landfills due to issues with it. Connecticut was the first state to do so in 2011 due to difficulties with commercial food waste in landfills (AR News, 2014). Massachusetts is the most recent state to declare a ban on commercial food waste from landfills. On the other hand, prohibiting the disposal of food waste in conventional landfills will only lead to issues in the future if workable alternatives are not offered.

2.4.1 Source Reduction

Avoiding the production of food waste is a key component of source reduction (US EPA 2016). Food that has produced in affluent countries, up to 40% of it is wasted before it is eaten (Trabold and Nair 2018). The United States threw out 63 million tons of food in 2016. (US EPA 2016). 18% of crop land, 21% of fresh water and 19% of fertilizer are used to produce those wasted food (Trabold and Nair 2018). The EPA also lists numerous instances of various organizations concentrating on it to reduce food waste. By measuring daily food waste in their kitchens and making necessary adjustments, Quicken Loans Arena was able to decrease food composted from 3.5 tons to 1.5 tons per month. In order to prevent food from rotting, Hannaford supermarkets, a chain operating out of the Northeastern United States, modified their delivery schedule and infrastructure so that food deliveries took place every day rather than assuming what food would be needed over a certain period (US EPA 2019). In 2009, the University of Texas at Austin also carried out an audit to ascertain ways to reduce food waste on the consumer level. Over the course of five days, they evaluated the amount of post-consumer food waste produced at one dining hall during two meal time and deducted edible food waste from inedible food waste. This causes a loss of food worth $588,659.33 annually and a loss of resources overall at $618,609.88 annually. These findings prompted a social marketing initiative to lessen food waste, and a follow-up food waste audit was carried out in the fall of 2008. Following the initiative, the amount of food wasted dropped by 32% to 81 tons per academic year (US EPA 2019).

2.4.2 Food Donation

15% of Americans are regarded as food insecure, while 13.2% of Americans are thought to have incomes below the poverty level (US EPA 2016). Over 40% of food that is edible is lost before it even gets to the table, as was previously indicated. This confluence of elements indicates a serious equity problem with the distribution of food in the nation. Food donation is one approach to achieving a more just food system. Government financing, businesses, private donations, and networks that distribute food are used to fund food donations (Trabold and Nair 2018). Given that men are less likely than women to experience food insecurity, food donations can highlight equity issues (FRAC 2015). Additionally, it is more difficult for people of color to receive government benefits, such as SNP (SNAPs). This is a result of the dearth of grocery retailers accepting SNAP benefits in communities that are largely racial. There were no grocery businesses that would accept SNAP in Leon County, Florida's predominantly black neighborhoods (Rigby et al. 2012). There are four different ways to donate food (Trabold and Nair 2018). Food gleaning is the first technique, when food that farmers have gathered but aren't planning to sell is collected and donated. Perishable food rescue is the second technique, in which perishable food is gathered from wholesalers and retail sources. The final problem is non-perishable food collecting, which is how the public sees it done most frequently. Public outreach initiatives like food drives help achieve this.

2.4.3 Landfill

According to the US EPA Food Recovery Hierarchy ("US EPA Food Recovery Hierarchy" 2016), disposal is the least preferable method for managing food waste. But 97% of US food waste is disposed of in landfills (Trabold and Nair 2018). Due to the low effectiveness of recovering greenhouse gases (GHGs) from landfills for the waste and the considerable path to reach the dump, landfilling emits more GHGs than any other method of waste disposal. Leachate from landfills can get into water systems during times of intense rainfall.

2.4.4 Incineration

Another alternative for towns to reduce the amount of municipal solid waste that needs to be landfilled is incineration (also known as thermal waste to energy). Incineration is the process of burning hazardous materials at that temperatures when it is enough to destroy contaminants, as per US EPA. Heat exchangers or steam turbines are frequently powered by incinerating waste (Pham et al. 2015). When burned, 1 kilogram of solid waste can produce 0.51 kilogram of CO_2 equivalents (Trabold and Nair 2018). Because it may reduce trash quantities by 80–85%, incinerators are favored to landfills as a waste management method (Pham et al. 2015). But when incinerators aren't constructed for the right MSW conditions, energy recovery drops (Trabold and Nair 2018). Due to its low solids composition, food waste is sometimes regarded as a poor combustion feedstock (Trabold and Nair 2018). After drying as a pre-treatment, Kim et al. (2013) assessed the incineration capability of food waste in Korea. The global warming potential (GWP) of this incineration process was -315 kg of CO_2 equivalents, making it a carbon-negative process. Yang et al. (2012) also analyzed the global warming potential of incineration of municipal solid waste and found that it ranged from 25 to 207 kg of CO_2 equivalents.

2.4.5 Anaerobic Digestion

Although it is increasingly well-liked in America, anaerobic digestion (AD) is a well-established technology that is frequently utilized in Europe and Asia to handle organic waste. The microbiology and operational aspects of AD are covered in detail in Section 2.6.1, along with a more in-depth analysis of the chemistry involved in the AD of food waste. Many American universities have already started using AD of food waste. At the University of California, Davis campus, one of the best instances can be found (UC Davis). Numerous studies were carried out by Ruihong Zhang et al. to categorize and improve the AD of Davis' food waste (Zhang et al. 2007). They constructed a sizable semi-continuous AD system that can handle all of the food waste from the college as well as garbage from the nearby industries. The generated biogas is then put to use for heating, cooling, or turning it into energy and re-entering the grid (Zhang et al, 2017). High-solids AD at the Washington University is another illustration of food waste AD on campuses. For a less diluted digestate and more biogas, Osh Kosh used high solids AD, which is frequently used in Europe. By approaching different technique, Osh Kosh functions as a semicontinuous reactor with recirculation ("Biogas Systems" 2016). Michigan State University's system uses 20% of the biogas for system heating as another example of university-scale AD (Stuever 2013). Currently, a portion of their campus is heated by the remaining biogas. Their method combines cow dung, leftover food from the dining hall, and fats, oils, and grease (FOGs) from nearby eateries (Stuever 2013).

2.5 Challenges to implements other waste management Hierarchy than AD

The primary method of waste management is thought to be landfills worldwide. Due to four main operating issues, landfills have been losing popularity over the last several decades. (Hettiaratchi, 2007):

- Operative aesthetics
- Pollution of groundwater and surface water from landfill leachate
- Emissions of greenhouse gases
- Need for additional space

As a result, experts in waste management are leaning toward creating a sanitary landfill that addresses at least the three problems mentioned above. However, the issue of additional space requirement has not been resolved over the years, and further research is needed to solve the space problems that appears to be growing in importance for trash management. Additionally, as the proportion of organic waste rises, more greenhouse gas (CH4) is released into the atmosphere, adding to the difficulties. The situation is worse in underdeveloped nations since their open dumps and non-engineered landfills typically contain more than 60% food waste. As is well known, food waste has a higher moisture content (more than 70 percent), which causes a greater production of leachate and a faster rate of degradation, both of which increase methane production. While there is some agreement among the various versions, there are also some differences, such as how anaerobic digestion (AD) is classified as either a resource recovery technology or a less preferred energy recovery option, or how aerobic composting and AD are distinguished at different scales of operation (Zero Waste Europe, 2016; Australian Government, 2017). Anaerobic digestion (AD), which enables both material and energy recovery, should typically be the first priority for this material within the hierarchy where there are considerable amounts of unavoidable and inedible food wastes. Therefore, an alternative solution to all of these could be an anaerobic digester.

2.6 Anaerobic Digestion Processes

The Anaerobic digestion is a complex biochemical process which gives the two main outputs, Biogas and Digestate. Following sub-sections provides the description of it.

2.6.1 Stages and Biochemical Reactions

In a series of procedures known as anaerobic digestion, microbes break down biodegradable material without the presence of oxygen. Anaerobic digestion is broken down into four main phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Figure 2-11 explains the different stages involved in the process of anaerobic digestion.

When organic material like glucose is biochemically digested by anaerobic microorganisms into carbon dioxide (CO_2) and methane (CH_4), the overall process can be represented by a chemical reaction.

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

Large organic polymers make up the majority of biomass. These chains must be disassembled into their smaller component pieces before the bacteria in anaerobic digesters can access the material's energy potential. Large organic polymers make up the majority of biomass. These chains must be disassembled into their smaller component pieces before the bacteria in anaerobic digesters can access the material's energy potential. Other bacteria can easily access

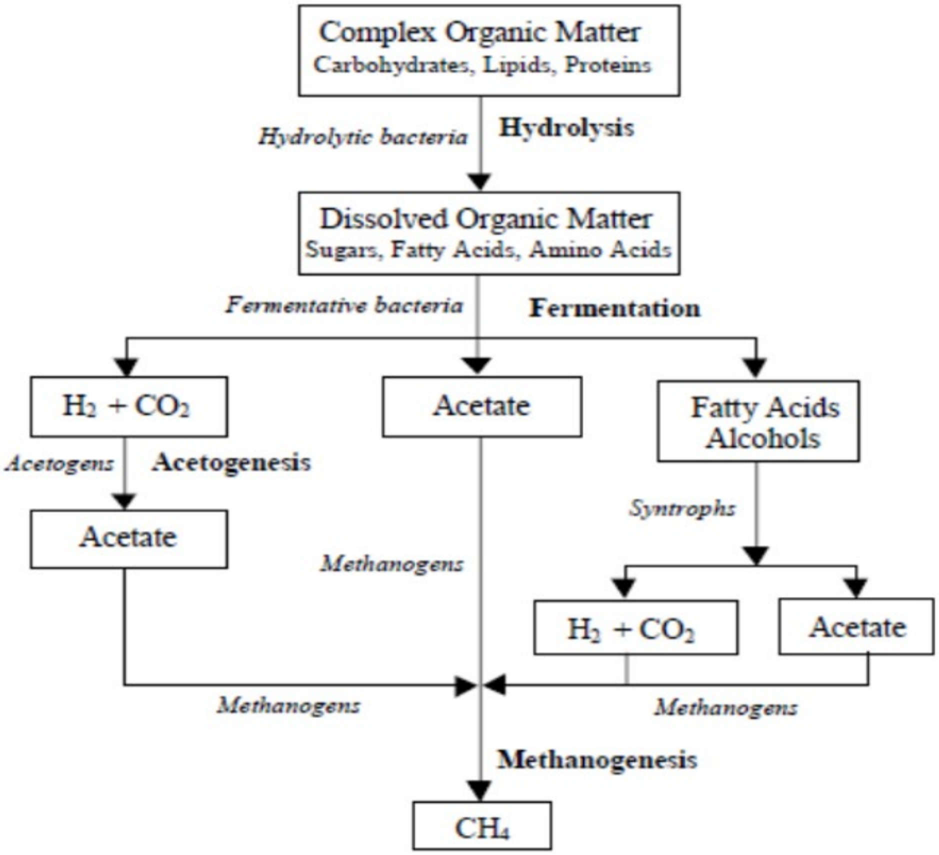


Figure 2-11 Simplified process in anaerobic digestion process (Jayasinghe, 2013)

component elements, or monomers, such as sugars. Hydrolysis is the process of rupturing these chains and putting the smaller molecules in solution. Therefore, the first stage in anaerobic digestion is the essential hydrolysis of these high-molecular-weight polymeric components. The complex organic molecules undergo hydrolysis, which converts them into simple sugars, amino acids, and fatty acids. Methanogens can immediately utilize the acetate and hydrogen generated in the early phases. Other chemicals, including volatile fatty acids (VFAs) with a chain length longer than acetate, first need to be catabolized into substances that methanogens may utilise directly.

The biological process of acidogenesis causes acidogenic (fermentative) bacteria to further degrade the remaining components. Here, carbon dioxide, ammonia, hydrogen sulfide, and other components are produced in addition to VFAs. Acidogenesis is a process that resembles how milk goes bad.

Acetogenesis is the third stage of anaerobic digestion. Here, acetogens continue to break down the simple molecules produced during the acidogenesis phase to primarily produce acetic acid as well as carbon dioxide and hydrogen.

Methanogenesis is a biological process that occurs as the final phase of anaerobic digestion. In this stage, methanogens use the byproducts from the stages before them and break them down into methane, carbon dioxide, and water. The majority of the biogas released from the system is made up of these elements. Methanogenesis takes place between pH 6.5 to pH 8, and it is sensitive to both high and low pHs. The digestate is made up of any deceased bacteria and any residual, indigestible material that the microorganisms are unable to utilise.

Methane (CH_4) and carbon dioxide (CO_2) make up the majority of the gaseous component of biogas, but it also contains other gaseous "impurities" such hydrogen sulphide (which may be easily identified by its rotten-egg odor), nitrogen, oxygen, and hydrogen. Higher than 45% methane content in biogas makes it combustible; the gas has a higher energy value as a result (Deublein and Steinhauser, 2011).

Table 2-1: Biogas Concentration from Waste (adapted from Buysman E., 2009).

Components	**Symbols**	**Concentration (Volume %)**
Methane	CH_4	55-70
Carbon Dioxide	CO_2	35-40
Water	H_2O	2-(20^{0}C)-7(40^{0}C)
Hydrogen Sulphide	H_2S	20-20000 ppm (2%)
Nitrogen	N_2	<2
Oxygen	O_2	<2
Hydrogen	H_2	<1

Ammonia	NH_3	<0.05

2.6.2 Anaerobic Digestion Products

Biogas and digestate, a wet solid that is often dewatered to generate a liquid stream and a drier solid, are the last byproducts of AD. Methane and carbon dioxide make up the majority of the biogas's constituents, which are dependent on the digestion process. The solid is an organic substance that resembles humus and is stable. Its quality and future use are based on the properties of the feedstock used in the AD process. There are soluble components in the liquid, including dissolved organic molecules. The gas mass makes up around 15% of the output stream in a typical AD facility processing OFMSW (Organic Fraction Municipal Solid Waste), while the liquid and solid make up almost equal portions, or 42.5% each.

2.6.2.1 Biogas

The most valuable component of the AD process is the creation of biogas, which comprises 50% to 70% methane. Methane and carbon dioxide make up the majority of biogas, with small amounts of other gases, as can be seen in the material balance. To prevent machinery from corroding, water vapor and hydrogen sulfide should be eliminated before being used to generate energy. Additionally, ammonia removal is common. Methane and carbon dioxide are combined to form the final gas, which can be used directly as fuel in electricity-generating machinery that is built to run on low heating value gas.

The smaller AD facilities, which are typically found on farms, frequently flare the biogas because they believe the expense of the necessary equipment outweighs any potential benefits. In some tiny AD plants, biogas is just utilized to generate heat, which is then used to raise the waste's temperature to the appropriate ranges for digestion. The larger facilities use cogeneration technology, which often generates electricity while also providing the necessary heat. There are various benefits to producing power in addition to reducing electricity costs. First, if applicable, renewable energy tax credits are available for power production because biogas is produced from biomass. Independence from the grid and the ability to continue producing electricity during blackouts are further benefits for the facility. For organizations like hospitals and computer data storage centers, this dependability is crucial. Since biogas from the anaerobic treatment of sewage sludge is used at the Red Hook Wastewater Treatment plant, Methodist Hospital, Montefiore Hospital, St. Mary's Hospital, Verizon, other locations, cogeneration has been operational in New York City for more than a decade.

Cleaning up the biogas to remove the carbon dioxide and selling it as natural gas is an alternative to using it to generate power. The infrastructure for natural gas has created a market for this alternative. The economies of AD would be improved by entering the higher value market for motor gasoline.

The most notable benefit of AD over composting is the creation of biogas. Because methane contains between 70 and 80 percent of the original organic components' energy, anaerobic digestion produces less bacterial biomass growth than aerobic digestion, which leads to a higher reduction in volume and mass (Mahony, O'Flaherty et al. 2002).

2.6.2.2 Digestate

The digestate that is being expelled from the chamber is a thick sludge with an approximate 80% moisture content that resembles a milkshake in consistency. Since it would be unprofitable to transport this, digestate is typically dewatered. The liquid content of the solid is decreased to between 50% and 70%, and the residual water can be collected. Since fresh digestate and putrescible waste both emit unpleasant smells, these processes need to take place inside a structure with continuous airflow and a biofilter.

The feedstock and the digesting procedure have an impact on the dewatered solid's quality and composition. Only soluble organics are broken down in the digester, thus if additional substances, like glass or plastic, or trace elements, such heavy metals or salts, were present in the feedstock, they would have made it into the solid. Due to these factors, businesses who want to market their digestate must be careful while screening incoming trash. Additionally, only a maximum of around 70% of the total organics are available for degradation, even if digestion were permitted to continue for extended periods of time (MataAlvarez, 2003). End consumers are very concerned about the digestate's safety as determined by the quantity of current pathogens. With a high SRT, pathogen killing can be ensured at thermophilic conditions (solid retention time). At mesophilic temperatures and lower SRT, pathogens can also be sufficiently destroyed. Generally speaking, the solid will be more physiologically active the lower the SRT. After at least 15 days of solid digestion, the majority of the organic materials have been broken down, and the resulting solid is stable. The biological activity of the digestate, as determined by BOD, should be as low as feasible if AD is employed solely to reduce the volume of trash before being dumped. On the other hand, a biologically active solid is advantageous if the digestate will be utilized as a soil amendment.

In order to generate high-quality compost, many AD facilities post-treat the digestate aerobically. This procedure is called as curing. The digestate is more beneficial as a fertilizer since AD does not lower the NPK concentration (Mahony, O'Flaherty et al. 2002). Many AD sites in Europe make compost from digestate, but without study on its safety and advantages over conventional compost, the market penetration will be quite low. Once this is established, AD can be viewed as a crucial component of the disease control system in both urban and agricultural contexts (Wheeler, 2001).

There are three uses for the liquid that remains after the dewatering process. The least desirable option is to send it as sewage to a wastewater treatment facility because it is too active to be released into fresh water directly. Additionally, it can be recycled to pre-treat waste or modify the digester's moisture level. It can also be offered for sale as a liquid fertilizer. This choice is appealing because the beverage contains nutrients. However, unless AD is used on farms, the constraints of moving large amounts of water typically make this approach prohibitively expensive.

Expanding the use of AD to treat solid waste is expected to happen, but how quickly and how much will depend on how effectively the products are promoted. This method is more difficult and requires more resources to enter the diverse markets because there are multiple items.

2.6.3 Types of Anaerobic Digesters based on operating temperature

Although there are a number of ways to handle trash, including composting, liming, and incineration, anaerobic digestion is the main method employed in most developed nations reported in Donoso (2012), claim that anaerobic digestion has been utilized since 1881 and is currently gaining popularity globally. For instance, according to the analysis by Donoso (2012), water utilities in England and Wales benefited from 600 gigawatt hours (GWhr) of renewable electricity produced by sludge treatment by AD during 2009 and 2010, which is equivalent to the electricity consumption of 180,000 houses.

With anaerobic digestion, renewable energy can be generated, non-putrescible, odorless products can be produced, sludge dewaterability can be improved, pathogens can be removed from the digestate, and most of the volatile solid elements are removed from the solids by using anaerobic digestion. (Panter, 2008). As much renewable energy as possible can be generated from organic wastes through the expanded use of anaerobic digestion resources and increased efficiency of anaerobic digestion processes (Fountain, 2009).

Historically, sewage sludge was viewed more as a waste than as a resource (Fountain, 2009), however today, sewage sludge is becoming a primary feedstock for anaerobic digestion. Since it is always (continuously) available, it is an ideal choice for anaerobic digestion, particularly in larger cities and towns where renewable energy is required.

The major objectives of the various digester types used in the anaerobic treatment process are sludge stabilization and pathogen reduction. The anaerobic digesters can be separated from one another based on the temperature ranges that are typical in the facility (Batstone *et al*., 2002) as:

- 40 – 70^0 C for Thermophilic anaerobic digestion.
- 20 – 40^0 C for Mesophilic anaerobic digestion.
- 4- 20^0 C for Psychrophilic or ambient temperature digestion.

Svensson (2005), however, distinguished between mesophilic (25-40^0C) and thermophilic (>45^0C) temperature ranges for anaerobic digestion. Anaerobic digestion rages were classified similarly by Archer (1983) and Fang et al. (1999). Therefore, anaerobic digestion takes place at steady temperatures, which is temperature-dependent (Liden and Alvarez, 2007).

The mesophilic and thermophilic anaerobic digestion procedures are the two that are most frequently utilized. Thermophilic anaerobic digestion is less prevalent than mesophilic anaerobic digestion.

2.6.3.1 Thermophilic anaerobic digestion

Thermophilic bacteria may thrive in geothermal waters or hot springs in addition to artificial conditions (man-made environment in anaerobic digesters).

At 60^0C, the thermophilic digestion process works well. It is the perfect temperature for the development of aceticlastic methanogens since methanogen activity will substantially decrease beyond this temperature (Lu, 2006). The temperature for the thermophilic anaerobic digestion process, however, must be maintained at 55^0 degrees Celsius, which is somewhat below the ideal temperature range. This is necessary to address operational security and compliance concerns. (Ahring, 2003).

Batstone (2002) found that thermophilic bacteria can function between 40^0 and 65^0 degrees Celsius, while Lu (2006) found that the optimal temperature range for thermophilic bacteria is 60^0 to 78^0 degrees Celsius. Furthermore, Hulshoff-Pol (1998), referenced in Parawira (2004), stated that the thermophilic temperature ranged from 42^0C to 75^0C, whereas Drawnel (2008) indicated that thermophilic anaerobic digestion temperatures ranged from 45^0C to 58^0C.

When compared to MAD (Mesophilic Anaerobic Digestion), the Thermophilic Anaerobic Digestion method has the capacity to treat at higher loading rates and is a proven treatment option (Kim and Lee, 2012). However, in order to remove the offensive material from the thermophilic digestion process' final product before it can be recycled to the land, mesophilic anaerobic digestion treatment is frequently necessary.

2.6.3.2 Mesophilic anaerobic digestion

Anaerobic digestion carried out in a mesophilic environment is an example of a biochemical process that is planned and has effects on the environment and the economy. Chen (2010) asserts that mesophilic anaerobic digestion, a biological process often used in many wastewater treatment facilities for degradation and stabilization, plays a significant role in wastewater treatment operations. There have been a number of studies, including those by Batstone et al. (2002), which define that for the mesophilic one, temperature range as being 20^0C to 40^0C.

However, an appropriate operating temperature range of 33°C to 37°C is described by Bidlingmaier and Schmeiz (2009) and Gerardi (2003), while the ideal mesophilic digestion temperature currently used in the wastewater business is from 37°C to 44°C (Fountain, 2009). It's interesting to note that there is no lower and maximum temperature limit that has been established by science for the mesophilic anaerobic digestion process, as can be seen from the majority of the authors' reports above. When the minimum and maximum temperature ranges are used as one of the essential control points for the digestion process, this has a substantial operational and regulatory influence (philosophy).

2.6.4 Types of Anaerobic Digesters based on operation system

A two-stage, batch system is a common classification for anaerobic digesters. Batch systems are the least expensive and least sophisticated systems available, but they have many drawbacks, including a significant environmental imprint and a reduced biogas production owing to clogging, among others.

Two-stage systems are the most challenging and expensive anaerobic digestion systems. Even though the two digesters used in the two-stage anaerobic digestion system are identical to one another, the major digestion takes place in the first digester, which is heated, has mixing equipment, and is utilized as a tank. The second digester, on the other hand, does not have a heating system because it serves primarily as a storage tank and a secondary digestion (Metcalf & Eddy, 2004). The installed system type and management style have a direct impact on how effectively an anaerobic digestion plant operates. While complex plants can be more easily developed, they are more difficult to maintain and are less efficient than simple plants. Complex plants, however, are built with error detection and operator warning systems, which increases their efficiency.

2.6.4.1 Single stage anaerobic digester

The four anaerobic biochemical digestion stages—hydrolysis, acidogenesis, acetogenesis, and methanogenesis—occur simultaneously in one reactor during a single-stage digesting process rather than being divided in time or location. The main benefits of these kinds of plants are their simplicity, ease of operation, and minimal investment costs. However, they are less efficient in producing biogas than multi-stage digesters, which is a drawback (Inman, 2004). Currently, this method is used in about 90% of the full-scale anaerobic digester of organic municipal solid waste (bio-wastes) plants in Europe (Bouallagui et al.,2005). The system can be classified into two categories: wet systems with total solid concentrations less than 15% and dry systems with total solid concentrations greater than 15%. (Lissens, 2001).

2.6.4.2 Two stage anaerobic digester

Pohland and Ghosh (1971) and Ghosh introduced the two-stage concept first (1975). By dividing the many steps of AD into two independent stages, two-stage AD processes, according to Inman (2004), can further improve digestion by giving flexibility to optimize each of these responses. Hydrolysis, acidogenesis, and acetogenesis take place in the first reactor, whilst methanogenesis happens in the second reactor. For soluble substrates and liquid waste, this two-phase method was initially employed (Cohen, 1983). The 80's saw the study of phase separation through the digestion of solid vegetable waste (Cohen, 1983, Cohen et al., 1983; Lane, 1984; Verrier et al., 1987; Viturtia and Alvarez, 1989).

Less detention time, a greater gas conversion efficiency, and a higher methane concentration were three key benefits compared to one anaerobic digestion that were demonstrated in several investigations (Brummeler et al., 1992; Ghosh, 1995; Bae et al., 1998).

2.6.5 Types of Anaerobic Digesters based on Feeding Mode

The anaerobic digesters are often categorized based on feeding mode. Following subsections describe the modes.

2.6.5.1 Batch anaerobic digester

In batch systems, the reactor is first filled, and once the whole anaerobic process is finished, the reactor is released. Batch digesters may provide a biogas output that is between 50 and 100% greater than landfills because to two essential characteristics: higher temperatures and continuous leachate recirculation. These kinds of reactors are really basic, and the best comparison would be to a dump in a box. An additional advantage of using batch fermentation is that it allows for the recovery of recyclables and other materials after the anaerobic fermentation process has been completed. To prevent explosions while releasing the reactor once the digesting process is finished, further safety precautions must be performed. Batch systems have not yet been able to capture a sizable portion of the market. They continue to be a preferred choice in developing nations due to the fact that their construction is straightforward, they are resistant to coarse and heavy pollutants, and their investment prices are low.

2.6.5.2 Continuous anaerobic digester

In a continuous feeding mode, new feedstock is continuously supplied while an equivalent volume of slurry continuously exits the digester. This maintains a continuous digesting process. The majority of biogas facilities in poor nations have historically been run continuously. It is possible to employ one or more digesters sequentially. Examples of this kind of anaerobic digestion include internal circulation reactors, prolonged granular sludge beds, upflow anaerobic sludge blankets, continuous stirred-tank reactors, and others. Continous anaerobic digesters come in a variety of forms depending on the environment, substrate accessibility, and geographic location.

2.7 Advantages of Anaerobic Digestion Process

There are two primary benefits associated with anaerobic digestion: first, it has the potential to have a favorable effect on the surrounding ecosystem, and second, it has the potential to generate direct financial gains.

2.7.1 Environmental Benefits

Anaerobic digestion's role in lowering greenhouse gas emissions is one of its most obvious environmental advantages. AD operations replace the usage of fossil fuels by capturing methane gas that could otherwise be lost to the atmosphere. This has a significant positive impact on all usage scenarios for AD technology and helps to mitigate climate change.

The use of AD technology on farms provides several examples of how anaerobic digestion improves the environment. As farmers work to meet the expanding need for food and maintain their viability and profitability in the present global market, they may reduce costs and environmental effects and contribute to safer, more productive farms by using water and nutrients effectively for crop and animal needs.

Digesters on farms can:

- Reduce infections to protect the health of both humans and animals.
- Increase crop productivity and yield by converting nutrients in waste into more usable forms for plants to use than in raw manure.
- Recycle nutrients on the farm to build a food production system that is environmentally as well as economically sustainable.

- Produce onsite heat, power, or fuel from biogas, reducing the reliance of the agricultural industry on fossil fuels.
- Accept food waste from establishments such as supermarkets and restaurants.

Consequently, less food waste is dumped in landfills. The additional benefit of food waste is that it makes farm digesters more effective.

2.7.1.1 Diversion of Organics from Landfills

An anaerobic digester can be used to process organic materials that have been taken out of the municipal solid waste (MSW) stream. These items include yard trash, fats, oils, and greases, commercial food processing waste, food scraps from restaurants and other companies, and food scraps from residential and commercial buildings.

The environment benefits when organic waste is kept out of landfills. If these materials are allowed to deteriorate in landfills, methane may be released into the atmosphere and contribute to climate change. The loss of vital nutrients from our environment is a drawback of dumping organic waste in landfills. When these materials are digested anaerobically, nutrients are created that may be used to feed and nourish the soil.

2.7.1.2 Renewable Energy Generation

Anaerobic digestion of organic compounds yields biogas. A green energy source is biogas. In order to generate mechanical power, heat, electricity, or a combination of these, biogas can be utilized to fuel engines and generators. The quality of the biogas determines how it is used and how effectively. To get rid of carbon dioxide, water vapor, and other small impurities, biogas is frequently cleansed. The energy value of biogas is increased by removing these chemicals. Usually, harsher, less effective engines like internal combustion engines employ low-quality biogas. Engines that are more sensitive but also more efficient can utilise higher grade biogas that has been cleared of trace contaminants. Biogas that has been processed to fulfill pipeline quality requirements can be supplied through the natural gas pipeline and used in residences and commercial buildings. Additionally, compressed natural gas (CNG) or liquefied natural gas can be made from biogas by cleaning it and upgrading it (LNG). Vehicles and trucks can be fueled by CNG and LNG. It may be processed for uses similar to those of natural gas and compressed for use as vehicle fuel.

2.7.1.3 Soil Health Benefits

In order to cultivate food to feed our local, national, and international populations, it is crucial to maintain soils that are productive and healthy. A nutrient-rich slurry called digestate is created during anaerobic digestion. Digestate can be used as a fertilizer and/or soil additive on agricultural land to improve the health of the soil. Both state and federal laws apply to the application of dikes to land.

The digestate can be divided using technology into its solid and liquid components, which can then be treated or reused separately. For instance, the solid component might be composted before being applied to the ground or heat-dried to create fertilizer pellets.

Digestate treatment on land may help our soils become healthier. Benefits of soil may include:

- Increasing the amount of biological matter;;
- Reducing soil erosion and nutrient runoff;
- Lessening the need for the use of chemical pesticides and fertilizers;
- increasing growth of plants;
- Reducing soil compactness; and

- Contributing to the soil's capacity to retain more water, which minimizes the need for irrigation.

2.7.1.4 Methane Emissions Reduction

When organic compounds break down without oxygen, like in landfills and manure lagoons, methane is produced. Methane is captured by anaerobic digestion systems, and this methane can be put to good use.

Methane is a potent greenhouse gas that must be trapped since, if allowed to escape into the atmosphere, it contributes to climate change. The Biden Administration's goals for methane emissions may be achieved by encouraging the use of technologies like anaerobic digestion (2030 Greenhouse Gas Pollution Reduction Targets).

2.7.1.5 Manure Management

On animal farms, anaerobic digesters are employed as part of an integrated manure management plan in order to provide farmers with other possibilities. The use of these technologies provides a means for farmers to:

- Reduce the amount of methane released by manure ponds, stockpiles, and lagoons;
- Reduce odors and pathogens;
- Produce items for use on the farm, such as high-quality fertilizer, animal bedding;
- Reduce solids content.

Livestock dung may also be mixed, or "co-digested," with other organic waste in anaerobic digesters to boost biogas output.

2.7.2 Economic Benefits

Utilizing anaerobic digestion technologies has a number of economic advantages in addition to several environmental advantages. For wastewater treatment facilities that use anaerobic digesters to handle food waste, the reduction of energy costs from on-site power production and the collection of tipping fees for taking the trash from food processing companies result in a twofold save. Adding food waste to wastewater treatment facilities has grown in favor recently, even though local food and beverage production sectors may benefit from the same benefits.

Possibilities come in many different forms thanks to the development and management of digesters at, which generates local employment opportunities and raises local tax revenue. Digesters create opportunities for:

- During the design and construction phase of the activities, local contractors with expertise in site work, concrete, electrical, plumbing, permits, and engineering.
- Skilled workers to maintain the system's performance at peak levels after it is finished and put into use.
- Companies that cater to the markets for fertilizers, manure solids, and energy.
- Agro-tourism; in which travelers can learn about environmental improvements and the source of their food by visiting farms.

In addition to opening up new possibilities, using AD technology might also provide a new source of income by allowing for the sale of the organic nutrients found in the by-products of digested waste to other sources in horticulture and agriculture. By using biogas to produce power and fuel on-site vehicles, decreasing reliance on local utilities, anaerobic digestion technology has the potential to cut energy costs for all industries. As well as offering locally sourced renewable energy to the particular community and tax credits, RINS, and LCFS to the processing source, AD operations have the option of selling surplus biogas or the power generated by the biogas to the neighborhood utilities.

2.8 Conventional Processes for overcoming AD challenges

There are numerous methods for solving the difficulties that AD faces. Not all digesting technologies are compatible with all sorts of procedures. The best approach will vary depending on the type of feedstock, digesting technology, and desired results.

It is possible to pretreat organic materials in the digester using a variety of thermal, chemical, and mechanical techniques. They become more soluble in water when the substrate is heated conventionally. Additionally, a pathogen-free diet is provided to prevent process inhibition. For the treatment of industrial-scale wastewater, this is especially helpful. Microwave radiation has recently been put forward as a low-energy option. This method increases the degradability of complicated polymers by applying concentrated direct heat. The addition of acids or bases can increase solubility and boost biogas production for substrates high in lignin. Even though it is expensive and energy-intensive, adding oxidants is beneficial when the waste substrate is primarily made up of refractory materials like lignin. To increase digestion efficiency, mechanical pretreatment techniques including grinding, shredding, milling, or screening are frequently used. The main effects of this technique are an increase in molecule surface area and an increase in bacterial activity during digestion. Another pretreatment method to homogenize the substrate is high-pressure homogenization (HPH). High pressure (30-150 MPa) induced shear is used to damage the membranes of the substrate cells.

Different strategies are used to reduce process inhibitions brought on by the accumulation of hazardous intermediate products and nutritional imbalance. The most typical method to lessen VFA accumulation is to optimize OLR. Any substrate cannot be mono-digested effectively due to an imbalance in nutrients and a lack of diverse microorganisms. Co-digestion and the addition of additional organic materials support nutritional balance and prevent process inhibition. Co-digestion can also be used to guarantee an ideal C/N ratio. Usually, the nitrogen-rich substrate, such animal manure, is combined with the substrate rich in carbohydrates.

In the digester, additives are utilized to increase material conversion and biogas generation. The main functions of additives are microbial growth support, inhibitory product adsorption, nutritional supplementation, and buffering capacity enhancement. Sand, molecular sieve, zeolite, charcoal, and other conductive materials are utilized to increase syntrophic activity while supplying a habitat for microbial development. Inhibitory substances like NH_3, H_2S, which they may also adsorb, allow for more effective conversion. Micro- and macronutrient supplements are provided to the digester if any substrate lacks a particular nutrient required for the digesting process. While preserving the stability of the process, it promotes the production of biogas.

2.9 Household Digesters

Adopting one particular digester type for residential use is never easy. Depending on the geographic location, substrate accessibility, and climatic circumstances, different digesters have different designs. For example, a digester utilized in a mountainous area is built with smaller gas volume to prevent gas loss. Due to the geothermal energy, it is preferable for tropical areas to have subterranean digesters. The fixed dome model created by China and the floating drum model created by India are the only digesters that have remained functional to this day out of all the numerous digesters that have been created. Because they are portable and simple to use, plug flow digesters have recently attracted attention.

2.9.1 Fixed Dome Digesters

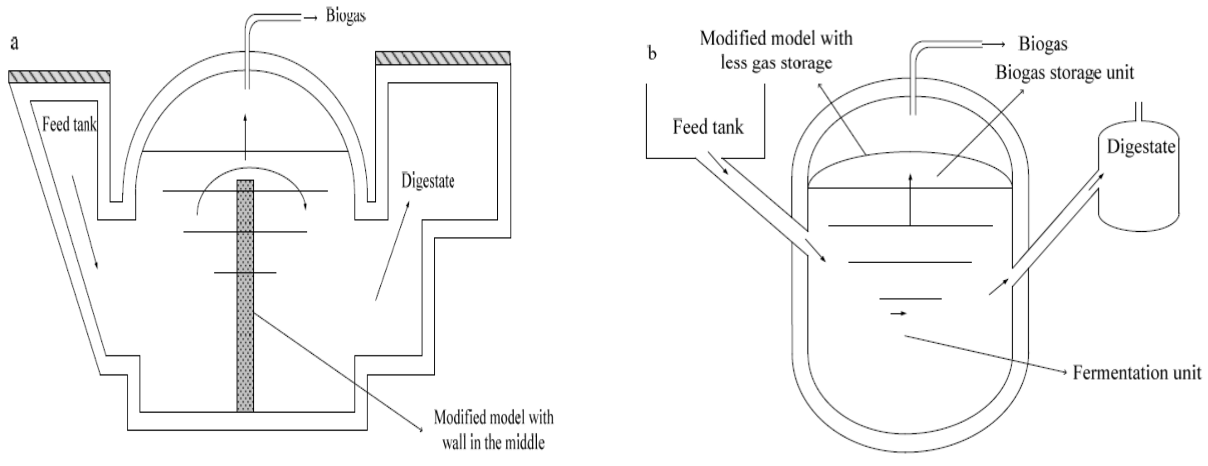
The most popular model created and utilized mostly in China for the production of biogas is the fixed dome digesters (

c) modified fixed dome digester with curved and straight intake and exit tubes

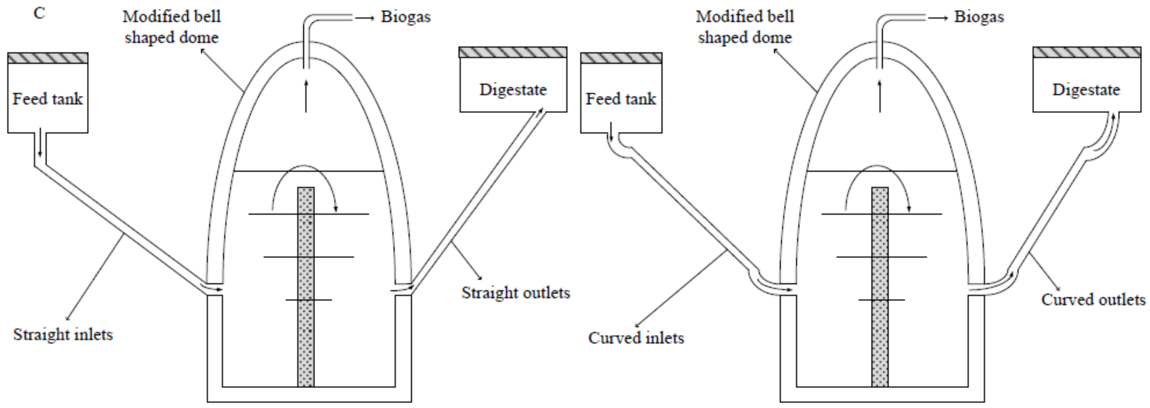
Figure 2-12) often known as "Chinese" or "hydraulic" digesters. The inflow hose is used to fill the digester up until the expansion chamber's bottom level is reached. The storage part of the digester's upper portion is where the generated biogas is gathered. The difference in level that exists between the slurry that is contained within the digester and the expansion chamber is what leads to the production of gas pressure. A portion of the substrate is forced into an expansion chamber by the collected gas, which needs room to expand. After the gas is released, the slurry instantly flows back into the digester.

Digesters with fixed domes are often built underground. The location, the number of houses, and the daily substrate supply all affect the digester's size. For instance, the size of these digesters can commonly range from 4 to 20 m^3 in Nepal, 6 to 10 m^3 in China, 1 to 150 m^3 in India, and about 6 m^3 for a family of nine in Nigeria. Community type biogas digesters are high volume digesters that are used to create biogas for 10 to 20 homes instead of one digester for each individual residence. These types of biogas digesters are more practical in nations with dense housing populations, such as Nigeria.

The Janta and Deenbandhu models of fixed domes were created in India. In 1978, the janta model was released (Figure 2-12a). A shallow well with a dome roof sits atop it. The gas line was installed on top of the dome, with the entrance and exit kept above the dome. The Janta model has a number of flaws, including a short circulation path for the slurry, an escape of undigested slurry at the top, and a lower amount of gas produced as a result of an increase in gas pressure. In 1984, Action for Food Production (AFPRO) introduced the Deenbandhu model, a modified version of the Janta model (Figure 2-12b). It is made up of two spheres with various diameters. While the upper sphere serves as a storage unit, the lower sphere serves as a unit for fermentation. This model was created to lower the cost without lowering the process's efficiency.



(a) janta model fixed dome digester | (b) deenbandhu model fixed dome digester



c) modified fixed dome digester with curved and straight intake and exit tubes

Figure 2-12: Schematic sketch of different models of digesters

The fixed dome model's basic shape has been altered by numerous nations. To provide two examples, the deenbandhu model was altered to have a reduced gas holding capacity and a smaller arch diameter, while the Chinese digester was changed to have a hemispherical form with a wall in the center as shown in Figure 2-12b. The upgraded model performs better than the Deenbandhu variant during the winter months in mountainous areas. Jash and Basu modified the dome by adding a bell-shaped gas storage and a vertical cylinder. Using bricks, the cylindrical vessel was divided in half. The lengthy, straight inlet and outlet tubes were modified to have a bent inlet and outlet tube because some of the heavy particles became lodged in them (Figure 2-12c). Fixed dome digesters, also known as French type digesters, were enclosed by a steel drum storing biomass to prevent temperature loss. Another change is the addition of an expanding plastic bag to the fixed dome digester's gas holding section. The cover is covered with a wooden roof, which serves to shield the light-sensitive polyethylene bag from the sun while also raising the gas pressure due to its weight.

2.9.2 Floating Drum Digesters

The Khadi and Village Industries Commission (KVIC) is a concept for a floating drum digester that was developed in 1962 (Figure 2-13). Despite the relatively outdated style, it is one of the most well-liked and regularly used versions in India for domestic usage. The design has a rotating, inverted drum sitting on a clearly defined digester. An upside-down steel drum that acts as a storage tank is supported by the digester. Depending on how much gas has gathered at the digester's top, the digester can move up and down. The pressure that is necessary for the gas to go through the pipeline and be utilized is applied by the weight of this drum that has been turned upside down.

Biogas is produced by floating drum digesters at a variable volume and constant pressure. The amount of biogas that has accumulated underneath the drum may be simply determined from the drum's location. To prevent rust, the floating drum must, however, be painted at regular intervals. Fibrous substances will also impede the digestion process. Thus, it is best to prevent their accumulation if at all possible. The floating dome in Thailand has received an expansion in the form of the addition of two cement jars, one on either side of the floating drum. These digesters have a volume that is commonly measured to be 1.2 m^3. Sizes for small- to medium-sized farms range from about 5 to 15 m^3. Using a floating drum model, Singh and Gupta investigated fourteen different biogas production facilities. Each digester had a capacity of around 85 m^3 of material. The ratio of the amount of waste that is brought to the facility on a daily basis to the total capacity of the facility is referred to as the plant utilization factor (PUF), and it was found to be 0.36. This outcome shows that the plant's full capacity was not used.

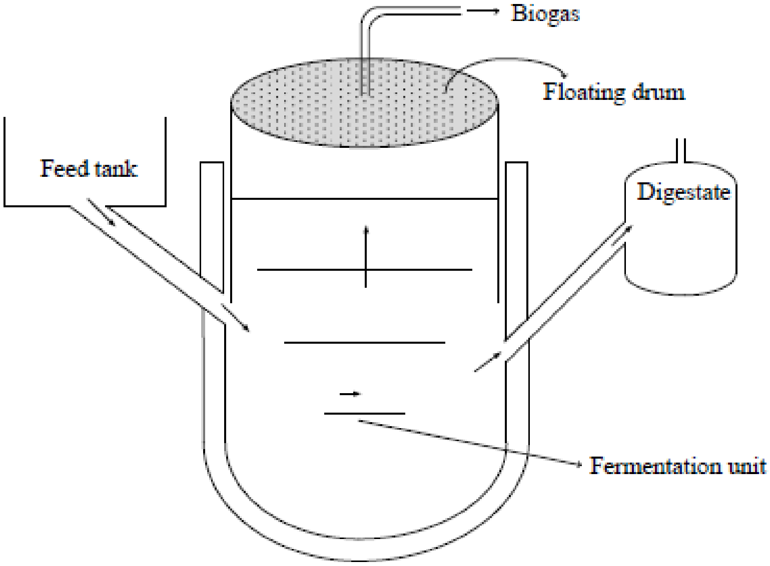


Figure 2-13: Floating drum digester

2.9.3 Plug Flow Digesters

The fixed dome and floating drum types have the drawback of being difficult to relocate once installed. So, over-the-ground portable types known as tubular or plug flow digesters were created. (Figure 2-14).

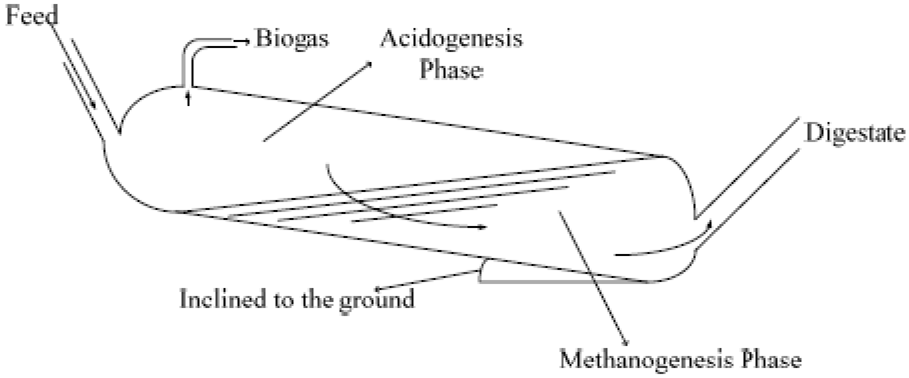


Figure 2-14: Schematic diagram of a plug flow digester

Plug flow digesters generate biogas at a changing pressure while maintaining a constant volume. These digesters range in size from 2.4 to 7.5 m3. The tank used in plug-flow digesters is long and thin, with an average length to width ratio of 5:1. The digester's intake and outflow are at its opposite ends and are kept above ground, while the rest of the digester is buried in the ground at an angle. The digestate moves toward the outflow at the other end of the tank as new substrate is fed from the intake. The inclined orientation allows for the longitudinal separation of acidogenesis and methanogenesis, resulting in a two-phase system. The digester is covered with a gable or shed roof that serves as insulation both during the day and at night to minimize temperature changes and keep the process temperature constant.

Due to their portability and affordability, tubular digesters have recently become more popular in Peru. These digesters are practical because they are simple to install, manage, and adapt to harsh environments at high altitudes with low temperatures. In hilly places, it is expensive to transport the materials needed to build the digester, which drives up the capital cost. However, plug flow digesters are simple to transport, which eventually lowers the digester's cost. A significant amount of earth must also be dug up in order to construct digesters at high altitudes.

For semi-continuous operation with a HRT of 20 to 30 days and solid contents ranging from 11 to 14%, plug flow designs are appropriate. The lack of moving parts in these digesters lowers the possibility of failure. Only one of the 99 digesters the Bureau of Animal Industry placed in the Philippines failed to produce any gas, and three others had delayed gas output.

2.10 Operating Parameters

The symbiotic relationship between all the microorganisms engaged in anaerobic digestion means that if one of them is not flourishing, the digester as a whole may become bad. This symbiotic relationship calls for a wide range of operational conditions in order to sustain a healthy digester and ensure that each organism is functioning as efficiently as is humanly possible.

2.10.1 Solids Concentration & Organic Loading Rate

The amount of influent that enters a continuous or semi-continuous digester of a specified size in a given amount of time is referred to as the loading rate. The organic loading rate (OLR) can be calculated using the following equation:

$$OLR = \frac{S_0 \times Q}{V}$$

where, where S_o is the influent solids content (kg/m^3 VS or COD), Q is the flow rate (m^3/time), and V is the reactor volume (m^3). The kind of reactor and the substrates used in the digester are frequently key factors in determining the proper organic loading rate. Studies on the anaerobic treatment of biowaste in industrialized countries have shown that VS removal of 50 to 70% occurs when organic loading rates of 4 to 8 kg VS/m3 reactor per day are used as per Vandevivere et al (2001). This works wonderfully for reactors that require constant stirring. On the other hand, for non-stirred AD systems, which are typically found in developing nations, an OLR of less than 2 kg VS/m3 reactor and day is recommended and seen as appropriate. To prevent stunning the microorganisms inside the digester, loading rates should be maintained steadily.

Equation states that higher flow rates or higher solids concentrations may result in higher loading rates. For bigger facilities like wastewater treatment plants, flow rates may be adjusted using holding tanks for this reason (Labatut and Pronto 2018). To avoid an excessive organic loading rate, solids concentrations must also be maintained at suitable ranges.

Different solids concentrations can also lead to anaerobic digestion. AD can be classified as high solids (>20% TS), medium solids (15–20% TS) or low solids (15% TS), depending on the concentration of total solids (TS) (Kothari et al. 2014). Although low solids AD consumes more water, stabilizing the system is simpler. High solids AD restricts the amount of water fed, but it may be more challenging to maintain a stable digester since it requires more inoculum, has longer retention durations, and has a higher risk for VFA formation (Kothari et al. 2014).

2.10.2 Temperature

Temperature has a significant impact on the production of fertilizer, methane, microbial growth, and enzyme activity. In anaerobic digestion, psychrophilic (10-30^{0}C), mesophilic (30-40^{0}C), and thermophilic are the three primary operating conditions (50-60^{0}C). An increase in temperature will cause the reactor to produce more methane gas up to about 60^{0}C. (Labatutand Pronto 2018). The majority of digesters, though, function in the mesophilic zone. The risk of the reactor souring is reduced since methanogens that live in the mesophilic range are more resistant to temperature changes. The solubilization of food waste can also be reduced by thermophilic settings (Labatut and Pronto 2018). Normal anaerobic digesters, which are frequently found in homes and small farms, are the only ones that use psychrophilic conditions. This range is not advised for large-scale applications since industrial sizes are not frequently considered as economically viable or lucrative given the high expense of larger reactors necessary for psychrophilic temperatures.

2.10.3 pH

The health of anaerobic bacteria is significantly influenced by the pH of a reactor. Neutral pH levels, which might be in the range of 6.5 to 7.2, are ideal for methanogenic archaea to grow (Rittmann and McCarty 2001). Because methanogens absorb acetic acid to create methane, the pH in the reactor rises as a result. Due to the creation of VFAs, acetogenesis and acidogenesis both utilize alkalinity concurrently. Methanogens are blocked if the pH lowers too far. As a result, the pH will drop much more quickly, souring the reactor (Rittmann and McCarty 2001). Methanogens also grow more slowly than other anaerobes, increasing the chance of the reactor spoiling while an anaerobic digester is starting up. One method that plants avoid this is by gradually raising the organic loading rates in the reactor to support the methanogens' gradual growth. The addition of an alkalinity source that can stabilize pH variations is another preventative measure. Additionally, the digester needs to have a VFA concentration of about 300 mg/l to make sure methanogens are fed (Schuyler 2013). When VFA concentrations are above 1500–2000 mg/l, methanogenic inhibition will start to appear (Labatut and Pronto 2018).

2.10.4 Volatile Fatty Acid (VFA) concentration

Substrates that are easily biodegradable include volatile fatty acids (VFA). They are the byproducts of the three primary anaerobic processes: acidogenesis, acetogenesis, and methanogenesis (Zaher, 2005). Due to the strong buffering ability of the simultaneously available alkalinity in the range of 5000–8000 mg per liter, anaerobic digestion processes with significant solid loads commonly generate high VFA concentrations in the range of 500–3000 mg/l. Nonetheless, the anaerobic digestion process continues to function well. In the anaerobic digestion process, high VFA levels do not pose a substantial risk of the digestion process failing as long as there is sufficient alkalinity in the system to buffer the acidity and maintain the pH in the range of 6.7 to 8.6. VFA concentration has been connected to AD stability in studies (Ahring et al., 1995)..

According to Horan et al. (2004), the digestive process is steady up to a maximum VFA content of 200 mg L^{-1}, beyond which it may falter. However, variations in VFA concentrations may signal imminent process disturbances and a lack of buffering power (Ahring et al., 1995). It was shown that the higher VFA content in thermophilic anaerobic digestion (TAD) compared to mesophilic anaerobic digestion demonstrated a relative difference in the rates of fermentation and methanogenesis rather than the existence of digestion process instability. (Kim and Lee, 2012).

2.10.5 VFA to Alkalinity Ratio

The ratio of volatile fatty acids to alkalinity is a reliable indicator of the state of the reactor's health and of whether or not the pH can be maintained at an appropriate level. (Rajagopal et al. 2017). Alkalinity, which is typically expressed in terms of CaCO3 equivalents, is a measurement of a solution's capacity to resist a change in pH. Methanogens are protected from a pH shock by having a high enough alkalinity level, especially during loading when hydrolysis increases significantly. It is advised that digesters contain at least 1000 mg/l of alkalinity (Roos et al. 2004). To prevent the methanogens from experiencing a pH shock, the VFA:Alkalinity ratio ought to be kept within the range of 0.1 to 0.35 at all times. This will ensure that there is adequate alkalinity. (Roos et al. 2004). If the ratio of VFA to alkalinity is greater than 0.35, it is likely that the reactor is being overloaded; therefore, the OLR should be decreased.

2.10.6 Carbon to Nitrogen Ratio

The efficiency of the anaerobic digester is significantly influenced by the carbon to nitrogen (C:N) ratio. The carbon-to-nitrogen ratio of organic matter refers to the proportion of carbon to nitrogen. In organic matter, carbon constantly predominates over nitrogen. The carbon-to-nitrogen ratio, abbreviated C:N, is often expressed as a single value (Flavel and Murphy, 2006). When the C:N ratio of an organic substrate is between 1 and 15, N quickly minerals out and is released, making it accessible for plant uptake. The faster nitrogen is released into the soil for usage by crops, the lower the C:N ratio (Watson et al., 2002). Microbial immobilization occurs when C to N ratio is greater than 35. A balance between mineralization as well as immobilization is reached at a ratio of 20 to 30. According to Meegoda et al. (2018), food waste contains a C:N ratio of around 14:1 to 18:1, which, when digested alone, can lead to free ammonia inhibition. To choose the best circumstances, it is necessary to study the C:N ratio carefully as it differs significantly different substrates. Food waste is frequently co-digested with other organic materials to assist achieve a more correct C:N ratio in order to avoid this from happening. Section 2.12 will go into further detail about co-digestion.

2.10.7 Food to Inoculum Ratio

The food/Inoculum (F:I) ratio illustrates the relationship between the volume of the food and the microorganism within the digester. Due to the fact that a healthy microbial population can guarantee adequate methane synthesis right from the start of the digestive phase, this aspect of AD is of the utmost importance (Lee et al. 2019). The literature values have varied from 3:1 to 1:7 (Hinds et al. 2017), and the substrates and inoculums have a significant impact on the best F:I ratios. An incorrect OLR will result in an unsuitable F:I ratio, which may either lead to an abundance of substrate that microorganisms are unable to metabolize or to an inefficient system that can handle more substrate than it is getting. Both of these outcomes are undesirable.The OLR of a continuous process is linked to the F:I ratio. A greater OLR results in a higher F:I ratio, which might overwhelm the system.

2.10.8 Retention Time

The average amount of time that liquid and soluble compounds stay in a reactor or tank. It is calculated by dividing the volume of a reactor (e.g. m^3) by the influent flow rate (e.t. m^3/day). In wastewater treatment systems the HRT influence the treatment efficiency and is therefore an important design parameter. It is often referred to as the typical duration of solids in the digester. The average amount of time that liquids stay in the system is known as hydraulic retention time (HRT). The HRT necessary to enable full AD reactions varies depending on the technology used, the process temperature, and the kind of waste. HRTs of 10 to 40 days are advised for wastes processed in a mesophilic digester. In digesters operated in the thermophilic range, shorter retention times—a few days at most—are needed (Verma, 2002). Although there is a difference between hydraulic retention time (HRT) and solids retention time (SRT), HRT and SRT are often regarded as identical for the digestion of solid waste. Both solids and liquids are present in the reactor for an equal amount of time when it is a continuous stirred tank reactor and there is no recycle and therefore,

$$SRT = HRT = \frac{V}{Q}$$

The SRT needed for an AD varies depending on the substrate, types of operation, and surronding factors. Single stage mesophilic ADs need longer SRTs for food waste, ranging from 10 to 60 days, but two-stage reactors only need 10-15 days per reactor (Zhang et al. 2014). Each microbial group in anaerobic digestion has a distinct maximum specific growth rate.

2.10.9 Digester mixing

By blending fresh material with digestate and stirring it around inside the digester, microorganisms are introduced to the fresh material. Such mixing prevents scum development and temperature disparities inside the digester. The digester's filamentous microorganisms are the cause of scum and froth. In AD plants, low substrate concentrations promote the growth of filamentous bacteria as opposed to flocculating bacteria. Scum in digesters should be avoided since it may cause the digester to foam over or cause the gas pipe to become blocked. This causes slurry to be displaced into pipes, machinery, and other devices, which may then malfunction or corrode. Since bacteria can regenerate, their loss is typically a minor issue. In large-scale systems, a consistent top layer of 20 to 60 cm of foam is typically regarded as "stable" and is either acceptable or simple to handle. However, a thicker impermeable scum layer can restrict gas discharge from the liquid and ultimately result in the structure failing (Deublein and Steinhauser, 2011). Depending on the kind of reactor and the amount of TS present in the digester, different equipment is used for mixing and stirring. Additionally, some research have confirmed that semi-continuous mixing, sometimes referred to as intermittent mixing, is preferable to continuous mixing. Semi-continuous mixing, as opposed to continuous mixing, allows for enough time for microbial growth, which improves the mass transfer from the liquid to gas phase and, as a result, raises the methane yield. Continuous mixing, on the other hand, disrupts the syntrophic relationship between acetogens and methanogens.

2.11 Anaerobic Digestion of Food Waste

Because food waste has a high biodegradability, it is a frequent substrate for AD. Due to its high biodegradability when dumped in the ground, food waste releases the most methane of all municipal solid trash (Labatut and Pronto 2018). Thus, by using anaerobic digestion to recover resources from food waste, methane from a waste product may be captured and turned into energy. The most widely used technique in Europe for handling organic urban garbage, including food waste, is anaerobic digestion (Labatut and Pronto 2018).

Large-scale uses of anaerobic digestion of food waste have been studied in depth. In Europe, where source separation has been vigorously advocated since the 1990s, it is frequently observed. Each year, Germany and Spain can each treat 2 million and 2.5 million tons (Baere and Mattheeuws 2015).

Since the beginning of the millennium, the number of food waste AD digesters in the US has significantly increased (US EPA 2019). Three main digesting processes stand-alone digesters, co-digestion with animal waste, and co-digestion at wastewater treatment plants—are frequently used to dispose of food waste in the US (Labatut and Pronto 2018). The United States has 62 stand-alone food digesters, 59 co-digesters, and 77 wastewater treatment plant food digesters, respectively. The aggregate yearly food waste processing capacity of these plants is 10 million tons, and they produce enough biogas to power 79,000 households (US EPA 2019).

Due to the inadequate buffering capacity of food waste, stand-alone AD frequently results in process instability (Labatut and Pronto 2018). Due to the production of VFAs, this causes a sudden drop in pH, which can stop methanogenesis. Proteins in food waste also contribute to nitrogen concentrations that are significantly higher than the optimal C:N ratio in the reactor. Fatty acids are produced as a result, and they have the ability to stop methanogenesis (Banks et al. 2011). Because food waste has a lower pH than other substrates, it requires inoculum with a higher buffering capacity (Pavi et al. 2017). To stop methanogenic inhibition, numerous experiments have tried to stabilize food waste AD.

In a 900 m^3 reactor with a HRT of 80 days and thermophilic operating conditions, Banks et al. (2011) examined the long-term operation of source-separated domestic food waste. These circumstances led to a 402 m^3/tonne VS methane output and a 62.6% methane content in the biogas. In this instance, food waste was pasteurized at 70^0C for an hour before being added to the thermophilic digester. First, it was crushed and combined with recirculated digestate. No methanogenic inhibition developed as a result of these operating parameters during the reactor's operation.

In batch reactors, Pavi et al. (2017) compared the digestion of organic municipal food waste with fruit and vegetable waste at a 1:1 and 1:3 mixing ratio to the two substrates digesting independently at a 1:1 F:M ratio. Their inoculum had an alkalinity of 906 mg/l as HCO_3^- and was already accustomed to handling food waste. They observed a maximum methane output of 396.6 ml g^{-1} VS at a 1:3 mixing ratio and a 34.7 C:N ratio. This is greater than the typical methane range of 20 to 30, but it also shows that the selection of substrate and inoculum affects the ideal C:N to maximum methane yield.

2.12 Co-digestion

Co-digestion is an efficient way to keep the C:N ratio in the digester at the proper level without having to buy more substrate. Co-digestion can also be advantageous for large-scale applications since it enables businesses to accept various substrates and make themselves more commercially viable. The ideal C:N ratio, as already mentioned, is 30:1, however food waste is only at 18:1. (Meegoda et al. 2018). It is obvious that constraints in anaerobic mono-digestion of a substrate can be readily overcome by co-digesting a substrate with a co-substrate at an appropriate mixing ratio. This can be done by co-digesting a substrate with a co-substrate (Prajapati and Singh, 2018). The co-digestion of organic wastes under anaerobic conditions appears to be a successful strategy for balancing nutrients and enhancing the synergistic interactions among the different organic substrates by creating a more stable environment inside the digester. The co-digesting of lignocellulosic waste and food waste has been shown to increase the rate at which biogas is produced and the amount of methane produced. Co-digesting cardboard with food waste increased the methane potential by 71-93%, according to Capson-Tojo et al. (2017). According to Yong et al. (2015), co-digestion of food waste and straw enhanced the output of methane production by 39.5% and 149.7%, respectively, as compared to mono-digestion. According to Brown and Li (2013), yard waste and food waste co-digestion increased methane production. The co-digestion of food waste and Chinese silver grass by Wan et al. (2013) and maize husk and food waste by Owamah and Izinyon (2015) also produced similar findings. Co-digestion of organic substrates therefore aids in improving biogas production by increasing the amount of material that is readily biodegradable, lowering the possibility of noxious compounds present in any of the co-substrates, regulating moisture content and pH, and a wider variety of microorganisms participating in the process (Agdag and Sponza, 2005; Esposito et al., 2012; Jiang et al., 2018). The symbiotic activity of the anaerobic bacteria within the biogas digester has a significant impact on the stability of the process of anaerobic digestion (Asri et al., 2017). A suitable mixing ratio must be utilized in order to maintain the reactor's conditions throughout the anaerobic co-digestion process. A suitable ratio of various waste products results in optimum digesting efficiency by recovering the nutritious content and minimizing the detrimental impacts of harmful substances (Murto et al., 2004; Tian et al., 2015). Therefore, various studies have been conducted to determine opportunities for co-digestion with food waste, shown in Table 2-2.

Table 2-2: Co digestion of different substrate with Food waste

Substrate	**Experimental Setup**	**Results**	**Source**
FW+ cattle manure	C:N ratios of 15.8,17.1 and 17.8 in Batch reactors	Maximum volume of biogas gained from C:N ratio of 15.8	Zhang et al. 2013

FW + dairy manure	30 day batch reactors	Greatest biogas yield from 100% food waste without dairy manure	El-Mashad and Zhang 2010
FW+ dairy manure	Batch test in 10 and 20 g VS/l loading rate	FW +NaOH achieved the highest methane yields (458.4 mL/g VS) but FW+cow manure at 20 g VS/l were highest non dosed option (310.8 ml/ g VS)	Li et al. 2010

2.13 Enhancement of Anaerobic Digestion Process

Since excessive volatile fatty acid (VFA) accumulation occurs in food waste during the initial stages of bacterial activity's degradation, this causes a lag period before methanogens may begin to produce gas (Shao et al., 2005). If this VFA buildup can be lessened, the lag phase will also be lessened, which will lead to early methane generation.

2.13.1 Inoculum Addition

When handling pure organic waste, inoculum addition might be quite beneficial. Wang et al. (1997) also demonstrated that a large percentage of inoculum for pure food waste lowers the lag phase. The inoculum source chosen by the researchers was well-decomposed trash. Other sources of inoculum, such as sludge or manure, can lower the required percentage while also shortening the time lag before methane generation.

2.13.1.1 Sludge as inoculum

Sludge addition can affect waste biodegradation in both favorable and unfavorable ways (Christensen et al., 1992). The addition of anaerobically digested sewage sludge to fresh waste initially lowers pH because of acid buildup and reduced microbial activity (Barlaz et al., 1990), but it also creates three times as much methane as the addition of primary sludge (Komilis et al., 1999). The benefit of sewage sludge is that it is a source of nutrients and methanogenic microorganisms. It also helps increase moisture content (Christensen et al., 1992).

Because of the numerous microorganisms present, sewage sludge aids in the quicker degradation of waste. Researchers Pacey (1989), Leuschner (1982), and Warith (2002) examined how adding sludge affected the decomposition of MSW. According to Warith, 2002, pH increase and BOD reduction were discovered in reactors with added sludge. According to Warith (2005), adding anaerobically digested sludge, which acts as a seed for microorganisms by providing moisture, a source of nitrogen, phosphorus, and other nutrients, has a good impact on waste decomposition.

By combining MSW with 10% anaerobically digested wastewater sludge in a test, Buivid et al. (1981) discovered that the production of CH4 increased by more than three times after 90 days. Alkalinity is raised via sludge addition, which serves as a buffer. Higher sludge to waste ratios resulted in a higher methane production rate because organic stuff degrades quickly. The addition of aerobically digested sewage sludge to fresh waste initially lowers pH because of acid buildup and reduced microbial activity (Barlaz et al., 1990), but it also creates three times as much methane as the addition of primary sludge (Komilis et al., 1999). The benefit of sewage sludge is that it is a source of nutrients and methanogenic microorganisms. It also helps increase moisture content (Christensen et al., 1992).

2.13.1.2 Manure as Inoculum

Manure is regarded as a reliable supply of the microorganisms and nutrients (such as carbon, nitrogen, and phosphorus) required for plant growth. Cattle, pig, and poultry manures are examples of animal waste. High nitrogen concentration and the presence of sulfur, ammonia, and hydrogen sulfide gasses that can be readily generated are frequently cited as the main characteristics of manures. Therefore, mono-digesting manures results in an oversupply of nutrients and organic matter in the digester, which reduces methane production. But because of its high nutrient level, it might serve as a co-substrate in place of the primary substrate's lower nutrient content. Manure can be an important source of inoculum when combined with landfill garbage since it contains a significant quantity of organic carbon and is an excellent source of bacteria like methanogens. This combination may even slightly increase methane generation. The kind and quantity of inoculum added to the trash determines how much gas is produced. Table 2-3 presents the characteristics of different livestock used as inoculum.

Table 2-3: Initial traits of many livestock inoculations (Dhamodharan et al., 2015)

Parameters	Cow Manure	Goat Manure	Pig Manure	Poultry Manure
Moisture Content (%)	79.8±2.3	45.7±0.6	72.23±1.6	78.42±0.8
Total Solids (%)	20.19±1.4	55.1±1.5	26.7±1.8	21.6±0.9
Volatile Solids (%)	15.25±1.1	39.2±0.9	22.18±1.3	16.2±0.5
pH	7.05-7.25	7.35-7.51	6.52-6.94	6.53-6.63
sCOD (g/L)	21.6±4.8	34.3±4.7	23.3±3.6	22.5±3.9
TKN (g/L)	5.3±0.6	3.9±0.1	3.1±0.5	3.0±0.2

The inoculum introduced has a substantial impact on the rate at which gas is generated from trash. Due to a lack of sufficient microorganism, adding inoculum is especially necessary for pure organics, such as food waste. Manure, a possible source of microorganism, can significantly improve gas production from trash. Food waste can also be supplemented with animal manure to achieve desired results (Chen et al, 2010). The accumulation of volatile fatty acids (VFA) during the acidogenic phase of organic waste is a major issue since it hinders bacterial activity. Therefore, adding manure has benefits because it increases buffer capacity, creates an environment to somewhat neutralize pH, and shortens inhibitory time (Zhang et al., 2013). The methane output increased by 41.1% and the overall methane yield was 388 mL/g VS, according to the authors who utilized a food waste to manure ratio of 2. Without the addition of manure, the amount of methane discovered overall was incredibly low compared to the other scenario. Another study by Li et al. (2009) revealed that the amount of methane produced from the kitchen trash increases by 44% when combined with calf manure. Figure 2-15 shows the result of digestion of food waste with different cases.

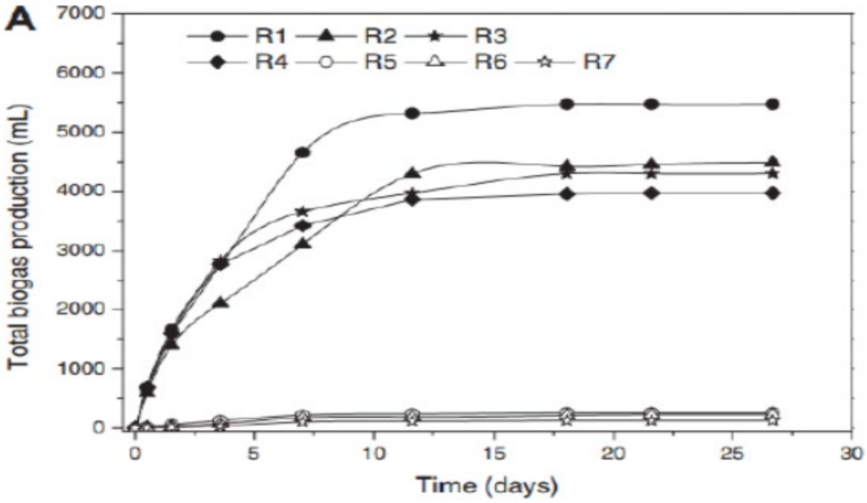


Figure 2-15: Food waste Digestion with and without inoculum (R1 through R7) (Zhang et al., 2013)

Table 2-4 : Biogas production from Co-digestion of waste with other Substance

Added material	**Specific added matter**	**Biogas production rate**	**Methane yield (L kg^{-1} VS)**	**Notes**	**References**
Waste from Household	Residual meat	900 (L kg^{-1} VS)	450		Garcia-Pena et al, 2011
	Municipal household waste				Cabbai, V et al, 2013
	Dairy products, meat and sugars		450		Alkanok, G et al,2014
Kitchen wastes	Food waste		351 – 455		Shen, F.et al, 2013
	Kitchen waste		725		Wang, L et al, 2014

	Kitchen waste				Yang et al, 2013
Livestock wastes	Slaughterhouse wastewater	2.53 (L day^{-1})	611	After the addition of wastewater, the yield of biogas increased by 51.5%	Bouallagui et al,, 2009
	Horse manure		510 – 610		Smith et al,2014
Agricultural wastes	Artichokes	354 ± 68 L kg-1 TS		Increased by 45.08%	Ros, M et al, 2013
	Wheat straw				Wang et al, 2014
Sludge	Primary sludge	4.40 (L day-1)	600	Biogas yield increased	Gomez et al, 2006
	Dewatered sludge	720			Liu et al, 2012
	Sludge		435		Di Maria et al, 2015

2.13.2 Addition of Nitrogen and Phosphorus

For a small size experimental investigation to investigate the effects of supplementing leachate during recirculation, Warith et al. (1999) used MSW-filled simulated landfill cells during a 65-week period. In order to balance the nutritional shortfall within the solid waste matrix, the recirculated leachate was supplied in two different ways: by adding primary sludge to boost the microbial population within the trash, and by providing nitrogen and phosphorus with a buffer as supplemental nutrients. By examining the properties of effluents, such as BOD, COD, TOC, and heavy metal concentrations, it was possible to determine the efficiency of adding these elements. According to experimental findings, additional materials added to leachate during recirculation greatly speed up the biodegradation of solid waste.

2.13.3 Acclimatized inoculum and its influence on anaerobic digestion

Anaerobic digestate containing microorganisms that have been exposed to a particular substrate and have improved their ability to break down that substrate is known as acclimated inoculum. This is brought about by the enrichment of bacteria that produce enzymes more suited for a substrate and the extinction of other microbes (Hinds et al. 2016). It has been demonstrated that using adapted inoculum can reduce lag periods at the start of digestion and can boost methane yield (Lee et al. 2019). By using acclimated inoculum during high solids anaerobic digestion of food waste, yard waste, and waste activated sludge, Lee et al. (2019) saw a 38% increase in methane output. It is believed that anaerobic sludge from a wastewater treatment facility is a better inoculum than other sources of anaerobic microorganisms, such as cattle, corn silage, or swine sludge, for the organic part of municipal solid waste, which includes a significant amount of food waste. Other sources of anaerobic microorganisms include: cattle, corn silage, or swine sludge (Forster-Carneiro et al. 2007). Additionally, pre-digested sludge is believed to be a superior source of inoculum for ligno-cellulosic waste than fresh calf manure. This is because pre-digested sludge has already been broken down (Sharma et al. 1988). Hinds et al. (2016) also investigated the enhancement of ligno-cellulosic waste biodegradation by employing anaerobic sludge from a pulp and paper anaerobic digester. This research was published in the journal Environmental Science & Technology. They discovered that pulp and paper sludge increased the rate of hydrolysis, which is typically the step in the AD of ligno-cellulosic waste that is the rate-limiting step due to the arrangement of the cellulose with the lignin. They came to this conclusion after observing that the hydrolysis rate increased.

2.14 Studies on Food waste with different Inoculum

Till date, several studies have been conducted with the food waste with different inoculum and various Food/Inoculum ratio or Organic Loading Rate. Following Table is the summary of those works till now:

Table 2-5: Studies on Food Waste with different Inoculum and various Ratio

Food Composition	**Inoculum**	**F/I**	**Biogas production rate**	**Notes**	**References**
Fruit and Vegetable, Residual meat (1:1)	Cow Manure	10:1	900 (L kg-1 VS)	FVW alone results in 70 L kg-1 VS of biogas with 0% methane	Garcia-Pena et al, 2011
Municipal household waste, Fruit and Vegetable (1:1)	primary sludge and waste activated sludge.	1:3	365.49 NmlCH_4/gVS of methane	CO-DIG1 (OFMSW-MIX:SwS ratio of 0.23 gVS/gVS.) and CO-DIG2 (OFMSW-MIX:SwS ratio of 2.09 gVS/gVS.) have highlighted an increase in methane production of 18% and 47% respectively,compared to SwS(a mixture of primary sludge and waste activated sludge)	Cabbai, V et al, 2013
Fruit and Vegetable	anaerobic waste water	9:1	450 L kg^{-1} VS of methane	Mix of Flower, fruit, vegetable waste, Sugar waste, Meat waste performed better than i) Flower, fruit, vegetable waste, ii) Sugar waste, iii)Meat waste alone	Alkanok, G et al,2014
Food waste (residues of vegetables such as carrot, tomato, cabbage, potato, and fruits such as apple, watermelon, and banana.) FW (cooked food residues, such as steamed rice, noodles, steamed bread, and cooked	sludge	-	351 – 455 L kg^{-1} VS of methane	Single-phase digestion achieved 4.1% more CH4 production than two-phase when OLR was <2.0 g(VS) $L^{-1}d^{-1}$	Shen, F.et al, 2013

Food Composition	**Inoculum**	**F/I**	**Biogas production rate**	**Notes**	**References**
vegetable, meat, fish.) FVW: FW= (5:8)					
Kitchen waste (FVW/KW ratio of 0:8, 2:8, 5:8, 8:8, and 8:0)	sludge	2.5:1	725 L kg^{-1} VS of methane	Out of FVW/KW ratio of 0:8, 2:8, 5:8, 8:8, and 8:0; FVW/KW ratio 5/8 performed best	Wang, L et al, 2014
Kitchen waste (70% rice, 20% Veg, 10% meat) (FVW/KW ratio of 3:1, 1:1, 1:3, 0:1)	Acclimated sludge	-		FVW/KW=3:1 was better than the others in Acidogenic-phase reactor. FVW/KW=1:1 was the best ratio in Methanogenic-phase reactor	Yang et al, 2013
Food Waste (Sweet onion, Cucumber, Red pepper, Celery, Lettuce, Broccoli, Cabbage, Melon, Cauliflower)	Horse manure	1:0, 9:1, 3:1,1:1,0:1	510 – 610 L kg^{-1} VS of methane	9:1 generated highest methane of 610 L kg-1 out of 5 combinations	Smith et al,2014
Food Waste (tomato, pepper, persimmon and peach)	Pig manure	1:0, 17:3, 3:2,1:1		After being mixed with tomato, pepper, peach and persimmon, the biomethane potential increased by 41, 44, 28 and 12% respectively when mixed in 1:1 F/I.	Ferrer et al, 2014
Food Waste + Artichokes	mesophilic sewage sludge and sludge from FVW	3:2	354 ± 68 L kg^{-1} TS	Fruit and vegetable sludge +chopped fresh artichoke waste Increased gas production by 45.08% than Fruit and vegetable sludge alone	Ros, M et al, 2013

Food Composition	**Inoculum**	**F/I**	**Biogas production rate**	**Notes**	**References**
Chinese cabbage, carrot, lettuce, and different fruits, such as apple, banana, pear, and watermelon. Wheat straw (0.22:1)	anaerobic granular sludge	-	250L	250L biogas produced on day 1 of stage 19 out of 21 stages	Wang et al, 2014
Fruit and Vegetable	Primary sludge	2.5 to 3.3 gVS fed/day	4.40 (L day^{-1})	The co-digestion of the FVW with primary sludge produced more biogas than primary sludge alone	Gomez et al, 2006
Fruit and Vegetable	Activated sludge (AS)	F/I ratios of 7:3, 4,:1, 17:3, 9:1,1:0	570 L kg^{-1}	When F/I = 7:3, the highest production of biogas was obtained.	Habiba et al, 2009
Food Waste, FVW	Dewatered sludge	FW:FVW:I=2: 1: 1	720 L kg^{-1}		Liu et al, 2012
Potato 55%, Fruit and vegetables 28%, Bread 5%, Paper 2%, Pasta 10%	Waste mixed Sludge	0:7, 0.2:1, 0.4:1	435 L kg^{-1} VS of methane		Di Maria et al, 2015
Potato 55%, Fruit and vegetables 28%, Bread 5%, Paper 2%, Pasta 10%	Mixed waste sludge	1.7, 2.08, 2.46, 2.8 gVS fed/day		When FVW = 10 – 20%, the yield of biogas increased. When FVW = 30 – 40%, the yield decreased.	Di Maria et al, 2014
Kitchen waste (5 to 8 kg)		-	2 m^3 of biogas per day		Mutungwazi et al. (2018)
25 kg of Kitchen waste		-		produce biogas enough for a household to cook for 2 h varied on the size of the household, substrate used.	Mutungwazi et al. (2018)

Food Composition	Inoculum	F/I	Biogas production rate	Notes	References
Kitchen waste / Manure		-		Involves only two phases i.e. acidogenesis and methanogenesis	Rajendran et al. (2012)
Kitchen waste(organic kitchen waste, Tithoniadiversifolia leaves)	Cow dung	-	Highest biogas 122 L		Kouya-takala et al. (2019)
Cow dung		1:2 (Cow Dung:Water)	Cumulative biogas generated: 0.055 m^3		Nkoi et al. (2018)
Kitchen waste (daal, chawal, chapatti, cooked and uncooked vegetable and different fruits)	Cow dung	2:1 (Food:Cow Dung)	Total biogas generated: 0.04 m^3		Singh et al. (2019)
Potato wastes	sewage sludge	1:9, 1:4,1:2.3, 1:1.5, 1:1, 1:2.5, 1:4	420 L/kg VS of methane gas	Co-digestion of potato waste and sugar beet leaves improved the methane yield by 31–62% compared with that from potato waste alone	Parawira et al.(2004)
Potato wastes+Beet sugar leaf waste	sewage sludge	2:03	680 L/kg VS of methane gas		Parawira et al.(2004)
Food waste	anaerobic sludge	initial loading 6.8 gVS/L, 10.5 gVS/L	435 L/kg VS of methane gas		Zhang et al. (2007)
Potato processing waste	effluent from digesting solid wastes	0.8–3.4 gl^{-1} d^{-1}	650–850 L/kg VS of biogas		Linke (2006)

Food Composition	Inoculum	F/I	Biogas production rate	Notes	References
Restaurant kitchen waste	Mesophilic digested sludge		180 L/kg VS of methane gas		Forster-Carneiro et al. (2008)
Fruit and vegetable wastes			997 L/kg VS of biogas		Bouallagui et al. (2005)
Fruit and vegetable wastes	cow dung	Loading Rate of 4%, 6%, 8% and 10% of TS	705 L/kg VS of biogas	Loading Rate of 6% achieved the highest biogas yield	Bouallagui et al. (2003)
Food waste	mesophilic sludge	20%, 25% and 30% TS and 20 –30% of sludge.	490 L/kg VS of methane	20% TS & 30% sludge performed best out of six combinations.	Forster-Carneiro et al. (2008)
Fruit and vegetable wastes	anaerobic sludge		480 L/kg VS of biogas		Bouallagui et al. (2009)
Fruit and vegetable wastes+ Slaughterhouse wastewater	anaerobic sludge		730 L/kg VS of biogas		Bouallagui et al. (2009)
Fruit and vegetable wastes	inoculated from a low ammonia concentration	OLR of .14, .31, .49, .78, 1.31, 2.03, 3.80	1360 L/kg VS of biogas	OLR of 1.31 performed best of all combination	Alvarez and Lidén (2008)
Canteen waste	Mixture of Glucose, Urea, Magnesium sulfate, Ferric Chloride, Calcium chloride		8.2 ml of biogas per liter		Ashok Kumar et al. (2014)

Food Composition	Inoculum	F/I	Biogas production rate	Notes	References
Food waste+sugarcane bagasse	waste activated sludge	1:1	2600 mL d^{-1}	(SB: FVW) ratio of 30:70 with F/I ratio 1.0 performed best	Vats et al., (2019)
Combined wastes (corn cobs, plantain peels)	cow dung	1:1	0.0305 L/kg VS of biogas		Ukpai C et al (2017)
Poultry waste + pig manure+ water		3:1:6, 1:1:3, 1:3:6	6660 L/kg VS of biogas	1:3:6 performed best out of 3 combinations	Anaswara MG et al (2015)
Abattoir cow liquor waste + cassava waste		1:3	30 L/kg VS of biogas		Uzodinma EO et al (2015)
Cow dung + poultry waste			300 L/kg VS of biogas		Uzodinma EO et al (2006)
Cow dung + dry hog + poultry dropping		1:2 (Waste: Water)	18 L/kg VS of biogas		Okoroigwe EC et al (2007)
Blends of palm oil sludge + cassava waste water			400 L/kg VS of biogas		Uzodinma EO et al (2007)
Cow dung + poultry waste		1:1 (Waste: Water)	370 L/kg VS of biogas		Chhipa RC et al (2014)
Kitchen waste (cassava + yam peels + vegetable waste)	cow dung	1:1	600 L/kg VS of biogas		Nwankwo CS et al (2017)
vegetable waste (Cabbage)	Donkey manure	3:7, 1:1, 1:0, 2:3, 3:2	12 890 L/kg VS of biogas	3:2 ratio performed best out of 5 combinations	Mukumba P et al (2017)
Cattle dung + buffalos wastes			155 L/kg VS of biogas		Kassem H et al (2106)

2.15 Methods of Utilization of Biogas in Domestic Digesters

2.15.1 Cooking and Heating

The biogas generated by home digesters is primarily utilized for cooking. In most cases, between 30 and 45 m^3 of biogas are used for cooking each month. The monthly usage of other widely used fuels such kerosene, which is between 15 and 20 L, and Liquefied Petroleum Gas (LPG), which is between 11 and 15 kg. For biogas, kerosene, and LPG, the energy equivalent was approximately 300, 200, and 150 kWh, respectively. The residential digester's extra biogas could be used for space and water heating.

2.15.2 Biogas Stoves

Due to the physiochemical characteristics of biogas, commercial butane and propane burners cannot burn it. After several adjustments, it is possible to utilize these burners. The gas injector, as well as its cross section and mixing chambers, have new burners installed. The biogas burners are intended to burn 1:10 combination of biogas, air. Different burners have been studied, including those with vertical flame diffusers, horizontal flame diffusers, and no diffusers for biogas. In comparison to other diffusers, a vertical flame diffuser has a high heat transfer efficiency. The efficiency of the process can be determined by adding up the heat added to the water during the heating process and the amount of fuel that was consumed throughout the process. The efficiency of heat entering the vessel from the stove was highest for biogas (with a value of 57.4%), followed by LPG (with a value of 53.6%), kerosene (with a value of 49.5%), and wood (with a value of 22.8%). The biogas burners' thermal efficiency ranged from 59 to 68% and their consumption ranged from 0.34 to 0.450 m3/h.

2.15.3 Fertilizer

The digestate that is produced after the digester has finished its work can be used as fertilizer because it contains a lot of nitrogen, phosphate, and potassium. Digestate boosted fodder production by 1.5% and potato culture by 27.5% as compared to no additional fertilizer. These nutrient concentrations were readily absorbed by plants due to the anaerobic digestion of organic waste. Direct application of the wastewater as agricultural fertilizer is possible. When exported, diarrhea has a significant commercial value. It is also possible to use the dried effluent as an adsorbent to filter lead out of industrial wastes. Growing algae, water hyacinth, duck weed, and fish in polyaquaculture could all benefit from the use of biogas slurry.

2.15.4 Lighting and Power Generation

Lighting and power generation are domestic biogas's other primary uses. In many industrialized countries, the biogas that is produced by the digesters is often sent to a combustion engine, where it is converted into both electrical and mechanical energy. A liquid fuel is necessary to ignite biogas. For the purpose of generating electricity, biogas and diesel fuel can be blended. According to Bari, utilizing biogas as a fuel will not cause carbon dioxide levels to drop below 40% without affecting engine efficiency. When combined with gasoline or diesel, biogas can also be used to power motors and to help pump water for irrigation. Biogas is used in cottage and small-scale enterprises for grinding, pumping, and other manufacturing processes. The average monthly energy use for a medium-sized farm in Jordan is 1282 kWh. Around 6.7 m3 of biogas are needed daily to produce 982 kWh, and 2 m3 is needed daily to heat the water. The use of a 1 kW generator demonstrated that a residential digester could provide half of the required energy. Tests for the production of power and water heating from biogas produced satisfactory results. Milking operations at Earth University (USA) are powered by biogas electricity. In a 12 kW diesel engine generator, biogas and jatropha oil are combined to serve as a dual fuel for rural electrification. Jatropha seeds are left over as trash after being used to make oil. Biogas is produced from this waste. In a dual fuel engine, methane and oil are blended to create energy. Jatropha plantations use biogas-produced fertilizer. Therefore, the closed cycle, which can serve as a bio-refinery, has the nutrients in it. The use of fuel cells to convert biogas into energy is a popular study area right now. However, because clean gas is needed and fuel cells are expensive, it is not commercially feasible. Although biogas lamps are more effective than kerosene-powered lamps, they still perform poorly when compared to electric-powered lights. But when compared to a kerosene lamp or an electric light bulb, the biogas lamp's light output was between 25 and 75 W. A 60-100 watt bulb may be lit for six hours using one cubic meter of biogas, or three meals can be prepared for five to six people each day. In contrast, 0.7 kg of gasoline may produce 1.25 kW of power or drive a 1 hp engine for 2 hours. Approximately 0.25 to 0.5 m3 of biogas is required to power a home with a family of five. Due to a lack of energy, many rural communities in India relied on kerosene lamps for lighting until recently. These kerosene-powered lamps were expensive and ineffective to use. Solar panels that ran on batteries were also an expensive option for lighting. This led to research towards creating a digester that could light a house. a small-scale methane digester created specifically for illumination.

2.15.5 Other Applications

Domestic biogas is used for a variety of other things in addition to the usual ones. On residential biogas, which is a widely used application in Kenya, gas-powered refrigerators or a chicken incubator can run. In order to improve the social living circumstances of the populace, a local NGO in India has connected over 4600 public restrooms to biogas digesters. Similar to this, methane digesters are connected to public restrooms in Nepal so that they can be lit.

2.16 Summary

Being the largest percentage of municipal solid waste in developing countries, food waste can be the source of renewable energy by anaerobically digested them with inoculum. For that purpose, the food composition of developing countries with readily available inoculum can be tested in lab scale as well as field scale to check the potentiality on the biogas generation and the potential usage of it.

Chapter 3: METHODOLOGY

3.1 Introduction

This chapter includes the methodology to accomplish the research objectives outlined in Chapter 1, including the procedures followed for a laboratory-scale study of an anaerobic digester and the key features and components of a full-scale anaerobic digester. Initially, Laboratory tests and experiments were conducted to analyze the effects of food/inoculum ratio and percentage of total solid on degrading organic fractions of food waste relative to enhancing gas production. After the successful completion of batch reactor, field scale continuous anaerobic digesters with the best performance have been conducted to check the feasibility. Along with measurements of the rate, volume, and composition of generated gas, other laboratory tests including physical characterization, moisture content, volatile organic content test, pH, alkalinity, and COD tests were carried out.

3.2 Study Plan

The current study is divided into two major experimental programs: i) a laboratory- scale study and ii) field design and field scale application of Anaerobic Digester in two different initial condition. A workflow diagram of this study is shown in Figure 3-1. The study started with a laboratory-scale anaerobic digester simulation, with reactors to evaluate the effects of food/inoculum ratio and total solid percentage on methane production from food waste and were operated anaerobically for 180 days.

For the field scale testing, two different initial conditions have been tested. Firstly, Total four anaerobic digester with two food/inoculum ratios were installed in the lab. Based on the results from the experimental study, the anaerobic digesters were installed and were operated anaerobically for 180 days. Critical parameters of the operation, such as gas and leachate, were monitored periodically. Performance monitoring and evaluation of the anaerobic digester were carried out based on the experimental results from the laboratory simulation. Secondly, total two anaerobic digesters with one food/inoculum ratio were installed in the lab and were operated anaerobically for 120 days to check the potentiality of reducing the lag phase at the very beginning of the operation.

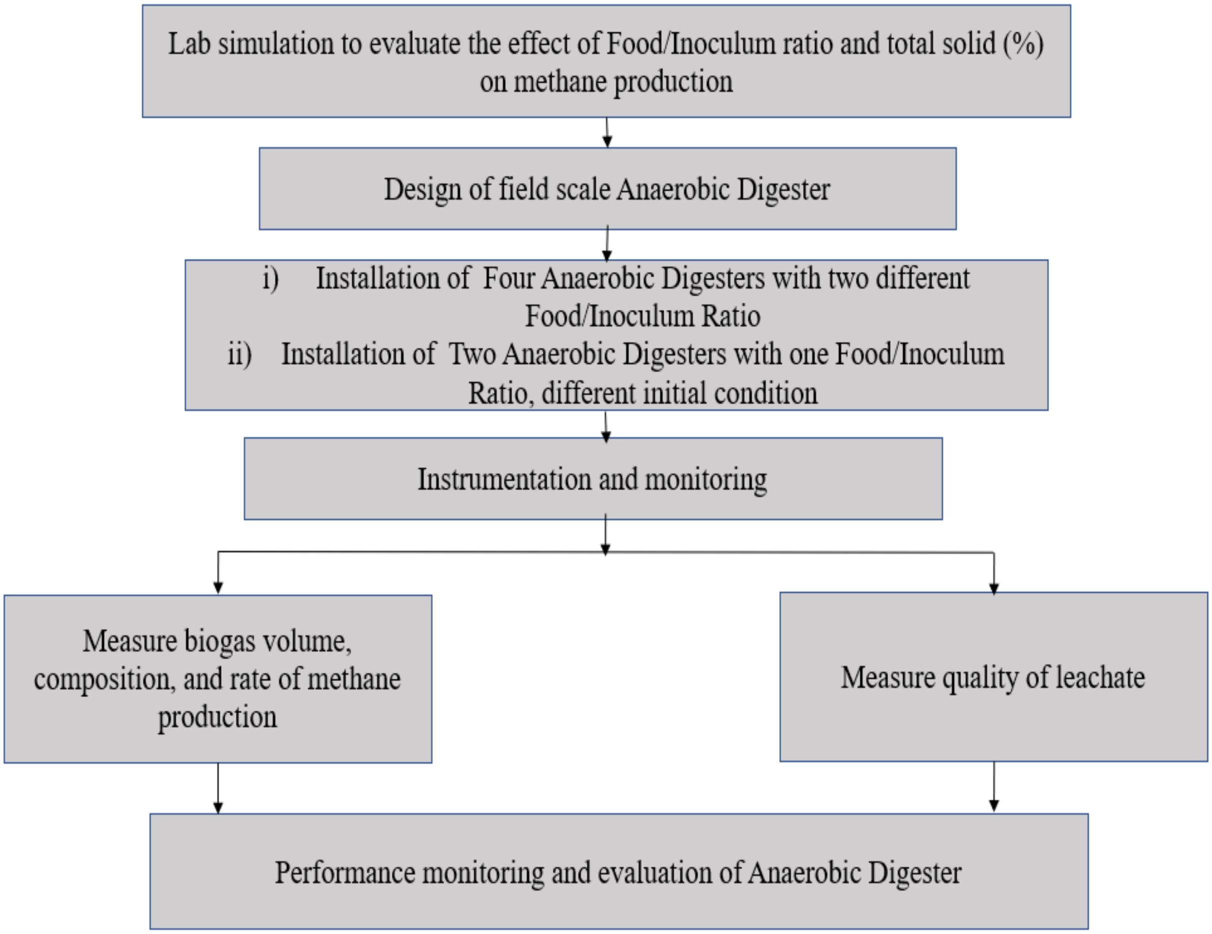


Figure 3-1: Experimental Flow Chart program

3.3 Experimental Study on Batch Reactors

The laboratory-scale simulation study on anaerobic digester is described in subsequent sections.

3.3.1 Collection of Food Waste

At the University of Texas at Arlington (UTA), in Arlington, Texas, food waste was collected from the University Center (UC) dining hall. From the UC dining hall, about 50 pounds of garbage from meat, seafood, and grain goods (rice, bread, etc.), fruit, and vegetables were gathered.

The collected samples were brought to the Civil Engineering Laboratory Building (CELB) at UTA in plastic bags, and then they were preserved within the environmental growth chamber (cold room) at a temperature of 4^0 Celsius. This was done in order to keep the moisture and other initial waste qualities that were displayed (38^0F) which is shown in Figure 3-3. In Figure 3-2, 3 types of sorted waste; which are fruit vegetables; meat, dairy products; waste from grain products are shown.

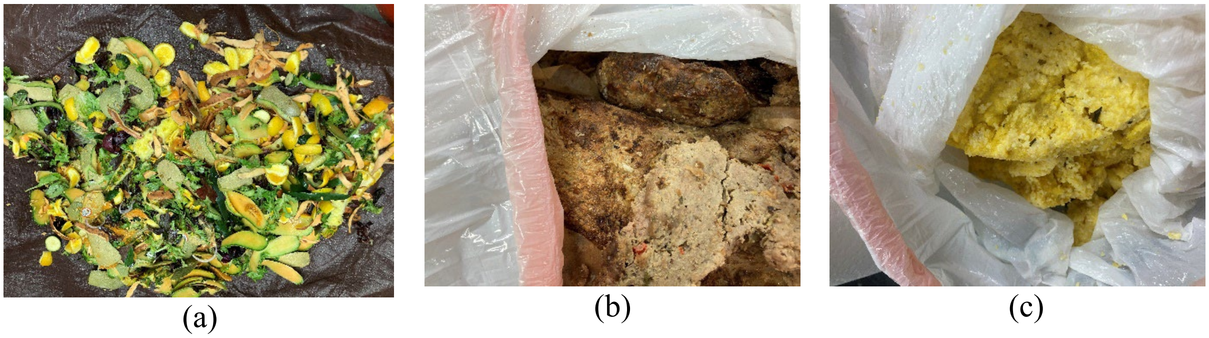

(a) (b) (c)

Figure 3-2: Sample collection from the University Café (a) Fruit Vegetable Waste; (b)Meat, dairy waste; (c) Waste from Grain Product

(a) (b)

Figure 3-3: a) Stored sample in cold room; b) Environmental Growth Chamber (Cold room and hot room)

3.3.2 Collection of Inoculum

Because of its high nitrogen ratio, low acidity bacteria, and prolonged hydraulic retention time, cow manure was chosen for this investigation. (Yazdani, 2010). Fresh cow manure was obtained from Double D ranch in Mansfield. The samples were stored at room temperature. Additionally, the chances of inhibition in gas production due to process limitation is more (Vandevivere et al., 2003). In order to provide the reactor with bacteria and serve as a buffer to counteract the acidic environment, two 5-gallon buckets of sludge were collected from the Village Creek Water Reclamation Facility in Texas. To maintain the anaerobic conditions of the sludge before adding it to the digesters, the samples were stored in an airtight container. Figure 3-4 demonstrates the collection process of sludge from Reclamation Facility and collection of cow manure from Double D ranch in Mansfield. For the continuous digester operation, they were collected monthly basis as per the requirement.


(a) (b)

Figure 3-4: (a) Collection of Sludge; (b) Collection of Cow Manure

3.3.3 Food Waste Composition

As the study focus is in developing countries, the composition of the food waste was chosen accordingly. From the Section 2.3, data was scrutinized and based on that Table 3-1 shows the approximate percentage of the three main commodities present in the generated waste in the region of developing countries. For this research, the percentage was simplified and decided to be used as follows: 60% of fruits and vegetables, 10% for meat, fish, and dairy and 30% for food produced from grain.

Table 3-1: Average Waste Composition in the Region of Developing Countries

	West & Central Asia	**South & Southeast Asia**	**Current Research**
Fruits & Vegetables (%)	66.53	58.60	60
Meat, Fish & Dairy (%)	6.50	12.60	10
Food produced from Grain (%)	27.14	28.83	30

3.3.4 Waste and Inoculum Combination

Four pairs of food waste reactors were built as simulators to analyze the effect of Food/Inoculum ratio and Total Solid content (%) on the degradation of food waste. Each reactor was filled 4 lbs. of food waste with varying inoculum types, as shown in Table 3-2. The food waste composition is described in Four pairs of food waste reactors, a total of eight reactors (AD1 to AD8) were fabricated with food waste. Based on literature studies and considering from economical and sustainable point of view, the combination of food waste and inoculum assessed in laboratory-scale batch reactor was decided and is presented in the following table. Control reactor's F/I and TS were decided based on the best result achieved by Zaman's (2016) biocell study. The inoculums were added according to the respective food/inoculum ratio. Each reactor contains approximately 86%-87% volatile solids of total solid. Additional water was added to maintain the desired moisture content in the reactors.

Table 3-2: Combination of Food waste and Inoculum for Laboratory Scale Batch Reactor

No.	**Name**	**Food Waste (%) (VS Basis)**	**Inoculum (%) (Cow Dung + Sludge) (VS Basis)**	**Food/Inoculum Ratio (VS Basis)**	**Total Solid (TS) (%)**
1	AD1 & AD2	94	6	15.0	28
2	AD3 & AD4	80	20	4.0	16
3	AD5 & AD6	75	25	3.0	18
4	AD7 & AD8	67	33	2.0	11

3.3.5 Batch Reactor Setup in Laboratory Scale

A mesophilic temperature of 37^0C was used in the incubation of eight reactors under laboratory conditions. Reactors were modified two-gallon High Density PolyEthelene wide-mouth buckets for collecting gas and leachate and adding and circulating liquid.

Building the reactors required tubing, connectors, gas bags and leachate bags with different diameters, silicone sealants, washers, clamps, geocomposites, and gravels. Figure 3-5 shows the materials and equipment used to set up the reactors. All reactors were tested for possible leaks before filling them with waste, and after they were sealed properly, leak tests were conducted using a water head column. In order to ensure that there would be no significant leaks, the reactors were monitored for a few days. It was determined that the head difference at 12 and 48 hours was within the permitted ranges of 0.5 in. and 3 in. of water column, respectively. (Mohammad Adil Haque 2007).

To collect gas and leachate, the bucket was modified, with three holes drilled on the lid and one on the bottom, and tubes were attached to the holes using threaded hoses. Thread tape was used to make the connections airtight. Gas collection was done with the three-way valve, and leachate collection was done with two-way valves. Silicon sealant was used to make these connections airtight, and it was allowed to dry for 24 hours. There was a layer of pea gravel and two geocomposites underneath the waste layer in order to assist in drainage of leachate from the bottom of the reactor.


(a) (b)

Figure 3-5: (a) Materials and (b) equipment used for construction of reactor

All valves and sealed connections underwent leak tests to see whether there were any leaks. The connections were examined using the pressure head difference technique. A hydraulic head was maintained as initial water was pumped from a water tank into the reactors. The reactor was linked to a clear tube and monitored for 48 hours while the hydraulic head level was recorded. If the hydraulic head level didn't change, the leak test was deemed a success for the reactor. The experiment's reactors all passed the leak test. Spraying water onto each layer of filler ensured that there was enough moisture for microbiological development. Additionally, proper compaction was kept up throughout the procedure.

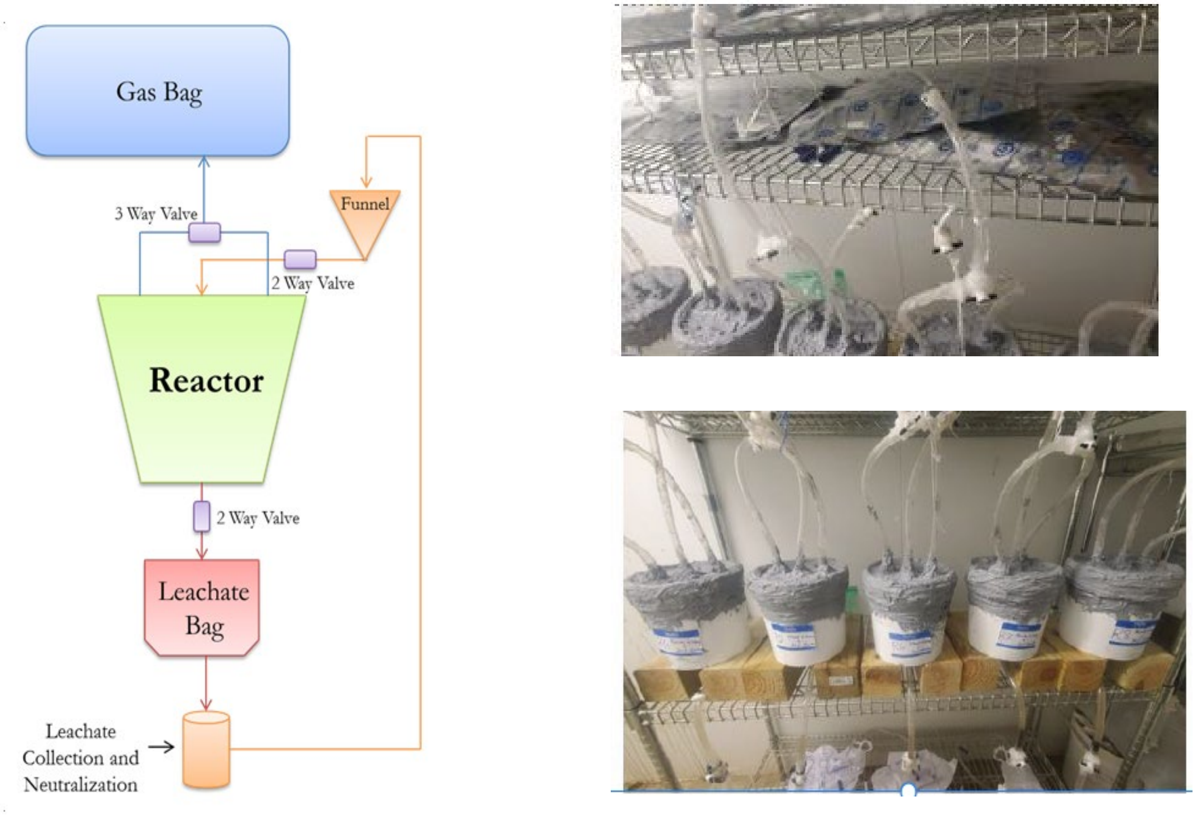


Figure 3-6: Laboratory scale reactor setup

Approximately one to one and a half inches of space were provided at the top of the reactors for gas to escape through the gas collection outlet. The lids of the waste-filled reactors were also sealed with two layers of sealant. Following sealing, the environmental growth chamber's reactor setup was maintained there at 37 °C. Figure 3-6 and Figure 3-7 shows the photo for the reactor inside the environmental growth chamber.

(a) (b)

Figure 3-7: (a) Preparation of Food Waste (b) Installed Laboratory Scale Reactor

Four pounds of food waste were placed in reactors along with various mixtures of sludge and manure. Sludge and manure would be added in order to add microorganisms and nutrients necessary to speed up the decomposition process as well as buffer the acidic environment.

3.3.6 Batch Reactors Operation and Monitoring

Routine monitoring was executed on the leachate and gas generation of the stimulated lab scale reactors. Throughout the whole monitoring period, measurements were made of the generated leachate's volume, pH, COD, volatile fatty acid (VFA), and leachate recirculation. Measurements of the gas' composition, flow rate, and volume were part of the monitoring program. Determined were the variations in volatile solids and moisture content before and after the deterioration. The sections that follow go over these activities.

3.3.6.1 Physical Properties of Waste and Inoculum

Physical properties such as moisture content, and volatile solids of collected food waste, inoculums (sludge and cow manure) were measured before and after the laboratory experiment. Details of each follow.

Moisture Content: The initial stage of the experiment involved determining the moisture content of the food waste contained in the collected bags. The initial and final moisture contents in this study, respectively, are the amounts of moisture before and after degradation. A consistent weight was attained at 65 °C (±5 °C) in the oven after drying food waste samples for 5 to 7 days, and moisture loss was then calculated. The percentage by weight of both wet and dry weight of refuse samples is expressed as the amount of moisture. The percentage by weight of both wet and dry weight of refuse samples is expressed as the amount of moisture.

Figure 3-8: Determination of moisture content by drying sample in the oven

Equations 3.1 and 3.2 were used to determine the moisture content on a wet weight basis (W_w) and dry weight basis (W_d), respectively.

$$W_w = Mw/Mt \text{ x100\%} \text{ ....} (3.1)$$

$$W_d = Mw/Ms \text{ x100\%} \text{ ....} (3.2)$$

Where M_w is the mass of water, M_t is the total wet mass and M_s is the dry mass of water after drying.

Volatile solids: One of the primary markers of how much MSW or food waste has decomposed is organic content, sometimes referred to as volatile solids (VS) and loss-on-ignition. Organic content in the waste decreases with decomposition. In this study, Method 2540-E (APHA et al., 2005) was used to measure the volatile solids of food waste. A sample of dry-milled refuse weighing approximately 50 grams was placed on a porcelain disk in a muffle furnace at 550 °C for 2 hours, until a constant weight was achieved. Figure 3-9 shows the residue or ash content of the food waste after the ignition. The percent of weight lost on ignition is the volatile organic content. Equation 3.3 was used to determine the percentage of volatile solids.

$$\text{VS (\%)} = \frac{Wl}{Wt} \text{x100\%} \text{...................................} (3.3)$$

Where, W_l is the weight loss after burning and W_t is the dry weight of sample before burning.

Figure 3-9: Residue or ash content of food waste after the ignition

3.3.6.2 Gas Characteristics

The generated gas was collected in five-layer bags, and its volume and makeup were continuously monitored. The composition gas, i.e. methane (CH_4), carbon dioxide (CO_2), and oxygen (O_2) contents in the bags were measured using the Landtec GEM 2000 (Figure 3-10). The volume of the gathered gas was measured using a Defender 330 scale and an air-sampling pump (Universal XR Pump model 44XR). A stopwatch was used to time how long it took to empty the gas bags after recording the fixed rate of gas flow. The volume measurement process is shown in Figure 3-10.

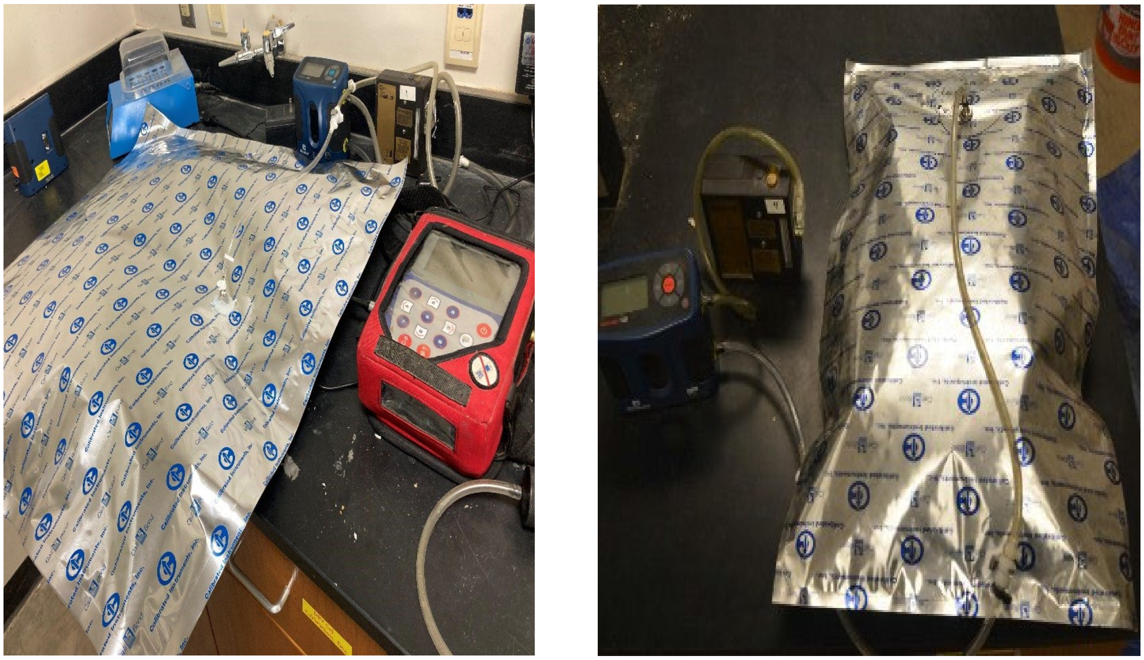

(a) (b)

Figure 3-10: (a) Gas composition determination using Landtec GEM 2000, (b) Gas sampling with Universal Sampler and Defender 330

3.3.6.3 Leachate Characteristics

Regular tests for pH, COD and volatile fatty acid (VFA) were conducted on generated leachate to monitor its characteristics and volume. Details are given in the following section.

3.3.6.3.1 pH

A benchtop Oakton pH meter, calibrated with the three-point calibration method, was used to measure the pH value of the collected leachate. A pH buffer of 4.00± 0.01, 7.00±0.01 and 10.00±0.01 was employed. In between readings, the probe was given a thorough cleaning with running water and then a final rinsing with deionized water. It was necessary to maintain the probe constantly submerged in a buffer solution with a pH of 7.0. Prior to recirculation, leachate was adjusted to pH 7.0 using KOH buffer solution.

Figure 3-11: Measurement of pH

3.3.6.3.2 Chemical Oxygen Demand (COD)

Leachate samples were subjected to chemical oxygen demand (COD) measurements using a spectrophotometer (Spectronic 200+). For each sample, the spectrophotometer calculated the absorbance of light and presented the result on the screen. Two tests were conducted for each reactor using a 1:100 dilution of the leachate from the food waste reactors. Before the leachate goes through COD tests, the dilution ratio needs to be established. Therefore, COD tests were run with several dilution factors, and the dilution factor that was below the calibration curve was utilized to fix the dilution. 2.5 ml of diluted leachate was introduced to the COD vials in a ratio of 1 part leachate to 99 parts distilled water. The vials were kept in a digester set at 150 °C for two hours. The samples were put in the spectrophotometer after being cooled to room temperature in order to calculate the absorbance values.

Figure 3-12: Determination of Chemical oxygen demand (COD): (a) COD vials, (b) digester heating, (c) vials after heating; (d) vials placing in Spectronic 200+, (e) measurement of absorbance by s Spectronic 200+

In order to calculate the COD values based on the absorption%, a calibration curve was utilized. A calibration curve was generated by utilizing a potassium hydrogen phthalate (KHP) solution that had COD values that were already known. The calibration curve utilized for this study is shown in Figure 3-13. To obtain the actual COD value for the leachate samples, COD values for corresponding absorbance values were calculated using the curve and corrected in accordance with the dilution factor.

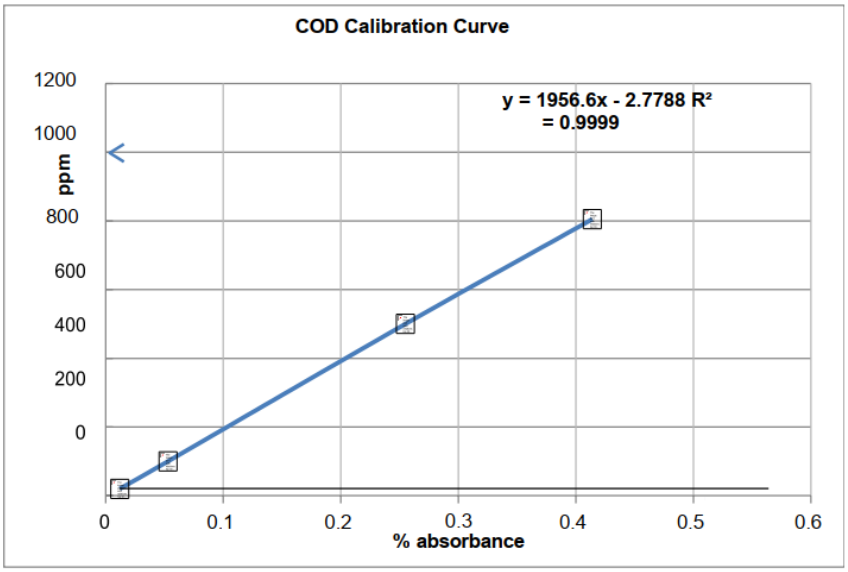


Figure 3-13: Chemical Oxygen Demand (COD) calibration curve

3.3.6.3.3 Volatile Fatty Acid (VFA)

Monthly Volatile Fatty Acid (VFA) tests were carried out. Leachate was diluted in each reactor's testing at a ratio of 1:100. VFA was measured using the titration method based on pH (DiLallo and Albertson, 1961). The 50 ml filtered sample's pH was first determined. H_2SO_4 was then used to raise the sample's pH to 3.3–3.5. The sample was then given three minutes to boil. After cooling, the sample's pH was brought down to 4, and the amount of NaOH needed to bring it to a pH of 7 was calculated. The procedure of VFA measurement are shown in Figure 3-14.

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

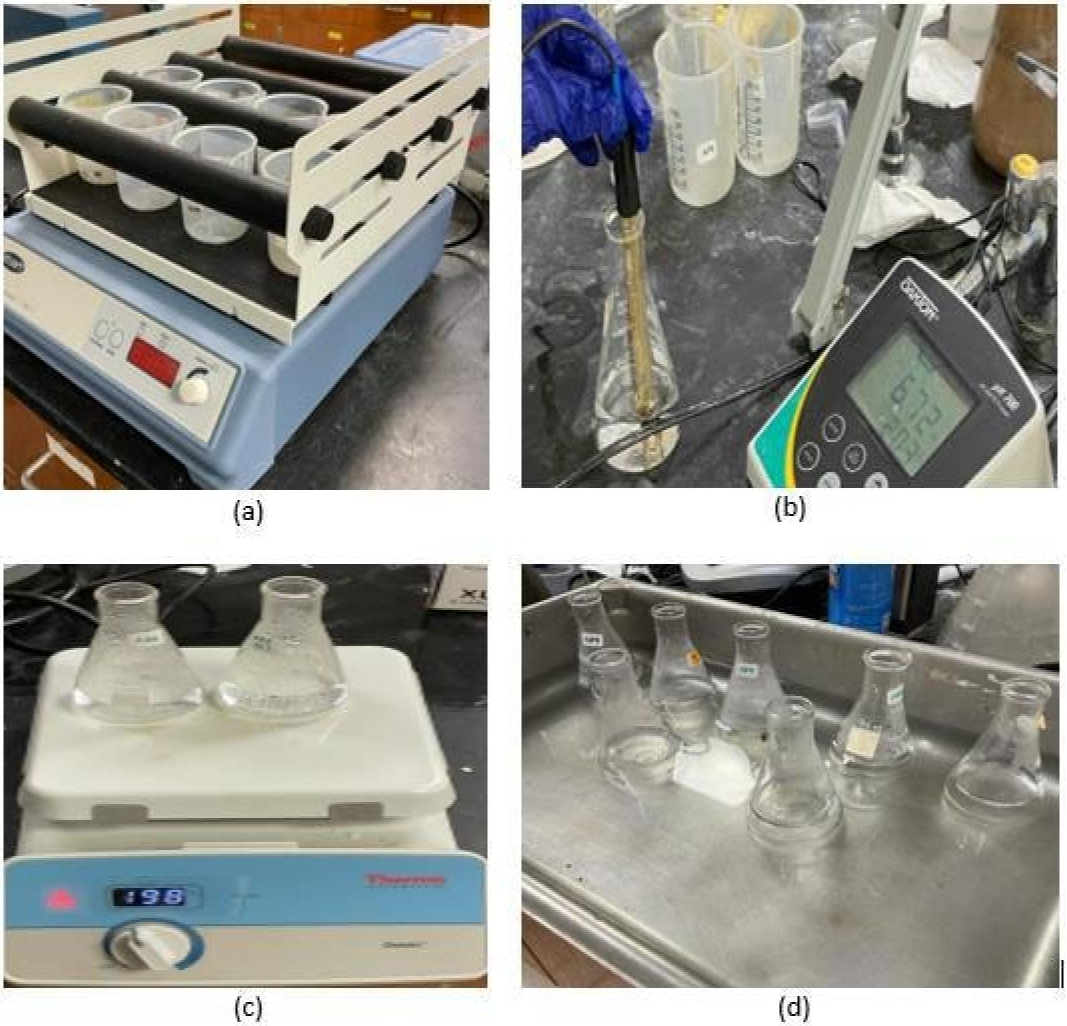
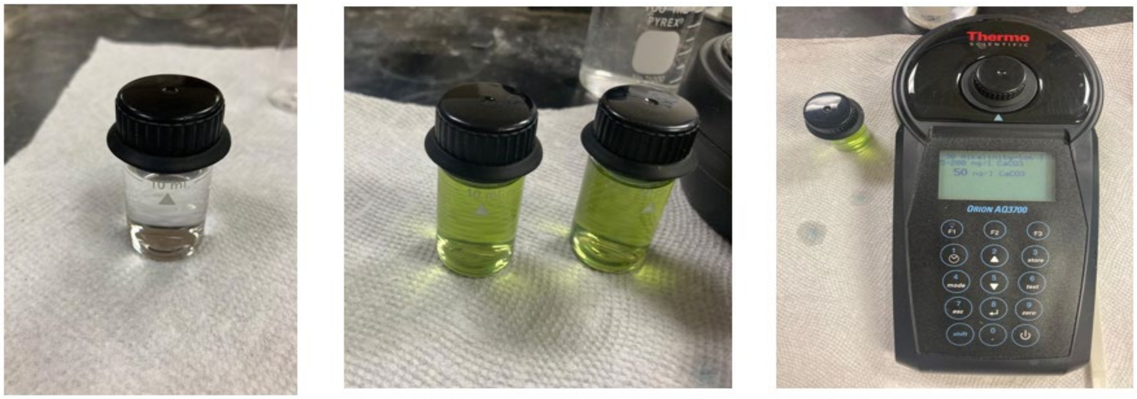

(a) (b) (c) (d)

Figure 3-14: VFA measurement: (a) Sample in mechanical stirrer, (b) adjustment in pH, (c) Sample in heater, (d) Sample in room temperature

3.3.6.3.4 Alkalinity

Monthly alkalinity testing were carried out. Leachate was diluted in each reactor's testing at a ratio of 1:100. Following the collection of the filtrate, 10 ml of the filtrate are pipette-transferred into the glass vile that is used in the particular colorimetric apparatus. The cap is snugly fastened after adding 10 ml of the water sample to a clean vial (24 mm). Making that the markers are in alignment, the vial is inserted into the sample chamber. One presses the ZERO key. The sample chamber is empty of the vial. One ALKA-M-METER tablet is introduced directly to the water sample from the foil after being crushed with a clean stirring rod. The vial is tightly closed with the cap, and the tablet is swirled around several times until it dissolves. Making that the markers are in alignment, the vial is inserted into the sample chamber. One presses the TEST key. Total Alkalinity is the outcome displayed on the screen. Figure 3-16 represents the procedure of Alkalinity measurement

Figure 3-15: Photograph of a Colorimeter used for Alkalinity determination



a) Filtrate transferred to Vial

b) Resulting solution after adding Alka M Tablet

c) Measuring Alkalinity Content in mg/L CaCO3

Figure 3-16: Test Method for Alkalinity Determination in Sample

3.4 Experimental Study on Field level Anaerobic Digester

For the field level study on anaerobic digester, experimental study was conducted on same pattern as the batch reactors. Food waste was collected weekly basis as need for it was daily. Inoculum were collected on monthly basis as per the requirement. For the better monitoring and getting the realistic daily data of the ADs, the gas volume and composition were monitored daily basis. The leachate quality was monitored bi-weekly basis unlike in batch reactors, where it was monitored monthly basis. The design considerations and construction of the field level anaerobic digesters have been discussed in separate Chapter 5.

Chapter 4: DATA ANALYSIS FOR LAB SCALE ANAEROBIC DIGESTER

4.1 Introduction

In this chapter, the findings that were obtained from the laboratory simulations of food waste bioreactors are evaluated in order to gain an understanding of the effect of Food/Inoculum ratio and Total Solid content (%) on food waste decomposition and gas generation. These findings are presented and discussed. Fresh food waste samples were acquired from various sources and then combined to a synthetic ratio in order to maintain the most consistent possible combination within the various reactors of the same kind. A total of eight (8) reactors were built with total four (4) pairs of Food/Inoculum ratio and Total solid content (%).

The following sub-sections provide discussions on the outcomes of initial waste characteristics (moisture content, composition, and volatile solids), inoculum qualities, leachate and gas volume, and composition during monitoring.

4.2 Properties of Food Waste

As discussed in chapter 3, sub-section 3.3.1, food waste was collected from University Center, UTA. The following subsections discuss the physical composition, moisture content & volatile solids of the collected waste.

4.2.1 Physical Composition

Food waste samples were sorted manually (hand sorting), and their physical composition was determined by wet weight basis. The food waste from the University cafeteria were then sorted based on the decided waste percentage, which is as follows: 60% of fruits and vegetables, 10% for meat, fish, and dairy and 30% for food produced from grain.

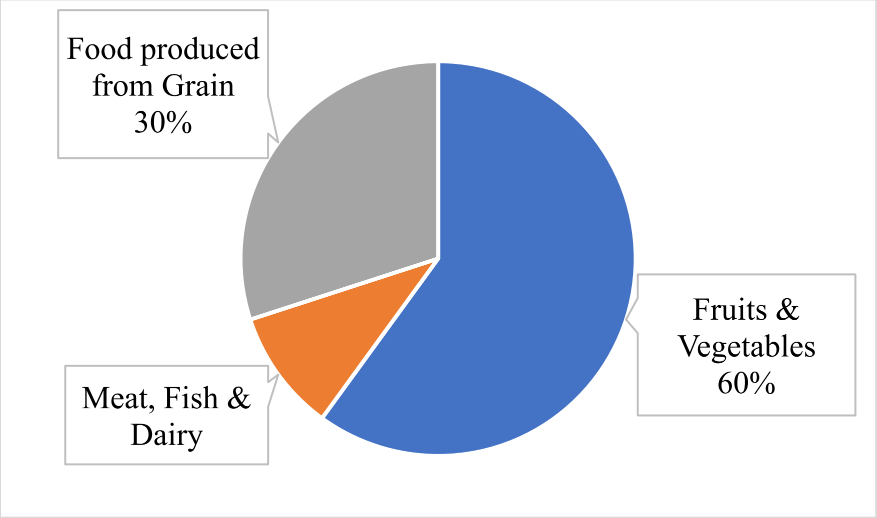


Figure 4-1: Physical composition of food waste used for the experiment

4.2.2 Moisture Content

Moisture content tests were performed on the food waste according to the procedure described in 3.3.6.1 in Chapter Three. The water content is the ratio of “pore” or “free” water in a given mass of soil to the dry or wet solid waste. It is typically presented in the form of a percentage. The dry and wet weight bases were both used to determine the moisture content; however, the wet weight basis was the only one used to describe the moisture content of the food waste. During the testing of the physical composition, the moisture content of the fresh waste samples was evaluated on a dry weight and a wet weight basis, respectively. Initial moisture content expressed as a percentage of wet weight for each reactor (described in Table 3-2) is listed in Table 4-1.

Table 4-1: Initial food waste Moisture Content

Reactors	**Moisture content (%)**	**Total Solid, TS (%)**
AD1, AD2	72	28
AD3, AD4	84	16
AD5, AD6	82	18
AD7, AD8	89	11

On a basis of wet weight, the average amount of moisture found in fresh food waste was around 80.71%. The results of a comparison between the moisture content of the mixed food waste observed in this investigation and the stated values found in the literature are presented in Table 4-2. According to the bar chart, the value of moisture content that was discovered in this study was discovered to be comparable with the values that were discovered in the prior investigations. (Figure 4-2).

Table 4-2: Food waste moisture content compared to earlier research

	Moisture content (%) (wet weight)	**Author**	**Current Study Moisture content (%) (wet weight)**
Food waste	50.00 ~ 80.00	Tchbanoglous (1993)	80.71
Food waste	82.86	Karanjekar (2013)	
Fruit wastes	83	Bouallagui (2003)	
Left over's food	84	Dueblein (2008)	
Vegetable waste	80-95	Martin Das Neves (2009)	
Food waste	82.86	Karanjekar (2013)	

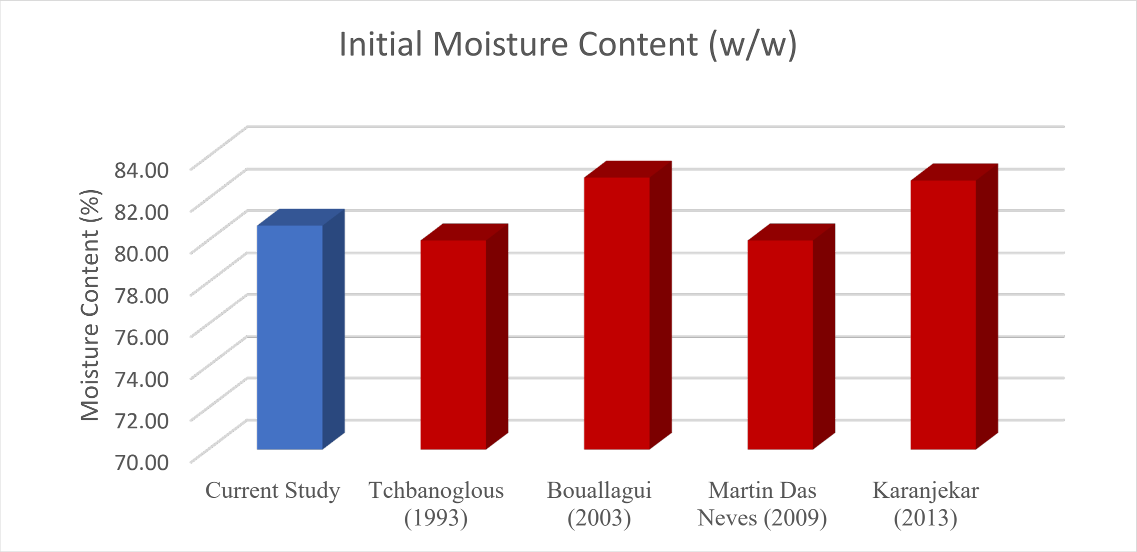


Figure 4-2: Comparison of moisture content of food waste

Reactor moisture was affected by the waste feedstock's moisture content, the inoculum's moisture content, and the amount of water added to the feedstock during the filling and compacting processes. Though similar types of feedstock were used in the reactors, to maintain different food/inoculum, moisture content in the reactors varied to various extent. Extra water was added to each of the reactors during waste filling to achieve the desired F/I Ratio. The extra moisture also guaranteed adequate trash compaction and, most likely, fostered healthy microbial activity. The food waste reactors had total solids of 20-28 %; depending on the F/I ratio which affected the amount of gas generation in the reactors. Excessive moisture content may hinder the gas production.

4.2.3 Volatile Solid Content

The Interstate Technology and Regulatory Council (2006) claims that the volatile solid test is the cheapest method for determining how much potentially biodegradable material remains in a given mass of garbage. The percentage of garbage that is composed of organic matter can be calculated from its volatile organic content. According to Chapter Three's explanation, the tests for volatile organic content were carried out twice on the feedstock samples: once before the reactors were sealed (to determine the initial volatile solid content), and once after the conclusion of the research project. The initial volatile solids of the food waste reactors are listed in Table 4-4. Volatile solids accounted for about 89.77% of the total solid of food waste feedstock. The findings of the analysis of volatile solids were compared to those found in the literature, as indicated in Table 4-3. According to the bar chart, the results of the most recent research on food waste's volatile solids were found to be comparable to those of the most recent research on food waste's volatile solids from prior studies (Figure 4-3).

Table 4-3: Analysis of the present study's VS in relation to previous research

	Volatile solids (%)	**Author**	**Volatile solids (%) of Total Solid of current study**
Mixed food waste	88.34	Abu-Qudias (2000)	89.77
Kitchen Waste	87	Rongping Li (2009)	
Food Waste	90.16	Karanjekar (2013)	

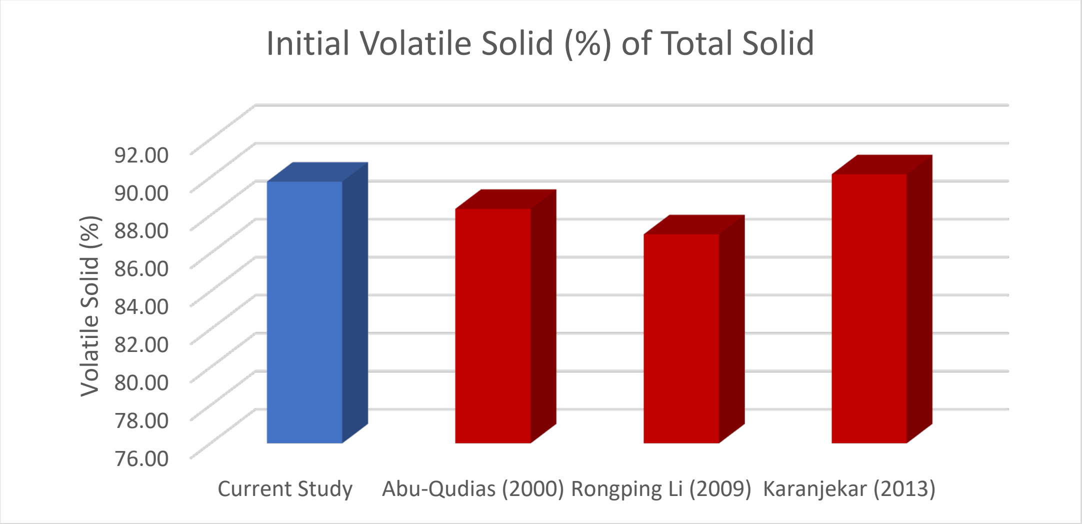


Figure 4-3 Comparison of volatile solid for food waste

Food waste has a higher gas generation potential because of the higher volatile solid content. The reactors AD7 & AD8 contained 1.31 lbs. of volatile solids, which is higher than the amount in the other food waste reactors (0.80-1.15 lbs.). Due to the high moisture content in the food waste reactors in this study, the total solid content was less in the food waste reactors. Volatile solid contents are important because they affect the amount of gas production.

Table 4-4: Initial volatile organic content

Reactors	**Food/Inoculum**	**Volatile Solid, VS (%)**	**Total Volatile Solids in lbs**
AD1, AD2	15	86.93	1.15
AD3, AD4	4	86.97	0.80

AD5, AD6	3	86.93	1.04
AD7, AD8	2	86.95	1.31

4.3 Properties of Inoculum

Inoculum is a source of microorganisms and plays a vital role in waste degradation and methane production. Literature cites examples of inoculum being used to enhance waste degradation, such as in sewage treatment sludge, animal manure, cellulose and lignocellulose enzymes, and old landfill leachate (Karanjekar, 2013; Al- Kaabi et al., 2009; Callaghan et. al., 2002; Lopes et. al., 2003; Sosnowski et. al, 2003; Sah, 2006; Cirne et al., 2008, Jayasinghe et.al., 2013; an Erses and Onay, 2003). The addition of inoculum shortens the duration of the waste degradation process and increases gas production significantly. Different amount of cow manure and sludge were used in this study depending on the F/I ratio to check the feasibility for field application. Three major properties of inoculum such as moisture content, volatile solid and pH, were measured in this study. The sludge used had a high moisture content (97.72% in wet weight basis) and high pH (7.39), which meant that it was rich in anaerobic microorganisms. The volatile solid content was 80.47% of total solid. The moisture content of fresh cow manure was 80.6 %. The pH of the cow manure was about 7.32, and volatile solid is of 82.9% of total solid. Because of the high pH of the inoculum that was employed in this study, the acidic environment was neutralized, which led to a reduction in the acidogenic and transition phases and an early start of the methanogenic phase.

4.4 Gas Characteristics

The primary sign that waste is being broken down is the production of biogas. In this study, composition, volume, and rate of gas generated from the food waste reactors (AD1 and AD8) were measured on a regular basis, as described in the section below:

4.4.1 Gas Composition

The first measurement of gas volume and composition was made on day 1 from food waste reactors AD1 to AD8. In the beginning, (Figure 4-4) methane content was low, and the carbon dioxide content was very high. The oxygen percentage was high as upto 10% for first few days before entering the anaerobic phase. With the beginning of the acidogenic phase, the pH began dropping due to an excessive accumulation of volatile fatty acids. Although the leachate generated from the reactors was neutralized by potassium hydroxide (KOH) and was recirculated frequently, the food waste reactors went into a long lag phase.

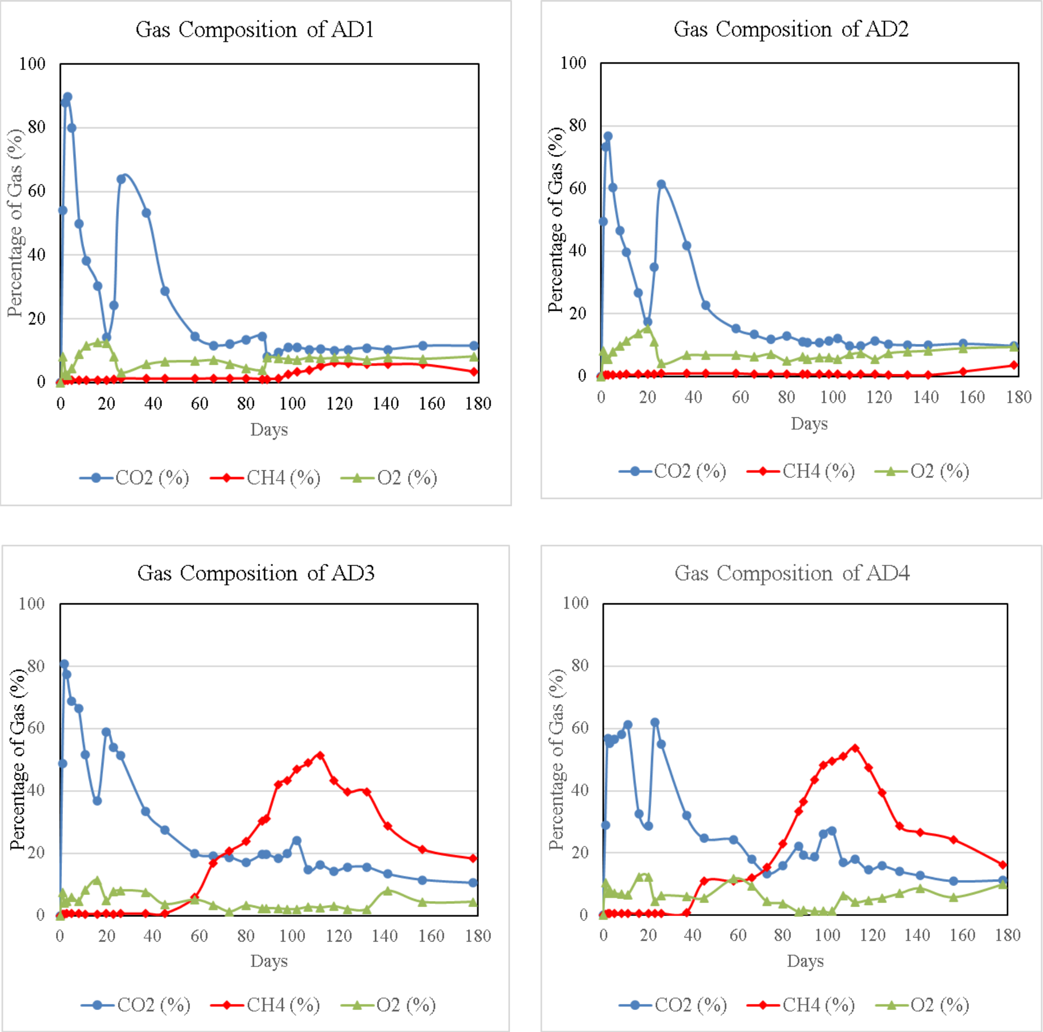


Figure 4-4: Composition of Gas for all AD

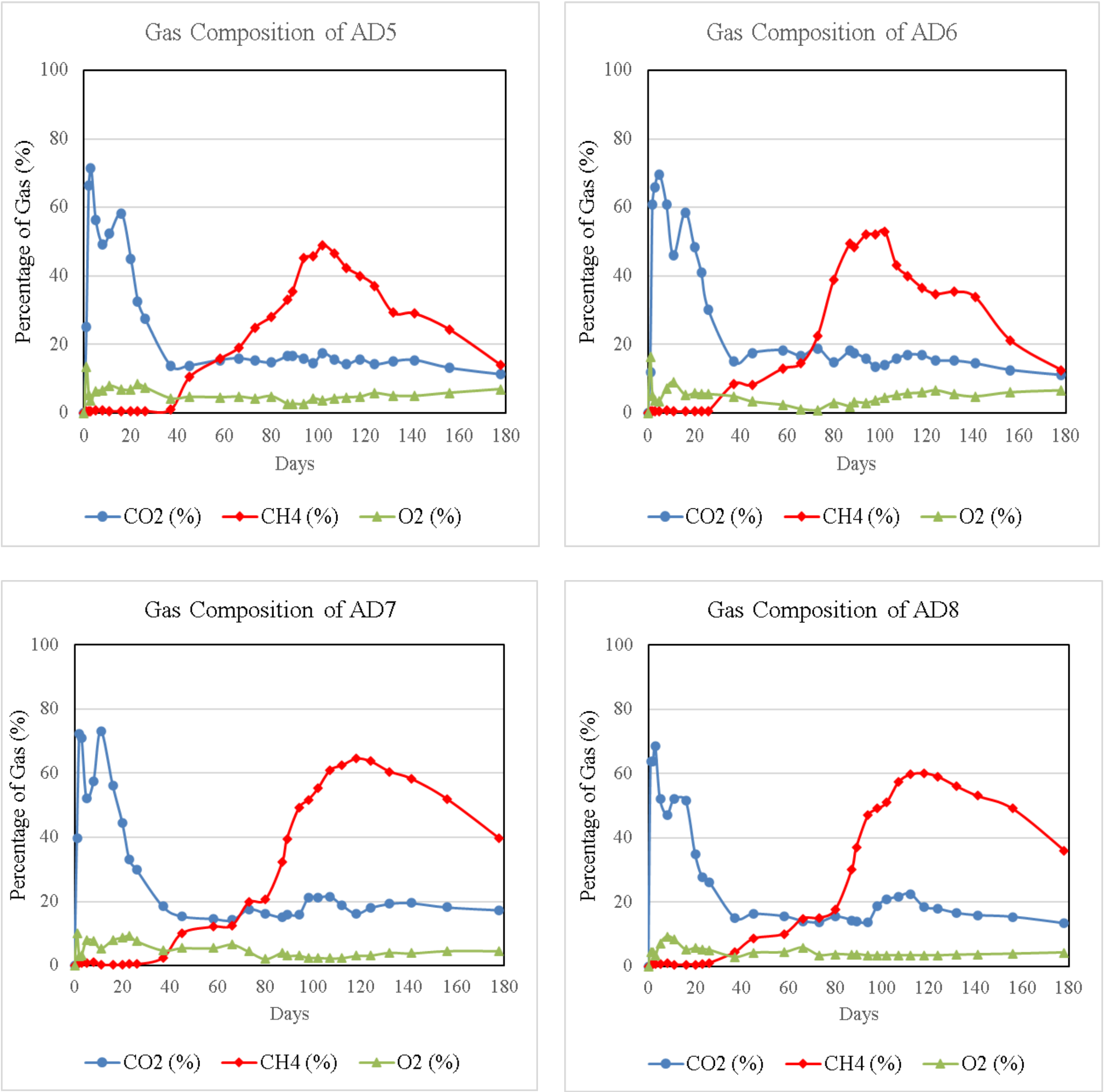


Figure 4-4: Composition of Gas for all AD (Contd)

After 40 days of operation, the food waste reactors started producing very small amounts of methane. Reactor AD7 & AD 8, with F/1=2, reached 40% methane production after 89 days of operation. One of the reactors, AD 6, with F/1=3, reached 40% methane production after 80 days; earlier than F/I=2. Reactors AD4, AD5, AD7 reached 40% methane production at around same time as others. The control ones (AD 1 & 2) could not make upto 40% methane production in its entire study period of 180 days. Figure 4-4 shows the methane content in the food reactors. The food waste reactors with F/I=2 (AD7 and AD8) produced more than 60% methane on 107 days. The maximum methane content was 64.5% in reactor AD7 on day 118. All the food waste reactors except control's one, achieved more than 50% methane during operation, which is similar to the methane content in an anaerobic digester.

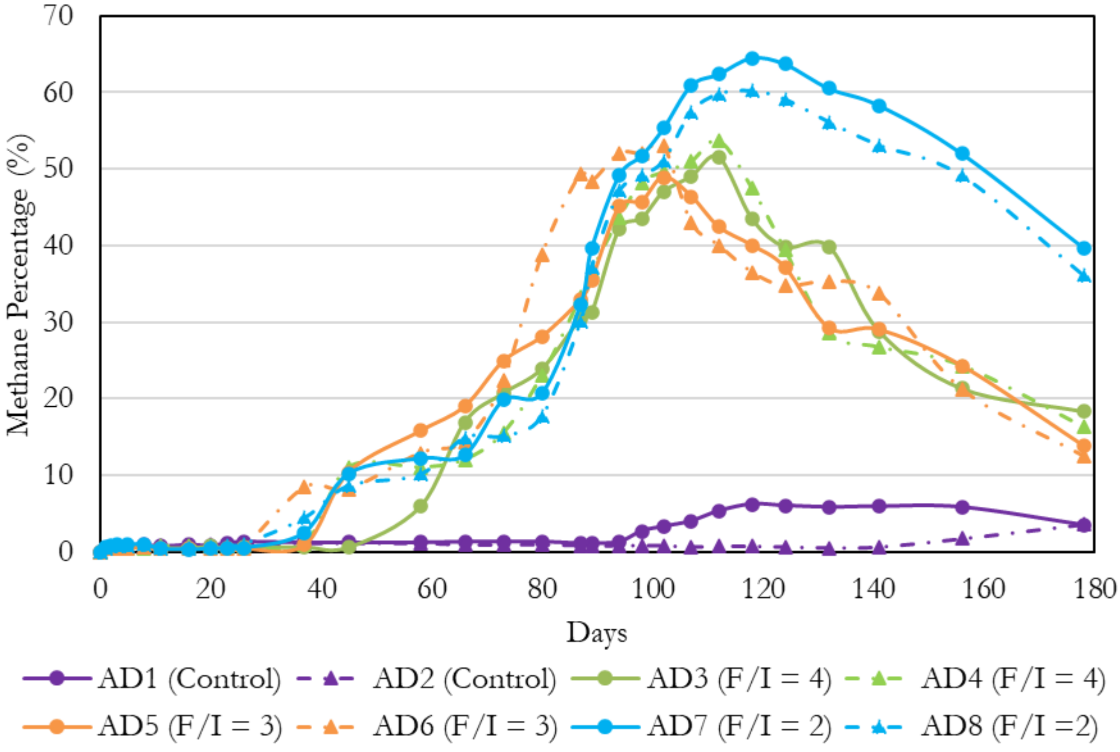


Figure 4-5: Methane content in food waste reactors

In the methanogenic phase, the percentage of methane increases as high as 60% to 65%, with the variation of pH of the leachate from 6.0 to 8.5 (Karanjekar, 2013). Carbon dioxide content reduces, which can be seen from the increase of methane to carbon dioxide ratio ($CH_4:CO_2$ ratio). In this study, after 80 days of operation, the $CH_4:CO_2$ ratio in reactor AD7 reached 1.5. Figure 4-6 shows the methane-to-carbon dioxide ratio in food reactors. Reactor AD8 with cow manure had the highest $CH_4:CO_2$ ratio (almost 4) after 118 days.

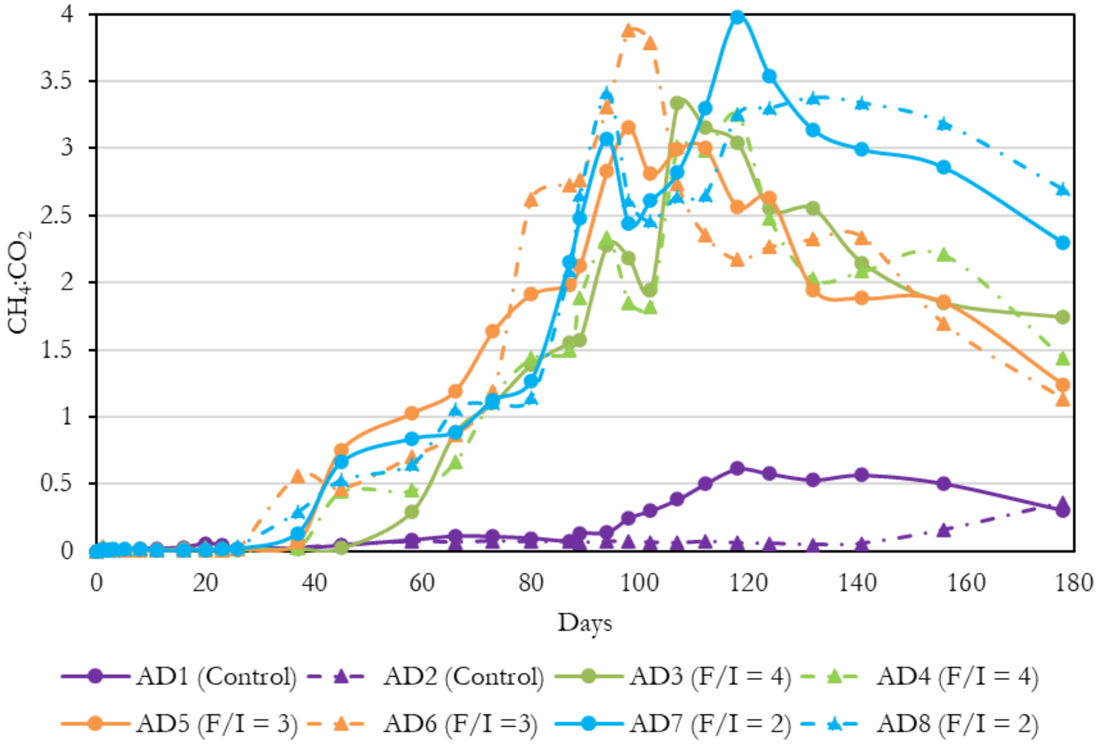


Figure 4-6: Ratio of Methane to Carbon dioxide in food waste reactors

Figure 4-7 shows the percentage of anaerobic activity in food reactors, as calculated by using Eq. 4.1, which is dependent on the concentrations of methane and carbon dioxide in the gas composition. The concentrations of the CH_4 and CO_2 gases can be used to estimate the fraction of waste that degraded anaerobically at any point in time. Biogas is usually composed of 45-60% CH_4 and 40-60% CO_2 (Tchobanoglous et al., 1983). Based on the stoichiometry of the reactions of aerobic and anaerobic degradation, the percentage of waste degraded anaerobically, P, can be estimated by the following equation developed by Yazdani (2010).

$$P = \frac{2\,C_{CH_4}}{2\,C_{CH_4}+(C_{CO_2}-C_{CH_4})} * 100 \text{ .... (Eq 4.1)}$$

Where C_{CH4} and C_{CO2} are the measured concentrations (% v/v) of CH_4 and CO_2, respectively.

The value of percentage of anaerobic activity (P) was plotted against time to observe the variations of anaerobic activity in the reactors. Between 40 to 60 days of operation, all reactors except control one had achieved 100% anaerobic activities. Control one fell behind due to a long lag phase. In the food waste reactors, the percentage of anaerobic activities varied from 0% to 160%. Consequently, it can be inferred that the potential for methane production is high for food waste if the lag phase can be reduced.

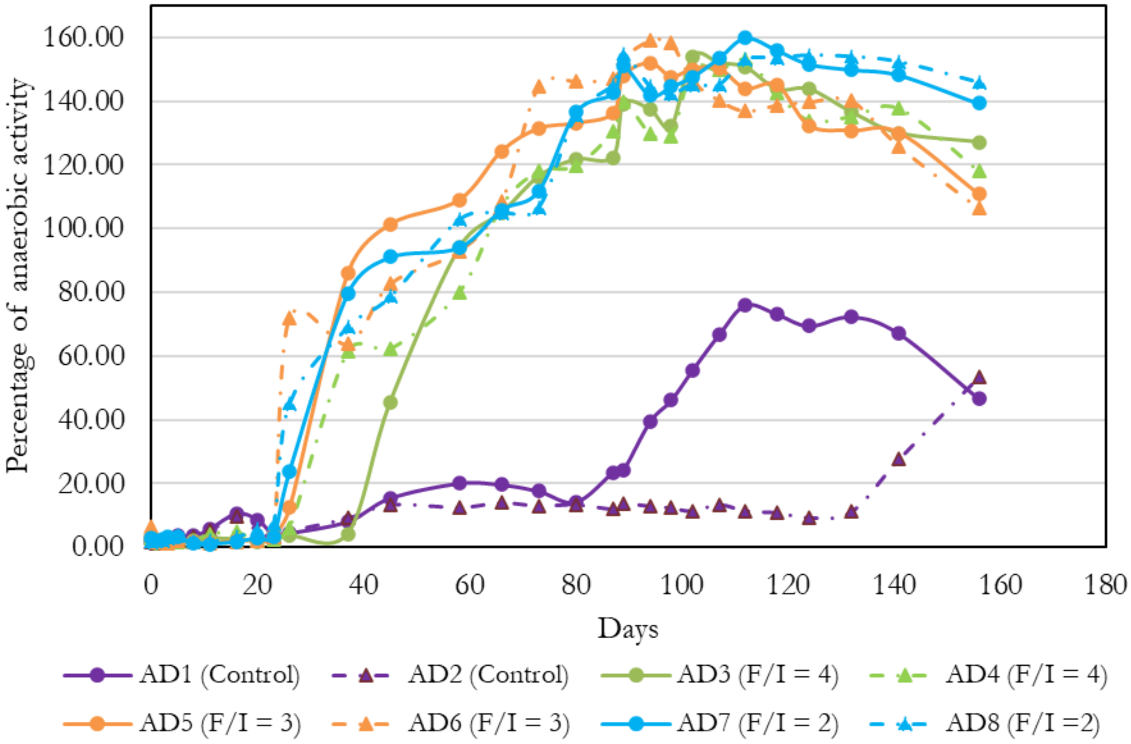


Figure 4-7: Percentage of anaerobic activity in food waste reactors

4.4.2 Gas Volume of Food Waste Reactors

In the food waste reactors (AD1 to AD8), the first gas volume was measured on day 1; it had a very high carbon dioxide content and very low methane and oxygen content. Sludge was added to all of the food waste reactors to eliminate the early lag phase. However, after three months of operation (91 days), all of the food waste reactors except AD7 and AD8 (with F/I=2) started to slow down in producing gas. Figure 4-8 shows the cumulative gas generation (L/lb.VS) in the food waste reactors (AD1 to AD8).

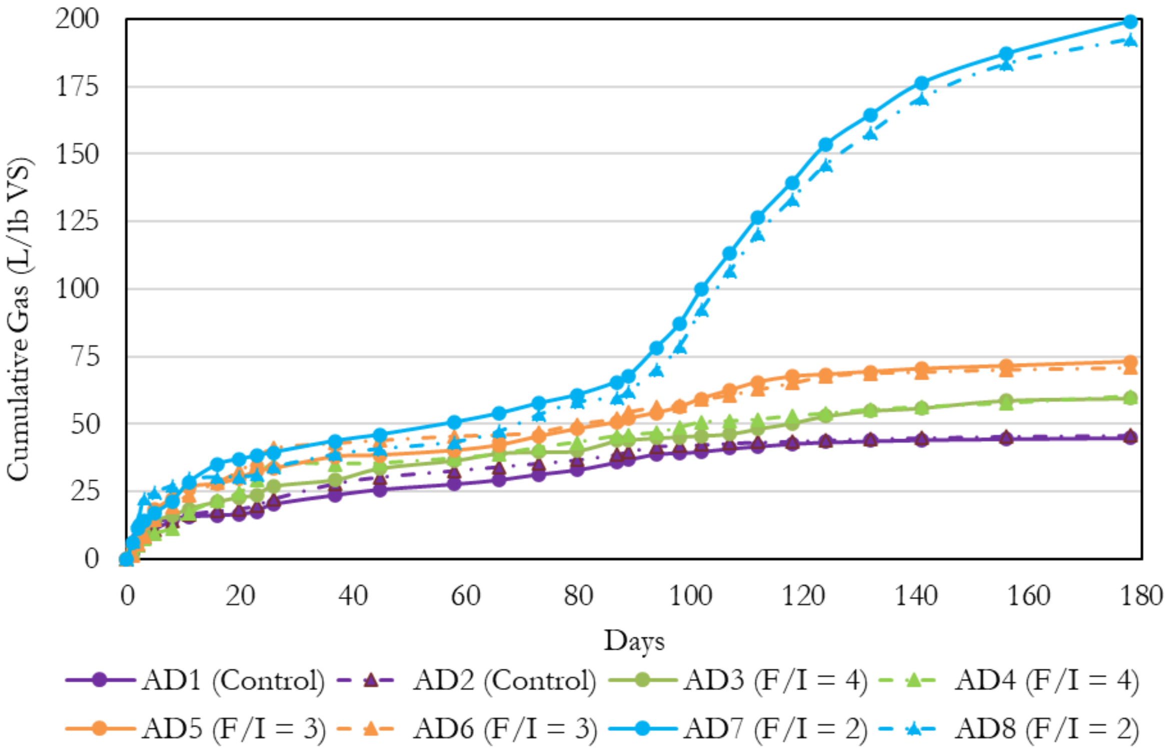


Figure 4-8: Cumulative gas generation (L/lb. VS) in food waste reactors

The food waste reactors with F/I=2 (AD7 and AD8) produced significant amounts of gas (200.0 L/lb. and 192.5 L/lb., respectively) in about 180 days. With regular neutralization and recirculation of leachate, the rest of the food waste reactors ultimately overcame the very long lag phase, Reactor AD5 with F/I=2 produced gas upto 72 L/lb in day 180. The reactors were monitored for 180 days and then were dismantled. The highest amount of gas was produced by AD7 (200 L/lb.), followed by AD8 (192.5 L/lb.) and AD5 (70.8 L/lb.). Food waste reactors with F/I=28 got the lowest amount (around 46 L/lb) in terms of gas production.

Figure 4-9 shows the cumulative methane generation in food waste reactors (AD1 to AD8). As mentioned in section 4.4.1, the methane content was high in almost all of the food waste reactors. The highest methane volume was generated from reactor AD8 (79.8 L/lb. VS). The lowest amount of methane was produced from food waste reactor AD1 (less than 1 L/lb.VS)

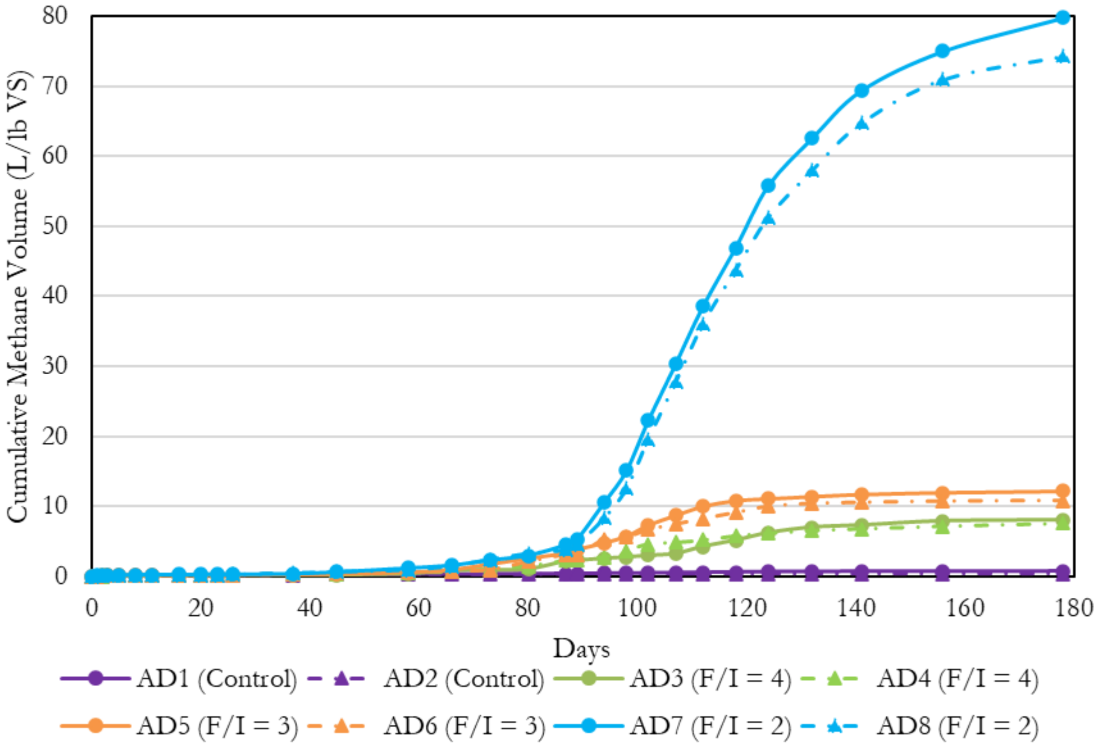


Figure 4-9: Cumulative methane generation (L/lb. VS) in food waste reactors

In conclusion, food waste reactors were able to generate substantial amounts of methane, but it required more time of overcome the lag phase. In this study, the moisture content of food waste was more than 70% (Table 4-1). The volatile solid content of food waste was 87-88%, which indicates that the feedstock had high potential for biodegradability (Table 4-4). Karanjekar (2012) discovered that the production of methane from 100% food waste is relatively low in comparison to the production of methane from other wastes. Karanjekar also discovered that the production of methane reached its peak after 160 days of operation. This could be because of the enhanced lag phase caused by rapid hydrolysis. The production of volatile fatty acids (VFA) is responsible for the lengthier lag phases observed in reactors containing a significant amount of food. An enhanced lag phase prior to methanogenesis was seen in trash containing a high percentage of food waste due to rapid hydrolysis and accumulation of volatile fatty acids (Shao et al., 2005). At least one study showed the effect of feed inoculum ratios on biogas yields, i.e., more inoculum in feedstock produces more biogas. Liu et al. (2009) showed that a 38% sludge addition has the highest methane yield. Inhibitory effects on the anaerobic digestion process can be caused by a wide variety of chemicals and environmental factors. Microbes that thrive in anaerobic environments require very particular physical conditions in order to preserve enzyme activities, which are necessary for the facilitation of biochemical events. When anaerobic reactors are subjected to unfavorable conditions, such as temporal overloading, a falling pH, and rapid temperature changes, anaerobic reactions are slowed down or stopped altogether (Gallert et al., 1998). Apart from these factors, ammonia and long chain fatty acids (LCFA) also inhibit the anaerobic digestion process. The breakdown of the nitrogenous matter that is present in the feedstock is the primary contributor to the production of ammonia during anaerobic digestion. This ammonia is produced predominantly in the form of protein (Kayhanian et al., 1999; Kotsyurbenko et al., 2004). Ammonia is inhibitory to methanogenesis if it exists at high concentrations (Gallert et al., 1998), but beneficial effects on bacterial growth have been observed at doses ranging from 50 mg L^{-1} to 200 mg L^{-1} as per McCarty (1964).

Figure 4-10 and Figure 4-11 show the gas generation rate and methane yield of the food waste reactors, respectively. From the gas yield versus time graph, the lag phases in food waste reactors can be observed clearly. Initially, there was a substantial amount of gas production in food waste reactors up to 30 days. The gas generation rate in reactor AD8 reached its peak of 2350.7 mL/lb. VS/day in only 11 days of operation, which is almost twice the rate of the rest of the reactors. Food waste reactors AD7 and AD8 again were in an increasing trend of yielding gas after 100 days. Both of these reactors displayed multiple peaks, with gas yield of 450 mL/lb.VS/day.

Reactor AD5 reached its peak of 800 mL/lb. VS/day on day 102; AD6 and AD4 reached their peaks (523 mL/lb./day) on day 102 and (512 mL/lb./day) on day 98.

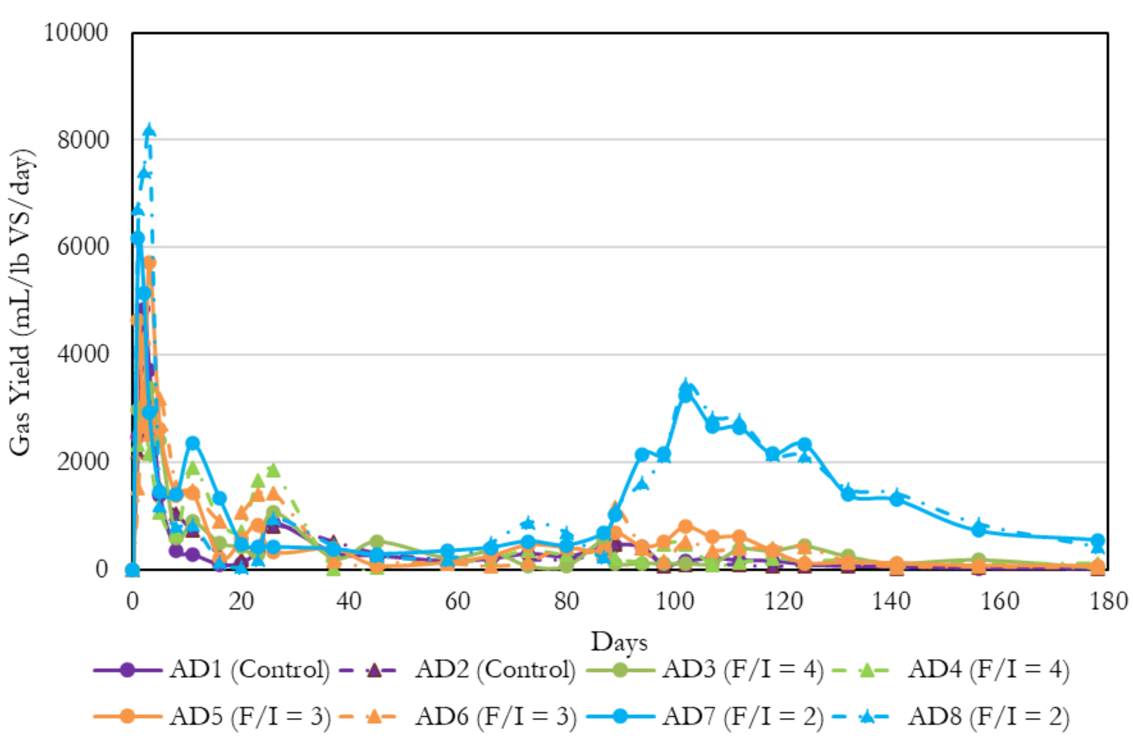


Figure 4-10: Gas yield (mL/lb. VS/day) in food waste reactors

The methane yield versus time graph shows the methane generation rate with time (Figure 4-11), and shows that methane and gas yields in food waste reactors follow the same trend. Food waste reactors with F/I=2 (AD7 and AD8) experienced the methanogenic phase earliest, with the decomposition of waste taking place from day 89 to day 160. One of the reactors (AD6) experienced methanogenic phase from day 90 to day 120. Food waste control reactors (AD1 and AD2) could not reach the methanogenic phase within 180 days of operation. When the reactors reached the methanogenic phase, the generation of methane peaked. Due to the heterogeneous properties of waste, the methane yields varied, even for the same pair of reactors. For example, reactor AD7 with F/I=2 had the peak methane yield on day 102 (1762.66 mL/lb. VS/day), and

AD8 peaked on day 98 (1756.2 mL/lb./day). AD5, one of the reactors with F/I=3, had the methane generation rate of 390 mL/lb. VS/day on day 101.

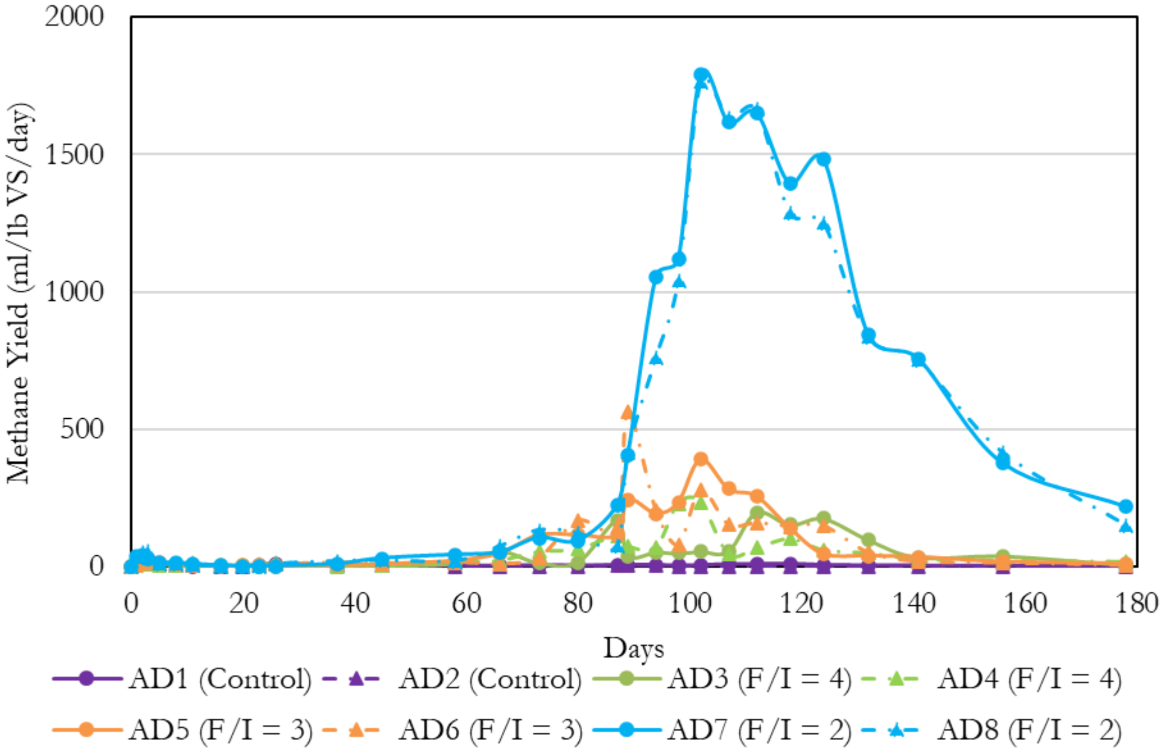


Figure 4-11: Methane yield (mL/lb. VS/day) in food waste reactors

4.5 Leachate Characteristics

Leachate is generated by excess water percolating through the waste layers in a waste decomposition system. The chemical and biological processes of the waste are significantly influenced by the characteristics of the generated leachate such as pH, VFA (Volatile Fatty Acid), COD (Chemical oxygen demand) and Alkalinity. The characteristics of generated leachate indicate the level of degradation of the solid waste. In this study, the pH, VFA, COD and Alkalinity were monitored for food waste reactors during their decomposition phases. Details are discussed in the following sections.

4.5.1 pH of Leachate of Food Waste Reactors

A significant drop in the pH in food waste reactors (AD1 to AD8) was observed throughout the initial monitoring period due to excessive volatile fatty acid (VFA) accumulation in food waste. Previous researchers (Shao et. al., 2005; Karanjekar, 2013) also experienced a pH drop in food waste due to VFA accumulation. KOH was added with the leachate during recirculation to neutralize the pH. From the pH vs time plot of food waste reactors (Figure 4-12) it was noticed that the initial pH was less than 5 for as long as 10 days, which may have retarded the bacterial growth in the reactor. After 43 days of operation, the pH of most of the reactors reached or surpassed 6. It took almost 100 days for all of the food waste reactors to attain the methanogenic phase.

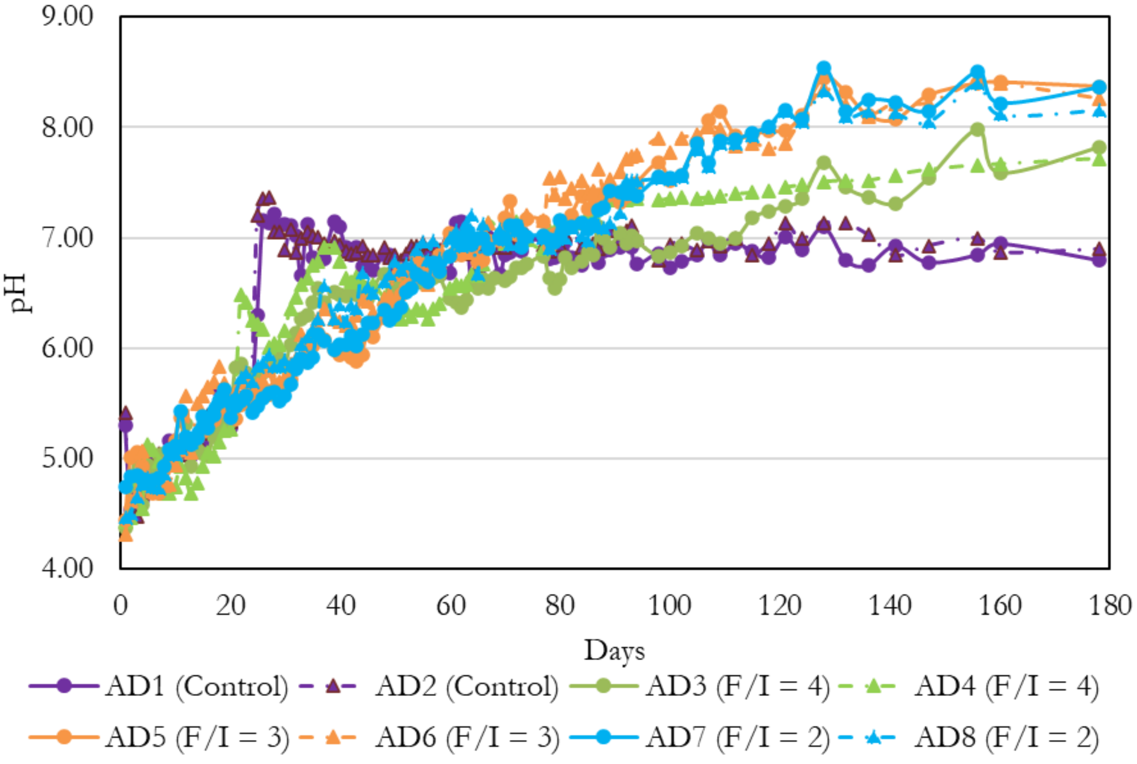


Figure 4-12: leachate pH variation of food waste reactors

Leachate was produced for the first time, and the pH (4.32 to 4.74) was the lowest on day 1 of 180 days of operation of the food waste reactors. The pH of the leachate of reactors AD7 and AD8 was 7.00 on day 55 and 6.97 on day 57, respectively, which indicated the methanogenic phase. Once the reactors reached the methanogenic phase, the pH remained at more than 7 and then stabilized with maximum values of 8.5 and 8.4 for AD7 and AD8, respectively. In the food waste reactors with F/I=3 (AD5 and AD6), the initial pH was 4.44 and 4.32, respectively, on day 1. Following a trend similar to AD1 and AD2, the pH of AD5 and AD6 was found to have increased on the next monitoring day and kept climbing. The pH of leachate of AD5 and AD6 was more than 6 on day 33, and entered the methanogenic phase on days 70 and 62, respectively. AD5 and AD6 had the highest values of pH, 8.4 and 8.42, respectively, on day 156. Food waste reactors with F/I=2 (AD3 and AD4) had an initial pH of 4.37 and 4.44, respectively, on day 1. From day 8, the pH kept rising, with AD3 attaining more than 6 on day 31 and AD4 attaining more than 6 on day 27. The pH of AD3 and AD4 was higher than 7 on day 90 and stabilized with a maximum pH of 7.82 and 7.72, respectively, on day 178. The maximum pH values for control reactor were 7.10 and 7.13, respectively, on days 128 and 132 days.

In this study, the low pH in the initial stage had an overall effect on methane production. In a study conducted by Wang et al. (1997), an initial pH of 3.4 to 3.7 in 70% food waste and 30% old refuse reactors caused high accumulations of VFA and ammonia, which led to the termination, on day 149, of reactors that had produced very little methane. Despite pH neutralization by sodium carbonate, these reactors failed to undergo methanogenesis. Methane generation was limited over the 149-day period due to the syntrophic activity of acetogenic and methanogenic bacteria, which was evidenced by the accumulation of volatile fatty acids and the high concentration of chemical oxygen demand (COD). (Wang et al., 1997).

4.5.2 Chemical Oxygen Demand (COD)

The COD of the leachate of the food waste reactors was also measured on monthly basis to determine the level of degradation of waste inside the reactors, as shown in Figure 4-13. There is a correlation between waste degradation and COD decline, as COD levels fall as waste breaks down over time.

The COD value decreases with the degradation of waste. The initial COD values were high in all of the food waste reactors. Control reactors with F/I=15, The initial COD for reactors AD1 and AD2 were 122,694 mg/L and 141,045 mg/L, respectively, and decreased to 67,811 mg/L and 87,770 mg/L, respectively, at the end of six month (180 days). Whereas, the initial COD for reactors AD7 and AD8 (F/I=2) were 27,799.33 mg/L and 26,625.37 mg/L, respectively, and decreased to 10,189.93 mg/L and 10,874.74 mg/L, respectively, at the end of six month (180 days). At the end of the study period, the lowest F/I ratio had the lowest value of COD, which signifies the highest percentage of waste degradation. The concentration of COD began to lessen as soon as the acidogenic phase came to an end, the degradation process began, and the transition into the methanogenic phase began.

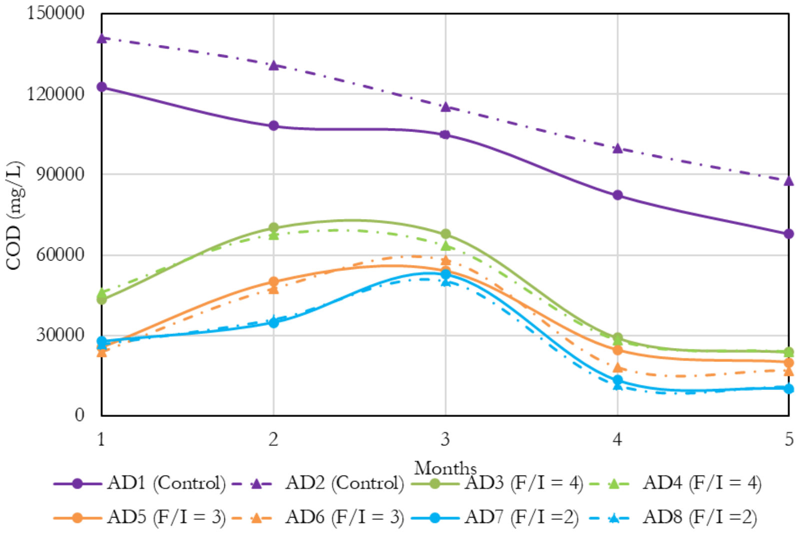


Figure 4-13: Chemical oxygen demand (COD) of leachate of food waste reactors

Figure 4-14 depicts a result that was discovered by Wang et al. (1997). This result demonstrates that the COD level reduced dramatically as the reactor entered the methanogenic phase. The values that were discovered from their research differ greatly from those found in the current research. This could be because they employed approximately 70% degraded garbage as inoculum, whereas the inoculum percentages used in the current study were 50%, 30%, 25%, and 7%. As a direct consequence of this, the duration of their lag phase was drastically cut down, and they reached the methanogenic phase much more quickly than in the present study.

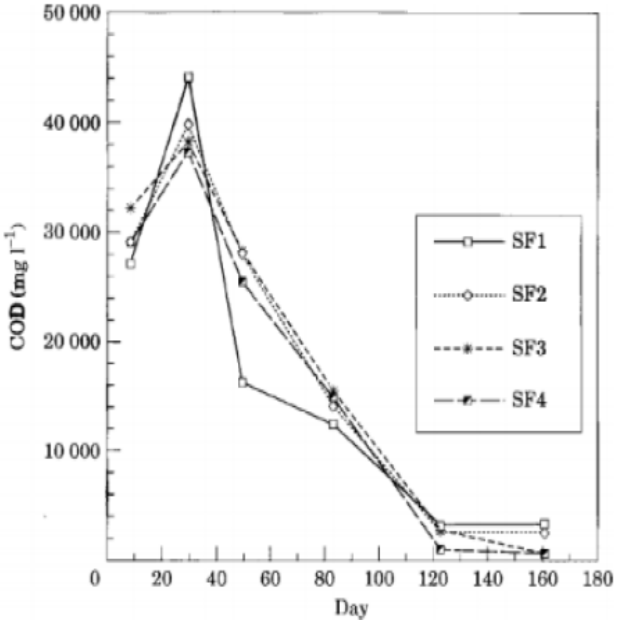


Figure 4-14: Change in COD with time in the digester (Wang et al., 1997)

4.5.3 Volatile Fatty Acid (VFA) of Food Waste Reactors

The Volatile Fatty Acid (VFA) of the leachate of the food waste reactors was also measured on monthly basis to determine the level of degradation of waste inside the reactors, as shown in Figure 4-15. The relation between VFA and waste degradation is that VFA started to increase with the advancement of the degradation initially. When the digestion process enters the methanogenesis phase, the VFA were used to convert into methane, thus decrease the amount of available VFA with time.

The initial VFA values were low in all the food waste reactors. The initial VFA for reactors AD7 and AD8 (F/I=2) were 6.00 g/L and 6.20 g/L, respectively, and increased to 35.00 g/L and 33.00 g/L, respectively, at the end of third month (90 days). After that when the reactors entered the methanogenesis phase, VFA values started to decrease and end up at 7.00 g/L and 7.50 g/L. For all the other reactors, the initial VFA was higher than the value for F/I=2. The initial VFA for F/I=15 (AD1 & AD2) were 11.25 g/L and 10.5 g/L which increased to 46.0 g/L and 47.00 g/L, respectively, at the end of third month (90 days) and then decreased to 35.00 g/L and 38.00 g/L, respectively at the end of the study period.

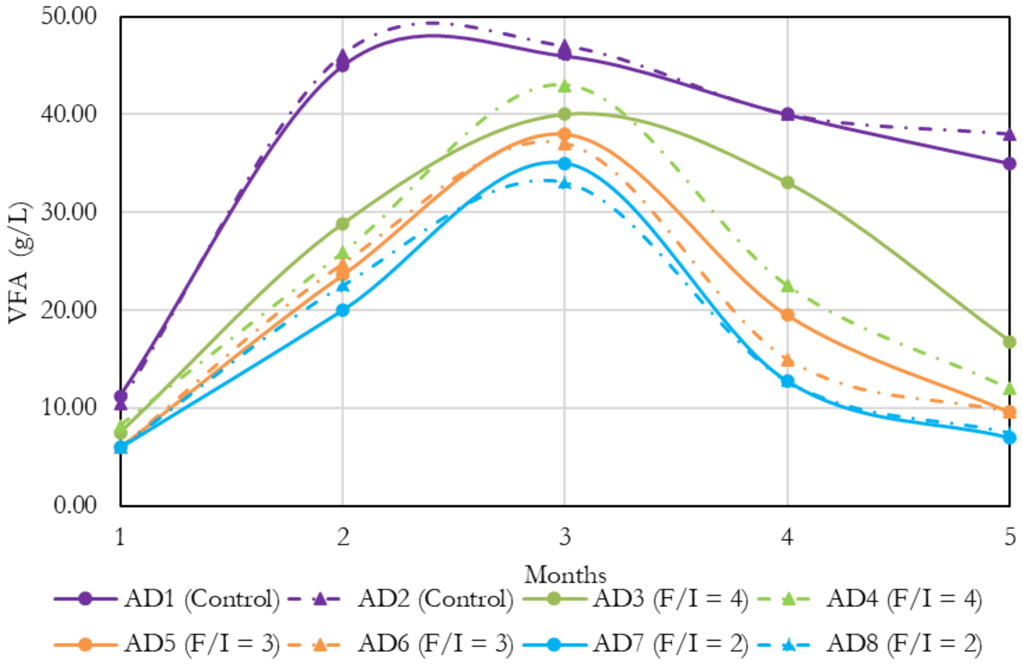


Figure 4-15: Volatile Fatty Acid (VFA) of leachate of food waste reactors

Figure 4-16 presents a finding that was discovered by Jiang et al. (2013). This result demonstrates that volatile fatty acids were created during the acidogenesis and acetogenesis processes. It demonstrates the numerous ways in which pH can affect the concentration of volatile fatty acids in the reactor. In every pH condition, the concentration initially climbed at a quick rate, and then it became reasonably steady and altered just slightly over time. VFAs synthesis peaked at pH 6.0, with maximum concentrations of 3.94, 17.08, 39.46, and 37.09 g/L. The same happened for reactors with food waste. When the pH was approximately 7.0, their VFA accumulation reached its highest point, and as soon as the pH was around 7.0, it began to decrease.

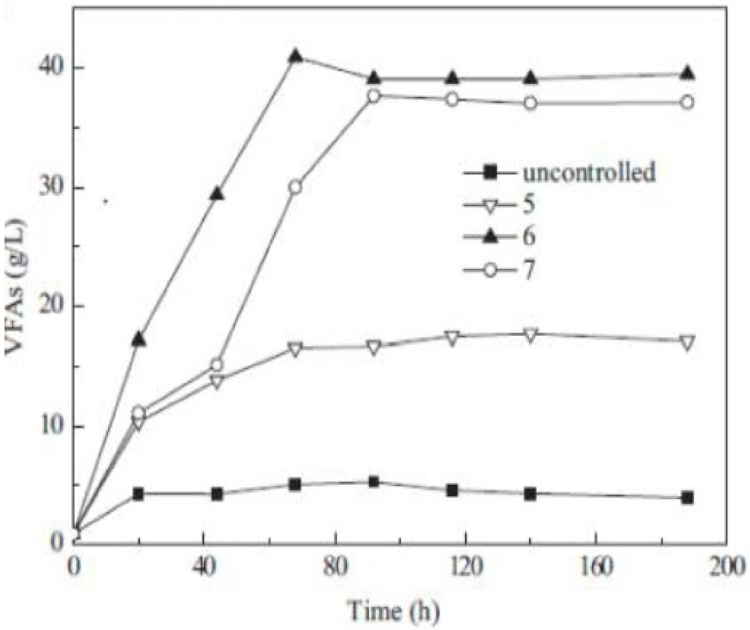


Figure 4-16: VFA concentration (at pH 5,6,7) (Jiang et al. 2013)

4.6 Reduction of Volatile Solid Content

The volatile organic content of degraded waste in the reactors was measured at the end of each month to investigate the effect F/I ratio on the degradation of food waste. The amount of volatile solids in the degraded food waste was measured each month and were compared to the initial values of the fresh waste of the reactors to measure the percentage of degraded volatile solids at the end of each month of the laboratory simulation of an anaerobic digester. It was concluded that the percent of the reduction of volatile solids in the waste is positively related to the total methane production from the waste, i.e. the more volatile solid reduction, the more methane generation. Figure 4-17 shows the changes in the volatile solid content of the feedstock of food waste reactors (AD1 to AD8) after decomposition.

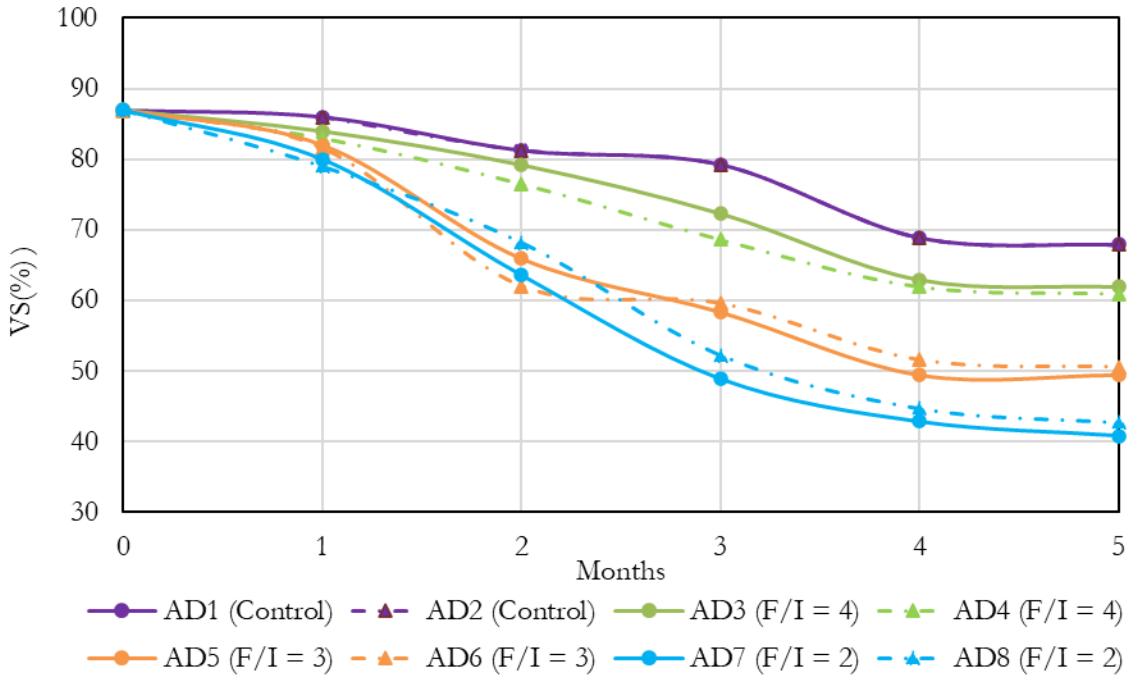


Figure 4-17: Volatile solid of Food Waste Reactors after degradation

Control Food waste reactors (F/I=15) having VS of around 86.5% at the end of one month, ended up being 66.5% at the end of study period; which indicated the VS removal of 23.54% at the end (Figure 4-18). Whereas for the reactors F/I=2 (AD 7 & 8), the VS was 79.5% at the end of one month, ended up being 41.8% at the end of study period. F/I=2 had the highest VS removal of 51.96%. AD 3 & 4 had VS removal of 29.37% and AD 5 & 6 had VS removal of 42.42% after the full operation of the study.

This recent investigation found a reduction in volatile solids that was comparable to that found in earlier studies. In order to ascertain the amount of volatile solids that remain after degradation, a number of investigations have been carried out. According to the findings of the research that was carried out by Haque (2007), the beginning volatile organic content was determined to be 91.5%; however, at the end, the percentage of volatile organic content had fallen to up to 46%. In this study, also, the volatile solid reduced up to 51.96% for the F/I=2 and 42.42% for reactors with F/I=3. According to the findings of a study that was carried out by Al- Kaabi et al. (2009), the reduction in volatile organic content was found to be 84%, 78%, 74%, and 66% after anaerobic degradation. This occurred when leachate was recirculated with the salinity level being either 0%, 0.5%, 1.0%, or 3%. According to Sivanesan (2012), the addition of the sludge resulted in a reduction in volatile solids of 84%, 82%, 77%, and 70% for the reactors with salinity levels of 0%, 0.5%, 1.0%, and 3% correspondingly. As a result, the incorporation of sludge results in a beneficial impact on the extraction of volatile organic compounds.

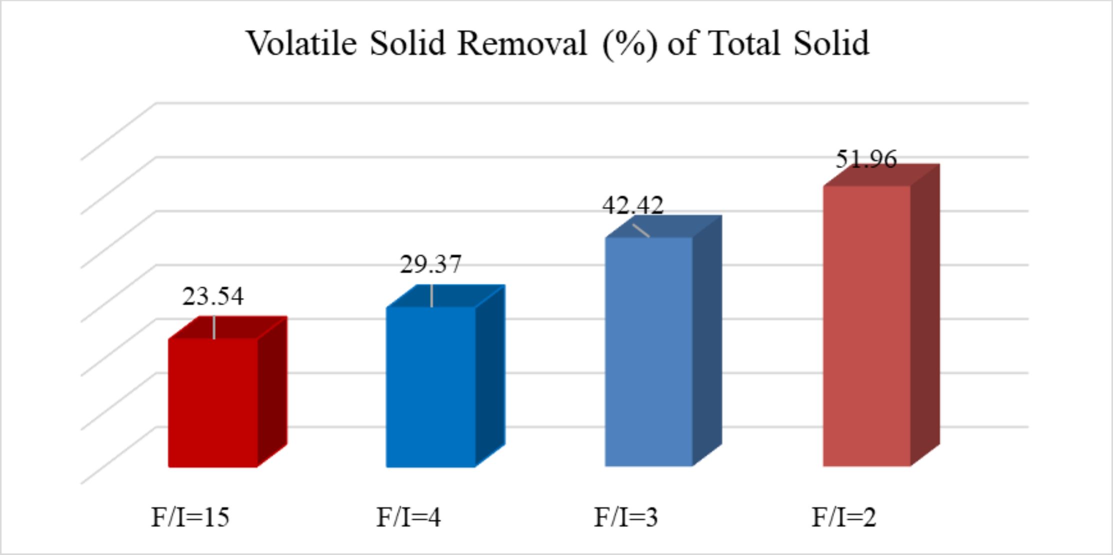


Figure 4-18: Volatile solid content removal after 180 days

4.7 Summary

The results obtained from the laboratory scale anaerobic digesters in this study showed the feasibility of food/inoculum ratio and total solid content (%) to enhance biodegradation of food waste and methane production. Various parameters of the waste degradation process, such as gas production, gas composition, leachate quality, and quantity were monitored, and the results aided in understanding the microbial behavior of waste and inoculum in the biodegradation process. It was concluded that food/inoculum ratio 2 and total solid content 11%, which is the lowest among tested, was effective for highest biogas generation.

CHAPTER 5: DESIGN AND IMPLEMENTATION OF FIELD SCALE ANAEROBIC DIGESTER

5.1 Introduction

This chapter describes the procedures followed for construction of the field scale anaerobic digester at Civil Engineering Laboratory Building in University of Texas, Arlington. Construction of the four anaerobic digesters was a time-consuming process which required a number of tasks (with multiple steps associated with each task). The field scale construction of digesters began with waste sorting, to get the desired food composition. Then collection of cow manure and sludge were done in a timely manner to facilitate the digesters. The construction and instrumentation of the digesters along with the operation and monitoring techniques are described in the following sections.

5.2 Design Considerations

The planning and design of an effective and efficient anaerobic digester require an extensive literature review before its construction, instrumentation, and monitoring. Several detailed designs of anaerobic digester were prepared, outlining specific drawing details of every component, feasible dimensions of the field scale cell, construction procedures and steps, intricate details of the instrumentation, and technical justification for critical components. The implementation of field scale was decided to be in two stages. The difference between two implementation stages is the starting phase of the Anaerobic Digester.

- For first study, it started with the same F/I ratio from Day 0. Total 4 AD with two Food/Inoculum ratio were monitored for 180 days. The extraction of digestate from digester started from the 31st day of operation as the hydraulic retention period was 30 days.

- For second study, the Inoculum for the whole hydraulic retention time has been provided on the day 0. Total 2 AD with one Food/Inoculum ratio were monitored for 120 days. The extraction of digestate from digester started from the 1st day of operation.

From Day 1, both stages were being performed same with same fixed F/I ratio. So, the design considerations were same for the cases.

5.2.1 Determination of Household Size and Waste Generation Rate in Developing Countries

For successfully designing an anaerobic digester for a developing country, comprehensive idea of rural household size and waste generation rate are of utmost importance. For determining the rural household size, attention was first given on a study by Bongaarts (2001). Bongaarts (2001) conducted a study on household size in the developing world in the 1990s. The relevant data is provided in the following table:

Table 5-1: Rural Household Size in the Developing World (1990-1998) (Bongaarts,2001)

Area	Rural Household Size
Asia	5.4
Latin America	5.0
Near East/North Africa	6.1
Sub -Saharan Africa	5.3

But with time the rural household size experienced decline due to industrialization and urbanization. Most recent data on household size was found for India and Bangladesh which are also part of developing world. The change in household size for these two countries is shown in Figure 5-1. Based on all these data, the average household size of the developing countries was decided to be used for this study is 5.

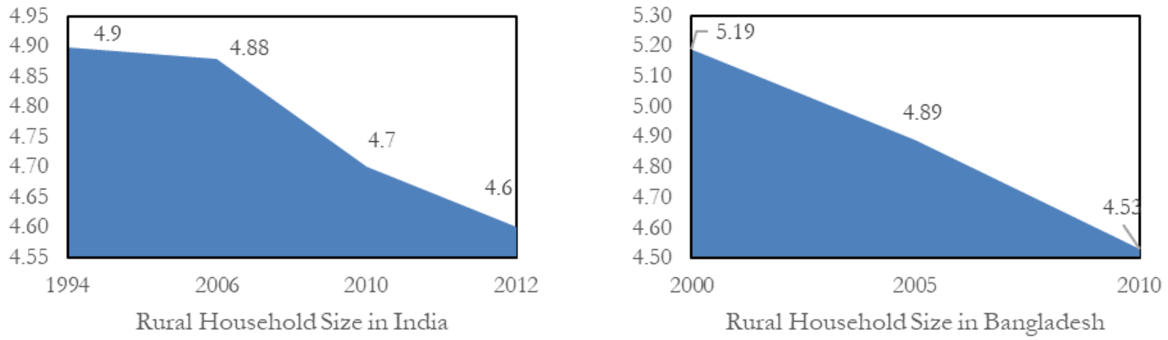


Figure 5-1: Rural Household Size in India & Bangladesh (CEIC Data)

Figure 5-2 represents the per capita waste generation rate in the seven main regions of the world. Highest and lowest waste generation was found in North America and South & Southeast Asia respectively. As this study mainly focuses on developing countries, attention was given particularly in two regions: North Africa, West & Central Asia & South & Southeast Asia. Average was calculated based on these two regions and found the waste generation rate to be approximately 0.5 Kg/day.

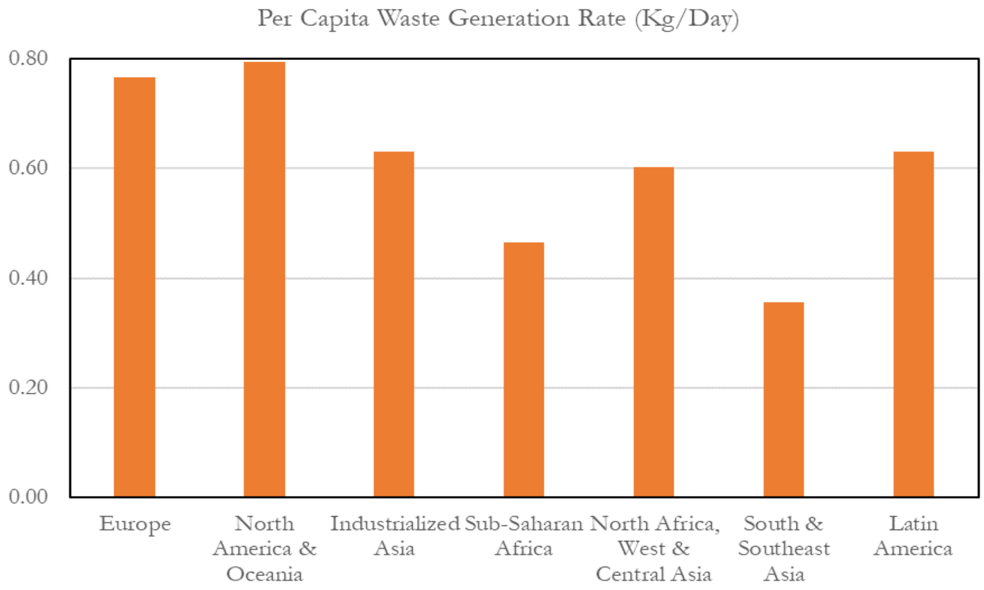


Figure 5-2: Per Capita Waste Generation Rate per Day (FAO, 2011)

5.2.2 Design of Household Scale Anaerobic Digester

Based on the laboratory scale study, the whole size of the digester and the feedstock amount was scaled to one-fifth to ease the operation. Four anaerobic digesters (F/I= 2 & 1.5) were installed in CELB. The layout of the anaerobic digester is shown in Figure 5-3 & Figure 5-4. The digesters were identical and contained the same feedstock, but nutrients were in different amount for 2 sets. The feedstock, construction, and instrumentation systems are discussed in separate sections. The key features of the household anaerobic digester are illustrated in the following section.

- 2 sets of household scale Anaerobic Digester have been decided to be set in the laboratory. The 2 sets of Anaerobic Digester will comprise of the characteristics shown in the Table 5-2.

Table 5-2: Combination of Food waste and Inoculum for Anaerobic Digester

No.	**Name**	**Food Waste (%)** (VS Basis)	**Inoculum (%) (Cow Dung + Sludge)** (VS Basis)	**Food/Inoculum Ratio** (VS Basis)
1	AD 1 & AD 2	67	33	2
2	AD 3 & AD 4	61	39	1.5

- The feeding of the digester was decided to be continuous mode where new feedstock will be added at regular intervals while an equivalent volume of slurry will be taken out the digester, thereby providing a continuous process of digestion. Vandevivere et al., (2003) stated that batch system can undergo high fluctuations in gas production until the system operates in a stable way and variations can be also observed in gas quality.

- In a developing country, the waste generation per household is obtained from Task 3. Reduced to one-fifth, the digester will be fed every day with 0.5 kg of food waste. In accordance with previous task, sludge and cow manure will also be added with this food waste keeping the food/inoculum ratio as per Table.

- According to Rapport et al(2008) .'s findings, single-stage systems are straightforward, straightforward in their design, straightforward in their construction, straightforward in their operation, and generally less expensive than multi-stage systems. According to Nichols (2004), single stage treatment is typically utilized for waste management units that are on the smaller and more decentralized scale. So, decision was made to operate the digester in single-stage which will be easily operable in developing countries.
- Vogeli et al., 2014 and Rajendran et al., 2012 stated that for tropical climate with an average ambient temperature of 25 – 30°C, the ideal hydraulic retention time is around 25 - 30 days. The hydraulic retention time for this study was decided to be 30 days based on this information.
- Based on the literature and judgment stated above, the calculated necessary size of the digester was found to be 15 gallons.
- As the digester will be operated in continuous mode, an inlet and an outlet pipe will be provided. The diameter of the inlet and outlet pipe will be 3 inches and 1.5 inches respectively. The pipes will be equipped with two-way valves of the same diameter of the pipe
- Two small sizes (0.5 inches) adapter will be installed on the top of the digester and will be connected to a gas bag with help of a 4 feet long flexible tubing. A 3-way valve will also be attached to the connection of the adapter and the gas bag.
- Mixing is a very important operating factor for achieving digestion of organic matter (Tchobanoglous et al., 1991). It is essential for achieving uniformity in the concentration of the substrate, the temperature, and the climatic conditions in order to lessen the likelihood of scum development and solid deposition (Agunwamba, 2001). So, a stirrer will be inserted inside the

digester from the top. Stirring will be manual and slow as excessive mixing can disrupt microbes (Khalid et al., 2011).

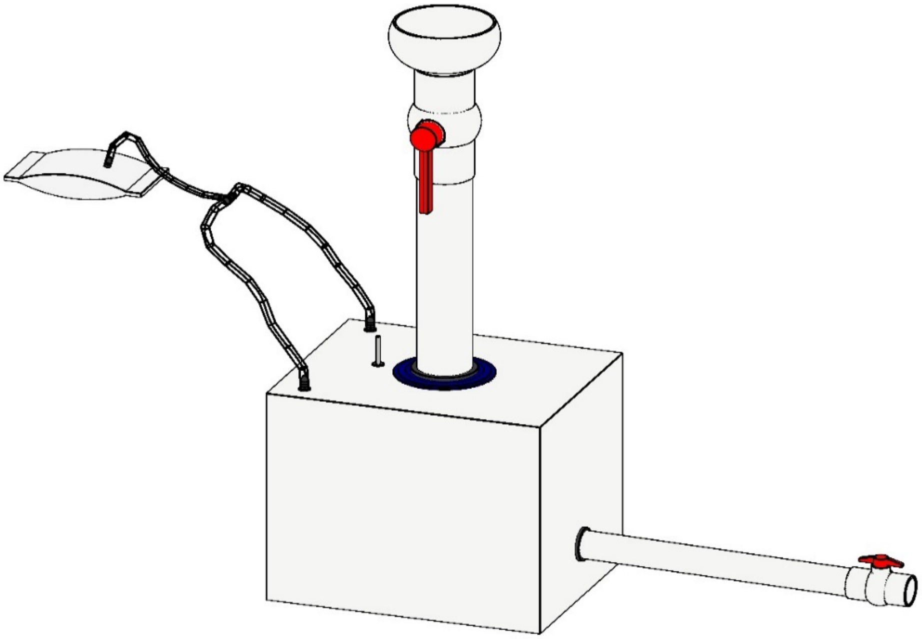


Figure 5-3: 3D View of the Designed Digester

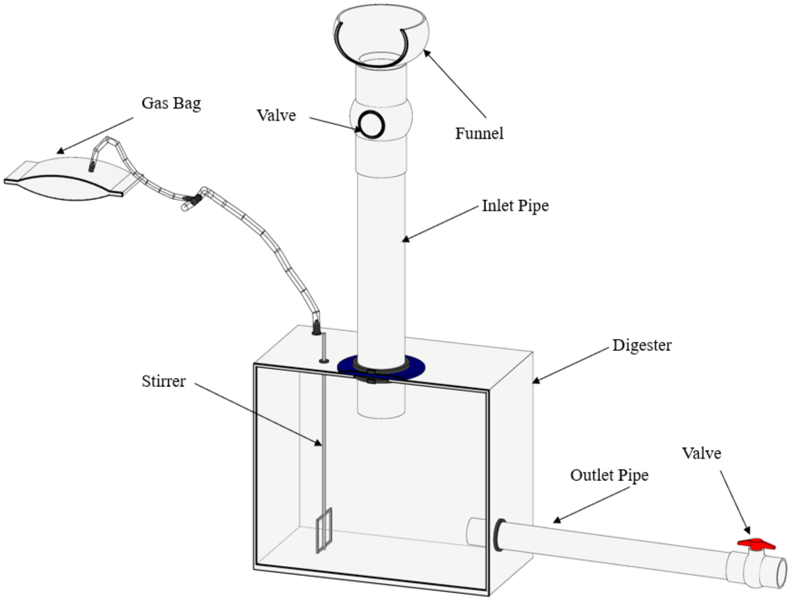


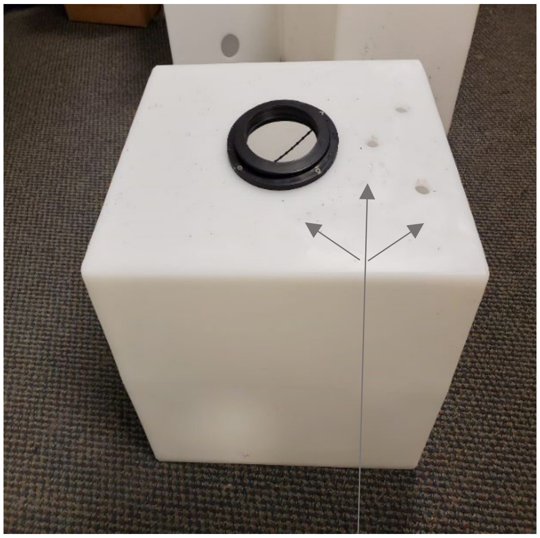
Figure 5-4: Cross Section of the Digester showing Different Components

5.3 Construction and Instrumentation

A 15-gallon horizontal tank with a length of 18.5”, width 15’’ and height of 16.5’’ was decided to be used as the anaerobic digester. The tank was made of Linear Low-Density Polyethylene (LLDPE) and can withstand temperature up to 140ºF. As an inlet for the feedstock, a 3 inches PVC pipe connected with 3 inches 2-way ball valve was installed. To ease the feeding operation, a funnel with an opening diameter of 6.5 inches which narrows down to 2.5 inches was also connected on top with the inlet valve. To take out the digestate, an outlet pipe made of PVC was fitted at 3.5 inches from the bottom of the digester. The diameter of the outlet pipe is 1.5 inches and a ball valve of the same diameter was also attached to it. For mixing, a stirrer made of metal was inserted inside the digester from the top. The total length of the stirrer is 17.25 inches with a mixing head diameter of 3.25 inches. Two 0.5 inches adapter were installed on top of the digester for gas collection. The adapters were connected with a 3-way valve and a gas bag with a total of 4 feet long flexible tubing. After all the components were installed, sealant was used heavily to ensure that the whole digester was airtight. The outlet pipe was placed a little be tilted to provide adequate gradient to the digestate to flow towards the outlet pipe.

The construction process described above is being picturized below:

(a) Making Holes for inlets and outlets



(b) Holes for the inlet, gas pipes, stirrer

(c) Holes for the Outlet

(d) Constructed Tanks

(e) Sealant for the anaerobic condition

(f) Placed in Mesophilic Condition

Figure 5-5: Household Scale Anaerobic Digester Construction Process

Four digesters were constructed having all the same properties and will be operated in completely similar manner. The digesters are now being set up in the laboratory and will be operated under mesophilic temperature of 37ºC. Figure 5-6 shows the four constructed digesters set up in the laboratory.

(a) Anaerobic Digester 1 (b) Anaerobic Digester 2

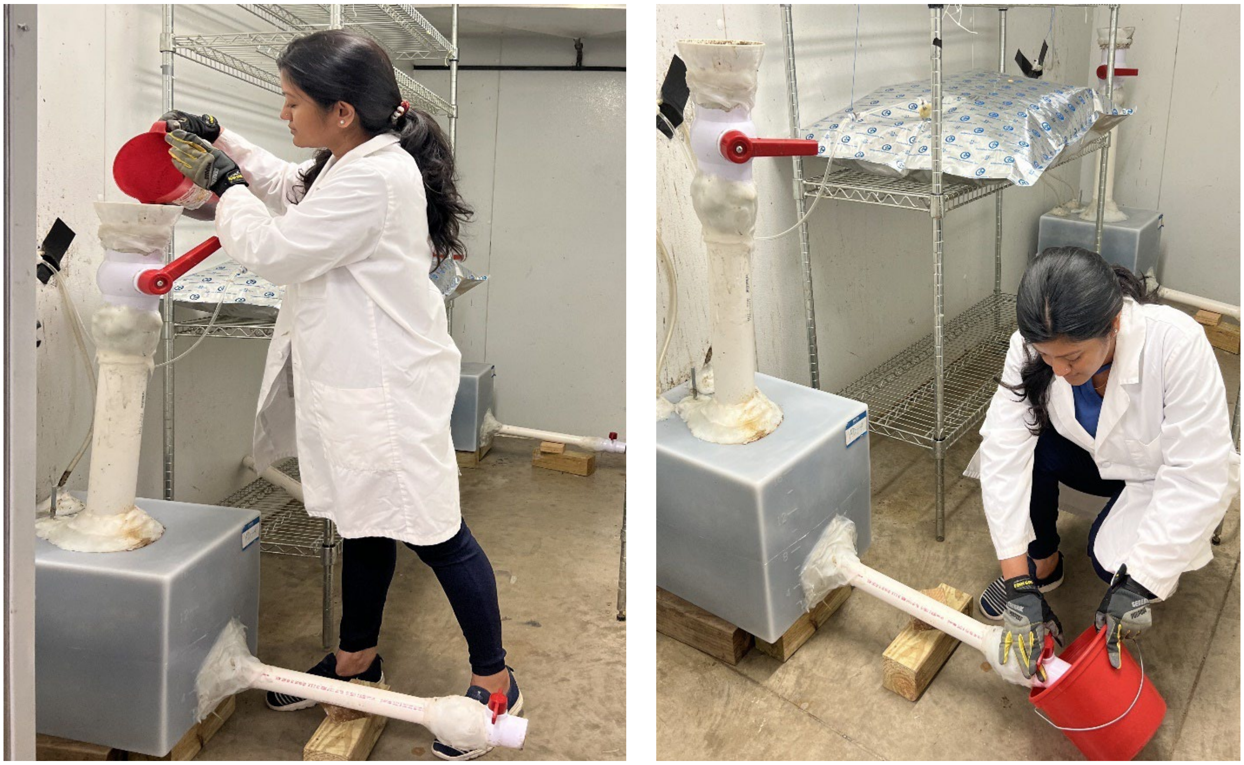
(c) Anaerobic Digester 3 (d) Anaerobic Digester 4

Figure 5-6: Constructed Digester Set Up in the Laboratory

5.4 Operation & Monitoring

An extensive operation and monitoring program was designed to allow collection of data related to gas production, and biochemical reaction, as well as to determine the general waste biodegradation characteristics. The operation of the anaerobic digesters will be carried out for four months. Each day the digesters will be fed a specific amount of feedstock. After passing the opted hydraulic retention time, before each day feeding, same amount of digestate will be taken out from the digesters through the outlet for study 1. For study 2, as total amount of inoculum has been added on day 0, before each day feeding, same amount of digestate will be taken out from the digesters through the outlet.

The continuous digester operation mode was different than the batch one described in Chapter 3, methodology. The operation process described above is being picturized below:



(a) Feeding procedure of the Digester (b) Extraction procedure of the digestate

Figure 5-7: Daily Operation of the Continuous Digester

Analysis of the collected data and specific environmental parameters described in Table 5-3 was performed to fulfil the research objectives. The procedure of the data collection methodology for the environmental parameters are already discussed in Chapter 3.

Table 5-3: Monitoring of environmental parameters

Environmental Parameters	Monitoring Techniques	Frequency
Leachate Quality	pH, Chemical Oxygen Demand (COD), Alkalinity, Volatile Fatty Acid (VFA)	Biweekly
Gas Composition	LandTec	Daily
Gas Volume	Flow Meter	Daily
Feedstock Characteristics Moisture Content (%) & Volatile Solid (%)	Before filling the digester	1 Time

Chapter 6: PERFORMANCE EVALUATION OF FIELD SCALE ANAEROBIC DIGESTER

6.1 Introduction

The results obtained from the field scale anaerobic digesters food are evaluated for the performance of them as source of energy. Gas generation and Leachate quality data are presented and discussed in this chapter. Fresh food waste samples were collected from sources and mixed to a synthetic ratio to keep the combination inside the similar digesters as identical as possible. As discussed earlier, the operation and performance monitoring were done on two stages to check the efficiency in reducing the lag phase. At first stage, A total of four (4) anaerobic digesters were built with total two (2) pairs of Food/Inoculum ratio and solid content (%). After completion of first stage, a total of two (2) anaerobic digesters were built with one (1) pair of Food/Inoculum ratio and Total solid content (%) at second stage.

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.

6.2 Food Waste and Inoculum Characteristics

While starting the continuous anaerobic digester, the collected food waste samples were sorted manually (hand sorting), and their physical composition was determined by wet weight basis. The food waste from the University cafeteria were then sorted based on the decided waste percentage, which is as follows: 60% of fruits and vegetables, 10% for meat, fish, and dairy and 30% for food produced from grain. The average moisture content of fresh food waste was about

80.57% on wet weight basis. Volatile solids accounted for about 88.94% of the total solid of food waste feedstock.

The inoculum-sludge used had a high moisture content (97.52% in wet weight basis) and high pH (7.39), which meant that it was rich in anaerobic microorganisms. The volatile solid content was 80.23% of total solid. The moisture content of fresh cow manure was 80.2 %. The pH of the cow manure was about 7.32, and volatile solid is of 82.5% of total solid.

6.3 Gas Characteristics of 1st set Anaerobic Digesters

The primary sign that waste is being broken down is the production of biogas. For the study, composition, volume, and rate of gas generated from the food waste anaerobic digesters (AD1 and AD4) were measured on a regular basis for 180 days, as described in the section below:

6.3.1 Gas Composition of 1st set Anaerobic Digesters

The first measurement of gas volume and composition was made on day 1 from food waste digesters AD1 to AD4. In the beginning, (Figure 6-1) methane content was low, and the carbon dioxide content was very high. The oxygen percentage was high as upto 10% for first few days, which indicated the existence of an aerobic condition in both ADs. After almost 7 days, the oxygen content in both ADs started decreasing, which indicated the start-up of the anaerobic phase. With the beginning of the anaerobic phase, the carbon dioxide content began increasing rapidly in both the ADs. With the beginning of the acidogenic phase, the pH began dropping due to an excessive accumulation of volatile fatty acids. After around 40 days, the methane percentage started to increase and ended up being around 10% on that time. Oxygen content in digesters dropped to less than 1% in 7 days and was stable for 180 days, showing that both of the cells reached the anaerobic phase.

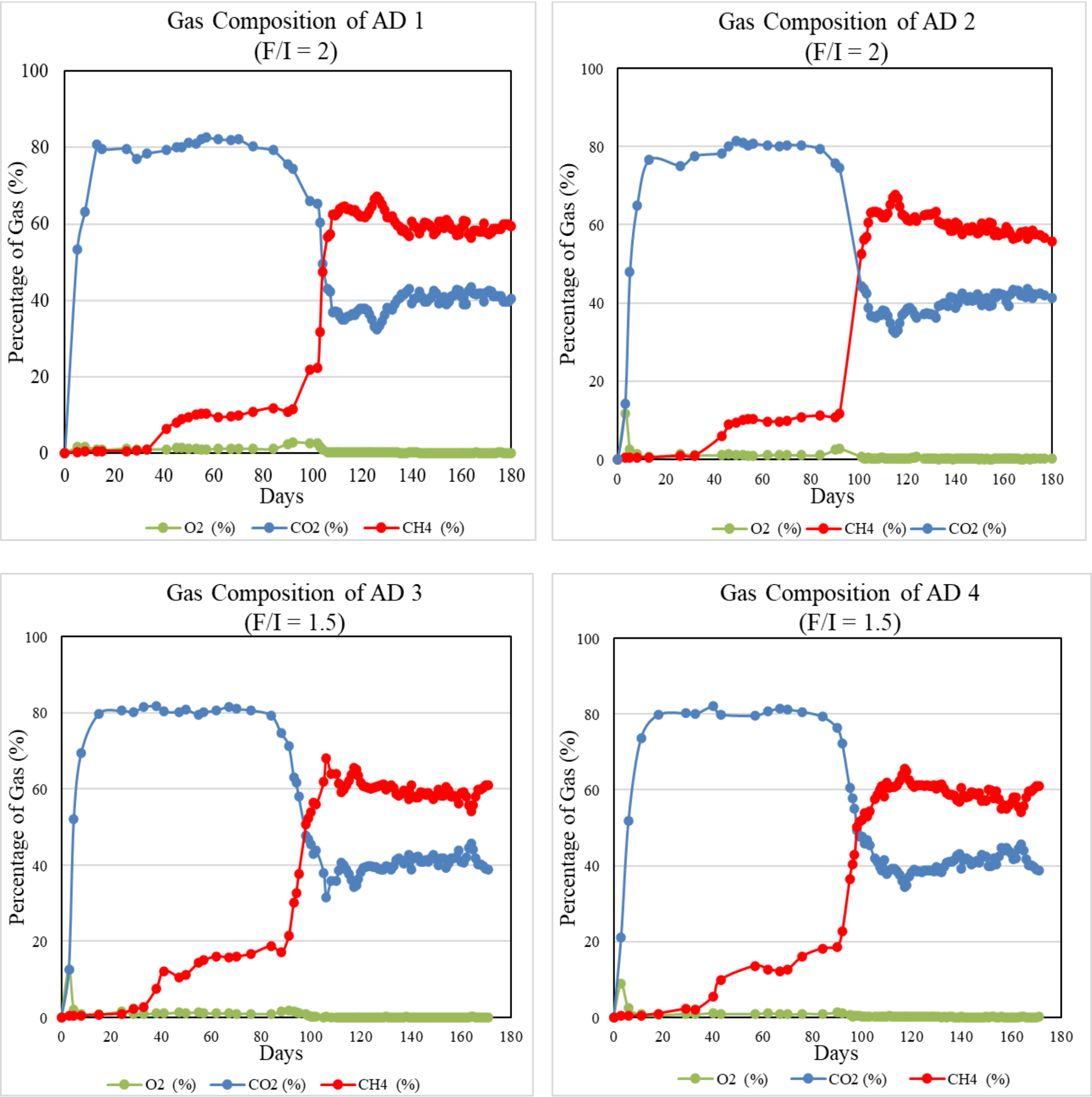


Figure 6-1: Gas composition data for all AD

Figure 6-2 shows the methane content in the anaerobic digesters. The methane content in the anaerobic digesters (AD 1 & AD2) reached 20% after 90 days and continued increasing. After almost 105 days of operation, they both reached 60%; The methane content in the other anaerobic digesters (AD3 & AD4) showed similar trend with peak at 69% of methane in 110 days in AD3 and 67% of methane in 110 days in AD4 respectively. A study by Erses et al (2008) found that an anaerobic digester didn't contain methane until day 165, due to the acidogenic conditions present. After that, methane began to appear and increased to 50% by composition. In the current study, the methanogenic phase began in the digester after 100 days, when the methane content exceeded 55%.

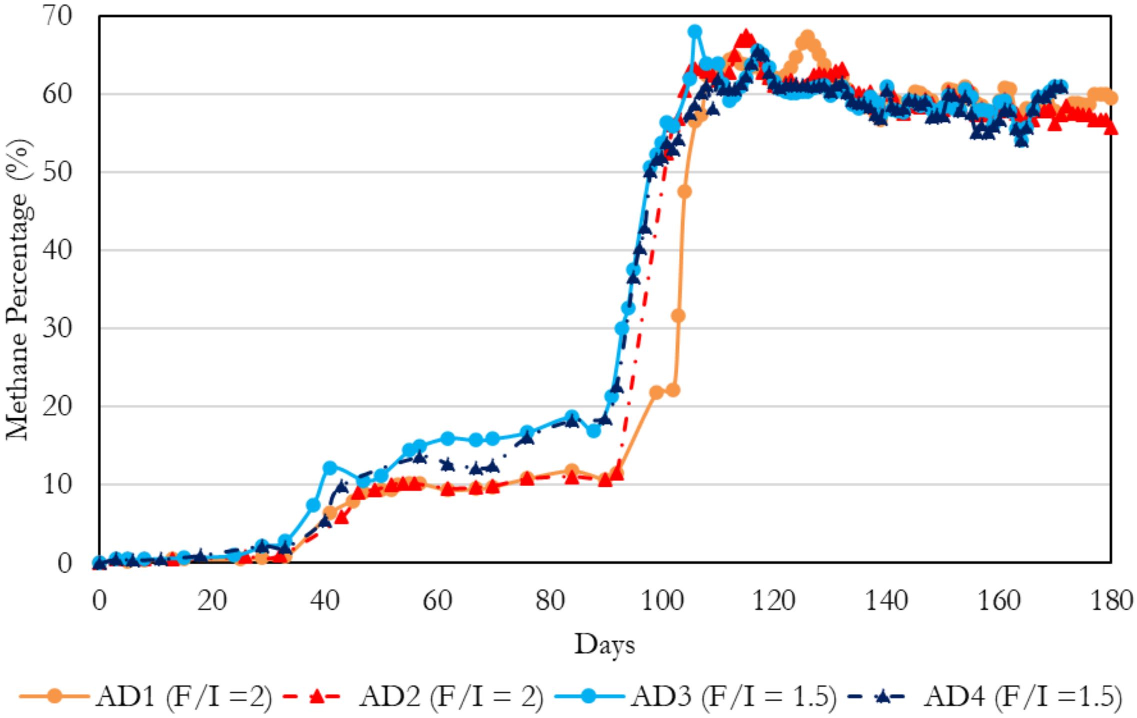


Figure 6-2: Methane content in food waste reactors

In the methanogenic phase, the percentage of methane increases as high as 60% to 65%, with the variation of pH of the leachate from 6.0 to 8.5 (Karanjekar, 2013). Carbon dioxide content reduces, which can be seen from the increase of methane to carbon dioxide ratio (CH_4:CO_2 ratio). In this study, after 100 days of operation, the CH_4:CO_2 ratio in digester AD1 reached 1.5. For AD3 & 4 it took 110 & 113 days respectively to achieve 1.5 ratio. Figure 6-3 shows the methane-to-carbon dioxide ratio in anaerobic digesters. AD1 to AD 4 had the CH_4:CO_2 ratio (greater than 1.5) after 113 days, which is favorable state for the stable operation of the anaerobic digesters.

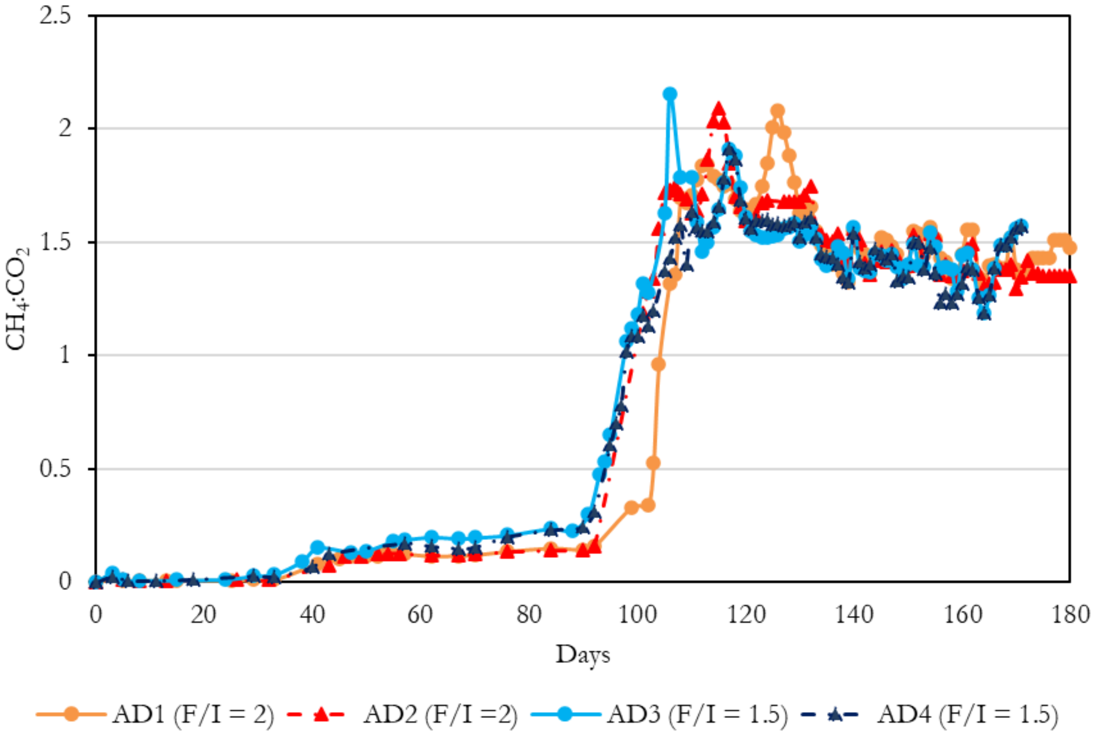


Figure 6-3: Methane-to-carbon-dioxide ratio in food waste digesters

Figure 6-4 shows the percentage of anaerobic activity in anaerobic digesters, as calculated by using Eq. 4.1 described in Section 4.4.1.

$$P = \frac{2\,C_{CH_4}}{2\,C_{CH_4} + (C_{CO_2} - C_{CH_4})} * 100$$

The value of percentage of anaerobic activity (P) was plotted against time to observe the variations of anaerobic activity in the digesters. At the starting of the operation, P value was less than 10%. After 45 days of operation, all the digesters P value crossed 20%. Between 80 to 100 days of operation, all digesters had achieved 100% anaerobic activities, which indicates the anaerobic activities of methanogenic phase. During this phase, all the digesters were having more than 100% P value ranging from 100 to 140 for the rest of the operation period.

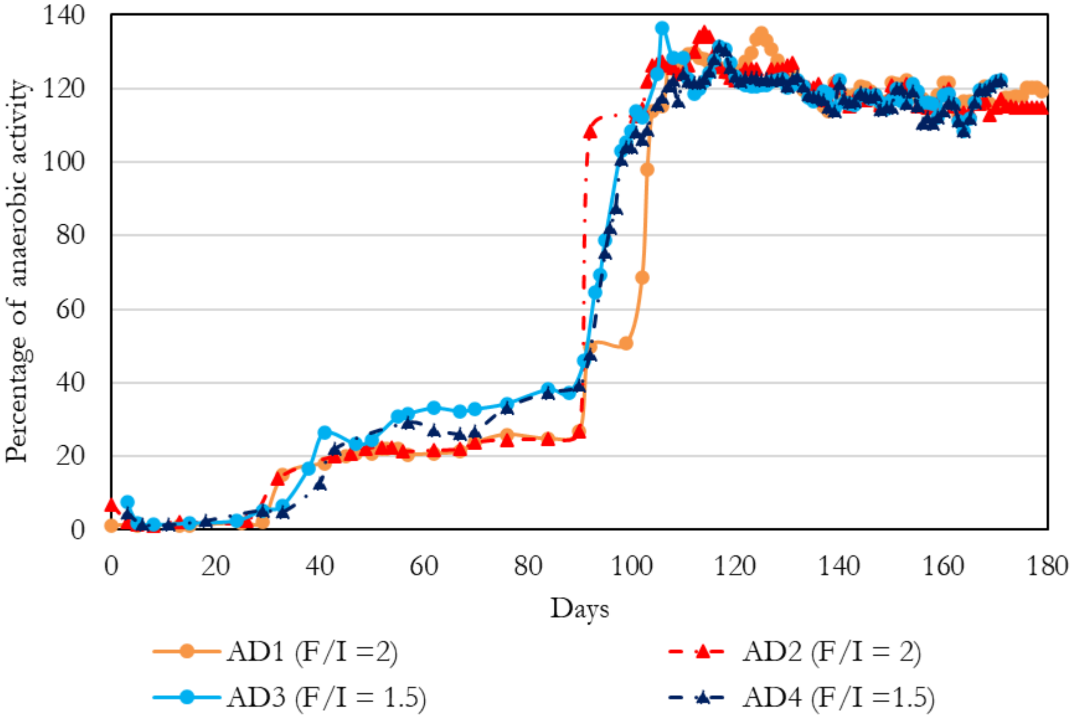


Figure 6-4: Percentage of anaerobic activity in anaerobic digesters

6.3.2 Gas Volume of 1st set Anaerobic Digesters

In the anaerobic digesters (AD1 to AD4), the first gas volume was measured on day 1; it had a very high carbon dioxide content and very low methane and oxygen content. Among 180 days of operation, all digesters showed increased pattern in producing gas. After passing the lag phase, the ADs follow that trend. Before being in the methanogenic phase, the slope of the increase in the gas production was relatively flatter than the slope when the ADs entered the methanogenic phase, which can be visible in Figure 6-5 that shows the cumulative gas generation (L/lb.VS) in the anaerobic digesters (AD1 to AD4).

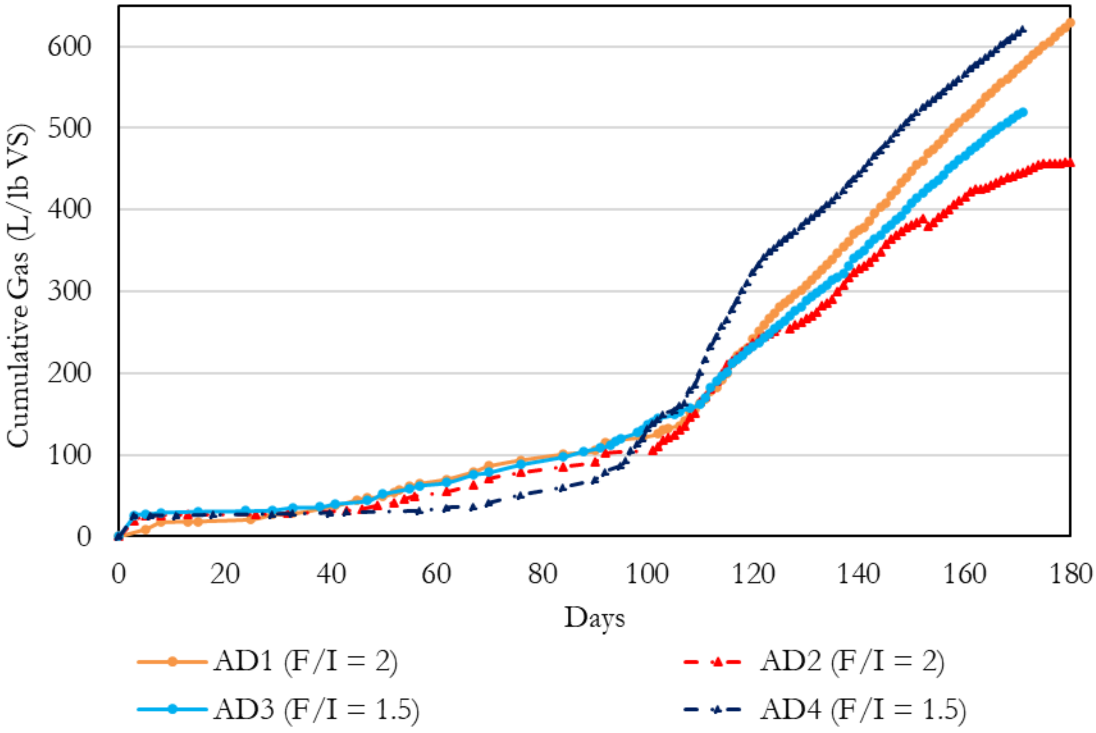


Figure 6-5: Cumulative gas generation (L/lb. VS) in Anaerobic Digesters

The digesters with F/I=2 (AD1 and AD2) produced significant amounts of gas (630.0 L/lb. and 457.8 L/lb., respectively) in about 180 days. With the daily operation of the AD, ultimately all of them overcame the very long lag phase, AD3 and AD 4 with F/I=1.5 produced gas upto 616 L/lb and 519.6 L/lb respectively in day 180. The digesters were monitored for 180 days and then were dismantled.

Figure 6-6 shows the cumulative methane generation in digesters (AD1 to AD4). As mentioned in section 6.3.1, the methane content was high in all of the digesters. The highest cumulative methane volume was generated from digester AD4 (324 L/lb. VS). The lowest cumulative amount of methane was produced from food waste digester AD3 (less than 253 L/lb.VS)

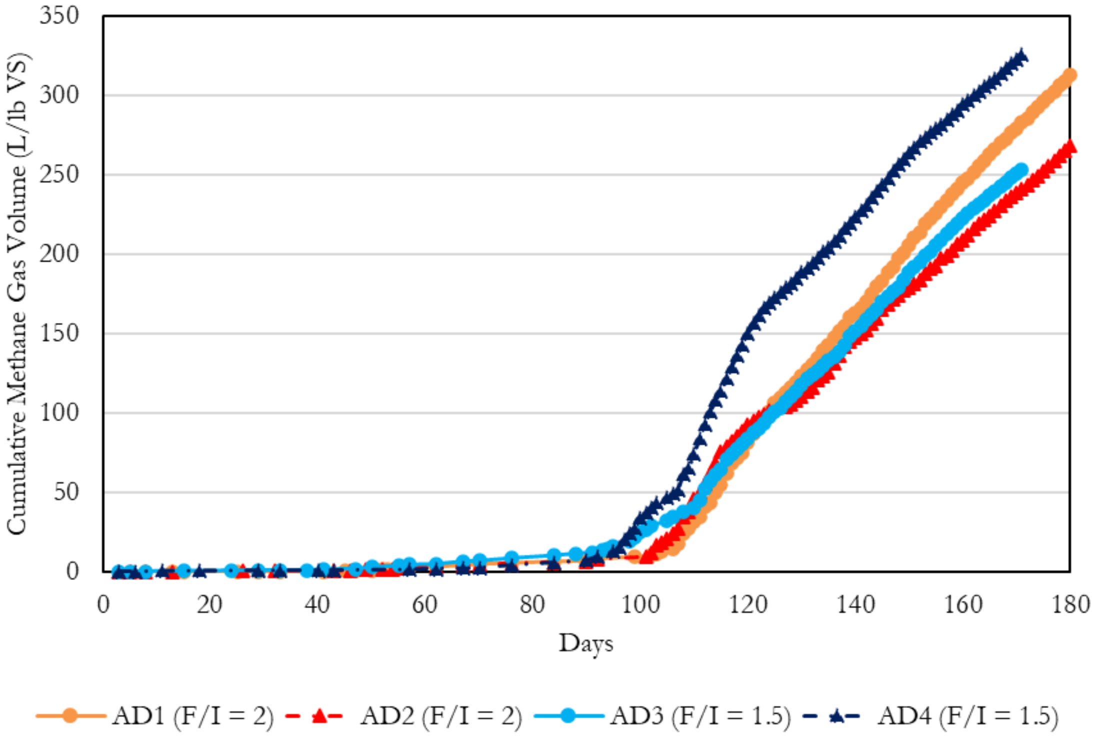
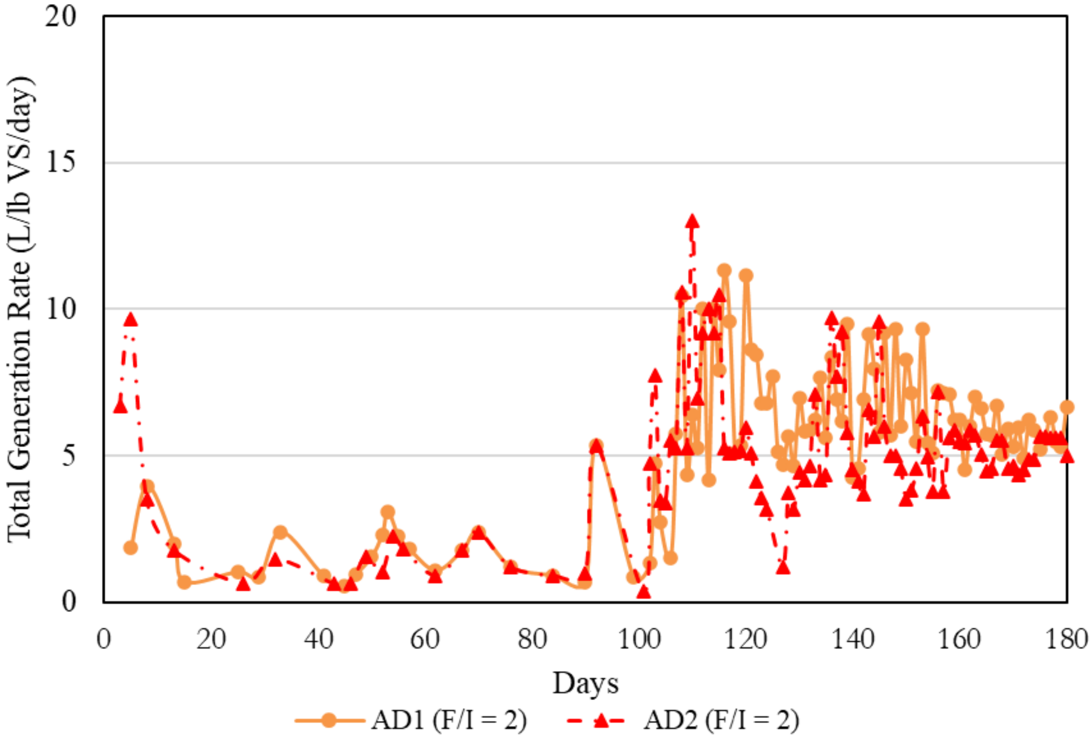


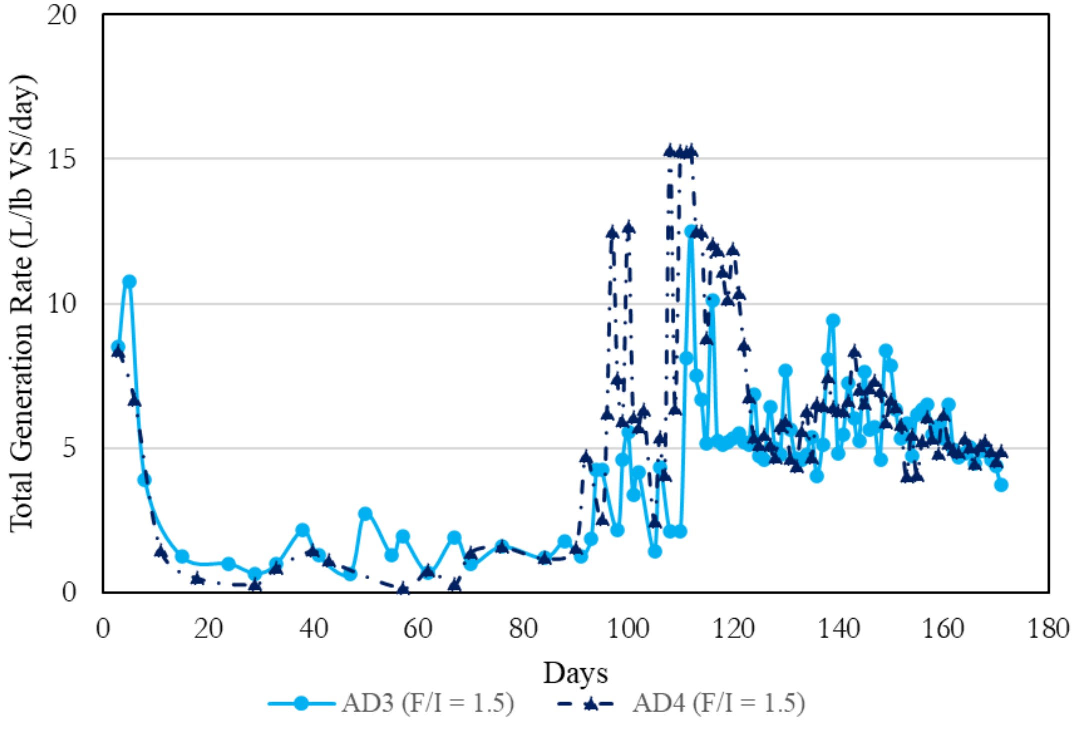
Figure 6-6: Cumulative methane generation (L/lb. VS) in Anaerobic Digesters

In conclusion, food waste digesters were able to generate substantial amounts of methane, but it required more time of overcome the lag phase. In this study, the moisture content of food waste was more than 70% (Table 4-1). The volatile solid content of food waste was 87-88%, which indicates that the feedstock had high potential for biodegradability (Table 4-4).

Figure 6-7 and Figure 6-8 show the gas generation rate and methane yield of the food waste digesters, respectively. From the gas yield versus time graph, the lag phases in food waste digesters can be observed clearly. The low number in the yield shows the slower degradation of the feedstock before entering the methanogenic phase. The initial steps of degradation, hydrolysis and acidogenesis resulted in less biogas in that phase.



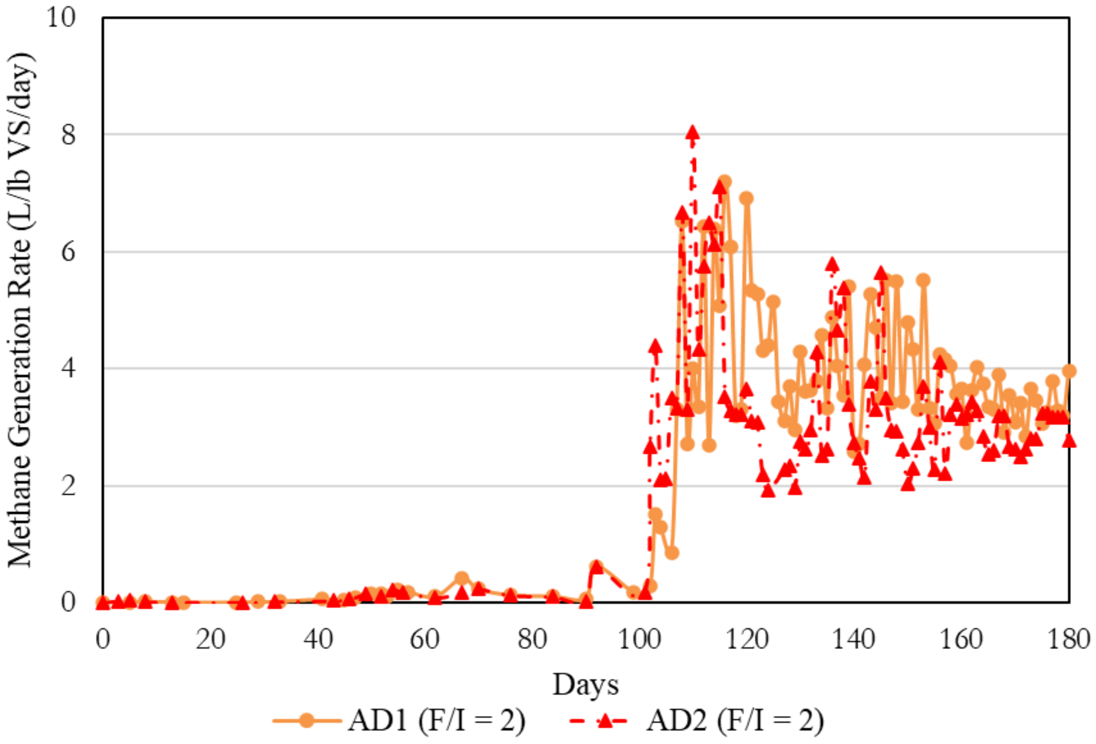
(a)



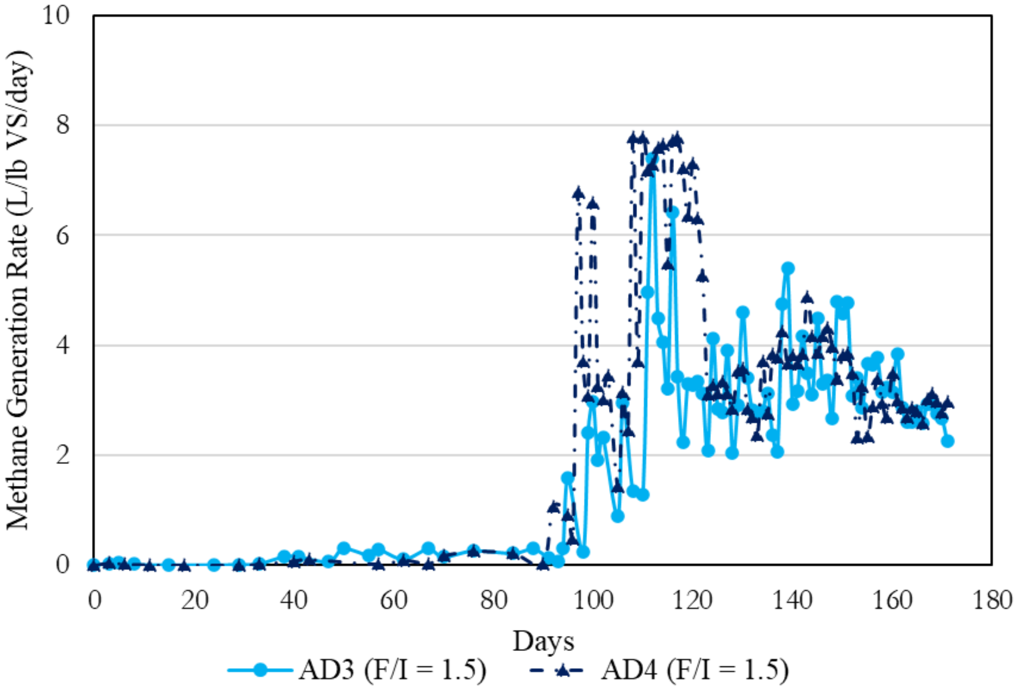
(b)

Figure 6-7: Gas yield (mL/lb. VS/day) for Anaerobic Digesters of (a) F/I=2, (b) F/I=1.5

Initially, there was a substantial amount of gas production in food waste digesters up to 5 days. The gas generation rate in digester AD1 reached its peak of 10.0 L/lb. VS/day in only 5 days of operation. Food waste digesters again were in an increasing trend of yielding gas after 100 days. All four digesters displayed multiple peaks, with highest gas yield of 15 L/lb.VS/day. Digester AD2 reached its peak of 13.1 L/lb. VS/day on day 110; AD3 and AD4 reached their peaks (15 L/lb./day) on day 110 and (12.5 L/lb./day) on day 111. The methane yield versus time graph shows the methane generation rate with time (Figure 6-8) and shows that methane and gas yields in food waste digesters follow the same trend. Food waste digesters with F/I=2 (AD1 and AD2) experienced the methanogenic phase 2 days earlier, with the decomposition of waste taking place from day 108 to day 180. Other two digesters (AD3 & 4) experienced methanogenic phase from day 110 to day 180. When the digesters reached the methanogenic phase, the generation of methane peaked.



(a)

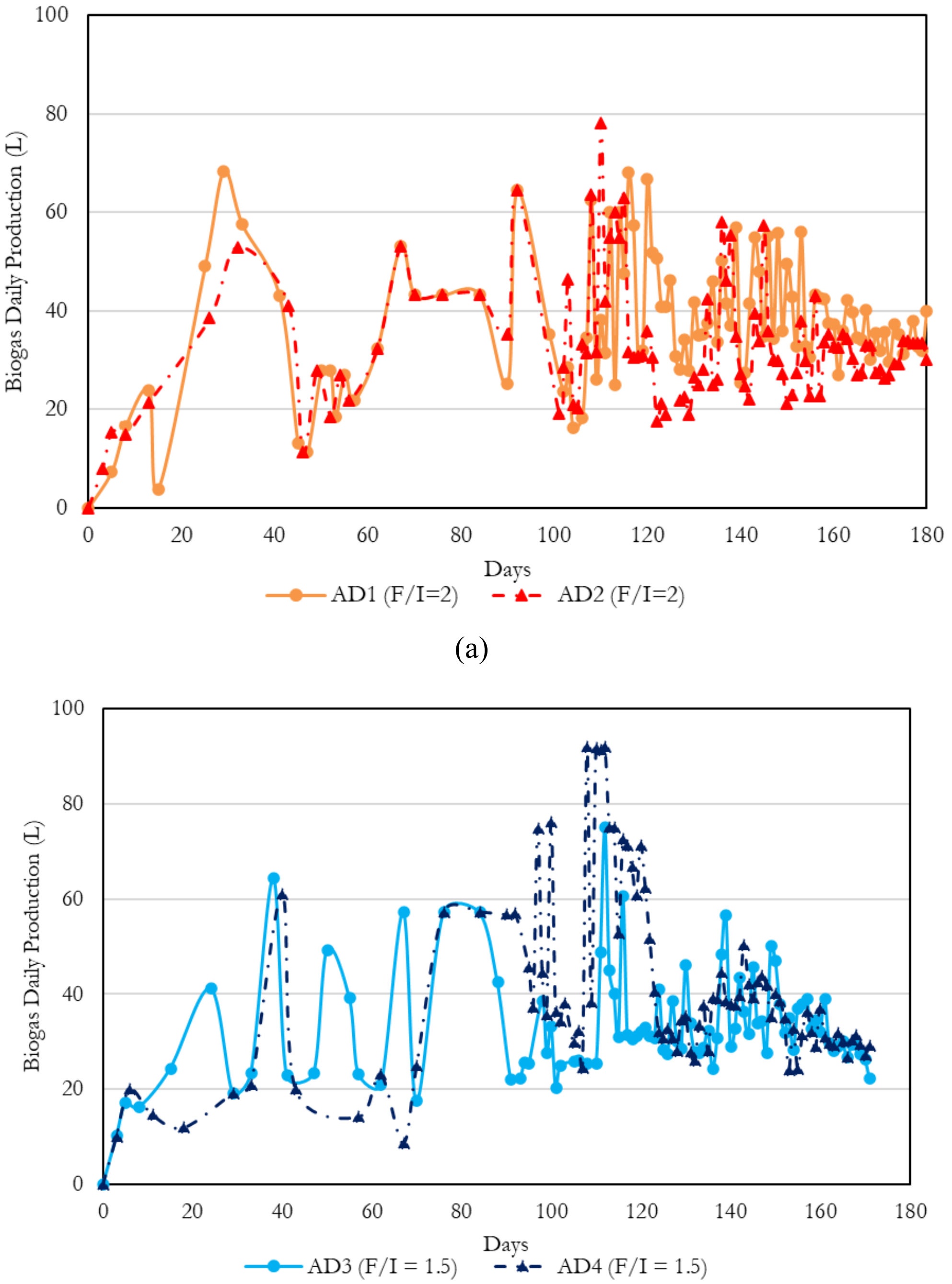


(b)

Figure 6-8: Methane yield (mL/lb. VS/day) for Anaerobic Digesters of (a) F/I=2, (b) F/I=1.5

Due to the heterogeneous properties of waste, the methane yields varied, even for the same pair of digesters. The variation for them were not that significant for different F/I ratio tested here. For example, digester AD1 with F/I=2 had the peak methane yield on day 110 (8.05 L/lb. VS/day), and AD2 peaked on day 115 (7.1 L/lb. VS/day). AD3, AD 4 with F/I=1.5, had the methane generation rate of 7.18 and 7.78 L/lb. VS/day on day 111 and 110 respectively.

Figure 6-9 depicts the daily biogas generation from the AD1 to AD 4. The daily gas generation in digester AD1 reached its peak of 68.9 L/day in 29 days of operation. Food waste digesters again were in an increasing trend of yielding gas after 100 days. All four digesters displayed multiple peaks, with highest gas yield of 91.8 L/day. Digester AD2 reached its peak of 78.2 L/day on day 110; AD3 and AD4 reached their peaks (75 L./day) on day 113 and (91.8 L./day) on day 111. The gas composition and measurement were done based on the requirement. After entering the methanogenic phase, the measurement was done daily because of the higher volume of gas continuously which is observed in the graph. For all the digesters, the biogas production has several peaks and lows. After passing the lag phase, which was 100 days, the biogas production was stable compared to the lag phase.



(a)

(b)

Figure 6-9: Daily Biogas Production (L/day) for Anaerobic Digesters of (a) F/I=2, (b) F/I=1.5

The mean biogas production for AD1 was 37.99L with standard deviation of 12.70L. The mean biogas production for AD2 was 48.05 L with standard deviation of 22.29L. Whereas, the mean biogas production for AD3 and AD4 was 49.97 L and 33.77 L with standard deviation of 20.85 L and 11.06 L respectively. Even with the stable situation then the lag phase, the variation was more than 20 L for two of them.

6.4 Leachate Characteristics 1st set Anaerobic Digesters

Leachate is generated by excess water percolating through the waste layers in a waste decomposition system. The chemical and biological processes of the waste are significantly influenced by the characteristics of the generated leachate such as pH, VFA (Volatile Fatty Acid), COD (Chemical oxygen demand) and Alkalinity. The characteristics of generated leachate indicate the level of degradation of the solid waste. In this study, the pH, VFA, COD and Alkalinity were monitored for food waste digesters during their decomposition phases. Details are discussed in the following sections.

6.4.1 pH of Leachate of 1st set Anaerobic Digesters

A significant drop in the pH in food waste digesters (AD1 to AD4) was observed throughout the initial monitoring period due to excessive volatile fatty acid (VFA) accumulation in food waste. Previous researchers (Shao et. al., 2005; Karanjekar, 2013) also experienced a pH drop in food waste due to VFA accumulation. The pH measurement started after the passing of hydraulic retention time of 30 days. From the pH vs time plot of food waste digesters (Figure 6-10) it was noticed that the initial pH was less than 5.5 for as long as 40 days of operation, which may have retarded the bacterial growth in the digester. After 70 days of operation, the pH of most of the digesters reached or surpassed 6. It took almost 100 days for all of the food waste digesters to attain the methanogenic phase, which also interprets from the gas graphs in the previous section.

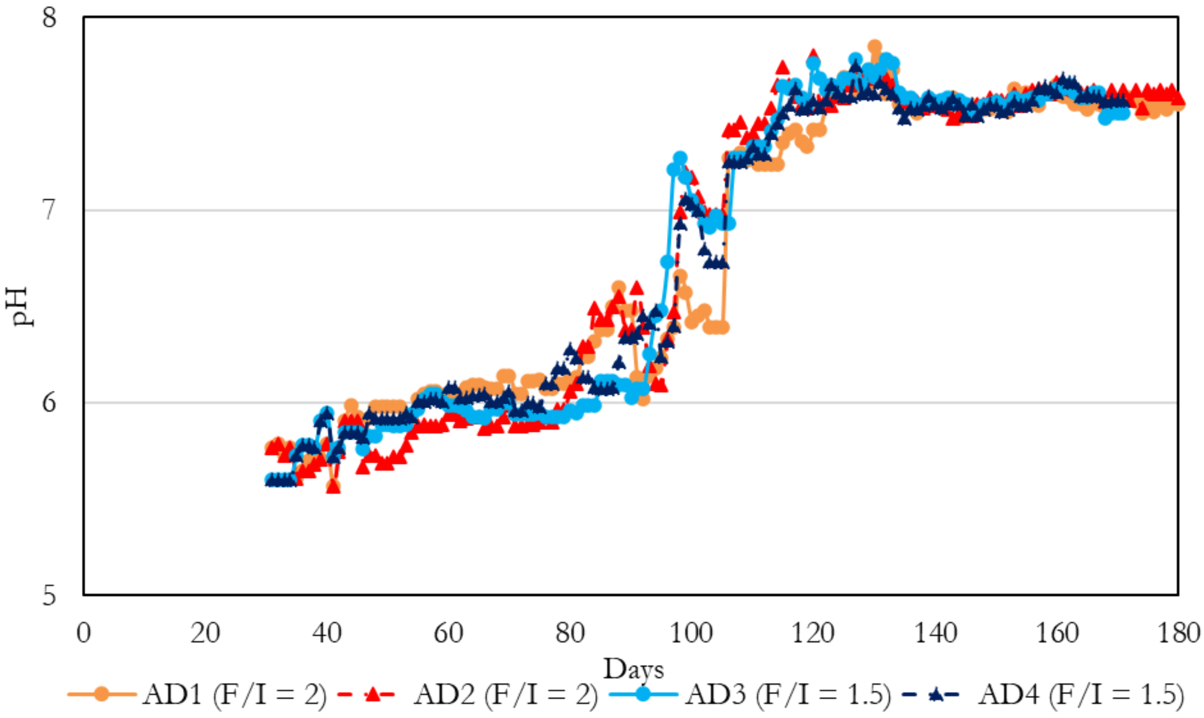


Figure 6-10: pH of leachate of food waste digesters

Leachate was collected for the first time on 31 day of operation, and the pH (5.6 to 5.77) was the lowest on day 31 of 180 days of operation of the food waste digesters. The pH of the leachate of digesters AD1 and AD2 was 7.00 on day 105 and 7.17 on day 100, respectively, which indicated the methanogenic phase. Once the digesters reached the methanogenic phase, the pH remained at more than 7 and then stabilized with maximum values of 7.85 and 7.77 for AD1 and AD2, respectively. In the food waste digesters with F/I=1.5 (AD3 and AD4), the initial pH was 5.61 and 5.55, respectively, on day 31. Following a trend like AD1 and AD2, the pH of AD3 and AD4 was found to have increased on the next monitoring day and kept climbing. The pH of leachate of AD3 and AD4 was more than 6 on day 33 and entered the pH zone 7 on days 97 and 99, respectively. AD3 and AD4 had the highest values of pH, 7.78 and 7.75, respectively.

In this study, the low pH in the initial stage had an overall effect on methane production. In a study conducted by Wang et al. (1997), an initial pH of 3.4 to 3.7 in 70% food waste and 30% old refuse digesters caused high accumulations of VFA and ammonia, which led to the termination, on day 149, of digesters that had produced very little methane. Despite pH neutralization by sodium carbonate, these digesters failed to undergo methanogenesis.

6.4.2 Chemical Oxygen Demand (COD) of 1st set Anaerobic Digesters

The COD of the leachate of the food waste digesters was also measured on biweekly basis to determine the level of degradation of waste inside the digesters, as shown in Figure 6-11. There is a correlation between waste degradation and COD decline, as COD levels fall as waste breaks down over time.

The COD value decreases with the degradation of waste. The initial COD values were high in all of the food waste digesters. Digesters with F/I=2, the initial COD for AD1 and AD2 were 28,540 mg/L and 27,375 mg/L, respectively, and decreased to 10,850 mg/L and 9,620 mg/L, respectively, at the end of six month (180 days). Whereas the initial COD for digesters AD3 and AD4 (F/I=1.5) were 26,290 mg/L and 25,891 mg/L, respectively, and decreased to 9,800 mg/L and 8,340 mg/L, respectively, at the end of six month (180 days). The concentration of COD began to lessen as soon as the acidogenic phase came to an end, the degradation process began, and the transition into the methanogenic phase began.

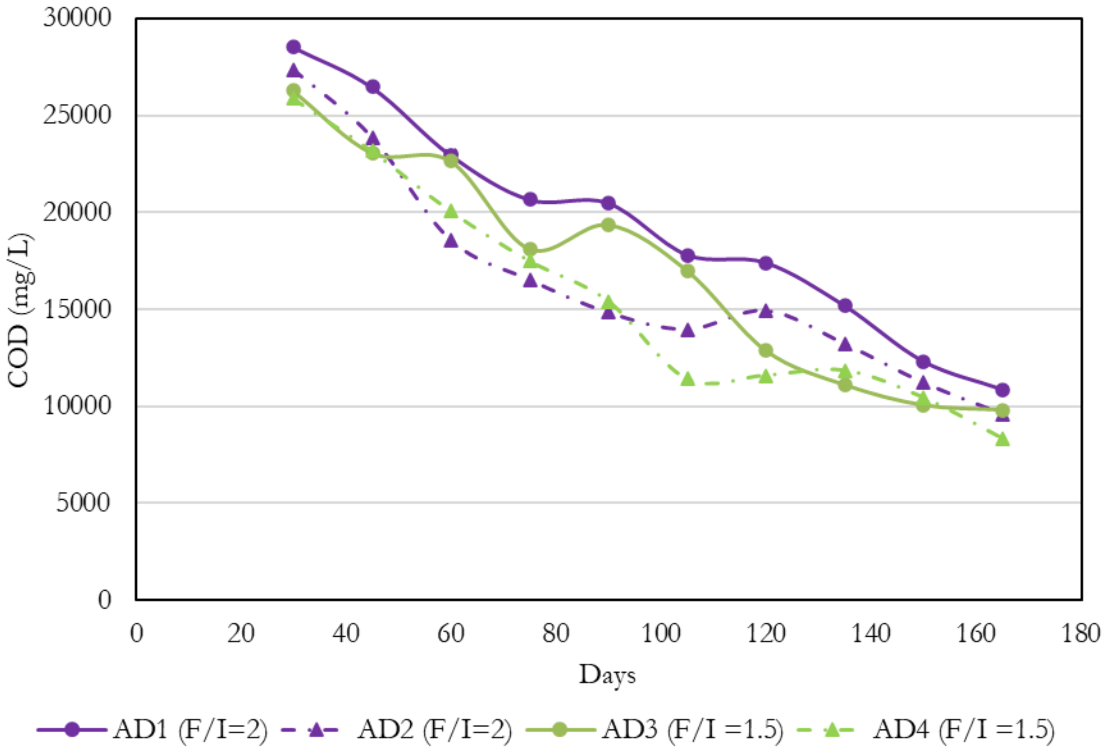


Figure 6-11: Chemical oxygen demand (COD) of leachate of food waste digesters

6.4.3 Volatile Fatty Acid (VFA) of 1st set Anaerobic Digesters

The VFA of the leachate of the food waste digesters was also measured on biweekly basis to determine the level of degradation of waste inside the digesters, as shown in Figure 6-12. The relation between VFA and waste degradation is that VFA started to increase with the advancement of the degradation initially. When the digestion process enters the methanogenesis phase, the VFA were used to convert into methane, thus decrease the amount of available VFA with time.

The initial VFA values were low in all the food waste digesters. The initial VFA for digesters AD1 and AD2 (F/I=2) were 19.5 g/L and 17.25 g/L, respectively, and when the digesters entered the methanogenesis phase, VFA values started to decrease and end up at 11.8 g/L and 10.25 g/L. The initial VFA for digesters AD3 and AD4 (F/I=1.5) followed the pattern of AD1 & 2, where VFAs were 17 g/L and 14.44 g/L, respectively, and when the digesters entered the methanogenesis phase, VFA values started to decrease and end up at 12.25 g/L and 10.75 g/L. at the end of the study period of 180 days.

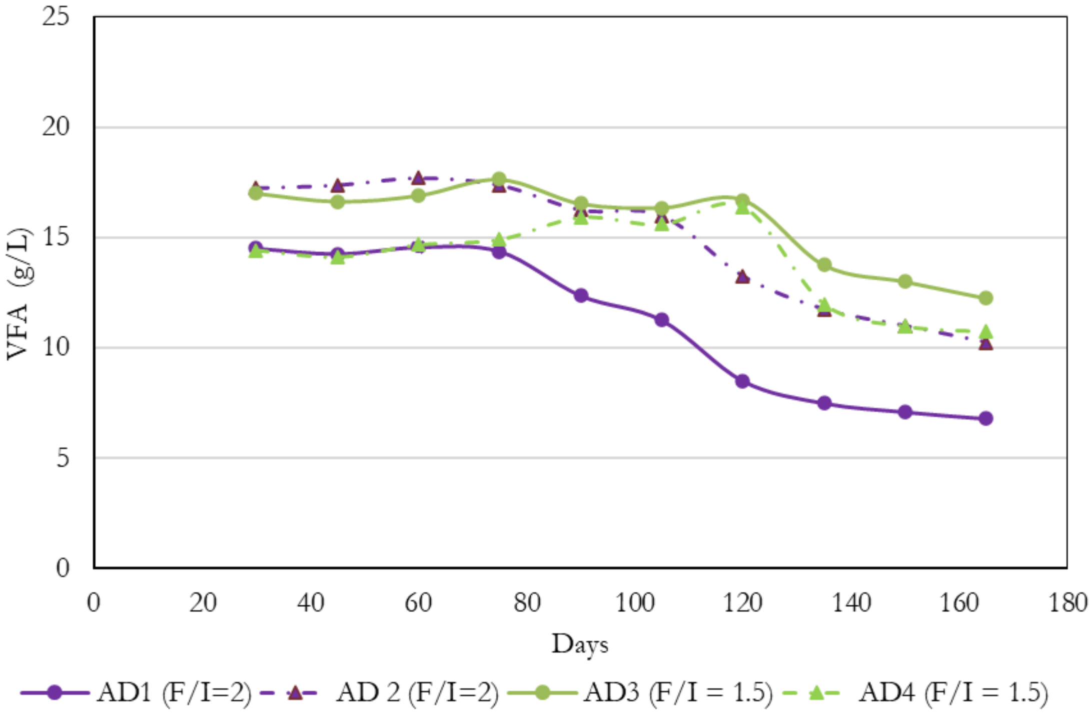


Figure 6-12: Volatile Fatty Acid (VFA) of leachate of food waste digesters

6.4.4 Alkalinity of 1st set Anaerobic Digesters

Sufficient alkalinity is essential for proper pH control. Enzymatic activity or digester performance are influenced by pH. Alkalinity prevents rapid changes in pH. Anaerobic digestion produces methane only when pH changes, whereas acid production is commensurate with a wide range of pH. For digestion to be stable, the digester contents must have sufficient buffering capacity. Values of alkalinity that are higher than average imply a greater potential to resist fluctuations in pH. The alkalinity of the leachate of the food waste digesters was measured on biweekly basis to determine the performance health of the digesters. Figure 6-13 shows the alkalinity variation with time for the study period.

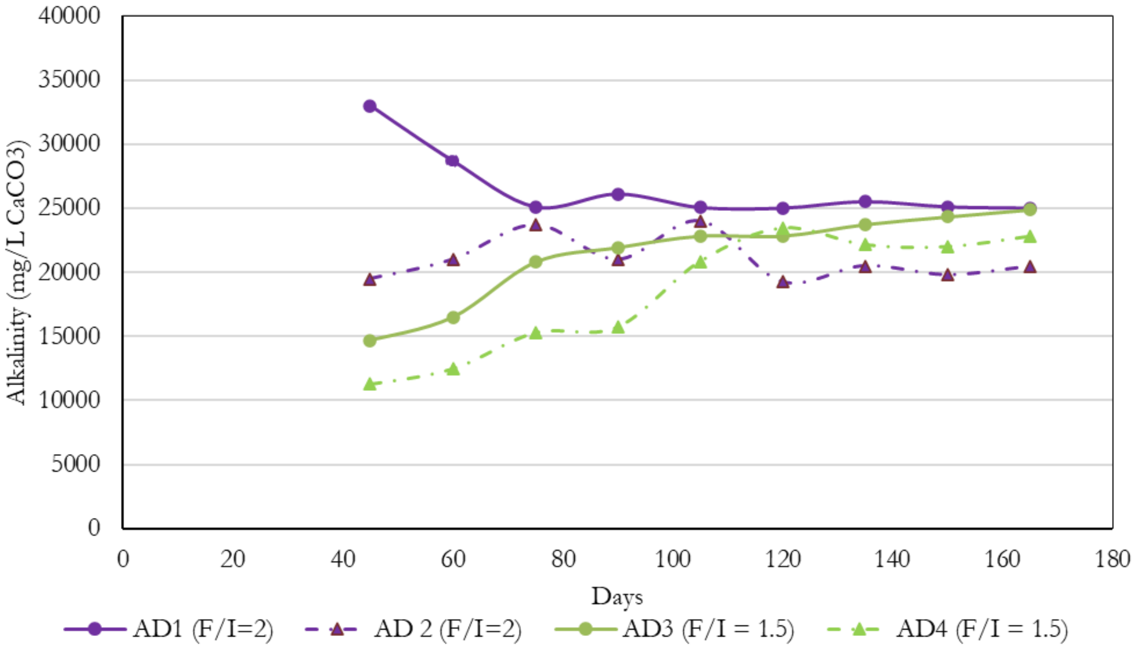


Figure 6-13: Alkalinity of leachate of food waste digesters

Alkalinity values for AD1 decreased from Day 45 to Day 75, but all other samples observed a steady increase in alkalinity throughout the entirety of the digestion period. The fact that alkalinity dropped for AD1 from Day 45 to Day 75 shows that hydrolysis is using up alkalinity at a faster pace than methanogenesis can produce it. The higher value of Alkalinity for the digesters indicated the good health of AD. AD 2 had 19500 mg/L at 45 days and ended up at 20450 mg/L after 180 days. AD 3 and AD 4 has followed the similar trend in alkalinity value. All the Anaerobic digester performed well based on Alkalinity, which helped to control the pH and also helped the methanogenic bacteria to produce methane after passing the lag phase.

6.4.5 VFA/Alkalinity Ratio 1st set Anaerobic Digesters

The ratio of volatile fatty acids to alkalinity is a useful tool for assessing the overall health of the digester and determining whether or not the pH can be kept at the desired level. . Values of VFA/Alkalinity that range between 0.3 and 0.4 are typically indicative of stable anaerobic digestions with maximal biogas output for a given temperature (Lossie et al 2001). Figure 6-14 shows the VFA/Alkalinity ratio for the digesters.

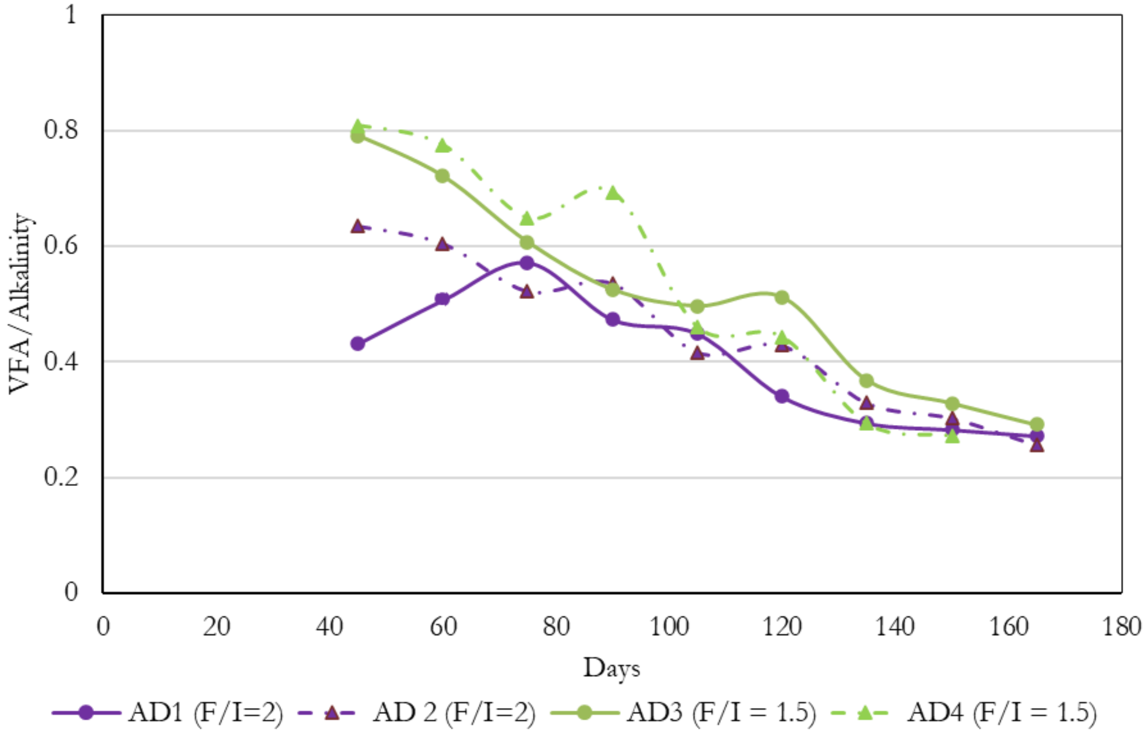


Figure 6-14: VFA/Alkalinity Ratio of leachate of food waste digesters

During the lag phase of the digesters, which is 100 days, the VFA/Alkalinity ratio was more than 0.5 for them. After entering into the methanogenic phase, the ratio started to get lower more. For AD 1, the ratio was 0.43 at 45 days and ended up being 0.27 at the end of operation. For AD 3 and 4, the ratio started with 0.79 and 0.81 respectively at the starting and ended up at 0.29 and 0.27. After passing the lag phase, all the digesters maintained the required ratio, which is within 0.4.

6.5 Gas Characteristics of 2nd set Anaerobic Digesters

After operation of 1st 4 Anaerobic Digesters, 2nd set of 2 Anaerobic Digesters were constructed and operated for 120 days to check the potential of them to reduce the lag phase. To check that, for second study, the Inoculum for the whole hydraulic retention time has been provided on the day 0. After the completion of 1st set, it was observed that F/I=2 and 1.5 did not produce significant different results. So, for the 2nd set, one set of digesters with Food/Inoculum 2 was tested. Biogas generation is the main indicator of waste degradation. In this study, composition, volume, and rate of gas generated from the food waste anaerobic digesters (AD1 and AD2) were measured on a regular basis for 120 days, as described in the section below:

6.5.1 Gas Composition of 2nd set Anaerobic Digesters

The first measurement of gas volume and composition was made on day 1 from food waste digesters AD1 to AD2. In the beginning, (Figure 6-15) methane content was as high as 34.60% for AD 1 and carbon dioxide content was similar to methane with 33.1 % with oxygen content of 2.9%. After that on Day 2, the methane content become 51.5% with lower oxygen content of 0.5% indicating the AD entering anaerobic stage. With the passing time, the amount of methane increased steadily and went upto 60.5% on day 65. For the whole operation phase of the digester, the variation of methane was very less. The highest and lowest was 60.5% and 47.7% respectively, which indicates the methanogenic phase of the ADs. For the carbon dioxide, the percentage was stable with highest 49.3% at day 5 to lowest at 38% at day 65. For AD 2, methane content was as high as 41.70% and carbon dioxide content was 18.6 % with oxygen content of 3.3% on day 1. After that on Day 2, the methane content become 59.1% with lower oxygen content of 0.3% indicating the AD entering anaerobic stage. With the passing time, the amount of methane was stabilized and went upto 60.4% on day 119. The highest and lowest was 60.4% and 47.1%

respectively, which indicates the AD was operating on methanogenic condition. Oxygen content in digesters dropped to less than 1% in 2 days and was stable for 120 days, showing that both of the cells reached the anaerobic phase.

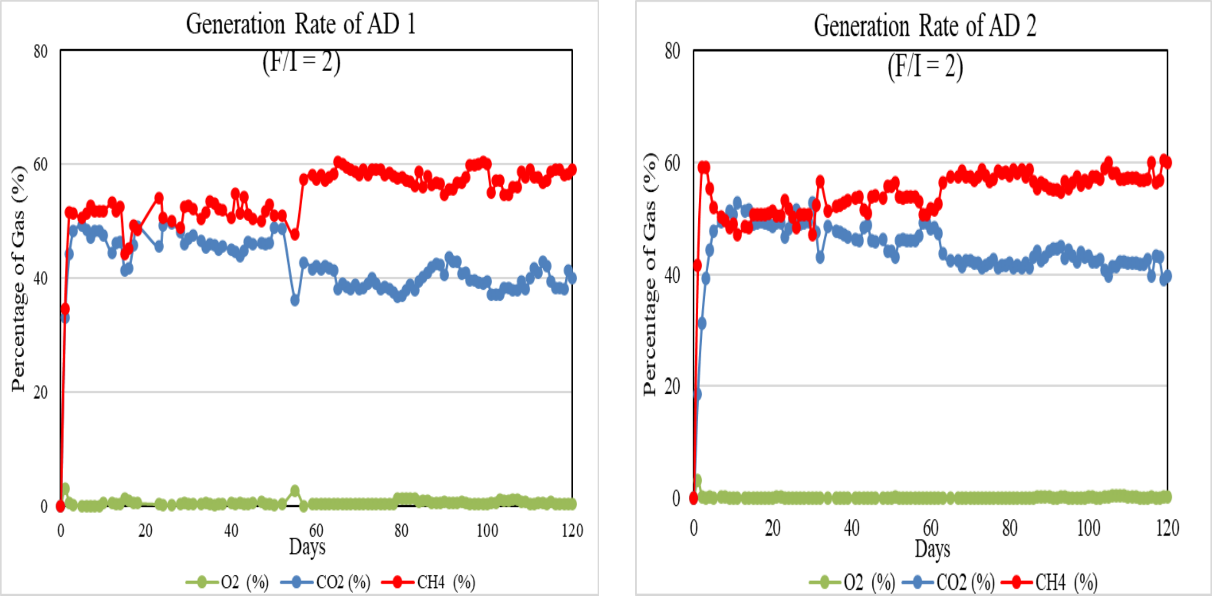


Figure 6-15: Gas composition data for AD 1 & 2

The percentage of biogas for the whole operation of 120 days was above 90% which signifies a good outcome for the Anaerobic digesters to be used an energy source. Methane (CH_4) and carbon dioxide (CO_2) make up the vast majority of biogas, with just trace amounts of water vapor and other gases present. As the biogas captured from the anaerobic digester is mostly of these basic components, it could be a good source of renewable energy which can be used for burning purposes as no further purification of it is needed before using.

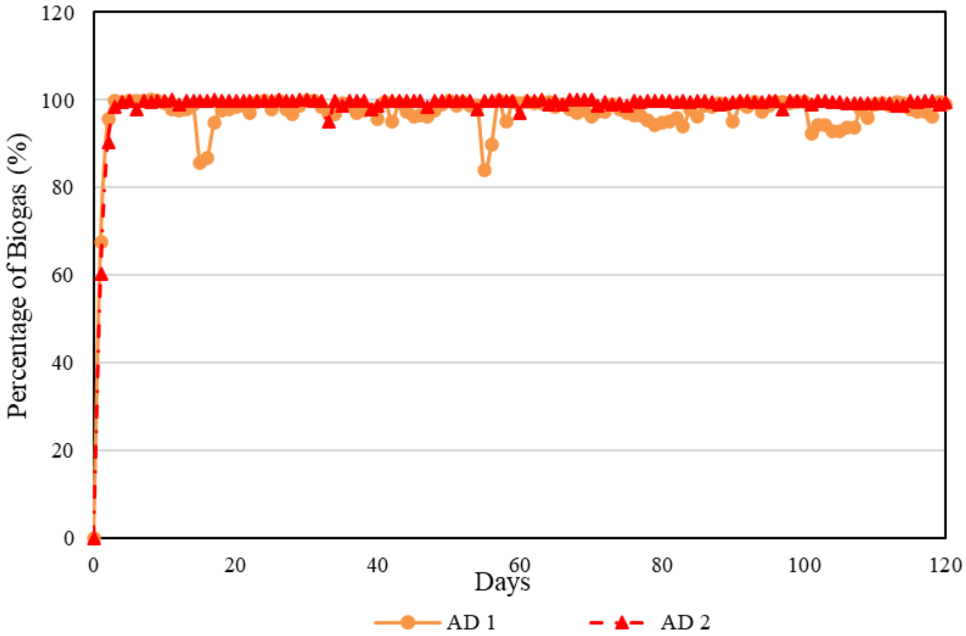


Figure 6-16: Biogas Percentage of the Anaerobic Digesters

Figure 6-17 shows the methane content in the anaerobic digesters. The methane content in the anaerobic digesters (AD 1 & AD2) reached more than 30% after 2 days and continued increasing. Both of the ADs, goes upto 60% in their operation phase. In the current study, the methanogenic phase began in the digester after 2 days, when the methane content exceeded 50%.

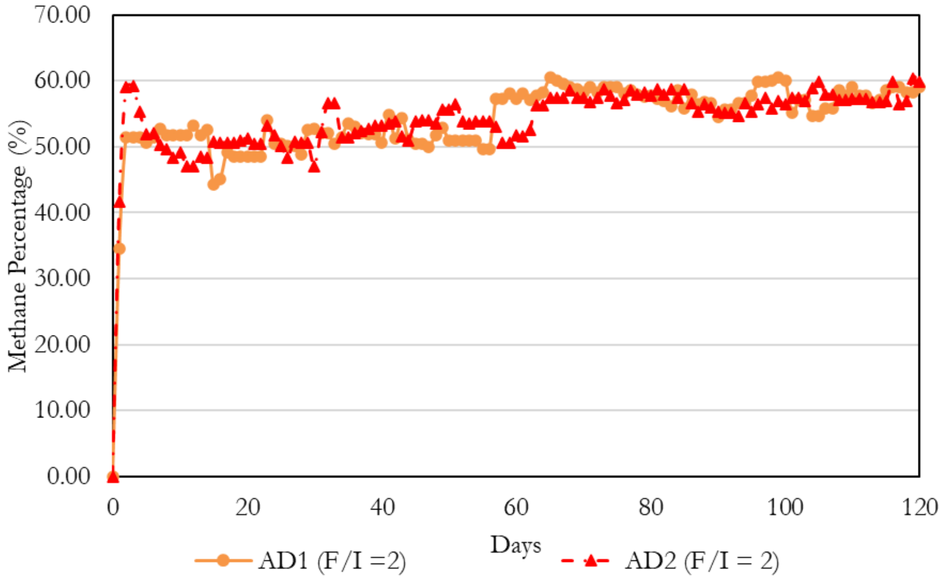


Figure 6-17: Methane content in food waste digesters

The mean methane percentage for AD1 was 54.65% with standard deviation of 3.80%. The mean biogas production for AD2 was 54.61% with standard deviation of 3.32%.

Carbon dioxide content reduces, which can be seen from the increase of methane to carbon dioxide ratio (CH_4:CO_2 ratio). In this study, from the very beginning, the CH_4:CO_2 ratio in digester AD1 reached more than 1. Throughout the period, the value was more than 1 for both the ADs. Figure 6-18 shows the methane-to-carbon dioxide ratio in anaerobic digesters.

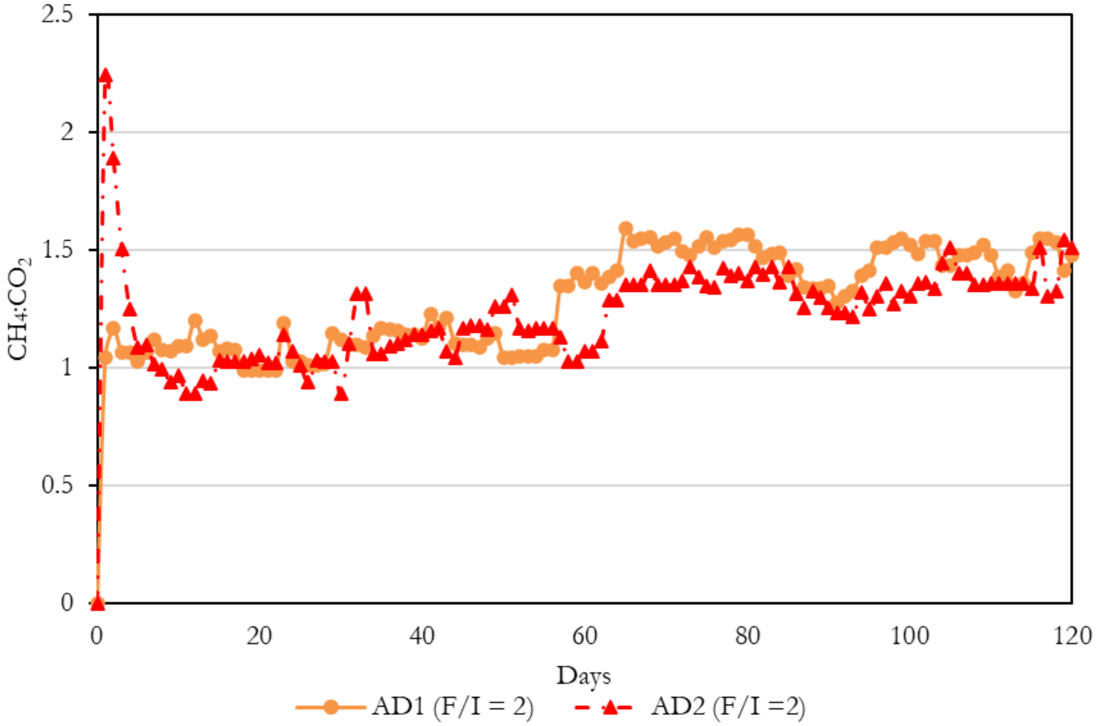


Figure 6-18: Methane-to-carbon-dioxide ratio in food waste digesters

Figure 6-19 shows the percentage of anaerobic activity in anaerobic digesters, as calculated by using Eq. 4.1 described in Section 4.4.1. The value of percentage of anaerobic activity (P) was plotted against time to observe the variations of anaerobic activity in the digesters. From Day 2 of operation, both digesters had achieved more than100% anaerobic activities; which indicates the anaerobic activities of methanogenic phase. During this phase, all the digesters were having more than 100% P value ranging from 100 to 140 for the rest of the operation period.

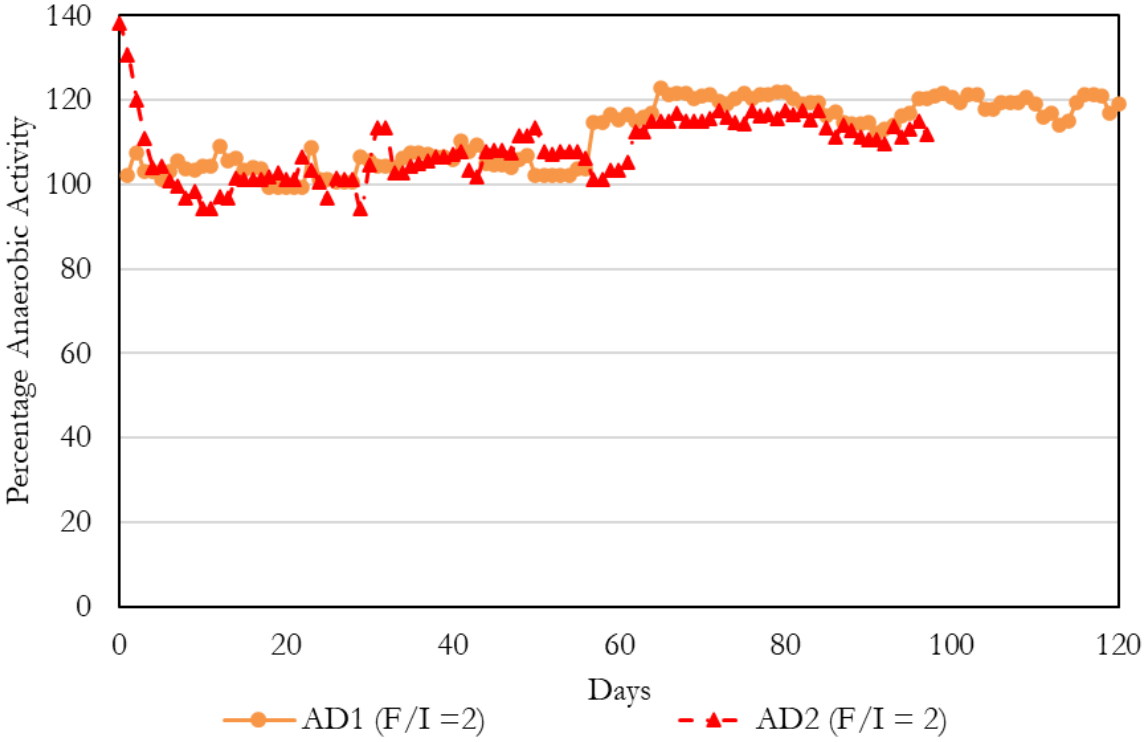


Figure 6-19: Percentage of anaerobic activity in anaerobic digesters

6.5.2 Gas Volume of 2nd set Anaerobic Digesters

In the anaerobic digesters (AD1 and AD2), the first gas volume was measured on day 1; it had high methane and carbon dioxide content and oxygen content was less than 5%. Among 120 days of operation, all digesters showed increased pattern in producing gas. After passing the lag phase, which is only 2 days, the ADs follow that trend. Figure 6-20 shows the cumulative gas generation (L/lb.VS) in the anaerobic digesters (AD1 and AD2).

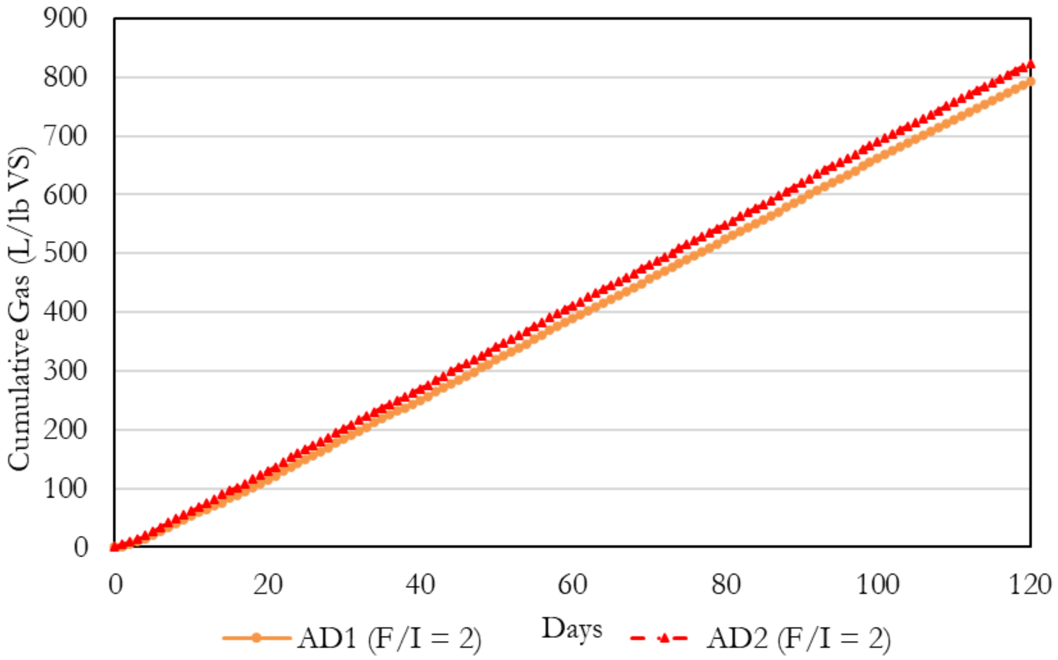


Figure 6-20: Cumulative gas generation (L/lb. VS) in Anaerobic Digesters

The digesters, AD1 and AD2 produced significant amounts of gas (810.0 L/lb. and 817 L/lb. VS, respectively) in about 120 days. The increasing pattern followed a linear trend which signifies the steady and constant increase in biogas volume for the whole study period. The 1st study of digesters had a slow start before entering the methanogenic phase which was overcome for this study. The input of the total inoculum on the day 0, have showed a positive effect on the whole operation of the system. The digesters were monitored for 120 days and then were dismantled.

Figure 6-21 shows the cumulative methane generation in digesters (AD1 and AD2). As mentioned in section 6.3.1, the methane content was high in all of the digesters from the very beginning. The highest methane volume was generated from digester AD2 (445.3 L/lb. VS). The lowest amount of methane was produced from food waste digester AD1 (less than 429 L/lb.VS)

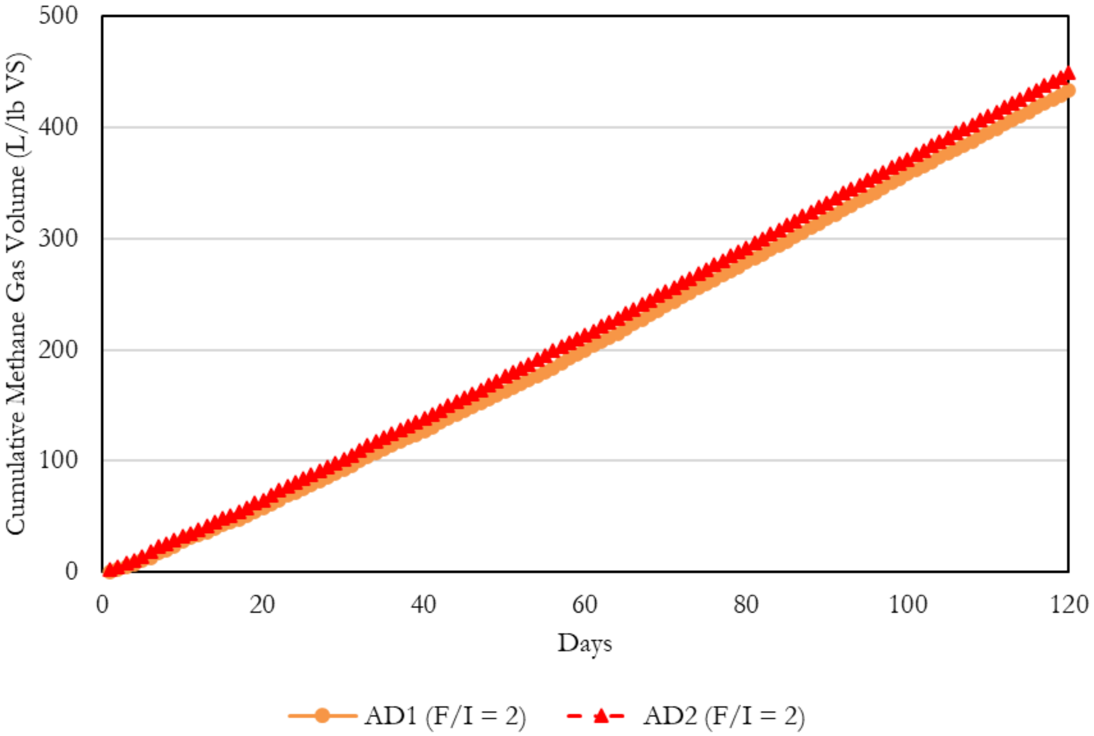


Figure 6-21: Cumulative methane generation (L/lb. VS) in Anaerobic Digesters

Figure 6-22 and Figure 6-23 show the gas generation rate and methane yield of the food waste digesters, respectively. From the gas yield versus time graph, the reduction of lag phases in food waste digesters can be observed clearly.

From the beginning, there was substantial amount of gas production in food waste digesters. The gas generation rate in digester AD1 reached its peak of 8.35 L/lb. VS/day in 21 days of operation. Both digesters displayed multiple peaks, with highest gas yield of 8.87 L/lb.VS/day for AD2 on day 22. The methane yield versus time graph shows the methane generation rate with time (Figure 6-23) and shows that methane and gas yields in food waste digesters follow the same trend. Food waste digesters, AD1 and AD2, experienced the methanogenic phase within 2 days, with the decomposition of waste taking place from day 2 to day 120. Due to the heterogeneous properties of waste, the methane yields varied, even for the same pair of digesters. The variation for them were not that significant for different F/I ratio tested here. For example, digester AD1 with F/I=2 had the peak methane yield on day 110 (8.05 L/lb. VS/day), and AD2 peaked on day 115 (7.1 L/lb. VS/day).

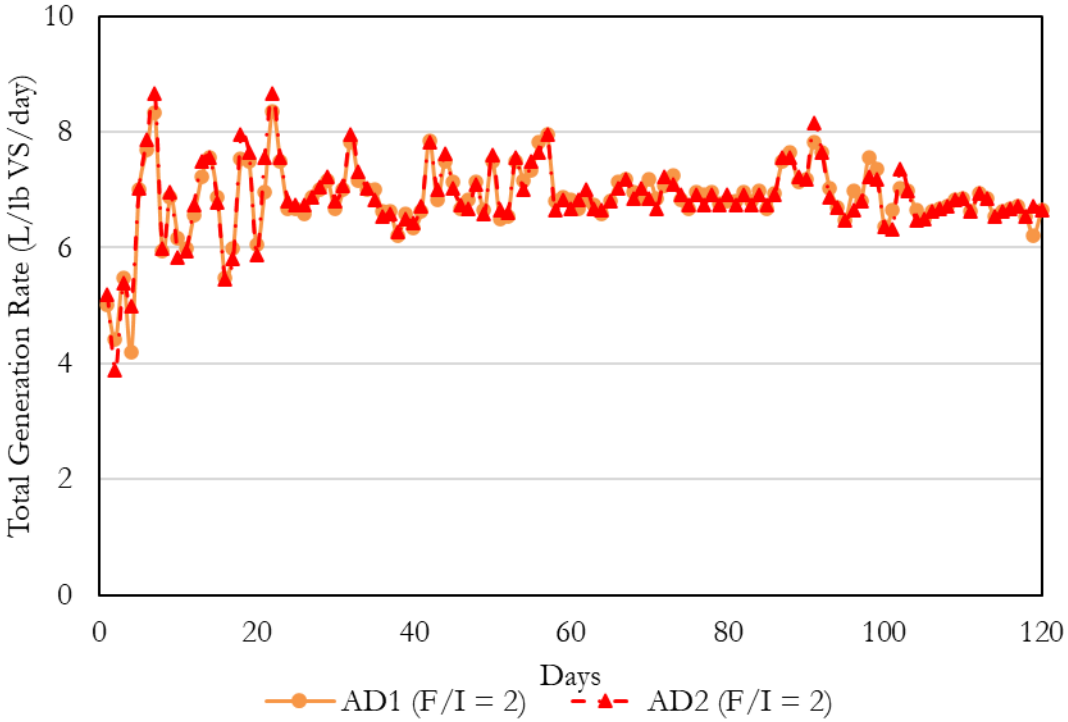


Figure 6-22: Gas yield (mL/lb. VS/day) for Anaerobic Digesters of F/I=2

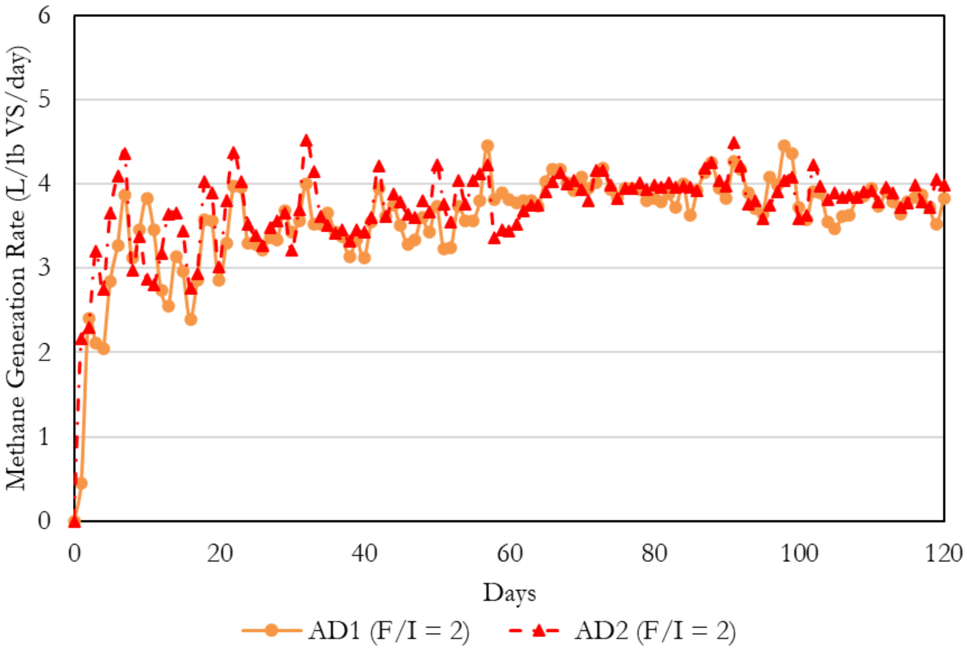


Figure 6-23: Methane yield (L/lb. VS/day) for Anaerobic Digesters of F/I=2

Figure 6-24 depicts the daily biogas generation from the AD1 and AD 2. The daily gas generation in digester AD1 reached its peak of 50.1 L/day in 22 days of operation. Digester AD2 reached its peak of 52 L/day on day 23. For all the digesters, the biogas production has less variation and steady volume for the whole operation period. The mean biogas production for AD1 was 41.2 L with standard deviation of 3.53L. The mean biogas production for AD2 was 41.3 L with standard deviation of 3.76L. For AD1, mean methane percentage was 54.65% with less standard deviation of 3.80%. For AD2, mean methane percentage was 54.64 % with less standard deviation of 3.32%. The inclusion of the inoculum at the starting for the whole retention period at the beginning of the operation could have helped the feedstock to acclimatize to the digester environment.

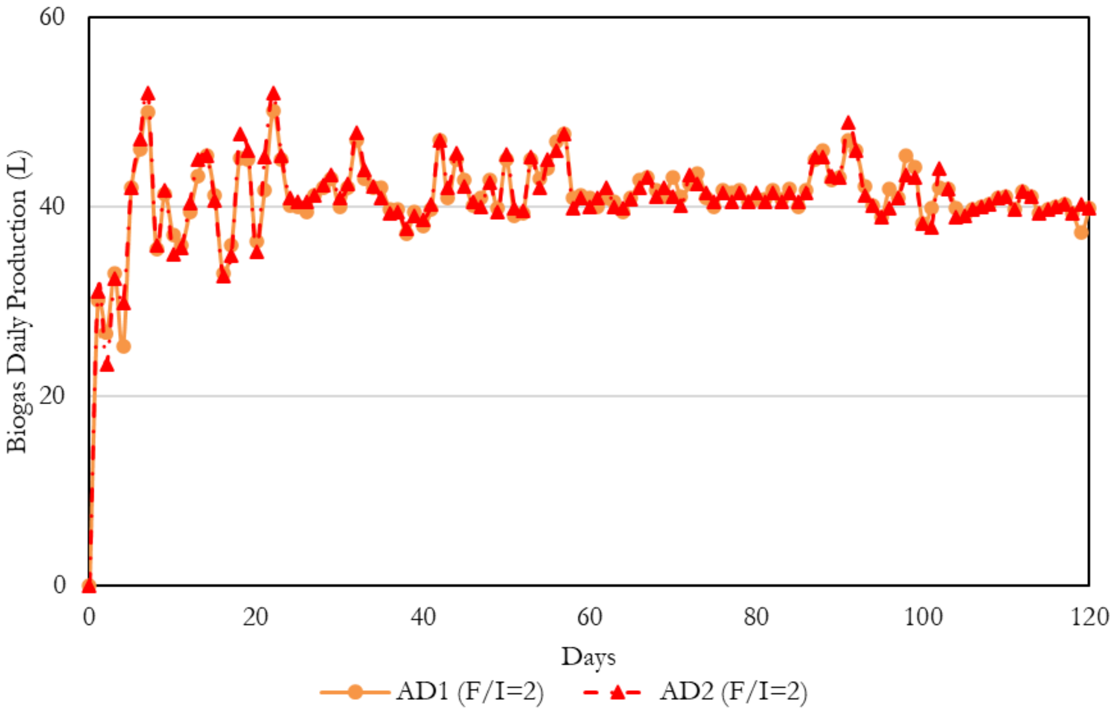


Figure 6-24: Daily Biogas Production (L/day) for Anaerobic Digesters of F/I=2

6.6 Comparison with Previous Literature

To compare the gas results obtained with previous literature, daily methane yield (L/kg VS Addition) graph is shown below. Traditionally, Biochemical Methane Potential results are reported as volume of methane produced per mass of VS digested (i.e., L CH_4/kg VS), thus contrasting results based on what is potentially digestible (organic matter), i.e. water and ashes removed. The majority of food wastes produce a lot of methane when stated on a VS basis (about 350–500L CH_4/kg VS food waste), which indicates good potential for energy recovery. The amount of methane generated by the various types of food wastes does not only vary considerably when expressed as-is, but it also varies significantly over time. It is indeed more accurate to use the as-is normalized values to represent actual methane produced by food waste as it is fed into a digester. Figure 6-25 shows the Daily Methane Yield if 1kg Volatile Solid were added daily on that basis, to compare the result from previous study.

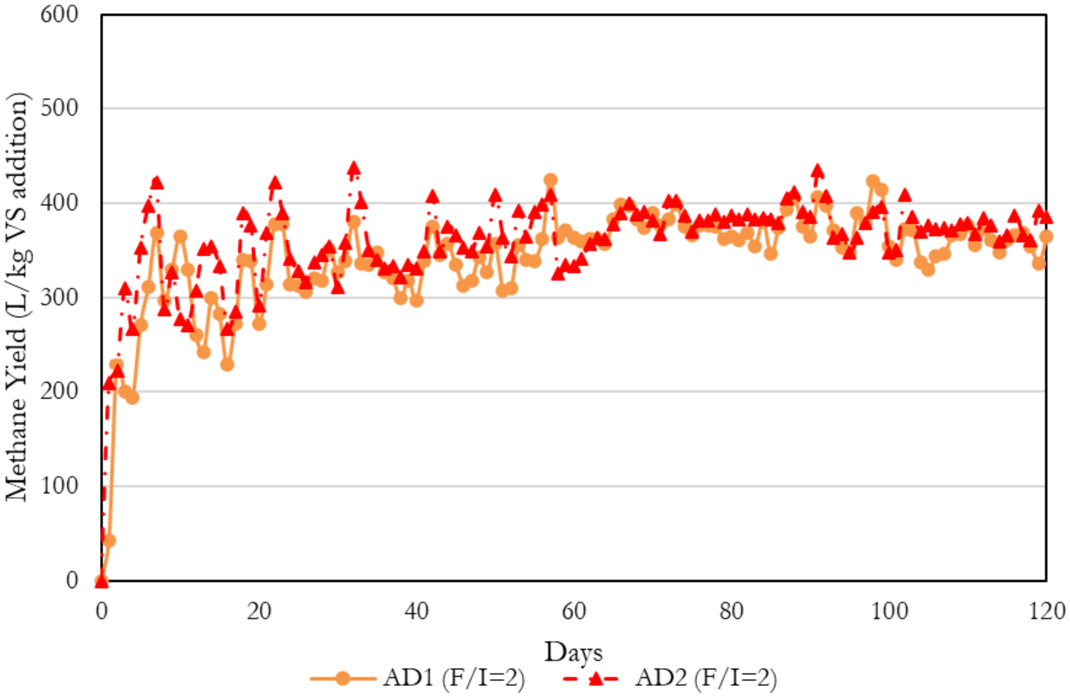


Figure 6-25: Daily Methane Yield for addition of 1kg VS addition

From here, it is observed that the variation in methane yield is less with the 2nd study case where the inoculum required for the whole hydraulic retention time were added at the very beginning of the study and then it was operated typically from Day 1 of operation. The inclusion of inoculum earlier, helped to create the proper environment for anaerobic processes to take place from the very beginning.

For both ADs, the average amount of methane made per kg of VS food waste that was digested was 370 CH_4/kg VS food waste, with a standard deviation of 39L.The mean as-is actual methane production 45 L CH_4/kg Food Waste with standard deviation of 4L.

Table 6-1 shows the comparison of the methane value with previous studies. Table shows that the current study is comparable with them and showed less variation for as-is condition, signifying the stable behavior of the Anaerobic digesters. The difference between the values from the literature are for the different modes they were operated and due to the heterogeneity of the feedstock.

Table 6-1: Comparison of Methane Volume with Previous Study

Feedstock	**L CH_4/kg VS Food Waste**	**L CH_4/kg Food Waste**	**Reference**
Fruit and vegetable waste	405 (63)	30 (5)	Bouallagui et al. (2005);
University dining hall	383 (28)	51 (7)	Carucci et al. (2005);
Assorted kitchen waste	251 (40)	36 (6)	Ebner et al. (2016
Food Composition of developing countries	370 (39)	45 (4)	Current Study

* value in bracket shows the standard deviation value

For the Biogas volume, the result of current study is compared with a field study on Dar es Salam Tanzania (Gyalpo et al (2010)) where the digester volume was 4 cubic meter and feedstock was from canteen waste. The daily gas production was 790L/day with higher feedstock. If the current study was done on that scale, it would produce 744 L/d, which is comparable with that study.

Table 6-2: Comparison of Biogas Volume with Field Study

Location	Digester Volume	Feedstock	Daily Load (wet weight)	Organic Loading Rate (OLR)	Daily Gas Production
	m^3	Waste type	kg/d	kg VS/m^3 d	L/d
Dar es Salaam, Tanzania	4	Canteen waste	8 (+60 L water)	0.52	790
Current Study	0.07	Food Waste	0.5 (+0.4 L water)	1.32	42

6.7 Leachate Characteristics 2nd set Anaerobic Digesters

Leachate is generated by degradation of the food inside the anaerobic digester. The chemical and biological processes of the waste are significantly influenced by the characteristics of the generated leachate such as pH, VFA (Volatile Fatty Acid), COD (Chemical oxygen demand) and Alkalinity. The characteristics of generated leachate indicate the level of degradation of the solid waste. In this study, the pH, VFA, COD and Alkalinity were monitored for food waste digesters during their decomposition phases. Details are discussed in the following sections.

6.7.1 pH of Leachate of 2nd set Anaerobic Digesters

Stable pH in food waste digesters (AD1 and AD2) was observed throughout the initial monitoring period due to the modification of operation method. From the pH vs time plot of food waste digesters (Figure 6-26) it was noticed that the initial pH was more than 7 for from the 2nd day of operation, which signifies the better environment for the bacterial growth in the digester. It took minimum time to attain the methanogenic phase, which also interprets from the gas graphs in the previous section.

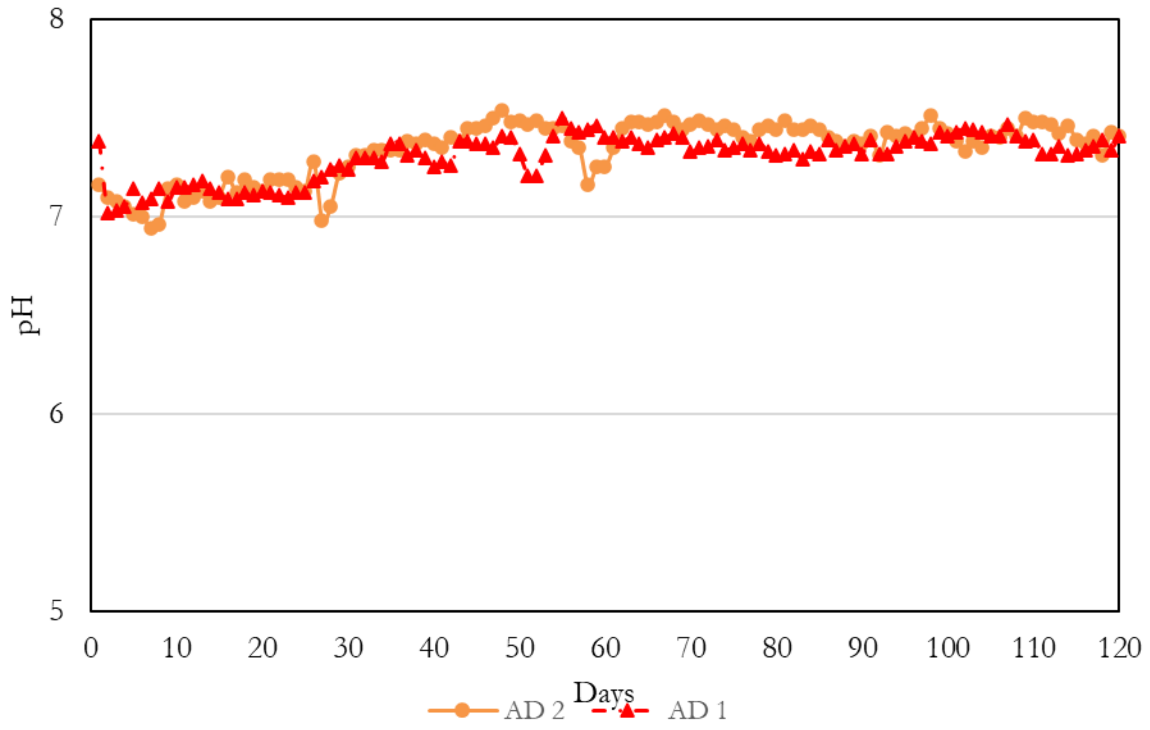


Figure 6-26: pH of leachate of food waste digesters

Leachate was collected from the 1st day of operation, and the pH was more than 7 on day 1 of 120 days of operation of the food waste digesters. It is because of the inoculum which has the pH of more than 7. Food waste pH which is around 5.5, could not suppress the pH of inoculum because of the high amount of presence of them at the initial phase. This helped them to acclimated in the initial phases of digestion, which in acidic in nature. The pH of the leachate of digesters AD1 and AD2 was 7.02 and 7.16 on day 2, respectively, which pushed the digesters to move quickly to the methanogenic phase. Once the digesters reached the methanogenic phase, the pH remained at more than 7 and then stabilized with maximum values of 7.5 and 7.48 for AD1 and AD2, respectively.

6.7.2 Chemical Oxygen Demand (COD) of 2nd set Anaerobic Digesters

The COD of the leachate of the food waste digesters was also measured on biweekly basis to determine the level of degradation of waste inside the digesters, as shown in Figure 6-27. There is a correlation between waste degradation and COD decline, as COD levels fall as waste breaks down over time.

The COD value decreases with the degradation of waste. The initial COD values were high in all of the food waste digesters. Digesters with F/I=2, the initial COD for AD1 and AD2 were 17,905 mg/L and 15,627 mg/L, respectively, and decreased to 5,885 mg/L and 7,500 mg/L, respectively, at the end of four month (120 days). The decrease in COD was continuous and decreased with steep slope with time as the system was going through the methanogenic phase for the whole operation. As the acidogenic phase was shorter and started to go into the methanogenic phase faster, COD started dropping significantly.

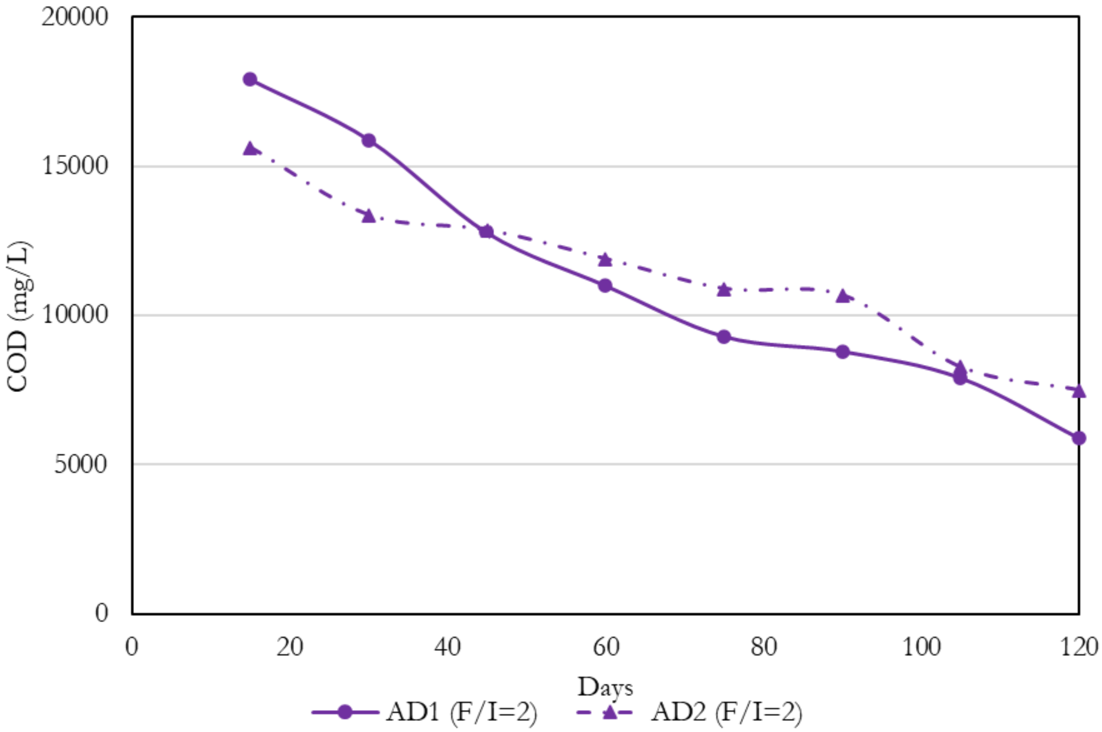


Figure 6-27: Chemical oxygen demand (COD) of leachate of food waste digesters

6.7.3 Volatile Fatty Acid (VFA) of 2nd set Anaerobic Digesters

The VFA of the leachate of the food waste digesters was also measured on biweekly basis to determine the level of degradation of waste inside the digesters, as shown in Figure 6-28. The relation between VFA and waste degradation is that VFA started to increase with the advancement of the degradation initially. When the digestion process enters the methanogenesis phase, the VFA were used to convert into methane, thus decrease the amount of available VFA with time.

The initial VFA values were low in all the food waste digesters. The initial VFA for digesters AD1 and AD2 (F/I=2) were 7.88 g/L and 8.25 g/L, respectively, and when the digesters entered the methanogenesis phase, VFA values started to decrease and end up at 6.75 g/L and 6.5 g/L at 120 days.

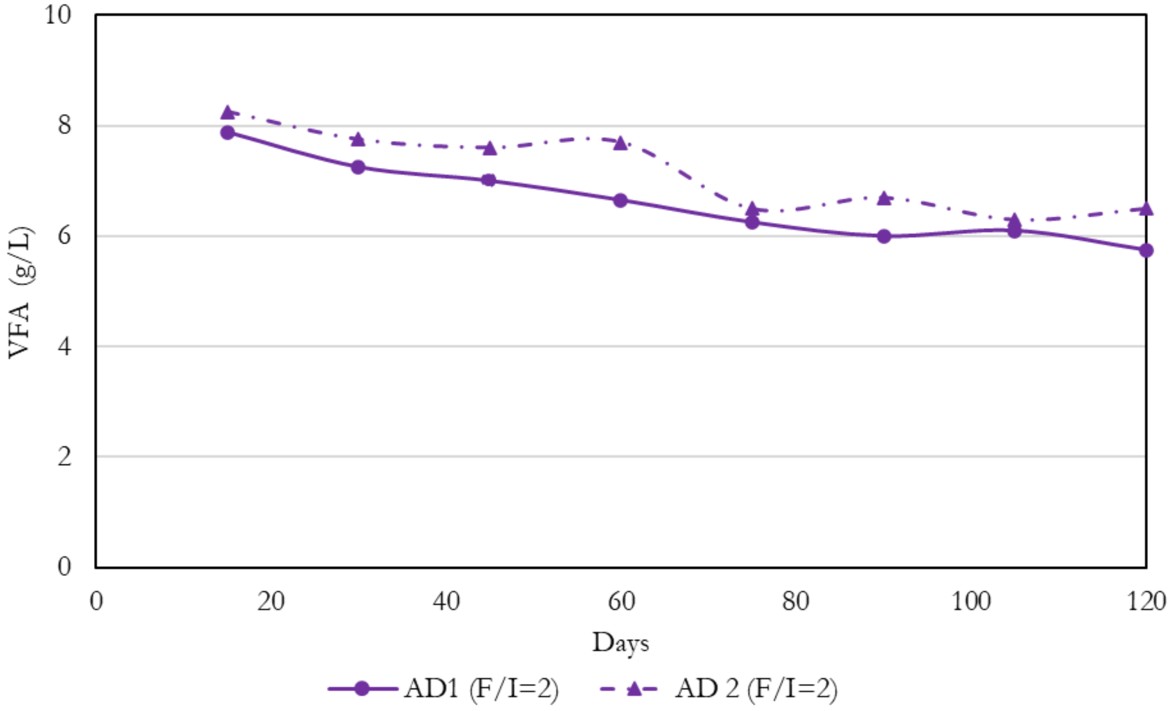


Figure 6-28: Volatile Fatty Acid (VFA) of leachate of food waste digesters

According to the findings of a study that was carried out by Viéitez et al. (1989), an environment in which the accumulation of volatile fatty acids is more than 13 g/L will be inhibitive to the synthesis of methane. From the figure above, it is observed that the VFA accumulation was less than 13 g/L from the very beginning which helps the digesters to perform healthy for the operating period.

6.7.4 Alkalinity of 2nd set Anaerobic Digesters

Sufficient alkalinity is essential for proper pH control. The quantity of alkalinity that is present in a system is what determines how well an anaerobic digester can buffer acidic or basic substances. The primary source of buffering capacity that keeps the pH of the system in the range of 6.5–7.6 is the bicarbonate ion, which has the chemical formula HCO_3^-. Typically, a buffering capacity of this kind provided by such alkalinity is sufficient to tolerate modest shock loads of VFAs. In this context, anaerobic codigestion can be a key method to transform high-strength, easily biodegradable food wastes into energy in an effective manner. Included in the mixture are substrates that have a high alkalinity. This helps to boost the buffering capacity and pH of the influent mixture, which ultimately results in improved performance and increased process stability. Values of alkalinity that are higher than average imply a greater potential to resist fluctuations in pH. The alkalinity of the leachate of the food waste digesters was measured on biweekly basis to determine the performance health of the digesters. Figure 6-29 shows the alkalinity variation with time for the study period.

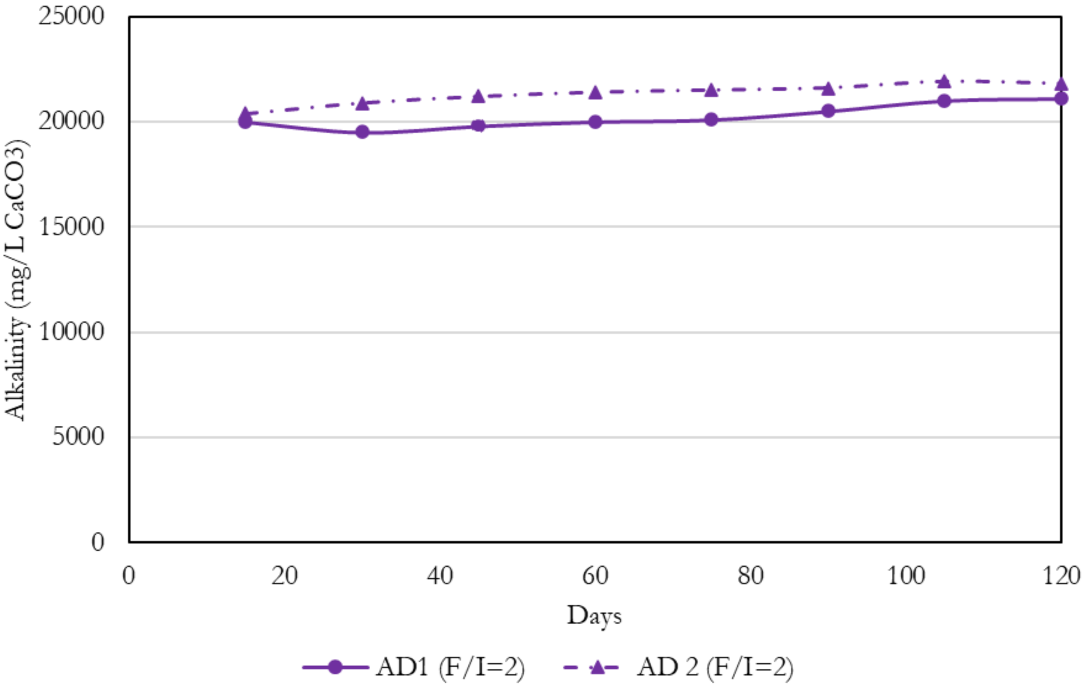


Figure 6-29: Alkalinity of leachate of food waste digesters

Alkalinity values for AD1 decreased from Day 15 to Day 30, but AD 2 has a steady increase in alkalinity throughout the entirety of the digestion period. The higher value of Alkalinity for the digesters indicated the good health of AD. AD 1 had 20000 mg/L at 15 days and ended up at 21100 mg/L after 120 days. AD 2 has followed the similar trend in alkalinity value. Both the Anaerobic digester performed well based on Alkalinity, which helped to control the pH and also helped the methanogenic bacteria to produce methane after passing the lag phase.

6.7.5 VFA/Alkalinity Ratio 2nd set Anaerobic Digesters

The ratio of volatile fatty acids to alkalinity is a useful tool for assessing the overall health of the digester and determining whether or not the pH can be kept at the desired level. Values of VFA/Alkalinity that range between 0.3 and 0.4 are typically indicative of stable anaerobic digestions with maximal biogas output for a given temperature (Lossie et al 2001). Figure 6-30 shows the VFA/Alkalinity ratio for the digesters.

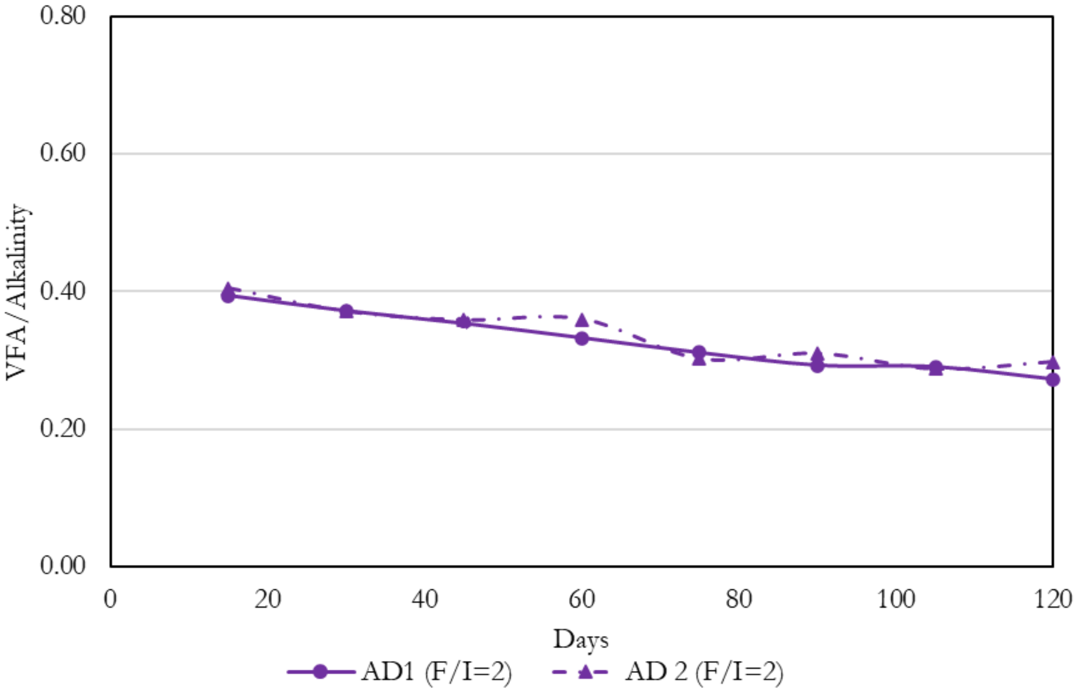


Figure 6-30: VFA/Alkalinity Ratio of leachate of food waste digesters

As these sets of AD has minimum lag phase (<5 days), the VFA/Alkalinity ratio was less than 0.4 from the starting. For AD 1, the ratio was 0.39 at 15 days and ended up being 0.27 at the end of operation. For AD 2, the ratio started with 0.4 at the starting and ended up at 0.30. Both the digesters maintained the required ratio, which is within 0.4.

6.8 Utilization of Biogas Produced

Biogas energy can be used to replace natural fuels like wood, charcoal, or liquid petroleum gas (LPG) in households in developing countries by burning it directly in stoves. When compared to the combustion requirements of other gases, biogas has a lower air requirement. In addition to this, it does not produce smoke when it is burned, which means that it does not contribute to the polluting of the air within. Methane molecules contribute 21 times more to global warming than carbon dioxide molecules (SUSANA 2009). Because of this, even though burning methane results in the production of carbon dioxide, it has a beneficial effect on the environment. It is possible that the use of biogas would be especially advantageous in rural areas, where there is no access to any other source of energy and where problems with deforestation and indoor pollution are prevalent.

Based on our experimental data, daily **210L** of Biogas (42 L from one-fifth size of our experiment) can be achieved from the full-scale size AD with 5 times more in size. According to Estoppey, 2010, the gas flow rate of the stove used by biogas is about 180 L /hour. To cook 500 g rice using 3 L water, it will need 35 minutes by burning 105L of gas. From the gas getting from the proposed AD, 1.25 cooking hours can be achieved daily, which can be used for cooking rice and one additional dish daily. By using the food waste and other inoculum for the anaerobic digester, one kg firewood can be saved from each household each day; as to produce 200 L biogas, 1 kg of firewood is needed. Previous study of Anderman et al. (2015) found that the presence of a biogas cook stove in a household was significantly positively correlated with the variety of foods consumed by the household. In addition, female heads of households that had a biogas cook burner reported spending nearly two fewer hours daily on the activities of cooking and collecting firewood. Rather than continue to rely on solid fuel for cooking, these women may choose to spend their free time earning income and relaxing; this presents an opportunity cost to families by using biogas.

When produced in household-level, other than cooking, biogas is suitable for lightening. 126 1/lamp of biogas is needed for lighting equivalent to 100-watt filament lamp (Vögeli et al 2014). So, the 2nd option can be used that biogas for lighting a 100-watt filament lamp for 2 hours daily.

6.9 Proposed Design of Household Anaerobic Digestor in Developing Countries

Based on the results observed from the study, the whole size of the digester and the feedstock with F/I= 2 were planned for the proposed design. The layout of the anaerobic digester is shown in Figure 6-31 & Figure 6-32. The key features of the household anaerobic digester are illustrated in the following section.

- The feeding of the digester was decided to be continuous mode where new feedstock will be added at regular intervals while an equivalent volume of slurry will be taken out the digester, thereby providing a continuous process of digestion.
- Based on the daily feedstock (2.5 kg food waste, 1 kg cow manure, 1.5 kg sludge), experimental judgment stated in Chapter 5, the calculated necessary size of the full-scale household digester was found to be 75 gallons, which is equivalent to 300 liter.
- For the tropical country consideration (average ambient temperature of 25 – 30°C), the hydraulic retention time for this study was decided to be 30 days.
- As the digester will be operated in continuous mode, an inlet and an outlet pipe will be provided. The diameter of the inlet and outlet pipe will be 4 inches and 3 inches respectively.
- To facilitate the feeding process, the upper portion of inlet pipe will be funnel shape with larger radius of 10 inch., and that funnel will be closed with additional cover to facilitate the airtight environment.
- The Digester Tank will be of 2 parts, one for digestion of the feedstock and another space for the digestate, which will be connected to the outlet pipe.
- To facilitate the digestate to travel from digestion tank to digestate space, an intermediate pipe will be facilitated in between the two spaces. With the pressure of the feedstock while filling up with time, the digestate will be pushed towards the empty space and will be taken out through the outlet pipe.
- One small size (0.5 inches) pipe will be installed on the top of the digester and will be connected to a gas collection system with help of a long flexible tubing. A 3-way valve will be

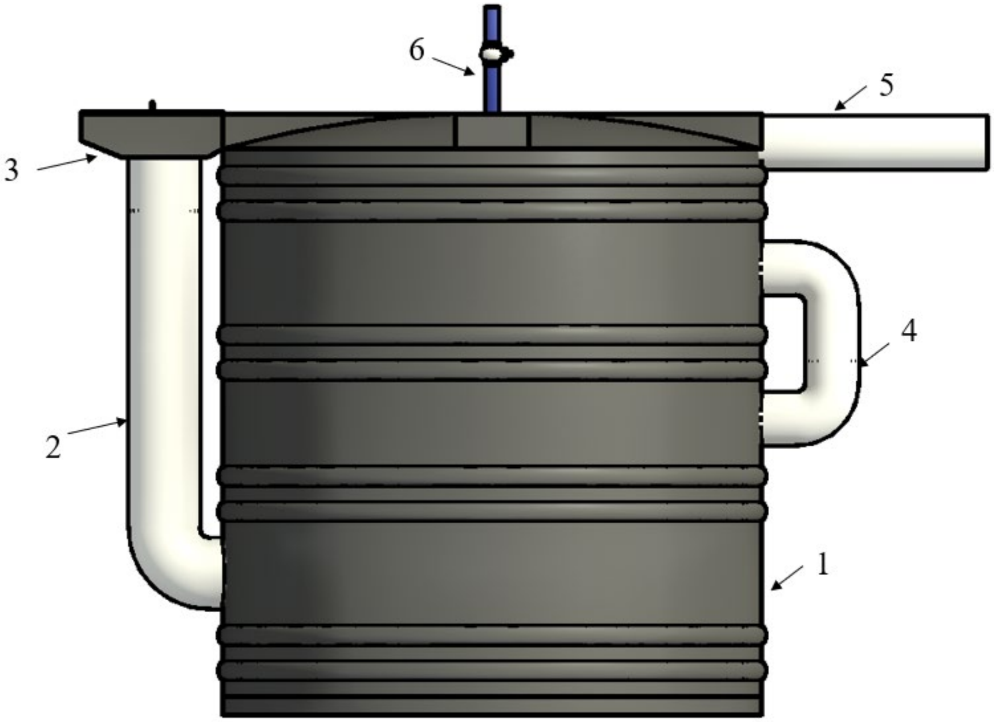
attached to the connection of the adapter and the gas collection system. With production of biogas, it will be collected through the gas pipe and will be either used or stored in a gas storage system.

- Mixing is a very important operating factor for achieving digestion of organic matter. So the design was thought to be in such a way that it will be self-agitating daily from the input of the feedstock, and pushing through the digestate towards the outlet.

Table 6-3: Features of Household Anaerobic Digester

	Diameter	Height *
Digester	29”	33”
Inlet Pipe	4”	31”
Outlet Pipe	3”	30”
Intermediate Pipe	3”	26”
Gas Pipe	0.5”	28”

* All Heights are Measured from the bottom of Tank



1) Biodigester
2) Inlet Pipe
3) Funnel
4) Intermediate Pipe
5) Outlet Pipe
6) Gas Collection Pipe

Figure 6-31: 3D View of the Designed Digester

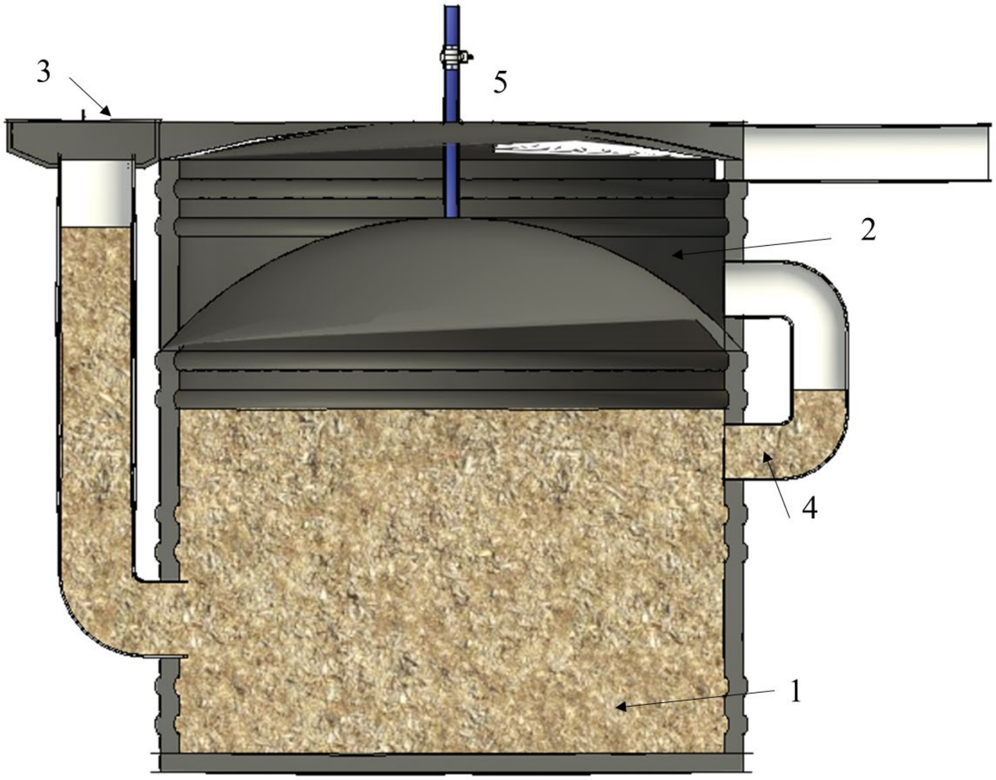
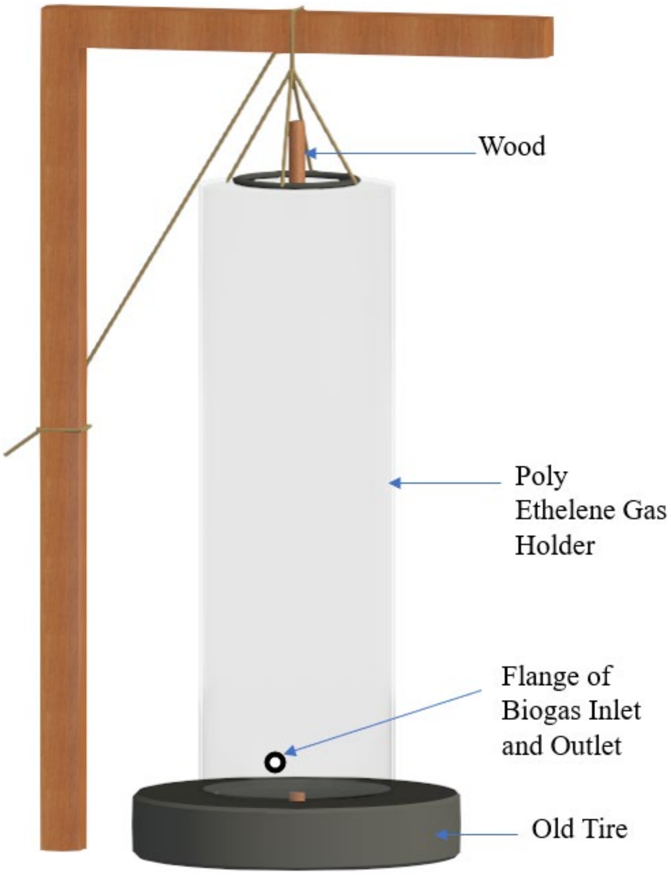
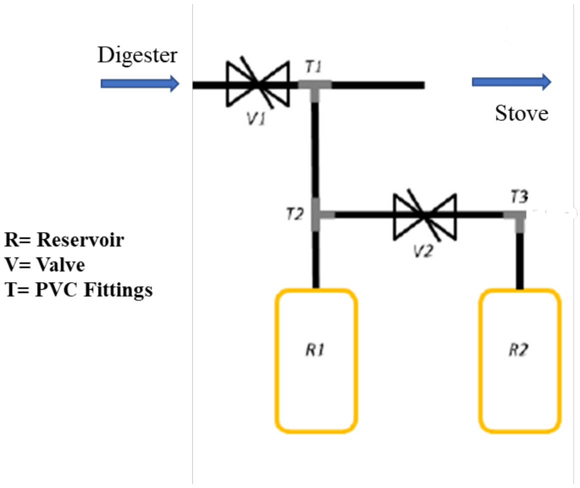


Figure 6-32: Cross Section of the Designed Digester

- In the event of gas storing, while not using the biogas, two tubular polyethylene reservoirs can be installed (Figure 6-33) close to the kitchen, which can additionally store 1300 L of biogas. The space requirement for the reservoirs is around 12.5 m² (2.5 feet x 5 feet) with a height of around 6.5 feet.
- To facilitate the gas flow, 0.5-inch flange will be installed at the bottom of the reservoir.
- A valve will be installed in the gas system near the cooking stove which will allow the biogas either to stove or to the storage (R1 and R2) depending on the demand of usage.



Diameter of PE Bag: 25”	Total Height: 75”
Wood diameter: 2”	Height: 8”
Flange Diameter: 0.5”	



(a) Biogas Storage Tank

(b)Scheme of the Biogas Storage Reservoirs

Figure 6-33: Biogas Storage Reservoir System

6.10 Summary

The process of enhancing methane production by optimization of the Food/inoculum ratio and total solid content (%) in laboratory-scale experiment was converted to the field scale successfully in this study. The increased biogas production from the inoculum enhanced field-scale household anaerobic digester confirmed the feasibility of optimizing F/I ratio and total solid content (%) to enhance methane production and waste decomposition. Based on the results and analyses of the field-scale study of the anaerobic digester, it can be concluded household anaerobic digester of food waste can be implemented and the produced biogas can be used for the cooking purposes.

Chapter 7: CONCLUSION & RECOMMENDATIONS

7.1 Summary and Conclusion

This study focuses on the design, operation and performance evaluation of anaerobic digester for field application as part of a sustainable waste management system. Solid waste management is a challenge in developing countries, and food waste, the largest organic fractions of MSW are difficult to manage. The anaerobic digester is capable of handling all of the issues that are related with food waste, including the production of large amounts of gas and leachate, and requirement of additional space as well as energy can be retrieved. AD also makes it possible to add nutrients that are necessary for the faster breakdown of food waste, which has been looking for a location to be disposed of since it was diverted from traditional landfills.

The main features of anaerobic digester operation are the addition of sludge and manure as inoculum to facilitate biodegradation. Due to the presence of microbes and moisture, the methane generation rate increases, with a higher gas generation yield over time. A number of studies have been conducted on laboratory-scale batch reactors to which sludge or cow manure was added, but no study has been conducted to observe gas generation rate on the developing countries food composition with addition of cow manure and sludge in a continuous anaerobic digester. This study focuses on a laboratory-scale study of the food/inoculum ratio and total solid content of the feedstock and then applies the best combination, in terms of biogas production, to the continuous digester study.

In the laboratory-scale study, food waste was collected from the University Center Cafeteria (Connection Café) at the University of Texas at Arlington. Four pairs of food waste reactors (AD1 to AD8) were built and monitored periodically to measure the gas volume and composition, as well as leachate quality. After 180 days of operation, the food waste reactors were dismantled. Once the laboratory tests on the reactors were complete, for the 1st study, two pairs (total 4) field-scale continuous anaerobic digesters were installed in the Civil Engineering Laboratory Building and it was monitored for 180 days and for the 2nd study, one pair (total 2) field-scale continuous anaerobic digesters were monitored for 120 days. The results from the laboratory-scale study and field scale study are summarized as follows:

- Food waste samples, collected from University Center Cafeteria (Connection Café) at the University of Texas at Arlington were sorted to mix them in the synthetic ratio of developing countries, which was 60% waste from fruit vegetable, 30% waste from grain products and 10% from the meat, fish, dairy products.
- The average moisture content of the fresh food waste was about 80.71% on wet weight basis. The moisture content of sludge and cow manure was found to be 97.72%, and 80.6%, respectively.
- The average amount of volatile solids in the food waste feedstock was about 89.77% of total solid. The moisture content and volatile content for the duplicate reactors were found to be similar because of the similar composition of waste in the reactors.
- The pH of cow manure and sludge was found to be 7.32 and 7.39, respectively. The volatile solid content of sludge and cow manure was found to be 80.5%, and 82.9%, respectively.
- Four pairs of food waste reactors (AD1 to AD8) were seeded with food waste. In the control reactors (AD1 and AD2), food/inoculum ratio was 15 which was based on the best result achieved by Zaman's (2016) biocell study. For the other three pairs of food waste reactors (AD3 to AD8), F/I ratio 4, 3 and 2 were tested. Each food waste reactor was seeded with 4 lbs. of food waste, then kept in an environmental growth chamber at 37^0C.

- Gas composition and flow from the reactors were observed periodically. The food waste reactors with F/I=2 (AD7 and AD8) produced more than 50% methane (highest 64.5 %) almost continuously for 60 days. The highest methane content was about 64.5% in reactor AD7 on day 118. All of the food waste reactors except AD1 and 2, achieved more than 50% methane during operation, which is significant for anaerobic digester.
- Food waste reactors with F/I=2 (AD7 and AD8) produced significant amounts of gas (200L/lb. VS and 192.5 L/lb. VS respectively) in their lifetime of 180 days.
- Among the food waste reactors, the highest methane volume was generated from reactor AD8 (79.8 L/lb. VS). The lowest amount of methane was produced from food waste reactor AD1 (0.38 L/lb. VS).
- The quality of leachate produced from the food waste reactors were also measured. Initially, the pH of leachate of all the food waste reactors was less than 7 due to the accumulation of acid during the acidogenic phase. The pH of the reactors exceeded 6 within 45 days of operation and 7 within 90 days of operation. After that, all reactors were stabilized with pH values between 7 and 8.5 signifying the methanogenic phase.
- At the beginning, the COD value for all the food reactors were high (from 140,000 to 30,000 mg/L). COD value of all the food waste reactors increased rapidly until the 3rd month, except the control reactors. After entering methanogenic phase, all the reactors showed decreasing trend for COD values, indicating entering towards methanogenic phase.
- The amount of volatile fatty acid value was low at the beginning and went up before entering methanogenic phase, which is more than 90 days of operation, for all the food reactors. The lowest VFA was found for F/I= 2, which where 7.00 g/L and 7.5 g/L after

180 days of operation. The control ones with F/I=15 ended up being 35.00 g/L and 33.0 g/L.

- The percent reduction of volatile solids in the waste is positively correlated with the total methane production from the waste. Among the reactors, volatile solid reduction after the degradation of waste was observed to be highest for the F/I=2 and they generated the highest amount of methane.
- Based on the laboratory scale anaerobic digester simulation, it can be concluded that food/inoculum ratio of 2 is optimum for continuous anaerobic digester.
- After the laboratory scale study was complete, two sets (total 4) scaled to one-fifth size field-scale anaerobic digesters (F/I=2 and 1.5) were installed in CELB and were monitored for 180 days in 1st study. All anaerobic digestors were equipped with leachate and gas management systems. Cow manure and sludge were used in the anaerobic digesters.
- The methane content of the gas in the digesters with F/I=1.5 reached 68.0% after 110 days of operation; in F/I=2, it reached 67.0% on day 116.
- The cumulative gas volume in the digester of F/I=2 during 180 days of operation was about 630 L/lb VS; in digester of F/I=1.5, it was 616 L/lb VS. Cumulative methane production was higher in the digester with F/I=1.5 (324 L/lb VS).
- The peak value of methane yield observed from the lab-scale reactors was 1.72 L/lb. VS/day on day 102, while in the 1st field-scale study, it was the highest (8.1 L/lb. VS/day) on day 110.
- The digesters with F/I=2 produced average 43.02 L/day of biogas daily in 180 days of operation, while digesters with F/I=1.5 produced almost 41.78 L/day of biogas.

- The pH of the leachate in the digesters were around 5.5 after 31 days of operation. It went up 7 and above after 100 days operation and on that time the maximum methane generation occurs indicating the methanogenic phase and it supports the volume of biogas on that phase.
- The COD value for all the food digester showed decreasing trend indicating the waste decomposition and biogas production for the study period.
- The amount of volatile fatty acid value was 19.5 g/L for AD1 (F/I=2) and 17 g/L for AD3 (F/I=1.5), ended up being 6.8 g/L and 12.25 g/L respectively after 180 days of operation. VFA after 110 days of operation reduced below 13 g/L. VFA more than 13 g/L starts creating an inhibitory environment for methane production.
- From the beginning, Alkalinity was more than 1000 mg/L which is recommended for healthy operation of digesters. After entering the methanogenic phase, the VFA/Alkalinity the ratio was 0.43 For AD 1 and ended up being 0.27 at the end of operation. For AD 3 and 4, the ratio ended up at 0.29 and 0.27. After passing the lag phase, all the digesters maintained the required VFA/Alkalinity ratio, which is within 0.4; which signifies the better performance of the digesters.
- To check the potential of lag phase reduction, after the 1st stage of field-scale anaerobic digesters, 2nd stage 2 digesters (F/I=2) of field-scale anaerobic digesters were installed in CELB and were monitored for 120 days.
- The methane content of the gas in the digesters reached 51.5% after 2 days of operation for AD 1, it reached 59.1% for AD2 indicating methanogenic phase.

- The cumulative gas volume in the digester during 120 days of operation was about 810 L/lb VS and 817 L/lb VS respectively. Cumulative methane production was 445.3 and 429 L/lb VS respectively.
- The digester AD1 produced average 41.2 L/day with standard deviation of 3.53L of biogas daily in 120 days of operation, while digester AD2 produced almost 41.3L/day with standard deviation of 3.76L of biogas; indicating stable biogas production for the whole study period.
- Throughout the monitoring period, the pH of the leachate in the digestors remained above 7 due to the addition of inoculum for the whole hydraulic retention time at day 0, which is an alkaline pH. This favorable range of pH supports the methane percentage of the study indicating the early start of the methanogenic phase.
- The amount of volatile fatty acid value was below 10 g/L for the whole study period in 120 days of operation for both AD. VFA more than 13 g/L starts creating an inhibitory environment for methane production, which was not visible in this 2nd study.
- From the beginning, Alkalinity was more than 1000 mg/L which is recommended for healthy operation of digesters. The VFA/Alkalinity the ratio was 0.4 For AD 1 and ended up being 0.27 and 0.3 at the end of operation for AD 1 & 2 respectively. Both the digesters maintained the required VFA/Alkalinity ratio, which is within 0.4; which signifies the better performance of the digesters.
- Based on our experimental data, daily 210L of Biogas could be achieved from the full-scale size AD from which 1.25 cooking hours can be achieved daily. The 2nd option can be for lighting a 100-watt filament lamp for 2 hours daily in developing countries.

From the results of biogas quality and quantity, and leachate quality, it can be concluded that F/I ratio 2 enhanced biodegradation in both the laboratory-scale simulation and 2 field studies done in this study. By operating food waste anaerobic digesters, enhanced methane production and waste decomposition can be achieved which can be used for cooking purpose in household level of developing countries.

7.2 Recommendation of Future Studies

Based on the observation and experience gained from experiments of the current study, several recommendations are proposed for future studies.

- The study presented both laboratory-scale and field-scale anaerobic digester scenarios; however, it is recommended that actual field anaerobic digester conditions be applied in developing countries in future studies.
- The utilization of the digestate can be checked as it could be a good source of fertilizer.
- Further research is recommended to study the effects of temperature on methane as well as biogas production.
- As combination of sludge and cow manure performed as the best inoculum combination for fresh food waste, the effect of them individually can be checked.
- There is some potential to study the effect of cellulose and hemicellulose on enzymes that degrade fresh waste, although the degradation of fresh waste is a natural process.
- A life cycle analysis (LCA) would be helpful on operating anaerobic digester to determine the environmental impacts of operation compared to other waste disposal techniques.

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