DRAFT: Beneficial Reuse Solutions for Landfill Operations and Management Final Report

April 2018

Author

Daniel E. Meeroff, Ph.D.
Florida Atlantic University
Department of Civil, Environmental & Geomatics Engineering

And

Co-Author

Rohan Sethi, M.S
Florida Atlantic University
Department of Civil, Environmental & Geomatics Engineering

Hinkley Center for Solid and Hazardous Waste Management
University of Florida
P.O. Box 116016
Gainesville, FL 32611
www.hinkleycenter.org

Report # (leave blank)

ACKNOWLEDGEMENTS

The researchers would like to acknowledge the William W. “Bill Hinkley Center for Solid and Hazardous Waste Management for the funding for this project. The researchers would also like to thank the Technical Advisory Group members and all the stakeholders for their invaluable advice, feedback, and support of this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FINAL (ANNUAL) REPORT

12/01/2016 – 06/30/2018

PROJECT TITLE: Beneficial Reuse Solutions for Landfill Operations and Management

PRINCIPAL INVESTIGATOR(S): Daniel E. Meeroff, Ph.D.

AFFILIATION: Florida Atlantic University

EMAIL: dmeeroff@fau.edu **PHONE NUMBER:** 561-297-2658

PROJECT WEBSITE: http://labees.civil.fau.edu/leachate.html

COMPLETION DATE: 06/30/2018

TAG MEMBERS: Mark Eyeington, Mark Maclean, Mark Bruner, Owrang Kashef, D.V. Reddy, Craig Ash, Ravi Kadambala, Ron Schultz, Jeff Roccapriore, André McBarnette, Dan Schauer, Damaris Lugo, Amanda Krupa, Richard Meyers, Amede Dimonnay, Art Torvela, Ted Batkin, Roshan Jachuk, Fred Bloetscher, Patrick Carol, Joseph Lakner, Kevin Leo, Hala Sfeir, Rebecca Rodriguez, Myles Clewner

STAKEHOLDERS: Nate Mayer, Mark Eyeington, Amede Dimonnay, Karen Moore, Hope Thigpen, Don Kree, Steve Roberge, John Culver, Michael Hewett, Kim Brunson, Peter Cooke, Alonso Griborio, Nandita Ahuja, Robert Flynn, David Gregory, Jane Gregory, David Dalton, Darren Hollifield, Scott Trainor, Lanette Sobel, Karen Doyle, Scott Trainor, Hannan Reynolds, Karen Doyle, Paul A. Pitt, Carrie Woodward, Leslie Nelson

KEY WORDS: Anaerobic digestion, landfills, biogas, methane, food waste

ABSTRACT: The anaerobic biodegradability of food waste (FW), meat waste and FOG (fats, oils and greases) with municipal primary sewage sludge was assessed using a laboratory scale anaerobic digester and by ultimate sludge digestibility, at mesophilic conditions by varying the inoculum to feedstock ratio (1:2-1:10) and solids retention time (SRT). Preliminary analysis assessed the anaerobic digestion of food waste and meat at a biogas production over 30 days at 1000 mL and 1400 mL, respectively. The maximum methane yield was 0.18 m^3/kg VS and 0.50 m^3/kg VS for 1:10 in meat and FOG, respectively in 28 days with 56-61% volatile solids of destruction and first order methane generation rate of 0.15 d^{-1} for both meat and FOG. The optimal ratio for meat and FOG was determined to be beyond highest ratio tested (1:10), and longer SRT should be considered to investigate the impact of feedstock on methane yield. Preliminary modeling suggests that for one 1.74 MG digester, diverting just 0.6% of the food waste generated in one-third of Palm Beach County could produce enough methane to power 130-360 homes for one full month.

METRICS:

1. List graduate or postdoctoral researchers **funded** by **THIS** Hinkley Center project.

Last name, first name	Rank	Department	Professor	Institution
Sethi, Rohan	MSCE Candidate	CEGE	Meeroff	FAU

2. List undergraduate researchers working on **THIS** Hinkley Center project.

Last name, first name	Department	Professor	Institution
Quddus, Ghulam	CEGE	Meeroff	FAU
Almeida, Joao	CEGE	Meeroff	FAU
King, Bertrand	CEGE	Meeroff	FAU

3. List research publications resulting from **THIS** Hinkley Center project.

None yet

4. List research presentations resulting from **THIS** Hinkley Center project

3 TAG meetings

Technical Advisory Group Meeting held on December 2, 2016, Technical Advisory Group Meeting held on August 28, 2016, Stakeholder Advisory Group Meeting held on October 23, 2017, Technical Advisory Group Meeting held on February 9, 2016

5. How have the research results from **THIS** Hinkley Center project been leveraged to secure additional research funding?

$1200 Undergraduate Research Grant, $250 NSF LEARN™ Grant

6. What new collaborations were initiated based on **THIS** Hinkley Center project?

Hazen and Sawyer, P.C.

7. How have the results from **THIS** Hinkley Center funded project been used (not will be used) by FDEP or other stakeholders? (1 paragraph maximum).

To date, the results have not been used by stakeholders; however, an informal presentation was made to three different Hazen and Sawyer, P.C. personnel to show the results of preliminary analysis to Broward County and Palm Beach County wastewater managers for continued

funding. A presentation conference call was made with Publix, and a proposal is being prepared. We plan to continue to work with our partners to share our results and continue the work.

EXECUTIVE SUMMARY

12/01/2016 – 06/30/2018

PROJECT TITLE: Investigation of Effective Odor Control Strategies

PRINCIPAL INVESTIGATOR(S): Daniel E. Meeroff, Ph.D.

AFFILIATION: Florida Atlantic University

PROJECT WEBSITE: http://labees.civil.fau.edu/leahcate.html

TAG MEMBERS: Mark Eyeington, Mark Maclean, Mark Bruner, Owrang Kashef, D.V. Reddy, Craig Ash, Ravi Kadambala, Ron Schultz, Jeff Roccapriore, André McBarnette, Dan Schauer, Damaris Lugo, Amanda Krupa, Richard Meyers, Amede Dimonnay, Art Torvela, Ted Batkin, Roshan Jachuk, Fred Bloetscher, Patrick Carol, Joseph Lakner, Kevin Leo, Hala Sfeir, Rebecca Rodriguez, Myles Clewner

COMPLETION DATE: 06/30/2018

In 2016, the Bill Hinkley Center for Solid and Hazardous Waste Management funded FAU Lab.EES to investigate organic waste diversion from landfills to anaerobic digestion to capitalize on existing anaerobic digester capacity in the wastewater sector. The project explored the impact of organic waste diversion on landfill gas recovery and landfill economics. Biogas is produced by wet organic waste decomposing under anaerobic conditions. First, the microorganisms break open the cellular substrate in a process known as hydrolysis. Then microorganisms turn those molecules into organic acids, which become the food for the methanogens that produce methane, the energy component of biogas. In Florida, organic wastes make up 6-20% of the municipal solid waste (MSW) stream, but only 2-5% is diverted from landfills meaning that about 2 million tons per year end up in the landfill. This material has a high moisture content (>70%) and a low heating value (<2500 BTU/lb) compared to MSW without organic waste (~5000 BTU/lb). Therefore, organics are not as desirable for waste-to-energy operations either, but they are ideal for anaerobic digestion. In 2015, there were 1497 anaerobic digesters in the US, of which 83% were being used strictly for wastewater applications.

Recent innovations in co-digestion have unlocked the potential for cleaner biogas (65-75% methane) with only 10% of the digester feed being diverted food waste, tripling the digester biogas output in some cases. Using the total amount of food waste reported for the State of Florida and estimates from Dung et al. (2014), this represents a potential to generate 1829 – 4043 GWh per year, which is equivalent to the energy required to power 321,000 – 710,000 homes (USEPA 2013) or 8% of all of the energy requirements for the State. However, since food waste is rich in carbon, if a fraction of this material is diverted from the landfill or waste-to-energy stream, it may ultimately impact LFG production and methane content at the solid waste facility. Therefore, we propose to quantify these effects by calibrating the USEPA LFG Emissions Model (LandGEM, Alexander et al. 2005) based on experimental measurements of methane production potential and first order decay rate at different food waste diversion ratios. Using the new data, this study will investigate if we can take advantage of unused anaerobic digester capacity in the wastewater sector to generate more clean biogas from diverted food waste and determine the life

cycle cost impact of organic waste diversion programs from the perspective of the solid waste industry and also holistically from the entire waste sector
if implemented.

1. INTRODUCTION

1.1 Background

Each year in the United States, 125 – 160 billion pounds of food is discarded uneaten, amounting to up to 40% of the food supply (NRDC 2017), and 85% of that food waste eventually is disposed of in landfills or combustion facilities (EPA 2017). The USDA's economic research service reported that 31% of food produced in the United States is wasted at the retail and consumer levels, corresponding to approximately $161 billion in 2010 (USDA 2010). Food waste is comprised of 75% organic material (Han et al. 2005; Dimitrios 2017) that is a source of methane when it undergoes anaerobic decomposition. When food waste, like other organics, decomposes in a landfill, it generates methane, which if allowed to escape is a potent greenhouse gas (GHG) with 21 times the global warming potential of carbon dioxide (NREL 2013). In fact, landfills are responsible for one-third of all fugitive methane emissions in the United States as shown in Figure 1 (Zhang et al. 2007; EPA 2015). Therefore, keeping food waste out of landfills will result in reduced fugitive methane emissions.

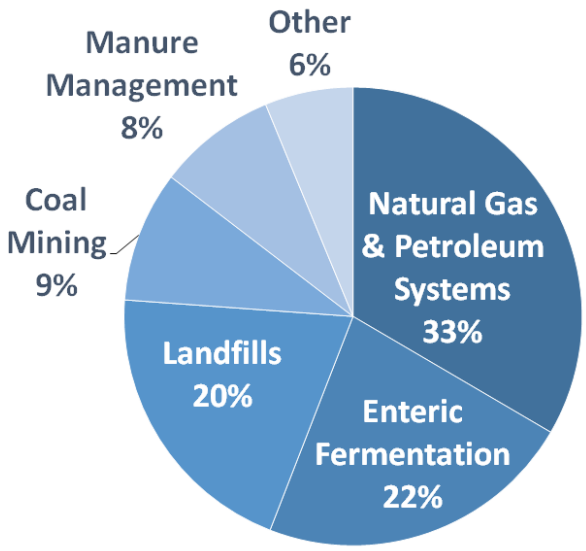


Figure 1: United States methane emissions, by source (Zhang et al. 2007; EPA 2015)

The preferred approach to reducing the amount of food waste disposed of in landfills is to eliminate food waste at the source. If elimination or minimization cannot be accomplished, then food waste can be recycled into compost or converted to a renewable form of energy. Compost improves soil health and structure, increases drought resistance, and reduces the need for artificial fertilizer applications (Mata-Alvarez et al. 2000). Also, food waste does not create methane in a compost system the way it does in a landfill because it is an aerobic process, so the carbon is converted to carbon dioxide instead of methane. However, food waste can be turned into renewable energy through anaerobic digestion, where the methane generation from broken down food is encouraged and captured to produce biogas (CH_4), heat and energy. The most useful part of the energy of biogas is the calorific value in its methane content (which is higher than coal) as compared in Table

1, which can be used for electricity and heat production via the use of an engine-generator (Fedailaine et al. 2015).

Table 1: Summary of heating value of fuels (adapted from Worrell, Vesilind, and Ludwig 2016, GREET Model Argonne National Laboratory 2010, and World Nuclear Association 2016)

Fuel	Heating Value	
	kJ/kg	Btu/lb
Unprocessed Refuse	10,300	4,450
Paper	24,900	7,500
Coal Bituminous	26,200	11,340
Coal Anthracite	29,500	12,700
Methane	49,980-55,617	21,230 – 23,900
Natural Gas	52,225- 54,750	22,453 - 23,170

The production of biogas through anaerobic digestion offers significant advantages over other forms of bioenergy production. It has been evaluated as one of the most energy-efficient and environmentally beneficial technologies for bioenergy production (Fehrenbach et al. 2008). As mentioned earlier, methane can be captured to generate clean electricity. Future estimates of methane generation will soon reach 4.2 trillion cubic feet per year, or about 4,318 trillion British thermal units (NPC 2013), which could displace about 46% of current natural gas consumption in the electric power sector and the entire natural gas consumption in the transportation sector (EIA 2013a). In Table 2, the total amount of energy content for fats, food waste (mixed) and meat for when collected, dry and dry ash-free is summarized.

Table 2: Typical proximate energy data for materials found in residential and commercial wastes (Kaiser 1966, Mantell 1975, Neissen 1977)

Type of Waste	Energy Content (Btu/lb)		
	As Collected	Dry	Dry ash-free
Fats	16,135	16,466	16,836
Food waste (mixed)	1,797	5,983	7,180
Fruit waste	1,707	8,013	8,185
Meat waste	7,623	12,455	13,120
Paper (mixed)	6,799	7,571	8,056
Yard wastes	2,601	6,503	6,585

Currently, Florida has 63 operational biogas projects and according to the American Biogas Council (2015) has a potential for 230 more projects to be developed based on the estimated amount of available organic material. Constructing this many projects would generate $690 million

in capital investment, and create 5,750 short-term jobs and 460 long-term jobs. If fully utilized, these biogas systems could produce enough electricity to power 47,566 homes (1.3 billion KWh) or enough to fuel the equivalent of 190,710 vehicles (American Biogas Council 2015) in Florida.

1.2 Biogas in Florida

Anaerobic digestion (AD) can be defined as the microbiologically-mediated breakdown of biodegradable organic material in the absence of oxygen to generate biogas and a soil amendment in an engineered reactor called an anaerobic digester (Dimitrios et al. 2017). One such anaerobic digester is located in Pompano Beach, FL, which is part of the 95-MGD North Regional Wastewater Treatment Plant (NRWWTP), shown in Figure 2.

Figure 2: North Regional Wastewater Treatment Plant, located in Pompano Beach, FL (Hazen and Sawyer 2012)

At this facility, waste activated sludge (WAS) is thickened by dissolved air flotation (DAF) prior to conventional anaerobic digestion, where methane and stabilized sludge (Class B biosolids hauled to either land application sites or to landfills) are produced. The two newer components of the plant include a 2-MW co-generation unit for conversion of biogas to electricity and a receiving station for fats, oils and grease (FOG) (Figure 3).

Figure 3: FOG receiving facility in North Regional Wastewater Treatment Plant, located in Pompano Beach, FL: (A) Fats, oils and grease (FOG) receiving station, (B) FOG receiving tank, (C) FOG blending tank, and (D) FOG dosing system (Hazen and Sawyer 2010)

The FOG receiving station (A) was constructed to collect and introduce additional feedstock to the digesters to enhance biogas production. This FOG material was formerly directed to the plant influent, resulting in increased aeration demands for the liquid stream and adverse impacts to operation and maintenance, including clogging. Redirecting this waste to the anaerobic digesters for resource recovery reduced other energy demands at the plant by an additional 250 kilowatts (Alonso et al. 2017).

1.3 Anaerobic Digestion

As stated earlier, anaerobic digestion is a common wastewater treatment process that decomposes organic waste to generate biogas and a stabilized soil amendment. The composition of the biogas is summarized in Table 3, in percent by weight (Alvarez 2000), which shows that the major portion of typical biogas is methane (50-75%) and carbon dioxide (25-50%).

Table 3: Main components of biogas (Alvarez 2000)

Biogas Component	Percent by weight
Methane	50-75 %
Carbon Dioxide	25-50 %
Nitrogen	0-10 %
Hydrogen Sulfide	0-3 %
Hydrogen	0-1 %
Oxygen	0.5 %
Water	5-6 %

As reported by Campuzano and González-Martínez (2016) and Capson-Tojo et al. (2016), food waste can be effectively degraded under anaerobic conditions. Co-digestion (the simultaneous digestion of two or more substrates) and substrate pretreatment are the strategies that are typically implemented to enhance biogas production, balance nutrients and control acidogenesis in the anaerobic digestion process (Esposito 2012). Furthermore, food waste composition and, consequently, its physicochemical characteristics, can be highly variable depending on the source, the type of feedstock, moisture content, nutrient value, buffering capacity, and volatile solids (Capson-Tojo et al. 2016), but many of its characteristics are desirable for anaerobic digestion.

1.3.1 Types of Anaerobic Digesters

Conventional anaerobic digesters can operate in batch, semi-continuous or continuous modes. Semi-continuous or continuous operations are preferable because maximum growth rates can be achieved at steady-state by controlling the feed rate. In batch systems, steady-state cannot be achieved as the concentrations of components in the digester are changing with time (Klass 1984). Broward County NRWWTP operates a continuous mode anaerobic digester. The choice of reactor type is dictated by the waste characteristics, especially particulate solid content. Solids and slurry waste are mainly treated in continuous flow stirred tank reactors (CSTRs), while soluble organic wastes are typically treated using high-rate biofilm systems such as anaerobic filters, fluidized bed reactors and up flow anaerobic sludge blanket (UASB) reactors (Angelidaki et al. 2002). In biofilm systems, the biomass is retained in the biofilm/granular aggregates such that sludge retention time (SRT) is 30-35 days. This is 25% higher than the hydraulic retention time (HRT), which has the advantage that the reactor can run at 25% higher flow rate and can tolerate higher toxic concentrations than CSTR systems (Zhang et al. 2007). High-rate biofilm systems are normally run in continuous mode with HRT less than 5 days (often below 24 hours) (Pind et al. 2003). The systems can operate in a wide range of temperatures from mesophilic conditions (30-35°C) (Lettinga et al. 1999) to extreme-thermophilic conditions (55-80°C) (Lepistö and Rintala 1997).

In CSTR systems, the biomass is suspended in the bulk liquid and is removed together with the effluent so that the SRT is equal to the HRT. This makes it necessary to run at longer HRTs, usually 10-20 days, to avoid washing out the slow-growing methanogens. In domestic sludge digestion, a sludge settler after the main reactor can be applied for recycling of biomass seed, which makes it possible to run at shorter HRT (Pind et al. 2003).

In single-stage systems, all the digestion/stabilization reactions take place simultaneously in a single reactor, while in multi-stage systems, the reactions take place sequentially in different reactors. Two stages are used where the relatively fast first stage of liquefaction-acidification reactions occur, which are rate-limited by the hydrolysis of cellulose, and the second stage is for the relatively slower acetogenesis and methanogenesis reactions occur, which are rate-limited by the slow microbial growth rate of methanogens (Liu and Ghosh 1997; Palmowski and Müller 1999).

The lag phase of anaerobic digestion depends on several factors, principle among these is the acclimation of the microorganisms. If the digestate from the mature digesters treating the waste is taken as the inoculum or seed, the lag phase is shorter because the microorganisms have already established the enzymes needed in the process of breaking down the substrate or feedstock. Another factor is the substrates used. For example, substrates that are not highly soluble will be necessarily more difficult to breakdown, such as meat waste, which is highly complex to mix with

available sludge and convert to slurry form due to the presence of bones, tendons, skin, contents of the gastro-intestinal tract, blood, and internal organs (Sielaff 1996). On the other hand, FOG consists of fatty acids from cooking processes, grease trap waste (brown grease) and residual fat, and suspended solids hosting microbial activity (He et al. 2013). It has been estimated that raw grease trap waste can have a FOG concentration of 4.23 wt.%, water concentration of 86.35 wt.%, and a solids concentration of 9.42 wt.% (Tu and McDonnell 2016).

Another important component is the ability of the slurry to resist large changes in pH during acidogenesis. The buffering capacity of an anaerobic digester is determined by the amount of alkalinity present in the system. In any anaerobic digester, sufficient alkalinity is essential for proper pH control (Dong et al. 2009; Jiang et al. 2013; Zhang et al. 2013). The alkalinity in a digester is to a great extent proportional to the solids feed concentration. The normal ratio for volatile fatty acid to alkalinity considered is 0.02-0.05 (Palacios-Ruiz et al. 2008), if it increases beyond 0.07, then this is the first warning sign of an upset digester after which the pH starts to decline and the digester turns sour killing the microorganisms that are responsible for the stabilization process (Martín-González et al. 2013). A well-established digester typically has a total alkalinity of 2000 to 5000 mg/L (WEF 1996). Alkalinity is consumed by the methane forming bacteria which stabilizes the digester by increasing the pH. The alkalinity can be restored by adding sodium bicarbonate and/or potassium bicarbonate (Dong et al. 2009). Excess alkalinity can be destroyed or neutralized with the addition of ferric chloride or citrate.

In anaerobic co-digestion based on manure slurry and organic wastes, which is similar to the main focus here, the process is commonly operated with a CSTR in semi-continuous mode where the digester is intermittently supplied with substrate after an equal amount of the mature digested material is withdrawn. Large-scale biogas systems normally have waste receiving tanks, which allow more stable operation on the influent side. The addition of organic waste to manure helps increase biogas production by 40-50% and is important for the economic viability of Danish biogas plants (Tafdrup 1995). Continuous feeding is preferred, if optimizing of heat-exchange is required. However, intermittent feeding saves pumping costs and ensures adequate times for pathogen reduction. Large-scale biogas plants in Denmark are normally operated under mesophilic conditions with HRT of 23 ± 4 days, or thermophilic conditions with HRT of 17 ± 4 days (Nielsen and Ahring 2006).

Yong et al. (2015) studied the methane potential of typical food waste (FW) and straw which were individually measured in a 1-L enclosed reactor at 35°C, and were 0.26 and 0.16 m^3/kg-VS (volatile solids), respectively. Lab-scale mixtures of different food waste and straw composition were conducted with a total organic load of 5 g VS/L. The optimum mixing ratio of food waste to straw appears to be close to 5:1, and the methane production yield reached 0.39 m^3/kg-VS, i.e., increased by 39.5% and 149.7% compared with individual digestion results, respectively. Also, after comparison, the biogas production and methane content reached 0.58 m^3/kg-VS and 67.6%, respectively.

Alvarez and Liden (2009) studied the potential of semi-continuous mesophilic anaerobic digestion for the treatment of food waste, fruit-vegetable wastes, and manure in a co-digestion process. A study was made at laboratory scale using four 2-L reactors working semi-continuously at 35°C. The effect of the organic loading rate (OLR) was initially examined (using equal proportion of the three components on volatile solids, VS, basis). Anaerobic co-digestion with organic loading in

the range 0.3–1.3 kg VS m^3/d resulted in methane yields of 0.3 m^3 /kgVS added, with a methane content in the biogas of 54–56%.

Zhang et al. (2012) assessed the anaerobic co-digestion of food waste and cattle manure, in order to identify the key parameters that determine the biogas and methane yield. Results of both batch and semi-continuous tests indicated that the total methane production is enhanced in co-digestion, with an optimum food waste to cattle manure ratio of 2. At this ratio, the total methane production in batch tests was enhanced by 41%, and the corresponding methane yield was 0.4 m^3/kgVS. In the semi-continuous mode, the total methane production in co-digestion, at an organic loading rate of 10 kgVS/m^3/d, increased by 55%, corresponding to a methane yield of 0.3 m^3/kgVS .

El-Mashad and Zhang (2010) investigated batch digesters under mesophilic conditions (35°C). The study determined the biogas production potential of different mixtures of unscreened dairy manure and food waste and compared them with the yield from manure or food waste alone. A first-order kinetics model was also developed to calculate the methane yield from different mixtures of food waste and unscreened dairy manure. The methane yields of fine and coarse fractions of screened manure after 30 days were 0.30, 0.23, and 0.24 m^3/kgVS, respectively. Approximately 93%, 87%, and 90% of the biogas yields could be obtained, respectively, after 20 days of digestion. Average methane content of the biogas was 69%, 57%, and 66%, respectively. The methane yield of the food waste was 0.35 m^3/kgVS after 30 days of digestion. Two mixtures of unscreened manure and food waste, 68/32% and 52/48%, produced methane yields of 0.28 and 0.31 m^3/kgVS, respectively after 30 days of digestion. After 20 days, approximately 90% and 95% of the final biogas yield could be obtained, respectively. The predicted results from the model showed that adding the food waste into a manure digester at levels up to 60% of the initial volatile solids significantly increased the methane yield for 20 days of digestion.

Wu et al. (2015) compared anaerobic digestion of oily food waste in single and two-stage systems at 35°C. Both systems had same organic loading of 0.16-0.26 kgVS/m^3/d, which resulted in a measured methane yield of 0.44 m^3/kgVS added after SRT = 30 days with pH ranging from 6.4 – 7.1.

Table 4 summarizes the food waste, FOG and meat anaerobic digestion data collected by other researchers in previous work.

Table 4: Summary of food waste, FOG and meat anaerobic digestion previous research data

Type of Feedstock	Digester configu-ration	Organic loading rate (kgVS/m^3/d)	Operating TS %	SRT (d)	Temper-ature range °C	Methane yield (m^3/kg VS)	VS removal (%)	Reference
Food waste and straw (5:1)	1-L bottles	0.16-0.26	4.26	30	35	0.58	67-82	Yong et al. (2015)
Food waste and manure (2:1)	2-L semi-continuous	0.3-1.3	1.8	30	35	0.27-0.35	54 and 67	Alvarez and Liden (2007)
Food waste and cattle manure (4:1)	1-L batch and semi-continuous	0.6	3.2	30	35	0.23	71.4	Zhang et al. (2012)
Food waste and daily manure (2:1)	1-L continuous	0.38	4.0	30	35	0.37	82	El-Mashad and Zhang (2010)
Oily food waste	6-L CSTR	1.4-2.6	2.57-3.58	30	30-35	0.44	80.1	Wu et al. (2015)
Meat and sewage sludge	5-L glass reactors	1.8-4.0	4.76	20	35	0.53	78.6	Sami and Sari (2009)
FOG, Primary sludge, Thickened waste activated sludge	4-L and 1-L glass reactors, 160 ml serum bottles	2.45-4.35	1.2	30-52	35 and 52	0.12-0.67	82.9	Kabouris et al. (2009)
FOG and kitchen waste	250 ml septum top glass bottles	2.56	2.12	30	37	0.32-0.63	-	Li et al. (2011)

The results from Table 4 reported values based on samples collected from restaurants, meat slaughter houses and industrial by-products. However, for the commercial collection of waste products, research has not established the engineering conditions and appropriate mixture ratios to optimize methane production from this feedstock (meat and FOG co-digested with primary sludge).

1.3.2 Design of Anaerobic Digesters

The main components of a typical biogas digester facility include the following:

1) **Influent collection tank**, which is used to collect fresh substrate for feeding the digester. Depending on the type of material (such as concrete, steel, plastics and bitumen) used for the tank, it typically holds the substrate for 1-2 days. An influent collecting tank is also used for preparing homogenous and consistent substrates to the digester. So the tank will be equipped with mixing and preheating components. The tank also acts as an equalization basin and prevents the substrate from coming into contact with any oxygen (since this is an anaerobic process).
2) **Inlet (feed) and outlet (discharge) pipes**, which are pipes that lead straight into the digester at a 45-47° angle. For liquid substrate, the pipe diameter is typically 4 – 6 in; whereas fibrous substrate requires 8 – 12 in (Samer 2010). It is common for the lines to cross and act as a heat exchanger, and depending on the configuration, the inlet feed can be used to agitate the digester contents. The position of both the inlet and outlet pipes must be accessible, for maintenance access to remove obstructions and clogging.
3) **Fermentation (digester) tank**, which is a water- and gas-tight vessel that holds the digester contents for the SRT and HRT. The tank must be sealed well enough to prevent leaks related to the digestate fluid or biogas. The tank must be properly insulated, since methane production yield is heavily influenced by local climate and the temperature inside the digester. It should be constructed to minimize the exposed surface area to keep cost of construction down and reduce heat losses through the walls. A spherical structure is preferred as it has the best ratio of volume to surface area. In practical construction, a hemispherical construction with a conical floor is optimal (Samer 2010). The tank structure must be durable and resistant to corrosion. In addition, it should be able to withhold all the internal hydrostatic forces and gas pressure as well as all the external forces from the surrounding earth (if buried). The materials used for construction of the fermentation tank are steel and concrete with cement plaster and several bitumen layers for a water-tight, gas-tight seal.
4) **Gas holders**, which are required for storage of biogas. Several different configurations are utilized in practice:
    a) Floating-drum: Most floating-drum gas-holders are made of 2-4 mm thick steel sheets, with the sides made of thicker material than the top in order to compensate for the higher degree of corrosive attack. Structural stability is provided by L-bar bracing that also serves to break up surface scum when the drum is rotated. A guide frame stabilizes the gas drum and prevents it from tilting and rubbing against the support walls.
    b) Fixed-domes: A fixed-dome gas-holder can be either the upper part of a hemispherical digester (CAMARTEC design) or a conical top of a cylindrical digester (e.g. Chinese fixed-dome plant). In a fixed-dome plant the gas collecting in the upper part of the dome displaces a corresponding volume of digested slurry.
    c) Plastic gas holders: Gas-holders made of plastic sheeting serve as integrated gas-holders, as separate balloon/bag-type gas-holders and as integrated gas-transport/storage elements.
5) **Gas pipes, valves and accessories**, which are needed to convey the biogas to the generator. At least 60% of all non-functional biogas units are attributable to defective gas

piping (Samer 2010). For the sake of standardization, it is advisable to select a single size for all pipes, valves and accessories. The requirements for biogas piping, valves and accessories are essentially the same as for other gas installations. However, biogas is 100% saturated with water vapor and contains hydrogen sulfide. Consequently, no piping, valves or accessories that contain any amounts of ferrous metals may be used for biogas piping, because they would be destroyed by corrosion within a short time. The gas lines may consist of plastic tubing made of rigid PVC or rigid PE. Flexible gas pipes laid in the open must be UV-resistant.

6) **Mixing facilities**, which are needed to homogenize the digester contents and dissipate heat. Optimum mixing substantially reduces the retention time by transporting fresh substrate to the hungry microorganisms. However, if agitation is excessive, then biodegradation can be limited as well. The ideal mixing regime is gentle with intensive stirring about every four hours. Of similar importance is the breaking up of a scum layer that has lost contact with the main volume of substrate and is, therefore, not further digested. This top layer can form an impermeable barrier for biogas to move up from the digester to the gas holder. Selection of mixing systems is based on costs, maintenance requirements, digestion process, screening grit and scum content, mixing is mostly attained mechanically by using pumps or stirring as causes minimum loss of digester performance. There are many different types of anaerobic digester mixing equipment that are available. For more information, refer to Sasse et al. (1991) and Metcalf and Eddy (2014).
7) **Heating systems** provide for maintaining mesophilic or thermophilic temperature depending on the type of substrate in the digester. Sludge may be heated by circulating through external heaters, heat exchangers, or by units located inside the digestion tank (Sasse et al. 1991).
    a) **External Heating** shall be designed to provide for the preheating of feed sludge before introduction into the digesters. Provisions shall be made in the layout of the piping and valves to facilitate heat exchanger tube removal and cleaning of the lines. Heat exchanger sludge piping should be sized for peak heat transfer requirements. Heat exchangers should have a heating capacity of 130% of the calculated peak heating requirement to account for the occurrence of sludge tube fouling. External digester heating includes integration of a hot water pipe loop or hot air loop on the outer wall of the digester tank to transfer heat by means of conduction to the influent feed. Additionally, under external heating, there is also the practice of pre-heating the feedstock using a shell tube and/or a heat exchanger. In addition, biogas digesters can be externally heated by integrating waste heat recovery from electricity generation and/or integrating solar thermal technology.
    b) **Internal Heating** is very common in biogas digesters. Different types are available under internal heating system. Some of them are:
    i. Hot water pipe loop at the base of the digester
    ii. Hot water pipe loop along the sides and base of the digester, heated from inside
    iii. Hot water pipe loop along the sides and base of the digester, heated from outside
    iv. Hot water pipes replaced by hot air/steam
    v. Biomass fuel integration in the digester – biomass stove to heat water that heats the influent slurry

vi. Biogas reactor using greenhouse technology (Sasse et al. 1991)

8) **Pumps** for when the amount of substrate requires fast movement and when gravity cannot be used for reasons of topography or substrate characteristics. Therefore, several pumps and types of pumps may be needed. The most commonly used are centrifugal pumps or positive-displacement pumps (reciprocating pumps).

1.3.3 Types of Feedstocks

A feedstock is defined as any biological material that can be used directly as a fuel, or converted to another form of fuel or energy product (USDE 2015). Biogas feedstocks do not have to be derived from waste products, so any biodegradable non-woody plant or animal material is a suitable feedstock for a digester. However, anaerobic microorganisms cannot breakdown lignin, the complex polymer that gives plants their strength, which means that wood products, paper and straw will slow down the digester process (Brown et al. 2012). The biogas potential of different feedstock materials or feedstock combinations is often difficult to predict due to differences in the source, processing, volatile solids concentration, chemical oxygen demand, moisture content, and/or inclusion of toxic compounds.

Feedstocks for AD are divided into three categories (Steffen 2010):

(a) **Agricultural** – comprised of solid agricultural residues and livestock wastes in the form of dry and wet manure (cattle, pig, poultry), energy crops and algal blooms.
(b) **Commercial –** comprised of spoilage and cuttings from restaurants, grocery stores, etc.
(c) **Industrial** – comprised of waste byproducts from the food/beverage, dairy products, starch/sugar, pulp and paper, slaughter house, and bio-chemical industries.
(d) **Municipal** – comprised of municipal solid waste, sewage sludge, yard waste (grass clippings/garden waste) and household food waste.

The yield of biogas from a particular feedstock will vary according to the following criteria:

- Digester configuration (Chunlan et al. 2016)
- Temperature (Hobsen er al. 1980)
- Dry solids content (Bernet et al. 2013)
- Amount of energy remaining in the feedstock (if it has undergone prolonged storage, it may already have begun to breakdown) (Mckendry 2002)
- Solid retention time (SRT) (Clara et al. 2005)
- pH (Adrien et al. 2012)
- Purity (quality) of the feedstock for processing to thermal and electrical energy (Steffen et al. 1998)

1.3.4 Case Studies of Anaerobic Digestion of Food Waste

Sami and Sari (2009) investigated anaerobic co-digestion of a mixture of animal by-products from meat-processing and sewage sludge. Three reactors were fed with ratios of 1:7, 1:5 and 1:3 with animal byproducts and sewage sludge. Mesophilic methane yields were measured at hydraulic retention times from 14 to 20 days and organic loading rates from 1.8 to 4.0 kgVS/m^3. The highest methane yields of 0.400 ± 0.040 m^3/kgVS were achieved with 20 days HRT.

Kabouris et al. (2009) analyzed the anaerobic biodegradability of a mix of municipal primary sludge (PS), thickened waste activated sludge (TWAS) and fat, oil, and grease (FOG) by using a

semi-continuous feed, laboratory-scale anaerobic digesters operated at mesophilic (35°C) and thermophilic (52°C) temperatures. Addition of a large FOG fraction (48% of the total VS load) to a PS + TWAS mix, resulted in 3 times larger methane yield, 0.15 vs. 0.45 m^3 methane @ STP/kgVS added at 35°C and 2.6 times larger methane yield, 0.20 vs. 0.51 m^3 methane @ STP/kgVS added at 52°C.

Li et al. (2011) found that co-digestion with FOG and synthetic kitchen waste consisting of potato (40 g), strawberry (16 g), orange (32 g), tomato (72 g), chicken breast (52 g), apple (24 g), green peas (40 g), cabbages (50 g), and pork (20 g) enhanced methane production, and FOG produced more biogas from kitchen waste as co-substrate from 0.12 m^3/kgVS for waste activated sludge to 0.42 m^3/kgVS from FOG and 0.32 m^3/kgVS from kitchen waste. Nonlinear regression showed that co-substrate addition shortened the lag phases of organic biodegradation from 81.8 hours (waste activated sludge) to 28.3 hours with FOG and 3.9 hours with kitchen waste. Okeh (2013) investigated laboratory scale biogas production from rice husks generated from different rice mills using cow rumen fluid as a source of inoculum. Manure/sludge is generally used as start-up material due to its high buffering capacity to maintain stability in the digester (Rongping, Chen, & Xiujiu 2010). The presence of oxygen will inhibit the microbes from producing biogas, though small quantities are acceptable (Scott, Williams, & Lloyd 1983). Temperature must also be controlled because the microbes are classified as mesophilic or thermophilic; therefore, the digester must operate at either 35°C or 55°C, respectively. Traditionally, mesophilic anaerobic processes (digestion temperature ~37°C) are more common compared to the thermophilic process (digestion temperature at 50 –55°C). It has also been reported that mesophilic processes are more stable, and process failures are more common in thermophilic installations (De Baere and Mattheeuws 2010). However, the thermophilic operation leads to more complete decomposition of the waste material (Ferrer et al. 2010; Kim et al. 2002) and to a higher methane yield that is sufficient to compensate for the energy consumption necessary to heat the digester (De Baere 2000).

Nipon et al. (2017) investigated methane production from raw banana waste under mesophilic conditions in 0.5-L batch reactor and varied total solids (TS) in concentrations of 2.5, 5.0, 7.5 and 10% w v^{-1}. Air and liquid samples were collected every 12 h for gas composition and volatile fatty acids (VFA) analyses. At 7.5% TS, maximum methane yield and production rate were 0.44 m^3/kgVS and 5.31 mL/hr, respectively.

1.4 Rationale

The main goal of this work is to study the behavior of food waste during anaerobic digestion by determining the maximum methane yield from various waste feedstocks. The implementation of anaerobic digestion to convert food waste to electricity at full-scale has been steadily increasing, particularly in Europe. For instance, in Germany, the total electric output produced by biogas in 2012 was 20 TWh, which is equivalent to the amount needed to power 5.7 million houses with electricity (WBA 2017).

This study focuses on the gap in research regarding current production volumes of biogas generated using alternative feedstocks. Many biogas systems are too small to handle the available supply of different types of feedstock readily available for decomposition; therefore, knowing the

SRT at which maximum methane is produced will help in designing better solutions for food waste disposal utilizing their potential to generate renewable energy in co-digestion. Therefore, this study provides new information regarding biogas production and composition using organic feedstocks derived from waste materials. Enhanced energy security and climate change mitigation are the main drivers for the transformation of the energy sector from fossil fuels to renewable sources. Worldwide, biogas accounts for more than two thirds of all renewable energy supplies (American Biogas Council 2017).

According to the American Biogas Council (2016), systems are reporting a two-fold increase in biogas yield from adding just 10% more food waste. As of now, food waste has three times the methane production potential of biosolids, and methane yields can be as high as 90.6 m^3 per ton of raw food waste (Kuo and Dow 2017). Florida has only 1 operational food waste biogas system, but has potentially 34 existing underutilized units to take advantage of (American Biogas Council 2016). Anaerobic digestion of meat processing by-products (Sami and Sari 2009) and other waste like FOG (Kabouris et al. 2009 and Li et al. 2011) been studied before but with feedstock derived from industrial sources, this study will investigate feedstocks derived from commercial sources.

1.5 Objective

The main objective is to test different ratios of organic feed to digested solids substrate (1:2 – 1:10) to determine if organics from two types of organic feedstocks derived from commercial waste materials can be used to increase the biogas/methane yield of mesophilic anaerobic digestion in 7 – 56 days.

2. METHODOLOGY

The aim of this study is to determine the biogas composition and production potential for the anaerobic digestion of organic feedstocks derived from commercial food waste such as meat waste and FOG with primary sludge as seed. The analysis was completed in two phases. The first phase tested biogas production using a pilot scale PDAN (Edibon International) anaerobic digester. The second phase measured multiple characterisitcs using the ultimate sludge digestibility test for various SRT values (7–56 days) and feedstock ratios of 1:2–1:10 (v:v), as described in the following sections.

2.1 Feedstock Sample Collection

Primary sludge seed was collected from the wastewater treatment plant in Boca Raton, FL. Primary sludge (4%) was collected on May 12, June 15, July 30, 2017, January 18, 2018 and February 23, 2018 in four 2-L labeled polyethylene sample bottles from the primary clarifier waste sludge sampling port at the wastewater treatment plant in Boca Raton, FL (Figure 4, 1). FOG samples (Figure 4, 2) were collected in two 2-L labeled polyethylene sample bottles from the receiving station at the Broward County Water and Wastewater Services, Pompano Beach, FL on January 18, 2018 and February 23, 2018. The organic waste feedstock samples were collected from waste generated by local supermarkets and restaurants on May 12, 2017 (Figure 4, 3). The waste was discarded food preparation cuttings that were mixed and unsorted from that same day. The vegetables and banana peels were removed from the mixed waste and supplemented with potato peels and tomatoes. On June 15, 2017, a third-party food waste collector provided meat waste samples from butcher cuttings, (Figure 4, 4). The bones and cartilage were not sampled (because they could not be grinded efficiently), but the fat cuttings and expired beef patties were taken. Primary sludge seed was mixed with the appropriate amount of feedstock within 6 hours to start the digestion process.

Figure 4: (1) Collection of primary sludge (4% solids) from the Boca Raton wastewater treatment plant for seed; (2) FOG collected in glass bottles from Broward County Water and Wastewater Services at the receiving station; (3) food waste samples collected from a third-party hauler for during the preliminary testing on anaerobic reactor; (4) meat waste

The sample for preliminary testing using the PDAN anaerobic digester unit was prepared by selecting organic food waste and mixing it thoroughly in a grinder (Waring commercial blender #51BL32) to achieve a slurry. Then the liquefied food waste was mixed with primary sludge in a ratio of 2 volumes of food waste to 3 volumes of sludge (2:3) with 100-mL graduated cylinder in 2-L bottles before being transferred to the reactor vessel. Similarly, for meat waste, it was thoroughly mixed in the grinder with primary sludge in the same ratio of 2:3.

The samples for ultimate sludge digestibility experiments were prepared by selecting types of meat waste that could be thoroughly grinded and FOG (fats, oils and grease). Meat waste had to be mixed and grinded properly with primary sludge in the selected range of ratios (1:2–1:10). The samples were transferred to 250-mL bottles using a plastic funnel and filled to the 200-mL mark to leave headspace for the gas to accumulate as shown in Figure 5.

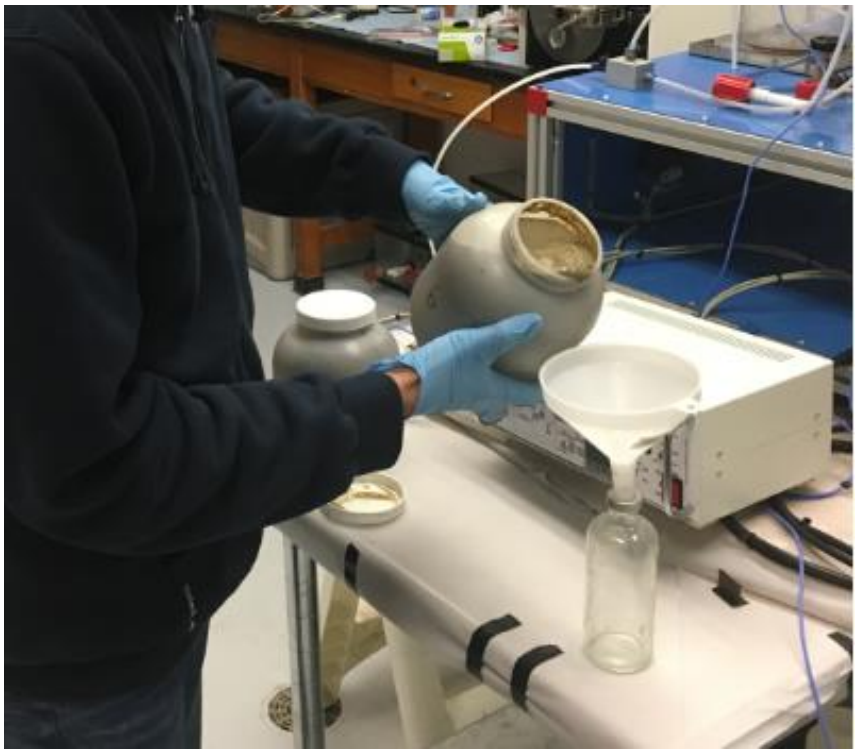


Figure 5: Transferring the FOG mixed with primary sludge (1:5) from the plastic bottle to a 250-mL glass bottle

2.2 PDAN Anaerobic Digester

Preliminary experiments were conducted using a PDAN (Edibon) anaerobic digester unit as shown in Figure 6.

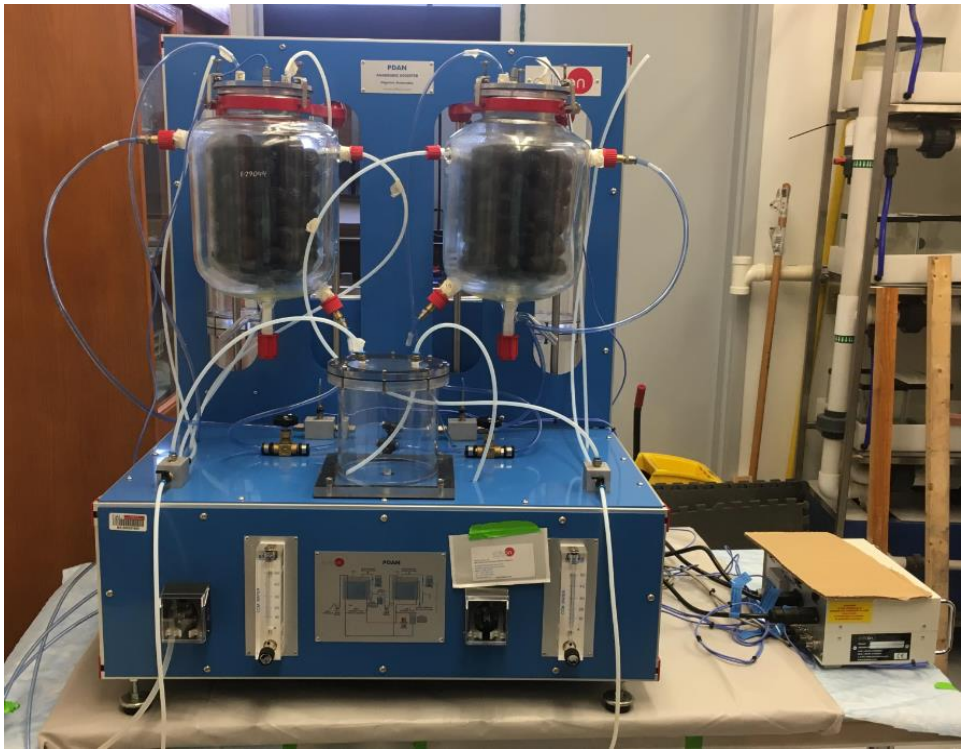


Figure 6: Initial setup for PDAN anaerobic digester

The different components of PDAN anaerobic digester unit are:

- Two jacketed 5-L glass reactor chambers
- Reusable bio-balls packing material (1.2-inch diameter)
- Thermostatic bath up to 90°C with water circulation pump
- Two 0-50 mL/min adjustable peristaltic pumps (not used in this procedure)
- Two 0-50 mL/min water flow meters
- Temperature sensor, Type J, Range -60°C to 200°C
- Two volumetric tanks to measure and store the volume of the gas generated

From the top of the digester, each glass reactor chamber has a pipe to transport the biogas generated during digestion to the volumetric tank (Figure 7), where its volume is measured by water displacement to measure the amount of biogas being produced. The digesters are temperature controlled by means of hot water coming from a thermostatic bath recirculated in a closed loop through the double-walled jacket of the digester. Each digester has a heating water circuit with valves to regulate the temperature of both digesters, independently. Reaction temperature was set at 35°C (mesophilic range) for testing.

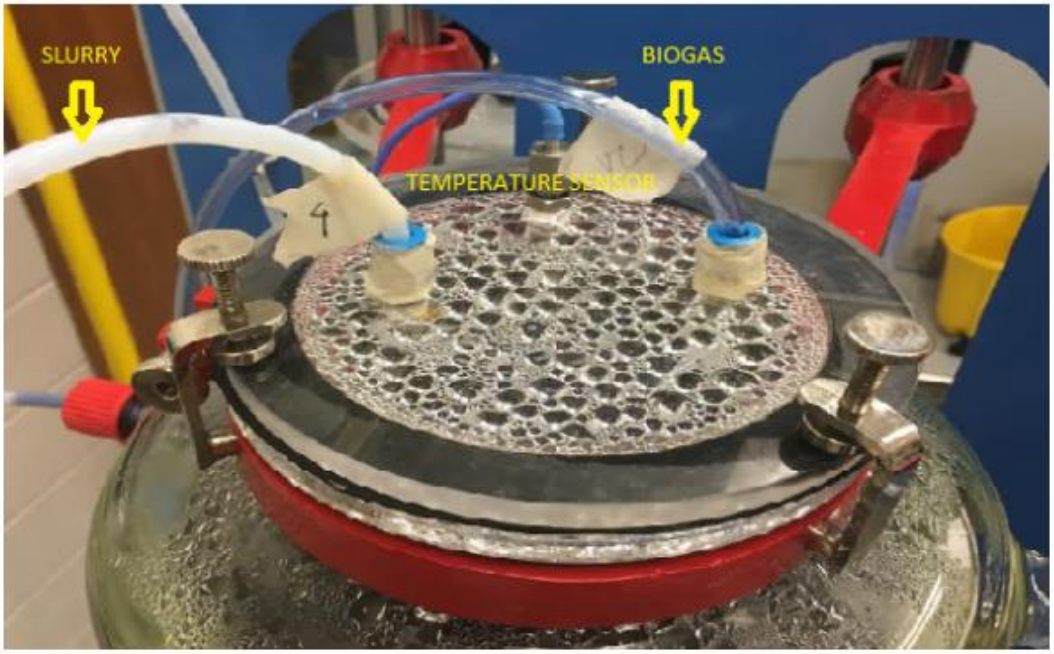


Figure 7: Top of the reactor with gas outlet pipe

To achieve a hermetic sealing of the reactors, so that no air can get inside, the contact surface between the lid and the vessel was smeared with a bead of silicone grease (Dow Corning). The thermostatic bath was filled with deionized water (18.2 MΩ-cm), the circulation pump (AB-3) was switched on, and as needed, makeup water was added to maintain the proper volume in the fill tank until all the circuit was filled with water, and the double-walled heating jacket volume reached the indicator line.

After preparation of the organic feedstock with primary sludge to create the initial slurry, as discussed previously (Figure 8 ,1), the three clamps on the top of the digester lid were unscrewed. Each digestor tank has a capacity of 5 liters, which was filled by directly pouring the mixture with the help of a glass rod (Figure 8 ,2). After loading the digester, the three clamps were closed tightly to make sure there is no leakage of gas, and a bead of silicone grease was then applied to the surface of the glass reactor so that no outside air could come in (Figure 8,3). It is important to note, that the preliminary samples were not purged with inert nitrogen gas to eliminate any oxygen. Therefore, the lag time was likely extended before favorable anaerobic conditions could be established in the reactor, naturally.

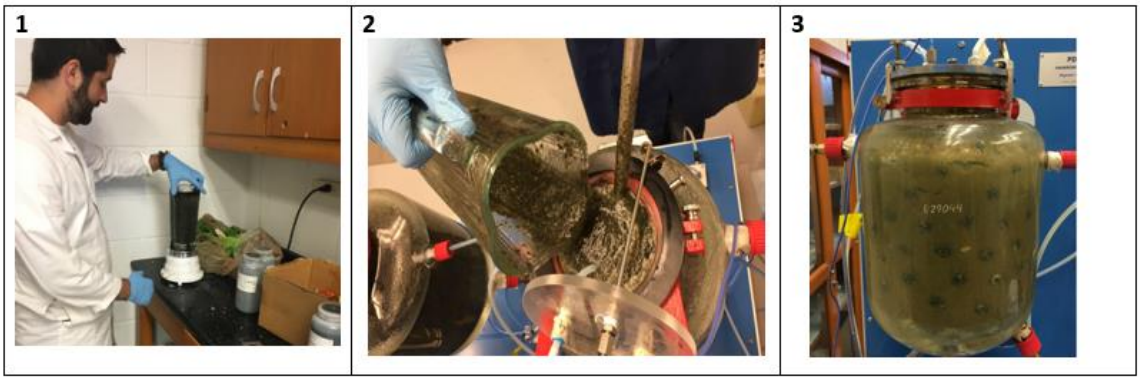


Figure 8: (1) Mixing of food sample by Joao de Almeida, (2) loading of digester reactors (3) digester loaded with mixed sludge and food waste

The biogas produced by the digester was measured by water displacement using two volumetric tanks located in the back of the digester (Figure 9).

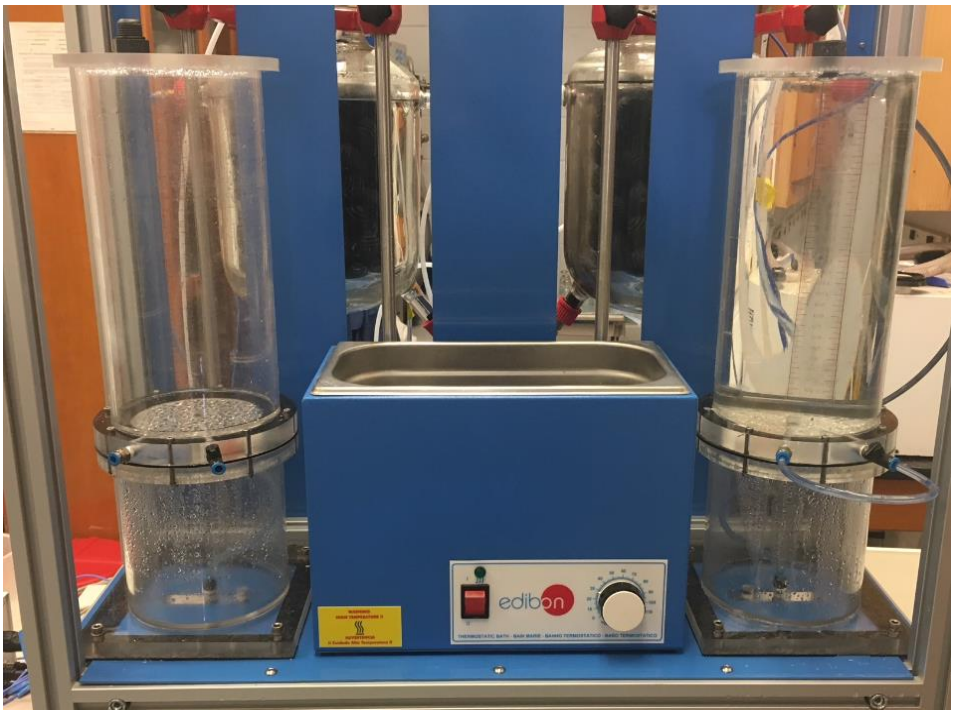


Figure 9: Collection of the gas from the reactors gets collected in the upper column, and water gets displaced in the lower column

The volumetric tank has two parts: 1) the upper tank is where the gas is collected and measured, and 2) a smaller tank underneath it, collects the displaced water before sending it to the drain. The maximum volume of each volumetric tank is 300-mL. Deionized water (18.2 MΩ-cm) was used to fill the volumetric tanks to minimize scale formation that would interfere with measurement. Water was added by placing a funnel in the opening after removing the 0.5-inch gray plastic covers every other day depending on the production of biogas.

To measure the pH, a 5-mL sample was collected every day in small glass containers and temperature was measured constantly using 4 temperature sensors present in the digester. Two temperature sensors were located on the outside of the heating blanket, and two were located inside the reactor connected to the controller unit shown in Figure 10.

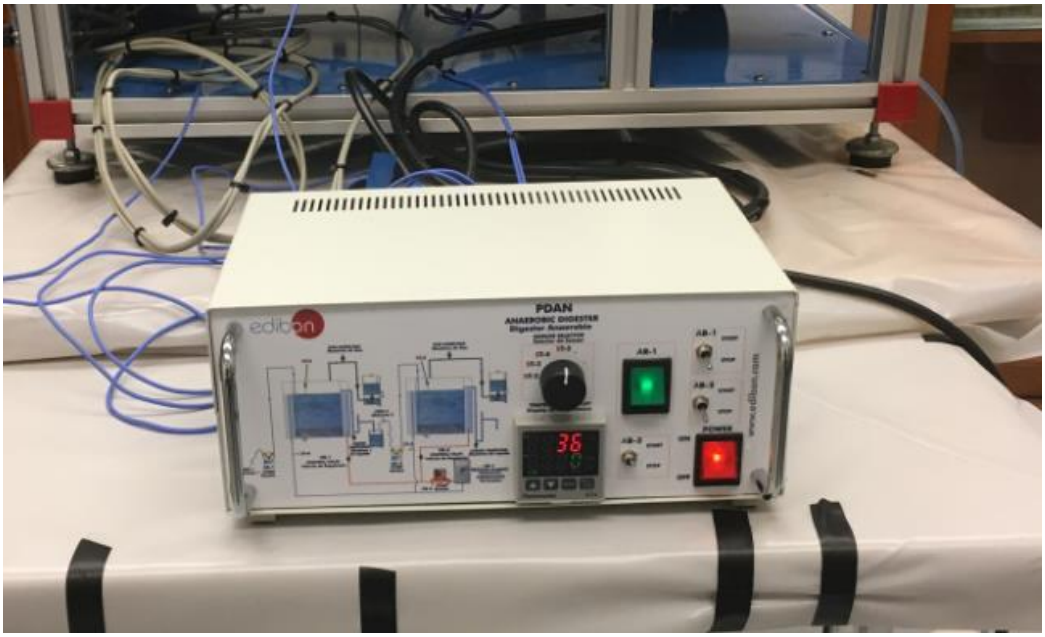


Figure 10: The PDAN anaerobic digester controller for temperature and heating

After the sample was monitored for production and composition of biogas for a period of 30 days, the digestate was unloaded using the valve shown in Figure 11 in 2-L sample bottles which were then transferred to a 10-L bottle for ultimate disposal by FAU Environmental Health and Safety officials. When the digestate was completely transferred into disposal containers, the reactors were chemically cleaned by unlocking them from the unit and filling each reactor with warm water mixed with 10-mL of liquid bleach to completely disinfect the glass reactors. Then after rinsing off the bleach solution, the reactors were locked back into place, the same way as described earlier to perform the next set of experiments.

2.3 Ultimate Sludge Digestibility

Following the method of Pavlosthasis (2010), borosilicate clear glass bottles of 250-mL (Figure 11) were used as mini anaerobic digester reactors.

1

2

Figure 11: (1) Glass bottles used as anaerobic digester reactors; (2) mixed samples in a water bath maintained at 35°C; (3) monitoring for gas production

The sample of organic waste feedstock was poured into a 250-mL bottle at a ratio of 1:2–1:10 by mixing with primary sludge seed. Before sealing, samples were purged with nitrogen gas to eliminate any oxygen present during loading. Bottles were then sealed airtight with an aluminum cap and rubber septum using a crimping tool. Then the caps were further sealed using a layer of parafilm wrap along the joint. Samples were mixed by inverting 5 times and then incubated at 35°C by two 200-W submersible aquarium heaters (Figure 12) in a large tank.

Figure 12: Submersible aquarium heater (200-W)

Bottles were carefully inverted 2 times once every day to mix the contents. Throughout the incubation period, total gas volume and composition (% CH_4) were measured weekly. The total gas volume was measured by inserting a 18 G × 1.5 inches (1.2 mm × 40 mm) disposable Blunt

fill needle into the rubber septum (Figure 13, 1) and attaching a balloon to the open end of the needle (Figure 13, 2 and 3). The end of the needle was sealed, and the collected gas from the bottles was weighed on a scale (Weighmax-2822-75LB) to the nearest hundredth of a gram. The weight of the balloon (1.72 g) and weight of the needle (1.30 g) was subtracted from the total weight to record the amount of biogas produced in grams. Next, the balloon along with the syringe was attached to the Landtec GEM 5000 (Figure 13, 4) air collection pipe to determine the gas composition. At the end of the incubation period, pH, temperature and volatile solids destruction was determined. The pH and temperature of the digester was measured weekly or biweekly using a HACH sensION3 digital meter and probe (sension Platinum series pH electrode with temperature probe), and the temperature of the water bath was constanlty checked by a thermometer in the tank.

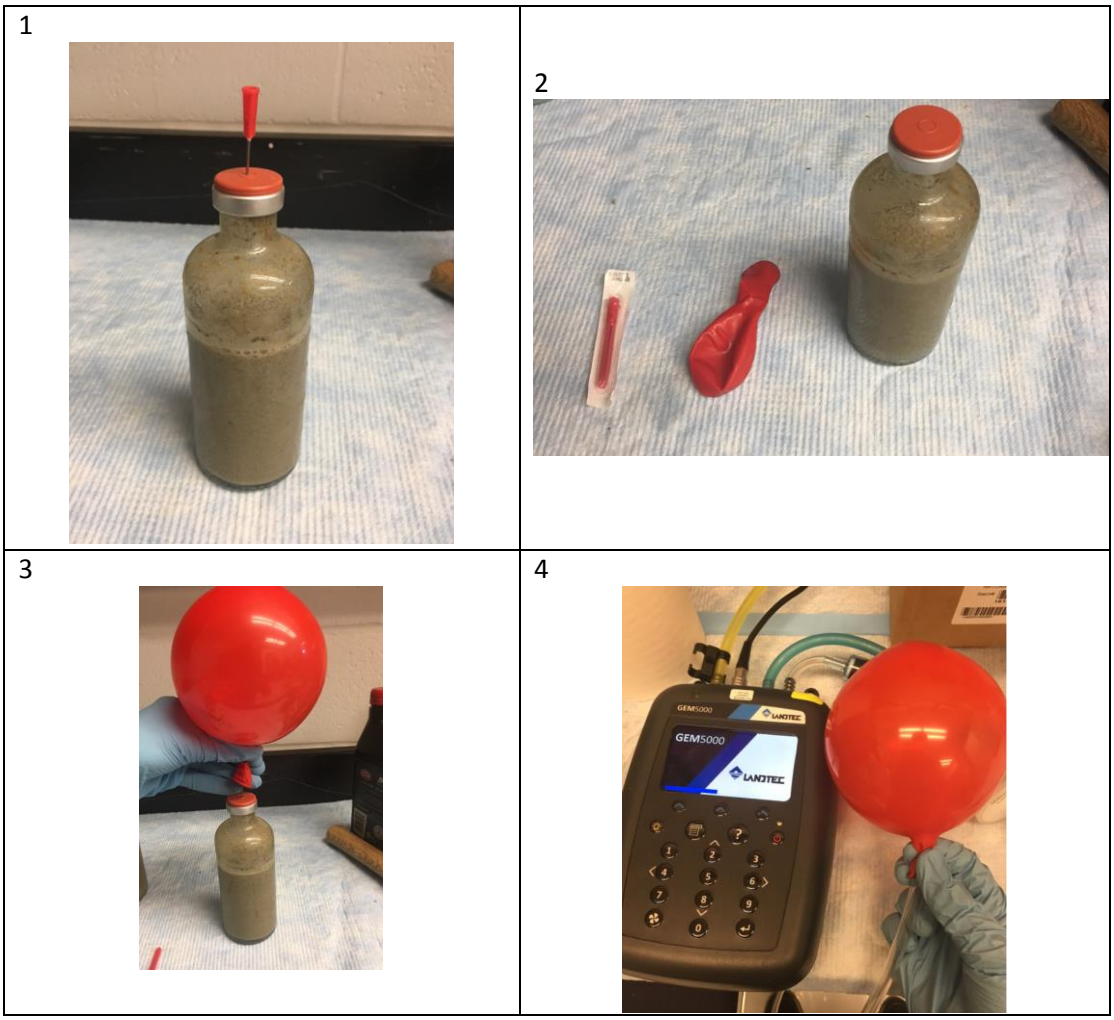


Figure 13: (1) Glass bottle with syringe and FOG sample mixed with primary sludge on Day 14; (2) syringe along with the balloon and glass bottle with FOG sample mixed with primary sludge; (3) balloon fixed over the bottle manually with the syringe over the glass bottle to transfer the biogas from the glass bottle for measurement, and (4) using a Landtec GEM 5000 for measuring the biogas composition

2.4 Analyses

The following parameters were measured during the course of the anaerobic digestion testing described in the earlier sections:

- Temperature (°C)
- pH (standard units)
- Volatile solids (g) and VS destruction (%)
- Quantity of gas (Lpd)
- Composition of gas (ppm)
- Alkalinity

2.4.1 Temperature

In anaerobic digestion, temperature is important in determining the rate of digestion, particularly the rate of hydrolysis and methane formation (Komilis et al. 2017). In anaerobic digestion at the mesophilic temperature range, which takes place around 37–41°C as controlled by the PDAN controller box (Figure 14) or at ambient temperature between 20–45°C was maintained by using a thermostatic bath as shown in Figure 15. In the ultimate sludge digestibility test, the temperature was measured by thermometer.

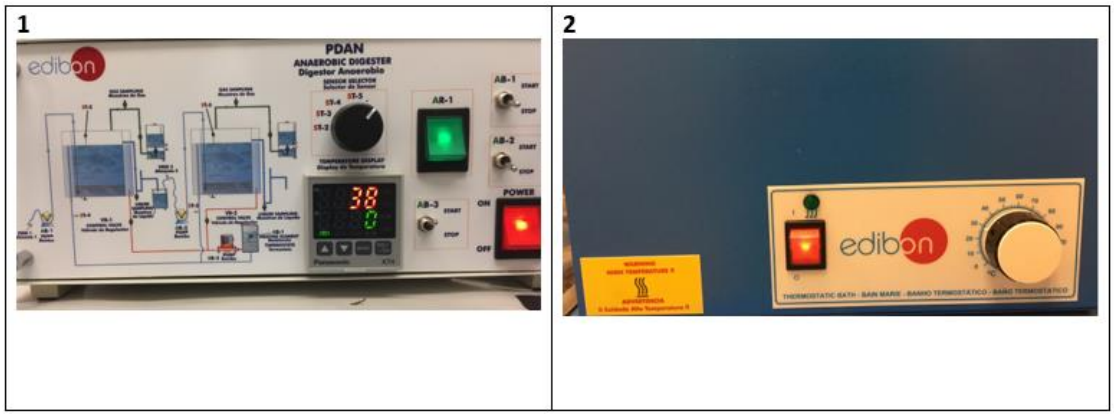


Figure 14 (1) Anaerobic digester electronic console and (2) temperature controller for thermostatic bath

Figure 15: Thermostatic bath with water heater inserted and circulating water

2.4.2 pH

The pH was measured using a HACH sensION3 digital meter and probe (sension Platinum series pH electrode with temperature). Probes were calibrated periodically with standard 3-point calibration buffer (4, 7,10), then rinsed with deionized water and dried with Kim wipes in between sample readings. For the PDAN unit, 10-mL samples were removed using a sample port (Figure 16) and then the pH was checked on a daily basis for each reactor separately. For ultimate sludge digestibility, the pH was checked before digestion and once again after the sample SRT was completed and tested for biogas production and composition (Figure 17).

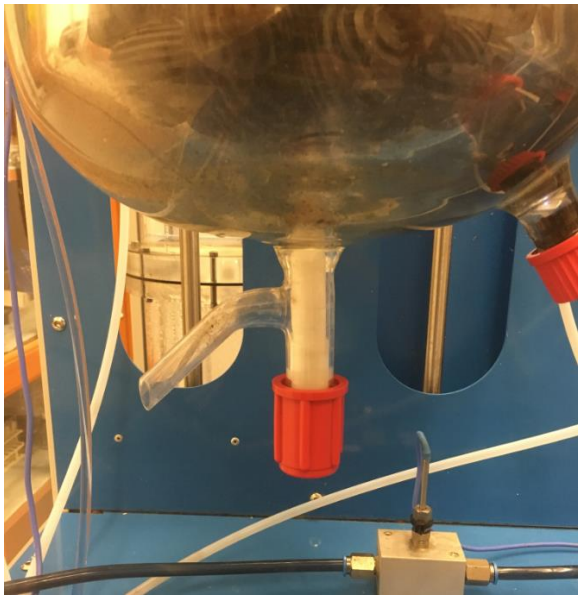


Figure 16: Sampling port for checking pH in the PDAN unit

Figure 17: Checking the pH of the FOG sample mixed with primary sludge (1:2) on day 7

2.4.3 Volatile solids (g) and VS destruction (%)

Method 1:

The degree of stabilization is often measured by the percent reduction in volatile solids (Metcalf and Eddy 2014). The reduction in volatile solids can be related either to the solids retention time or hydraulic detention time based on the untreated sludge feed. The number of volatile solids destroyed in a batch digester can be estimated by the following empirical formula.

$V_d = 13.7 \ln (SRT) + 18.9$

Where V_d = Volatile solids destruction %

SRT = time of digestion, days

Method 2:

Using about 25 to 50 g sample aliquots, the samples were stirred to homogenize and placed on a prepared evaporating porcelain dish (100-mL capacity diameter = 90 mm). Each sample was covered with a watch glass, weighed to the nearest 0.01 g, and the weight of the samples were recorded ("W_{sample}"). The evaporating dishes containing the sample were then placed in the drying oven (VWR Model-1300U) at 105-155°C for 24 hours (Method 1684, EPA 2001). To find the percent total solids, the following equation was used:

$$\%\, Total\ Solids = \frac{W_{total} - W_{dish}}{W_{sample} - W_{dish}} \times 100\% \qquad \textbf{Equation 1}$$

Where W_{dish} = weight of dish (g)

W_{sample} = weight of wet sample and dish (g)

W_{total} = Weight of dried sample and residue (g)

To find the percent volatile solids, the following equation was used:

$$\%\, Volatile\ Solids = \frac{W_{total} - W_{volatile}}{W_{sample} - W_{dish}} \times 100\% \qquad \textbf{Equation 2}$$

Where $W_{volatile}$ = weight of residue and dish after ignition (g)

2.4.4 Volatile Fatty Acids

Volatile fatty acids (VFAs) were measured using the Waters 2487 Dual λ absorbance detector (Figure 18), Waters 1515 Isocratic Pump (Figure 19), and with an Atlantis T3 Column, 100 A, 3µm (4.6×100 mm) (Figure 20). The detector and the pump are controlled by the Waters Empower system software. To achieve the desired results, phosphoric acid (1.2 mL/L) in the mobile phase was chosen. The eluent flow was set to 0.5 mL/minute.

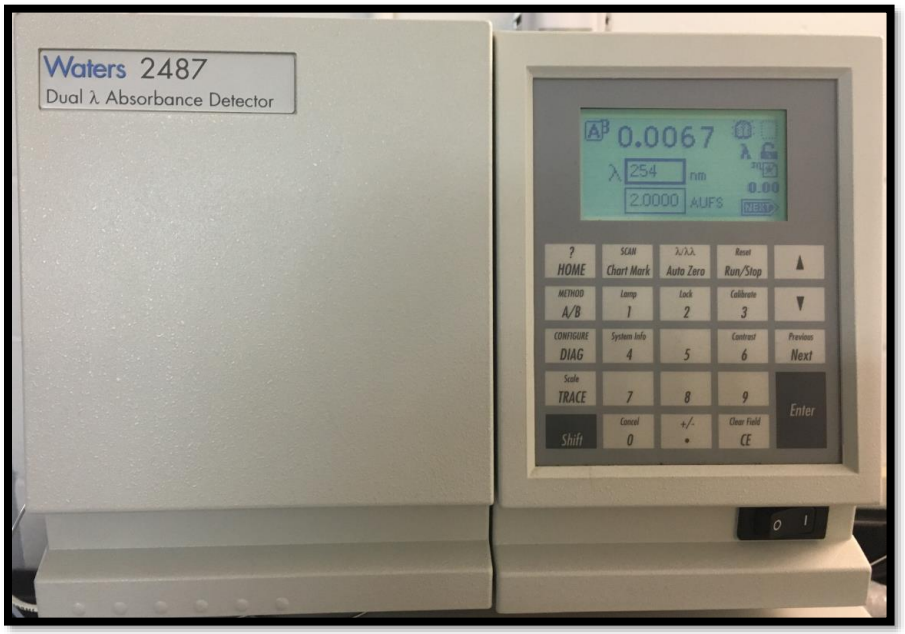


Figure 18: Waters 2487 dual absorbance detector

Figure 19: Water 1515 isocratic HPLC pump

Figure 20: Atlantis T-3 column

The sample to be tested was loaded manually to the injector port (Figure 21) using a Rheodyne 10-µL syringe (Figure 22)

Figure 21: Sample injector

Figure 22: Manually loading the sample in HPLC pump

The identification of individual compounds in the sample is achieved by its retention time (the time it takes for that specific compound to elute from the column after injection), as demonstrated in Figure 23.

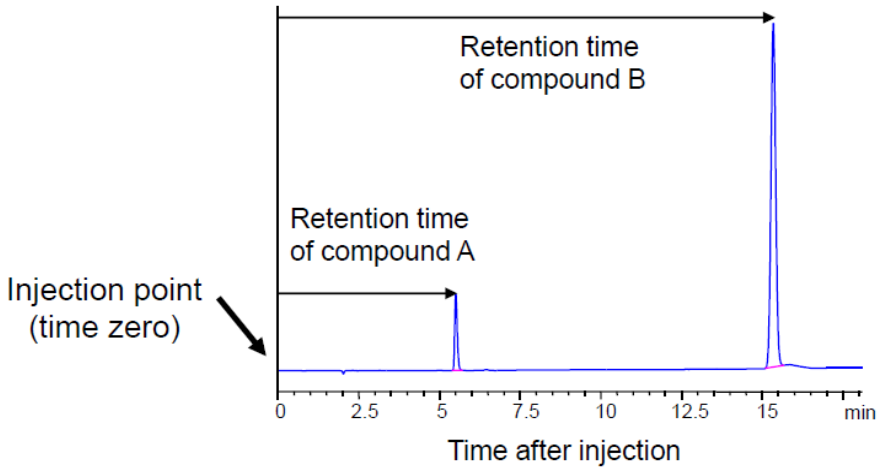


Figure 23: Identification of individual compounds

2.4.5 Biogas Production

During preliminary tests using the PDAN anaerobic digester, the total gas production was measured (mL) by displacement of water in the volumetric tanks as described earlier (refer to Figure 9). The volumetric tank is completely filled with water, and the caps on the top were tightly sealed. The biogas displaced the water into the second volumetric tank attached to the bottom. To measure the biogas during the ultimate sludge digestibility testing (Figure 24), the gas was collected in a balloon by using a needle, as described previously and shown in Figure 24,1. The balloon containing the biogas was then weighed on a scale to the nearest hundredth of a gram, as described earlier and shown in Figure 24(1, 2 and 3). As the gas was measured in grams, it was converted to m^3 by first converting g to kg by dividing by 1000 and then to m^3 by dividing it by the density of biogas which is 1.15 kg/m^3 at 28-30°C.

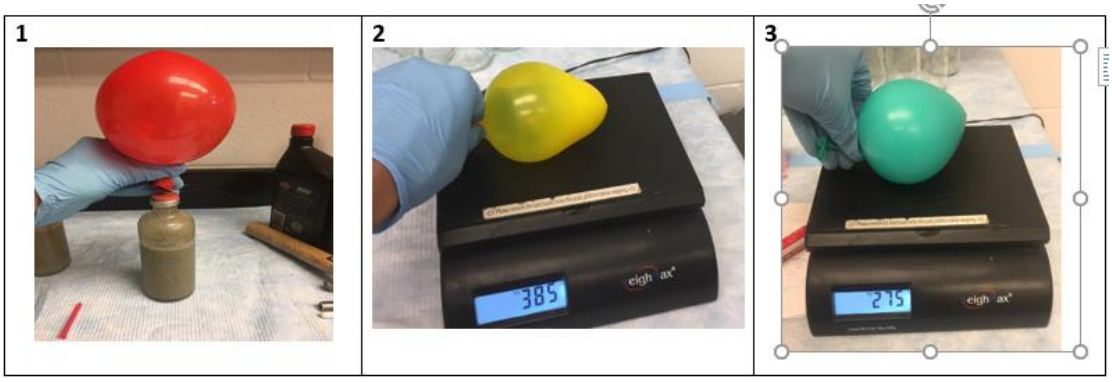


Figure 24: (1) Transferring biogas from the glass bottle to the balloon; (2) & (3) weighing the balloon after collection of gases

2.4.6 Composition of Biogas

The composition of the biogas was measured using a Landtec Gem5000 (Figure 25). The instrument is designed specifically for use at landfills to monitor landfill gas (LFG) collection and control systems. The unit samples and analyzes the methane, carbon dioxide and oxygen content of landfill gas with options for additional analysis. The equipment is calibrated with certified calibration gas available in either 29 L, 34 L or 58 L gas canisters, supplied with the Landtec calibration kit. For gas analysis, the calibration options can be found by selecting the 'Menu' key followed by soft-key 'Operation Settings'. Select 'Key 2 – Gas Check' then follow the instructions on the analyzer screen by selecting 'Key 2 – Gas Check' (Figure 26).

Figure 25: Landtec GEM5000

Figure 26: Gas analyzer screen

The biogas composition was checked by inserting the rubber tube from the Landtec device (Figure 27) inside the balloon containing the total amount of biogas produced by each bottle. The biogas composition was checked by repeating the same procedure as stated earlier.

Figure 27: Landtec GEM 5000 checking the biogas composition

2.4.7 Alkalinity

For the total alkalinity measurements, SM 2320B titration method (Hach Method 8203, EPA approved, equivalent of SM 2320B) with a Hach digital titrator was used. A sample volume of 100-mL was selected with a dilution ratio of 100. The Hach digital titrator was loaded with a 1.600 N H_2SO_4 titrant cartridge for all analyses. After pouring the sample into a clean 250-mL flask, one phenolphthalein indicator powder pillow was added. If the sample turned pink, titrant was added until the phenolphthalein endpoint was reached (pink to clear), if necessary. The reading on the digital titrator was recorded as corresponding to the phenolphthalein alkalinity in mg/L as $CaCO_3$ by multiplying the dilution factor by the number of digits. No phenolphthalein alkalinity was measured during any of the experiments, meaning that all alkalinity was in the form of bicarbonate ion. Then the Bromcresol Green-Methyl Red indicator was added to the sample, and again titrant was added until the second endpoint was reached (blue-green to light pink). This is the Bromcresol Green Methyl-Red alkalinity. The total digits required to reach the final end point were multiplied by the dilution factor (100) and the digit multiplier of 1. This value corresponded to the total alkalinity.

2.5. Stakeholders

In the event that the results of the experiments would show enhanced biogas production and elevated methane content when using waste feedstocks, the next step would be to conduct a field scale pilot test. In order to explore this scenario, a stakeholder task force was created consisting of solid waste facility managers, waste facility managers, waste/septage haulers, wastewater utilities, food waste generators, end users of methane, and regulators from the Florida Department of Environmental Protection (FDEP).

Participating stakeholders included the following:

- **Utilities:**
    - Mark Eyeington (Chief Operating Officer, Solid Waste Authority of Palm Beach County)
    - Don Kree (Quality Control Manager, Utility Services Department, Boca Raton)
    - Steve Roberge (Waste Water Treatment Plant Superintendent, Utility Services, Boca Raton)
    - David Gregory (Section Manager, Orange County Utilities Department)
    - David Dalton (O&M Water Reclamation Manager, Palm Beach County Water Utilities)
    - Darren Hollifield (Assistant Director of Public Utilities, West Palm Beach)
    - Nate Mayer (Director of Land Management, Solid Waste Authority of Palm Beach County)
    - Scott Trainor (Biosolids Facility Operations Manager, Solid Waste Authority of Palm Beach County)
- **Regulators:**
    - Amede Dimonnay (Florida Department of Environmental Protection)
    - Karen Moore (Environmental Administrator, Florida Department of Environmental Protection)
    - Hannan Reynolds (Environmental consultant, Florida Department of Environmental Protection)
    - Hope Thigpen (Environmental Planner, Florida Department of Environmental Protection),
    - Jane Gregory (Environmental Program Supervisor, Orange County)
- **Commercial Generators:**
    - Michael W. Hewett (Director of Environmental and Sustainability Programs, Publix)
    - Kim Brunson (Recycle and Solid Waste Program Manager, Publix)
    - John Culver (Sustainability Program Manager-Orange County Convention Center at Orange County government, Orlando, FL)
    - Lanette Sobel (Managing Partner of Fertile Earth Worm Farms)
    - Karen Doyle (Senior Maintenance and Facility Manager, Whole Foods Market, Florida Region)
- **Consultants:**
    - Paul A. Pitt (Vice President & Wastewater Process Design Director, Hazen and Sawyer)
    - Alonso Griborio (Senior Associate & Director of Clarification Technology, Hazen and Sawyer)
    - Nandita Ahuja (Assistant Engineer, Hazen and Sawyer)
- **End Users of Methane**
    - Robert Flynn (NEFCO)
- **Haulers:**
    - Carrie Woodward (Sales Manager, Republic Services, West Palm Beach)
    - Leslie Nelson (Territory Account Manager, Republic Services West Palm Beach)

Questions selected for the stakeholders were as follows:

1) Who are the major contributors to food waste in Florida, and who might be major users of biogas?
2) Who are the success stories of food waste diversion to anaerobic digestion for energy production?
3) What are the major regulatory issues/roadblocks/incentives/policies that should be considered regarding organics processing?
4) How can we overcome the major challenge of contamination of food waste at different levels? (pre-and post-consumer)?
5) How can the infrastructure for waste hauling companies be improved for collecting food waste (residential vs commercial)?
6) What are the major food waste components that produce more biogas and higher methane content?

A video conference call was attended by Karen Moore, Hope Thigpen, Christopher Perry and Shannan Reynolds from FDEP (Florida Department of Environmental Protection), and 3 stakeholders answered our questions previously by email.

3. RESULTS AND DISCUSSION

Alternative feedstocks were collected and characterized for their potential to stimulate biogas production and methane generation in a mesophilic anaerobic digestion process. The anaerobic digestibility and biogas/methane yields were evaluated using a batch anaerobic digestion test performed at 35°C. In the first phase of the experiment, the co-digestion of food waste with sewage sludge seed was studied in batch experiments using the PDAN reactor with a seed to feedstock ratio of 2:3 (v:v). In the second phase of the experiment, the ultimate sludge digestibility test was used.

3.1 PDAN Anaerobic Digester Results

3.1.1 Preliminary Testing of Mixed Food Waste in PDAN

During the first phase of this experiment, different kinds of food waste were tested as summarized in Table 5**: Composition of food waste for preliminary testing**

Type	**Weight (g)**	**Weight Fraction (%)**
Tomato	210	22%
Banana peels	185	19%
Carrots	167	17%
Potato peels	136	14%
Basil leaves	130	13%
Cauliflower	110	11%
Cucumber	40	4%
Total	978	100%

The food waste was mixed with 4% primary sludge and investigated between May and July 2017, in which pH, temperature, volatile solids reduction and quantity of biogas were monitored. Figure 28 and Figure 29 show the preliminary experiment change in pH and quantity of biogas produced by both the reactors, respectively. In reactor 1, the pH was not stable, and biogas production completely stopped by the end of the 20 days, so sodium bicarbonate 8.6 g/100 mL was added to the reactor because the proper pH was not maintained for the microorganisms to exist (i.e. reactor "soured"). In reactor 2, the pH was relatively stable (6.8–7.2), and the biogas production kept on increasing until day 29, but on day 30, there was a 0.5-pH unit decrease.

.

Table 5: Composition of food waste for preliminary testing

Type	Weight (g)	Weight Fraction (%)
Tomato	210	22%
Banana peels	185	19%
Carrots	167	17%
Potato peels	136	14%
Basil leaves	130	13%
Cauliflower	110	11%
Cucumber	40	4%
Total	978	100%

The food waste was mixed with 4% primary sludge and investigated between May and July 2017, in which pH, temperature, volatile solids reduction and quantity of biogas were monitored. Figure 28 and Figure 29 show the preliminary experiment change in pH and quantity of biogas produced by both the reactors, respectively. In reactor 1, the pH was not stable, and biogas production completely stopped by the end of the 20 days, so sodium bicarbonate 8.6 g/100 mL was added to the reactor because the proper pH was not maintained for the microorganisms to exist (i.e. reactor "soured"). In reactor 2, the pH was relatively stable (6.8–7.2), and the biogas production kept on increasing until day 29, but on day 30, there was a 0.5-pH unit decrease.

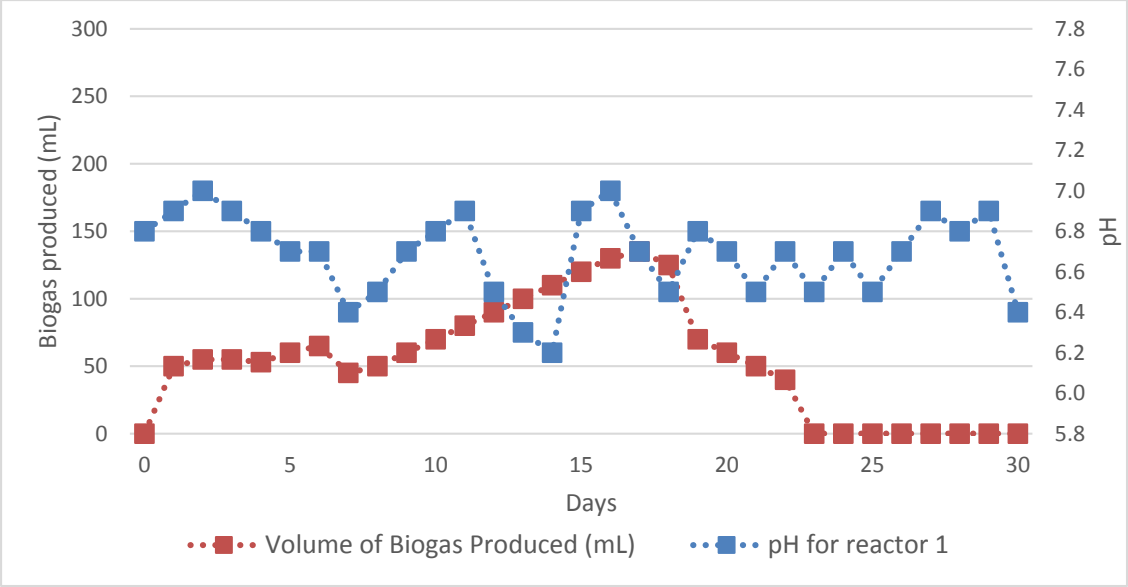


Figure 28: Measured pH and volume of biogas in reactor 1 in 30 days

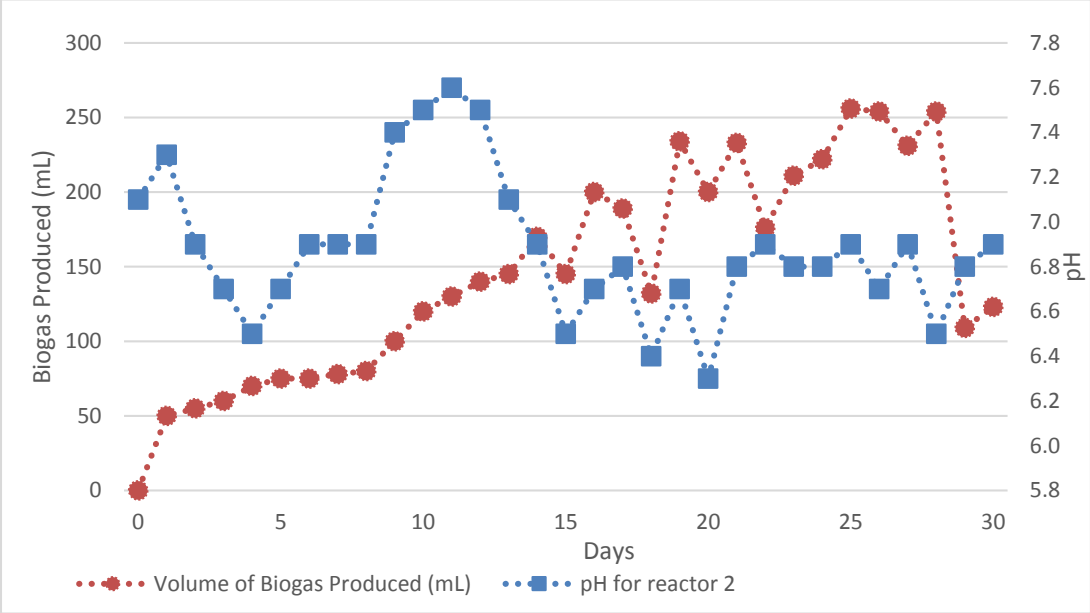


Figure 29: Measured pH and volume of biogas in reactor 2 in 30 days

3.1.2 Preliminary Testing of Meat in PDAN

In Figure 30, biogas production for primary sludge:meat (1:2) started immediately on day one for both reactors with over 0.0012 m^3 of gas in approximately over one week. The biogas production reached its peak value on day 17 for reactor 1 and day 12 for reactor 2.

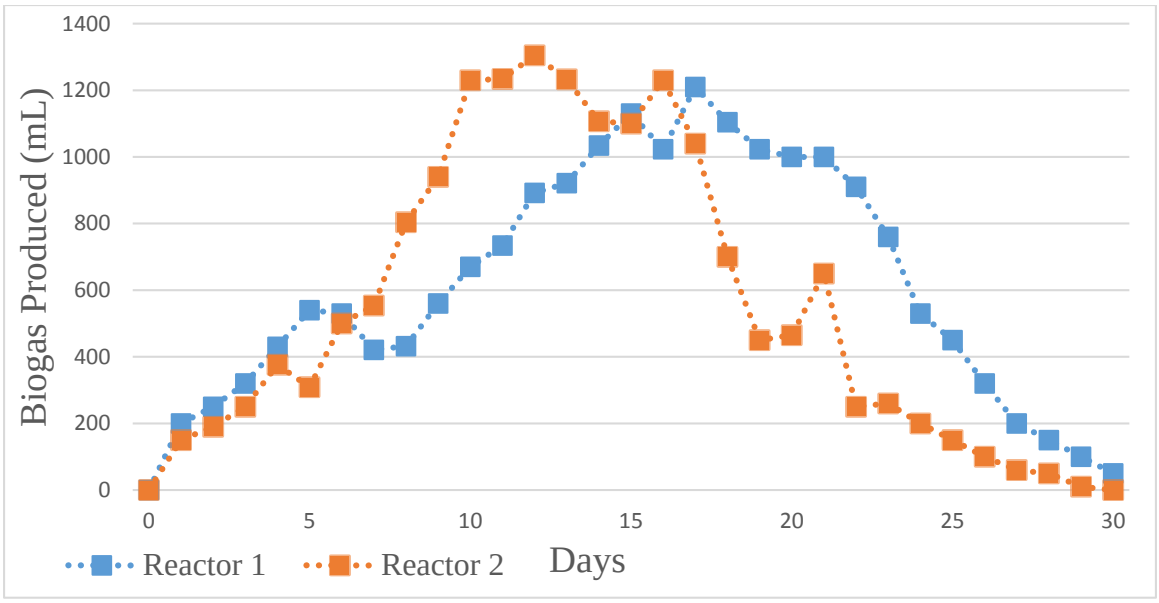


Figure 30: Biogas produced in the anaerobic digester in 30 days for meat

In Figure 31, the biogas production for the control with 4% primary sludge only shows that the biogas production increased in the first three weeks for both reactors, with reactor 1 reaching its peak on day 16 and for reactor 2 on day 20. Compared to the control with only primary sludge solids (900-1000 mL), meat feedstock (1210-1305 mL) increased the maximum biogas production by an average of 40%.

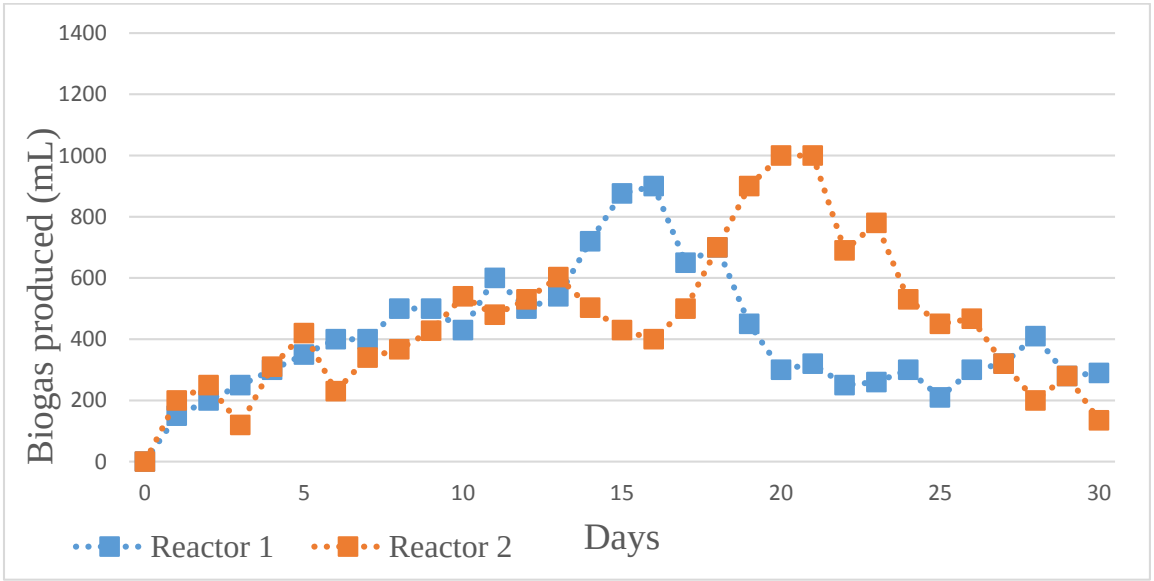


Figure 31: Biogas produced in the anaerobic digester in 30 days for primary sludge (4% solids)

Table 6 shows the solids retention time for maximum biogas yield attained in each type of waste selected for testing in the anaerobic digester. The maximum biogas production was seen in reactor 2 (meat) with the least SRT (12 days).

Table 6: Summary of maximum solid retention time and biogas produced for all the different ratios.

Type of Waste	SRT	Biogas Produced (mL)	Biogas Production Rate (mL/d)
Reactor 1 (Food waste)	16	130	8.1
Reactor 2 (Food waste)	25	175	7.0
Reactor 1 (Meat)	17	1250	73.5
Reactor 2 (Meat)	**12**	**1350**	**112.5**
Reactor 1 (Primary sludge)	16	950	59.4
Reactor 2 (Primary sludge)	20	1090	54.5

Meat had lower SRT, and biogas production was higher as compared to FW and controls, as there was leakage detected in the pipework connecting the reactor to the volumetric tanks while food waste samples were being tested, which limited the ability of this experiment to make conclusive findings. Many attempts at rectifying the leaks and managing the problem led to lengthy delays because the glasswork had to be sent for repairs to a specialist. To reduce downtime in the PDAN reactor, it was decided to run ultimate sludge digestibility tests.

3.2 Ultimate Sludge Digestibility Results

3.2.1 Short SRT Experiments

The first set of digestibility tests was carried out for up to 28 days. At an organic loading rate of 0.7 to 1.8 kg VS/m^3/day. The volume of material in each bottle was 200-mL. At the end of the incubation period, the pH was measured between 5.5 to 6.0. The results of the primary sludge:FOG slurries in the different ratios (1:2, 1:5, 1:10) are shown in

Table **7**, for different SRT at mesophilic temperatures (26-35°C). The maximum methane production was recorded on day 28 with a value of 0.5 m^3/kg VS at 1:10.

Table 7: Summary of the methane produced and its composition for SRT =7, 14, 21, and 28 days for primary sludge: FOG in 1:2, 1:5, 1:10 ratios

SRT days	Ratio (Primary sludge: FOG)	Initial pH	Final pH	Methane (m^3/kg VS)	Methane %	Temperature °C
7	1:2	6.9	6.7	0.008	11	34
7	1:2	7.0	6.8	0.014	13	33
7	1:2	7.2	6.7	0.010	12	32
7	1:5	6.8	5.9	0.022	13	33
7	1:5	6.6	6.1	0.010	14	33
7	1:5	6.7	5.6	0.015	11	29
7	1:10	6.9	6.4	0.019	14	30
7	1:10	7.2	6.9	0.019	13	30
7	1:10	7.0	7.1	0.013	16	31
14	1:2	6.7	6.5	0.058	25	30
14	1:2	6.8	6.5	0.079	26	32
14	1:2	7.0	6.4	0.055	26	34
14	1:5	6.5	5.9	0.077	21	35
14	1:5	6.5	6.1	0.074	24	32
14	1:5	6.8	5.8	0.081	23	34
14	1:10	6.8	6.3	0.058	27	32
14	1:10	6.7	6.5	0.066	26	33
14	1:10	7.0	6.9	0.066	29	32
21	1:2	6.0	5.5	0.186	33	32
21	1:2	6.7	5.6	0.190	32	33
21	1:2	7.0	6.1	0.181	36	35
21	1:5	6.5	5.4	0.202	39	30
21	1:5	6.7	5.8	0.214	36	33
21	1:5	6.8	5.8	0.235	35	32
21	1:10	6.7	5.2	0.226	38	33
21	1:10	6.9	5.3	0.242	37	33
21	1:10	6.7	5.5	0.184	35	29
28	1:2	6.0	5.5	0.279	41	32
28	1:2	6.7	5.6	0.384	52	33
28	1:2	7.0	6.1	0.322	55	35
28	1:5	6.5	5.4	0.332	56	30
28	1:5	6.7	5.8	0.327	52	33
28	1:5	6.8	5.8	0.437	54	32
28	1:10	6.7	5.2	0.367	57	33
28	1:10	6.9	5.3	0.343	51	33
28	**1:10**	**6.7**	**5.5**	**0.500**	**59**	**29**

Table 8 shows the difference in initial and final pH of the different ratios selected for meat mixed with primary sludge (1:2, 1:5, 1:10) and the cumulative amount of methane produced (m^3/kg VS) during SRT = 7, 14, 21 and 28 days. It shows the total percentage of methane gas produced for different SRT at mesophilic temperature (26-35°C). The maximum production for primary sludge to meat (1:10) was on day 28 with a maximum production reaching 0.18 m^3/kg VS.

Table 8: Summary of the total gas produced and its composition for SRT =7, 14, 21, and 28 days for primary sludge: meat in 1:2, 1:5, 1:10 ratios

SRT days	Ratio (Primary sludge: meat)	Initial pH	Final pH	Methane (m^3/kg VS)	Methane %	Temperature °C
7	1:2	7.2	7.1	0.007	14	30
7	1:2	6.9	6.7	0.007	16	32
7	1:2	6.7	6.2	0.007	13	34
7	1:5	6.2	5.5	0.009	12	34
7	1:5	7.0	6.9	0.009	11	35
7	1:5	6.5	5.9	0.007	9	35
7	1:10	6.7	5.7	0.005	10	33
7	1:10	6.7	6.8	0.010	13	30
7	1:10	6.2	5.6	0.008	9	32
14	1:2	6.2	5.6	0.066	29	34
14	1:2	7.1	6.9	0.022	21	32
14	1:2	7.0	6.8	0.026	22	31
14	1:5	6.7	5.4	0.018	19	33
14	1:5	7.0	6.9	0.026	16	32
14	1:5	6.5	5.9	0.039	25	33
14	1:10	6.8	6.4	0.028	20	35
14	1:10	7.0	6.2	0.017	17	30
14	1:10	6.2	5.6	0.023	19	31
21	1:2	6.2	5.2	0.032	26	34
21	1:2	7.1	5.3	0.054	31	32
21	1:2	7.0	6.4	0.068	36	31
21	1:5	6.7	5.4	0.089	37	33
21	1:5	7.0	6.5	0.085	31	32
21	1:5	6.5	5.2	0.089	32	27
21	1:10	7.2	6.7	0.084	32	37
21	1:10	6.2	5.6	0.069	33	29
21	1:10	7.0	6.4	0.095	39	26
28	1:2	6.2	5.2	0.135	49	34
28	1:2	7.1	5.3	0.109	45	32
28	1:2	7.0	6.4	0.120	43	31
28	1:5	6.7	5.4	0.139	42	33

SRT days	Ratio (Primary sludge: meat)	Initial pH	Final pH	Methane (m^3/kg VS)	Methane %	Temperature °C
28	1:5	7.0	6.5	0.145	48	32
28	1:5	6.5	5.2	0.171	56	27
28	1:10	7.2	6.7	0.138	55	37
28	**1:10**	**6.2**	**5.6**	**0.173**	**59**	**29**
28	1:10	7.0	6.4	0.129	54	26

In Figure 32, the methane produced (m^3/kgVS) for different SRT = 7, 14, 21 and 28 days and ratios are compared for meat with primary sludge along with control (200 mL primary sludge only with no feedstock added). For waste meat feedstock, the ratio of 1:10 demonstrated higher methane production and methane percentage as compared to others, and 2 times the production when compared to the control sample. The typical values for methane production reported by Metcalf and Eddy (2003) are 0.35 – 0.50 m^3/kg VS for high rate, mesophilic anaerobic digestion. The range is depicted on Figure 33-36 using a shaded box.

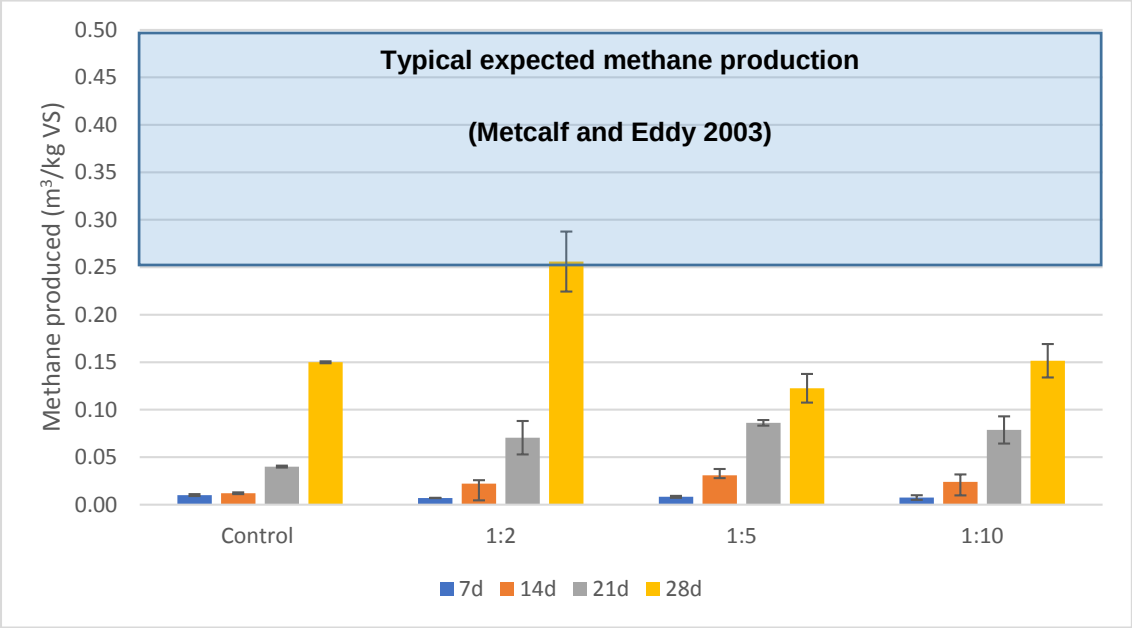


Figure 32: Methane produced for meat mixed with primary sludge for solids retention time up to 28 days

In Figure 33, the methane produced (m^3/kgVS) for different SRT = 7, 14, 21 and 28 days and ratios are compared for FOG with primary sludge along with controls (200 mL primary sludge only with no feedstock added). For FOG feedstock, the ratio of 1:10 demonstrated higher methane production and methane percentage as compared to others, although there was not much difference in the ratios tested. Similarly, to the meat, the FOG feedstock generated a 2 to 3-fold increase in biogas production compared to the control, and both food-related waste feedstocks generated 0.17-0.43 (m^3/kgVS) of biogas after 28 days.

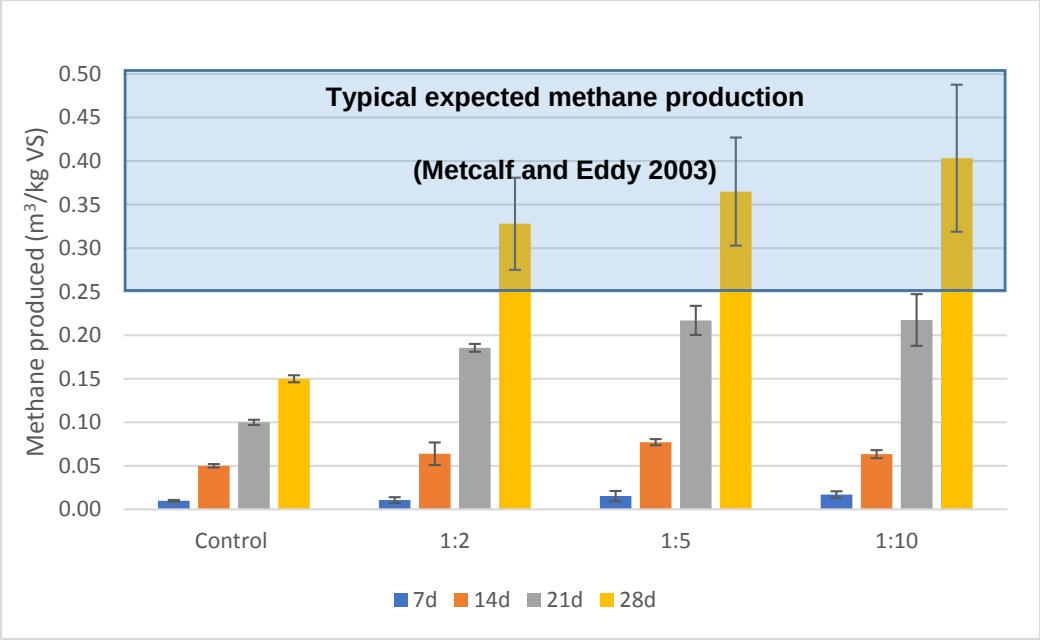


Figure 33: Methane produced for FOG mixed with primary sludge in different ratios for solid retention time of 28 days

3.2.2 Extended SRT Experiments

After conducting the first set of ultimate sludge digestibility experiments, the methane production was still increasing on the last day (SRT=28 days), so it was desired to extend the SRT beyond 28 days. So, a second batch was prepared using two different ratios of 1:4 and 1:7 in comparison with primary sludge controls to get the most reliable and most efficient ratio to maximize methane production by testing longer SRTs. In Figure 34, the methane production from meat and primary sludge for SRT = 14, 28, 42 and 56 days for ratios of 1:4 and 1:7 are compared to controls. The maximum methane production was observed for ratio 1:7 in 56 days (0.27 m^3/kg VS). This ratio generated 0.12 m^3/kg VS after 28 days, which is not more than was observed for 1:10 during the first experiment. Although direct comparisons cannot be made due to differences in the inoculum and feedstock composition between the two experiments, it is interesting to note that the 1:2 - 1:10 ratios achieved 0.12-0.26 m^3/kg VS in just 28 days of incubation. Therefore, the optimal ratio could be on the order of 1:1 – 1:3.

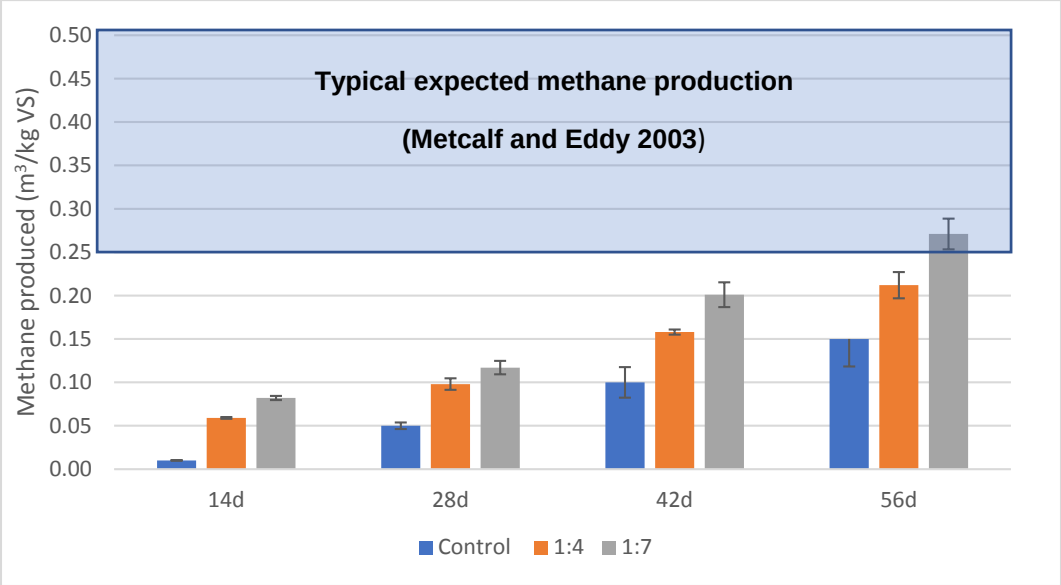


Figure 34: Methane produced for meat mixed with primary sludge in different ratios for solid retention time of 56 days

In Figure 35, the methane production from FOG and primary sludge for SRT = 14, 28, 42 and 56 days for ratios of 1:4 and 1:7 are compared to controls. The maximum methane production was observed for ratio 1:7 was in 56 days (0.43 m^3/kg VS). This ratio generated 0.29 m^3/kg VS after 28 days, which is not more than was observed for 1:10 during the first experiment. Again, although direct comparisons cannot be made due to differences in the inoculum and feedstock composition between the short SRT and extended SRT experiments, it is interesting to note that the 1:2 - 1:10 ratios previously achieved 0.33-0.40 m^3/kg VS in just 28 days of incubation. Therefore, the optimal ratio could be on the order of 1:10 or higher. Further investigation is required to determine the optimal ratio for FOG feedstocks in this scenario.

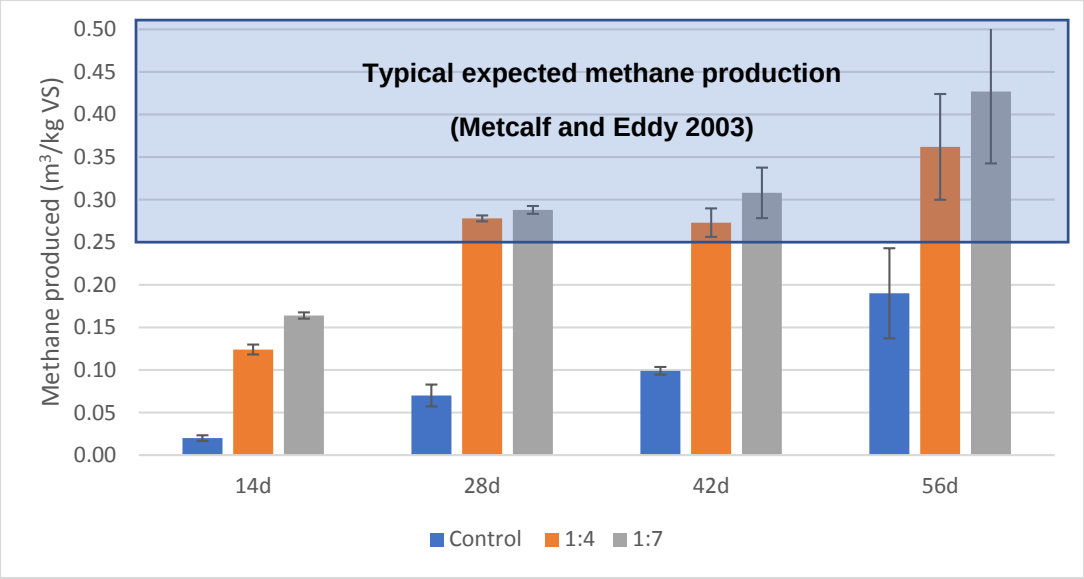


Figure 35: Methane produced for FOG mixed with primary sludge in different ratios for solid retention time of 56 days

Table 9 summarizes the maximum SRT, maximum methane production and volatile solids content for all the different feedstock ratios with meat and FOG.

Table 9: Summary of maximum solid retention time and volatile solids content for different ratios.

SRT	Ratio (FOG: 1° sludge)	Maximum methane production (m^3/kg VS)	Volatile solids (%)	Ratio (Meat: 1° sludge)	Maximum methane production (m^3/kg VS)	Volatile solids (%)
28	1:2	0.38	2.3	1:2	0.14	2.3
56	1:4	0.52	3.1	1:4	0.15	3.4
28	1:5	0.44	3.6	1:5	0.17	3.5
56	1:7	0.43	3.7	1:7	0.19	4.5
28	1:10	0.50	3.2	1:10	0.18	4.5

The maximum methane production was observed to be 28 days for the first batch (which was the longest SRT for that experiment) and 56 days for the second batch (which was also the longest SRT for that experiment). Comparison provides insights that longer SRTs and ratios higher than 1:10 should be investigated further for improving the methane yield.

3.2.3 Alkalinity

Table 10 summarizes the measurement of alkalinity for SRT = 56 days for meat and FOG (1:4 and 1:7). The alkalinity varied from 1250 – 2420 mg/L as $CaCO_3$ for meat and 2120 – 2690 mg/L as

$CaCO_3$. These values are relatively low compared a typical digester, which is reported to be on the order of 2000-5000 mg/L as $CaCO_3$ (Dong et al. 2009; Jiang et al. 2013; Zhang et al. 2013). These results suggest that alkalinity adjustment may be needed prior to initiating the ultimate sludge digestibility tests.

Table 10: Selected measurements of alkalinity for 56 days for meat and FOG (1:4 and 1:7)

	Alkalinity (mg/L)	
Ratio	**Meat**	**FOG**
1:4	2420	2300
1:4	1550	2500
1:4	2140	2690
1:7	1350	2560
1:7	2244	2300
1:7	1650	2120

3.2.4 Volatile Solids Destruction

In Figure 36, differences in volatile solids destruction among samples of meat were found within SRT = 7-28 days. The 1:10 ratio (primary sludge:meat) for day 21 and 28 shows the highest VS destruction (25-55%), and appears to continue to increase after a 2-3-week lag period.

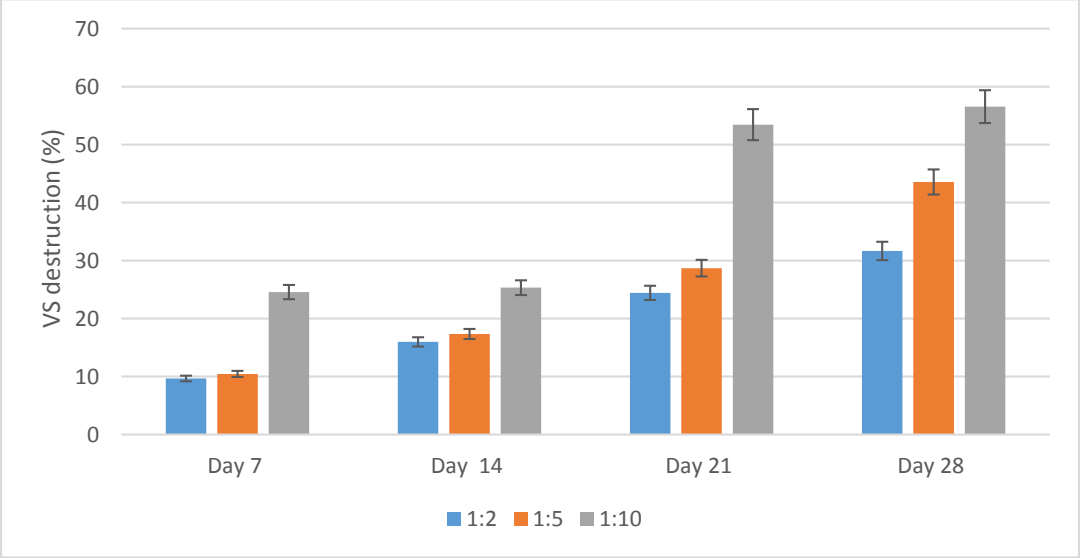


Figure 36: Volatile solids destruction for meat mixed with primary sludge at SRT = 7, 14, 21, and 28 days) for selected ratios

Figure 37 shows differences in volatile solids destruction among different ratios of FOG within SRT = 7-28 days. The 1:5 ratio (primary sludge:FOG) shows the highest VS destruction (25-55%), which means that the maximum value likely lies between 1:2 and 1:10. Also the trend is increasing, and thus it is likely that extending the SRT beyond 28 days would reveal higher volatile solids destruction and more thorough degradation.

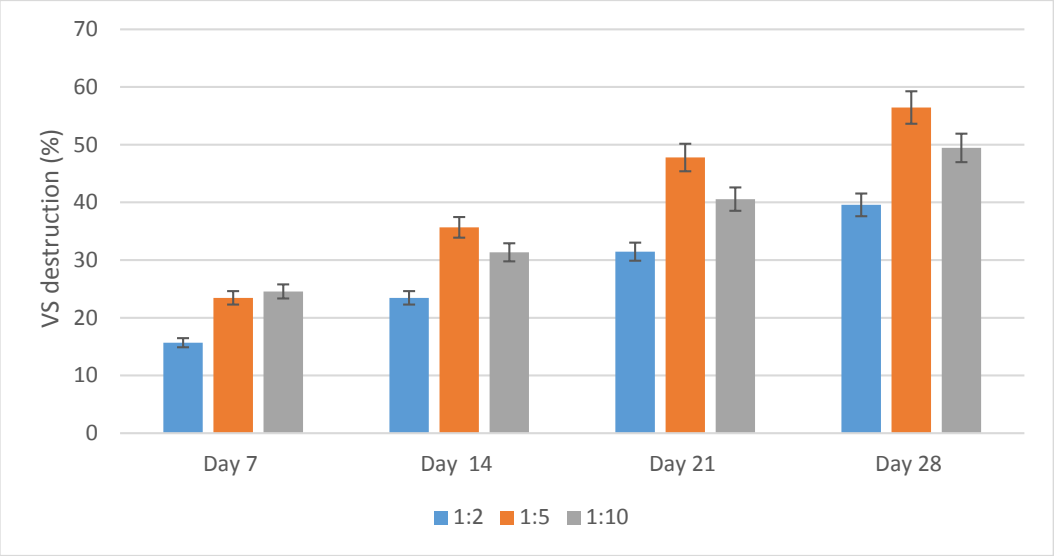


Figure 37: Volatile solids destruction for FOG mixed with primary sludge at SRT = 7, 14, 21, and 28 days for selected ratios

In the second batch of ultimate sludge digestibility experiments, SRT was doubled as compared to the first batch to study the biogas production trends over longer detention times. The difference between methane generation between 28 and 42 days is not very large. Therefore, it would be helpful to investigate the methane production daily for the period between 15-35 days (refer to Figure 34 and Figure 35), keeping in mind that 20-30 days is a typical SRT in the field.

As compared to Zhang (2008), who reported average volatile solids destruction of 81% after 28 days, the values reported here at SRT = 28 days were 10-15% lower. This is likely due to lack of continuous mechanical mixing and lack of acclimation of inoculum in our experiments. The typical expected methane yield for mesophilic anaerobic digesters is 0.23-0.58 m^3/kg VS according to Metcalf and Eddy (2003), and a summary of the recent literature is shown in Table 11 (Alvarez and Liden 2007; Sami and Sari 2009; Kabouris et al. 2009; El-Mashad and Zhang 2010; Li et al. 2011; Zhang et al. 2012; Wu et al. 2015; Yong et al. 2015).

Table 11: Summary of mesophilic anaerobic digestion of food-related feedstock operating parameters from previous work compared to this study

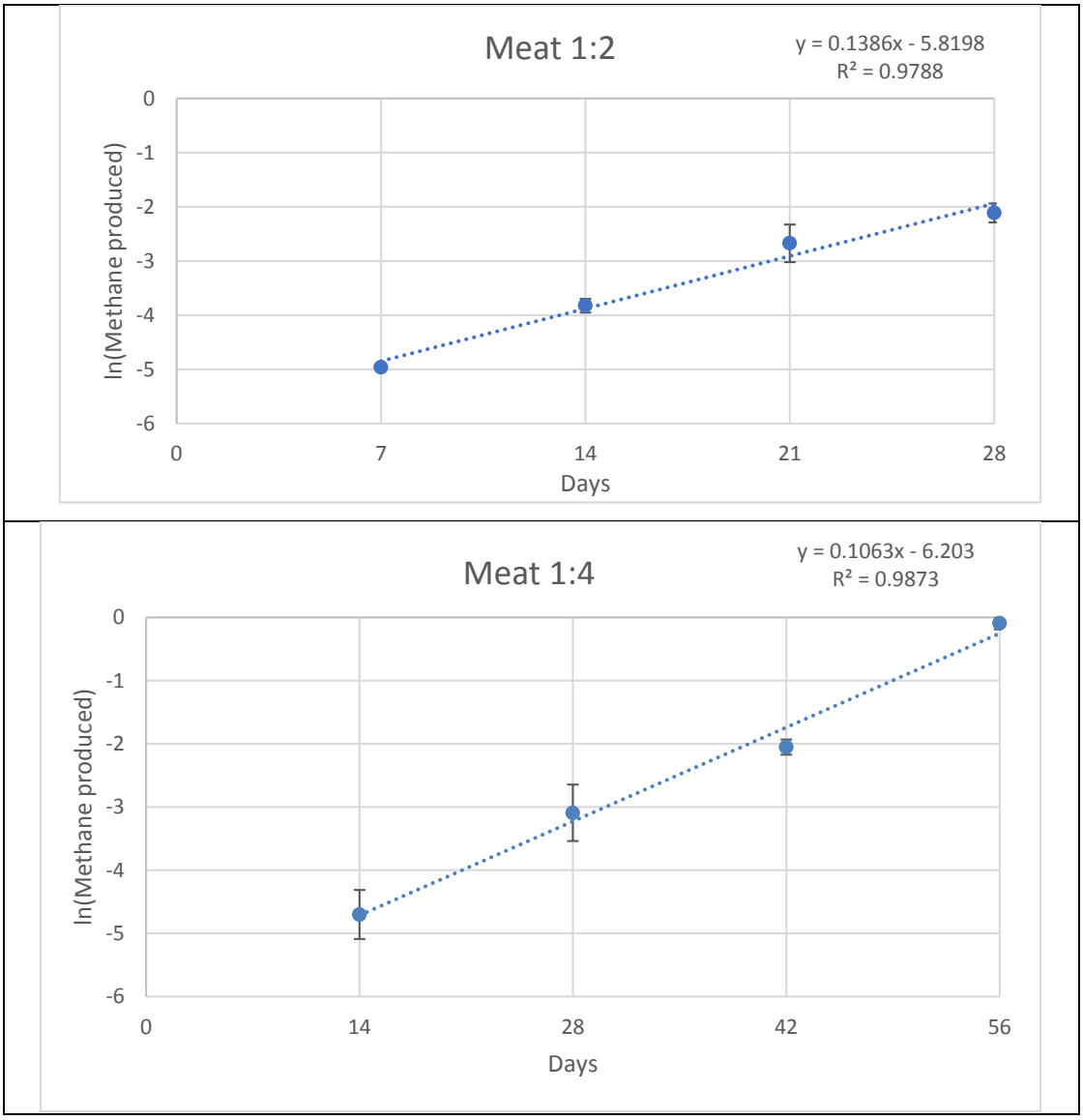
Type of Feedstock	Digester configura-tion	Organic loading rate (kgVS/m^3/d)	Opera-ting TS (%)	SRT (d)	Temperat-ure range (°C)	Methan e yield (m^3/kg VS)	VS removal (%)	Refer-ence
Food waste and straw (5:1)	1-L bottles	0.16-0.26	4.3	30	35	0.58	67-82	Yong et al. (2015)
Food waste and manure (2:1)	2-L semi-continuous	0.3-1.3	1.8	30	35	0.27-0.35	54 and 67	Alvarez and Liden (2007)
Food waste and cattle manure (4:1)	1-L batch and semi-continuous	0.6	3.2	30	35	0.23	71.4	Zhang et al. (2012)

Type of Feedstock	Digester configura-tion	Organic loading rate (kgVS/m^3/d)	Opera-ting TS (%)	SRT (d)	Temperat-ure range (°C)	Methan e yield (m^3/kg VS)	VS removal (%)	Refer-ence
Food waste and daily manure (2:1)	1-L continuous	0.38	4.0	30	35	0.37	82	El-mashad and Zhang (2010)
Oily food waste	6-L CSTR	1.4-2.6	2.6-3.6	30	30-35	0.44	80.1	Wu et al. (2015)
Meat and sewage sludge	5-L glass reactors	1.8-4.0	4.8	20	35	0.53	78.6	Sami and Sari (2009)
FOG, Primary sludge, Thickened waste activated sludge	4-L and 1-L glass reactors, 160 ml serum bottles	2.45-4.35	1.2	30-52	35 and 52	0.12-0.67	82.9	Kabouris et al. (2009)
FOG and kitchen waste	250 ml septum top glass bottles	2.56	2.1	30	37	0.32-0.63	Not reported	Li et al. (2011)
Food waste and FOG	5-L Batch and 250 ml Bottles	0.7-1.8	4.6	30-56	28-35	0.18-0.52	55-65	This Study

The expected methane yields were surpassed in 21-28 days for meat and FOG in this study, with the FOG feedstock yield being slightly higher than for meat waste by-products (refer to Table 9). In previous research, methane production typically varies from 0.1 – 0.7 m^3/kgVS for mesophilic anaerobic digestion. In this study, the methane yield was within this range, but the volatile solids destruction requires further investigation because it continues to increase at the maximum SRT tested, but it is still below expected values from literature (>65%) due to high volatile acid to alkalinity ratio, which may have caused lower pH conditions that would have slowed down microbial growth leading to less volatile solids destruction. Furthermore, the lack of mixing may have exacerbated this effect and also caused difficulty in dissipating the locally elevated temperatures experienced during digestion.

3.3 First Order Kinetics

Anaerobic digestion is a complex process that is comprised of at least 5 thermodynamically independent steps (acclimation, hydrolysis, acidogenesis, acetogenesis, and methanogenesis) (Seadi et al. 2008; Paul and Liu 2012). Furthermore, the process is critically dependent upon several different parameters including temperature, pH, alkalinity, enzyme production, carbon to nitrogen ratio, and other factors (Angelidaki et al. 1999; Gavala et al. 2003). An oversimplified description of the complex kinetics of mesophilic anaerobic digestion has been put forth using first-order kinetics models (Andara and Esteban 1999; Linke 2006; Biswas et al. 2007). The analysis of methane production is used here to estimate the first order rate coefficient by calculating the slope of the natural log of the methane production versus the SRT. In Figure 38, the first order kinetics for meat are plotted against SRT. For meat ratio 1:5, a first order coefficient of 0.14 d^{-1} was observed, and similarly the 1:10 ratio demonstrated a higher coefficient (0.15 d^{-1}).


Meat 1:2
y = 0.1386x - 5.8198
R² = 0.9788
ln(Methane produced)
0
-1
-2
-3
-4
-5
-6
0
7
14
21
28
Days
Meat 1:4
y = 0.1063x - 6.203
R² = 0.9873
ln(Methane produced)
0
-1
-2
-3
-4
-5
-6
0
14
28
42
56
Days

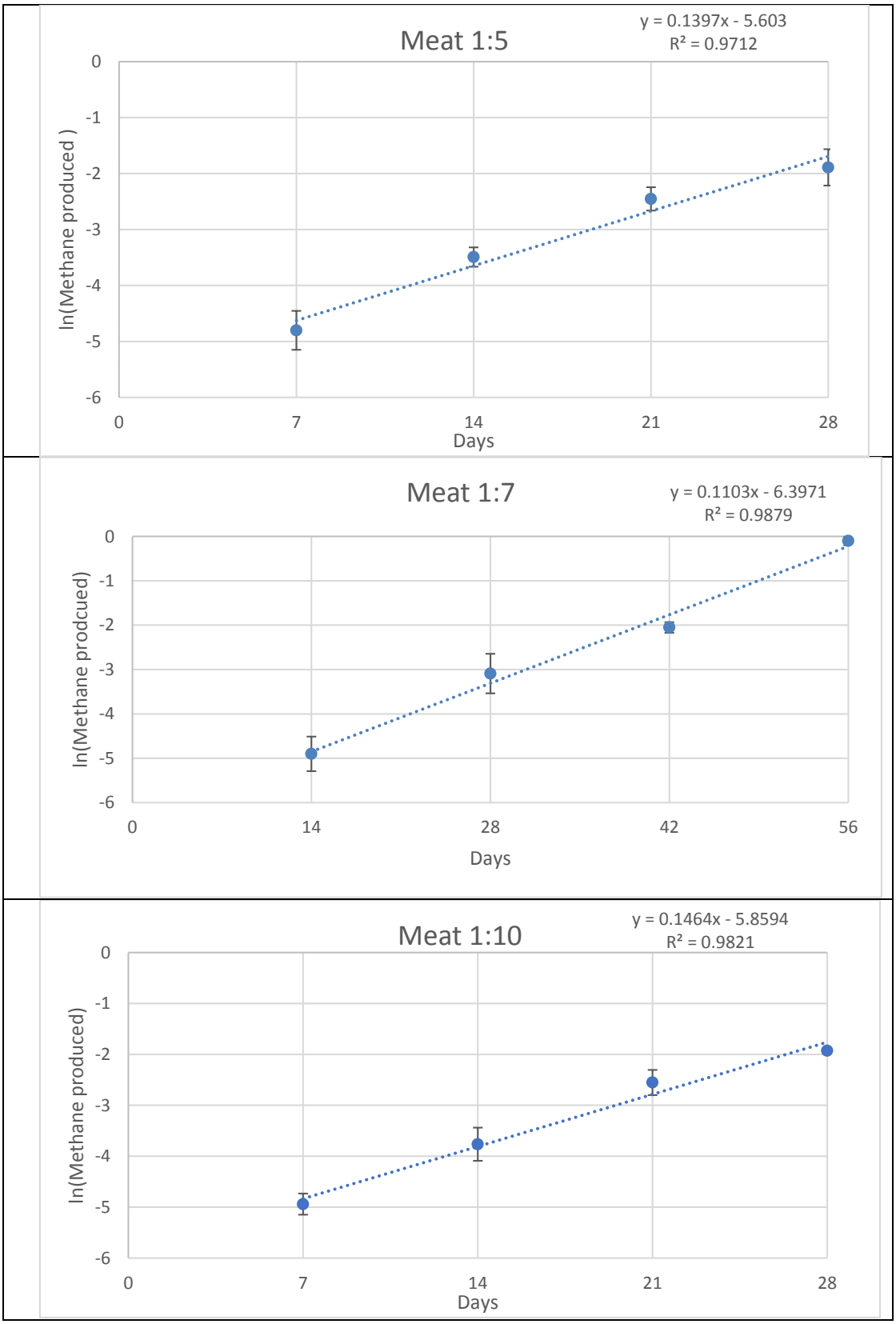
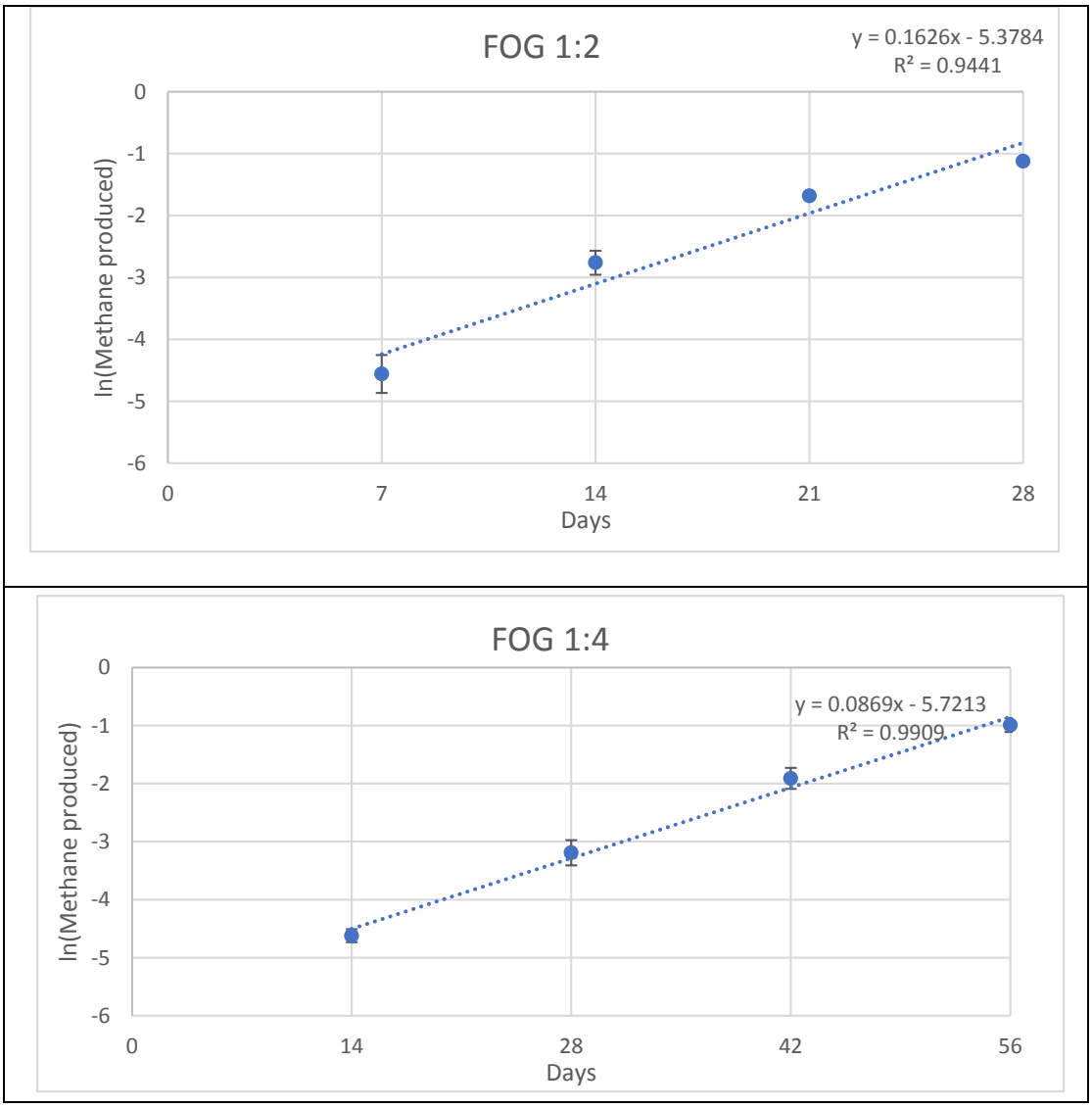


Figure 38: First order kinetics of primary sludge: meat in selected ratios

In Figure 39, the maximum first order coefficient value was observed to be for FOG ratio 1:2, 1:5 and 1:10 with a value of 0.15-0.16 d^{-1}, which is the same as for the meat samples tested previously.



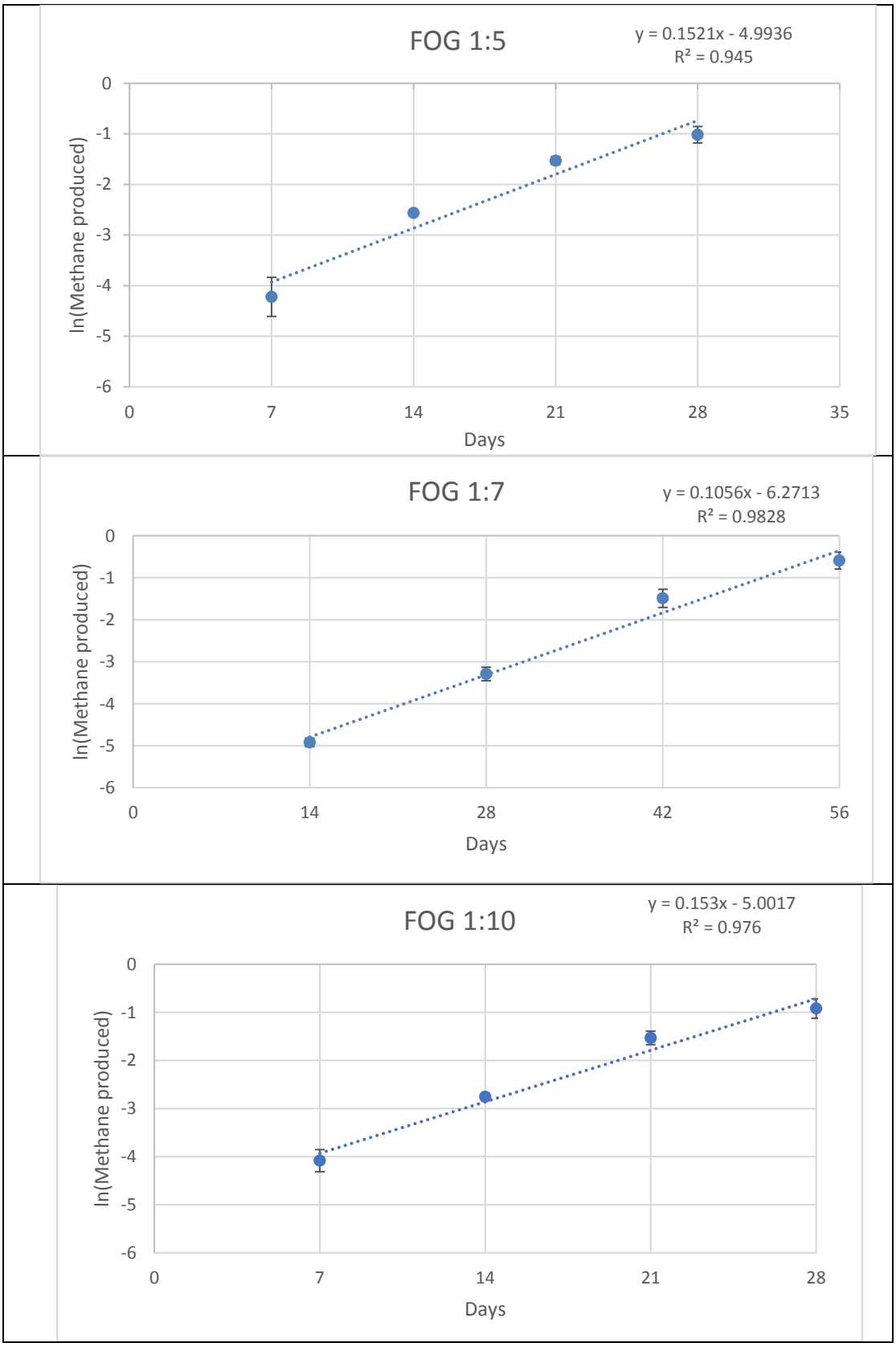


Figure 39: First order kinetics of primary sludge: FOG in the selected ratios

To evaluate the soundness of the model results, the values of the natural logarithm of methane production were plotted against SRT. The model is considered to have a strong fit if the correlation coefficient, R^2 is greater than 0.80. The comparison of the first order kinetics for different ratios of meat and FOG showed positive trends and high values of R^2 >0.95 for all ratios of meat and FOG tested.

Table 12 summarizes the correlation coefficients and first order rate coefficient values for meat and FOG, which can be used to predict the methane production for different SRTs, ratios and feedstocks.

Table 12: Analysis of first order kinetics for methane production

Type of Feedstock	Ratio	R^2	k day^{-1}
FOG	1:2	0.94	**0.16**
	1:4	0.99	0.08
	1:5	0.94	**0.15**
	1:7	0.98	0.10
	1:10	0.97	**0.15**
Meat	1:2	0.97	0.13
	1:4	0.98	0.11
	1:5	0.97	0.14
	1:7	0.98	0.12
	1:10	0.98	**0.15**

Table 13 summarizes the typical range of first order coefficients for methane production in order to compare this study with previous research.

Table 13: Summary of k value from other authors

Type of Feedstock	k-value (d^{-1})	Reference
Piggery slurries	0.048-0.75	Andara and Esteban (1999)
FOG and meat	0.08-0.16	This Study
FOG and kitchen waste	0.012-0.14	Li et al. (2011)
Potato processing	0.089	Linke (2006)
Activated sludge	0.02-0.04	Metcalf and Eddy (2003)

The rate coefficients determined in this study compare favorably with wastewater (Metcalf and Eddy 2003), food waste (Linke 2006), and FOG waste (Li et al. 2011), but not with industrial waste feedstocks (Andara and Esteban 1999). The values of first order coefficients for Andara and

Esteban (1999) were the highest reported because they were mechanically mixed with a helicoid stirrer to mix the substrate, and mixing has a notable influence in the rate coefficient.

3.4 Stakeholder Conference Results

The technical advisory stakeholders meeting was held to collect more information on the current scenarios on anaerobic digestion, diverting food waste and increasing methane content for biogas produced during anaerobic digestion. A video conference call was attended by Karen Moore, Hope Thigpen, Christopher Perry and Shannan Reynolds from FDEP (Florida Department of Environmental Protection), and 3 stakeholders answered our questions previously by email. Karen Moore provided Florida rules for organic processing and biosolids and also provided information about FORCE (Florida Organics Recycling Center for Excellence) launched by FDEP. It was recommended by FDEP that developing a commercial infrastructure framework is more realistic compared to residential food waste due to volume, contamination with non-food waste, number of permits required, and collection/sorting/processing issues. The major challenge in terms of contamination at pre-and post-consumer level is plastics used for packaging. Table 14 provides a summary of the recommendations by the shareholders team.

Table 14: Recommendations provided by the stakeholders of the technical advisory group meeting

No.	Information	Recommendations
1	Major contributors to food waste in Florida	• Grocery stores • Restaurants • Educational institutions • Hospitality industry
2	Major users of biogas	• Wastewater services • Transportation • Electricity
3	Success stories of food waste diversion to anaerobic digestion for energy production	• Safe utilization of spent grains at breweries for mulch and for livestock feed

No.	Information	Recommendations
4	Major regulatory issues/roadblocks/incentives/polices	• Rules for Organics processing 62-709 and Biosolids 62-640 still needs more strict rules • Major food being transported to Miami port from rest of the world and is being distributed to United States but there are no proper regulations and laws to prevent any kind of food waste at that level
5	Major challenge of contamination of food waste	• Pre-and post-consumer level plastics contamination from packaging waste used for packing
6	Improve infrastructure for waste hauling companies	• It was recommended by FDEP that commercial should be targeted
7	Major food waste components that produce more biogas and higher methane content	• The major producers for biogas are FOG, pig manure, cattle manure and food waste comprising of water content

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary

Anaerobic digestion of food waste and meat processing by-products and other wastes like FOG has been studied before but with feedstocks derived from industrial sources; however, this study was conducted to investigate feedstocks derived from commercial sources, with an objective to test different ratios of digested solids inoculum to organic feed (1:2-1:10, v:v) to determine if specific feedstocks derived from food waste materials of commercial origin can be used to increase the biogas/methane yield of mesophilic anaerobic digestion with SRT = 7-56 days.

Two anaerobic digester configurations were tested in this study (PDAN and ultimate digestibility). In the PDAN test, mixed food and meat processing waste were seeded with primary sludge. Mixed food waste produced 300-350 mL of biogas compared to the control with only primary sludge solids (1000 mL), but meat waste products feedstock (1400 mL) increased the maximum biogas production by an average of 60%. The main reasons for this difference was likely due to inadequate seed acclimation, moisture content out of range, and leakage in the glass reactor biogas collection system. Judging from the data collected, it appears that the seed inoculum was not properly acclimated to the feedstock substrate. In addition, favorable anaerobic conditions may not have been established at SRT = 0 because the preliminary samples were not initially purged to eliminate any oxygen present that might have affected the initial stages of anaerobic growth. For the ultimate sludge digestibility, the smaller reactors were purged, which may have led to earlier activation of anaerobic bacteria acting on the feedstock for improved methane yield. In the PDAN tests, the pH was fluctuated and periodically dipped below 6.0, which is a signal of digester souring. Inadequate alkalinity can be one reason for this observed variation as it would have stabilized the pH during AD, but alkalinity was not tested during PDAN.

In the ultimate sludge digestibility tests, meat and FOG were selected as the feedstock options seeded with primary sludge. The first set of ultimate sludge digestibility tests were conducted with SRT up to 28 days and mixing twice per day by manual inversion. Meat (1:10) produced 0.18 m^3/kgVS methane yield and 560 g of biogas in 28 days at 35°C with initial volatile solids of 4.5% and volatile solids destruction of 56%. FOG (1:10) produced 0.50 m^3/kgVS methane yield and 1256 g of biogas in 28 days at 35°C with initial volatile solids of 3.2% and volatile solids destruction of 61%. FOG feedstock was more than double the methane and biogas yield as compared to meat. In the second set of ultimate sludge digestibility tests with ratio 1:4 and 1:7, longer SRTs of 56 days were conducted. Meat (1:7) produced 0.23 m^3/kgVS methane yield and 670 g of biogas in 56 days at 35°C with initial volatile solids of 4.5%, alkalinity of 2260 mg/L as $CaCO_3$, and volatile solids destruction of 65%. FOG (1:4) produced 0.52 m^3/kgVS methane yield and 1304 g of biogas with initial volatile solids of 2.8%, alkalinity of 2560 mg/L as $CaCO_3$ and volatile solids destruction of 67%. Similar to the shorter SRT first set, the FOG performed about 2 times better in terms of methane and biogas generation. Between the first set of experiments with SRT up to 28 days and the second set with SRT up to 56 days, the methane production was found to vary due to feedstock and inoculum compositional differences.

First order kinetics was used to compare the selected ratios of inoculum to feedstock methane production performance over time (SRT). All of the data demonstrated positive trends with strong correlation coefficients (R^2>0.94), and the data points collected were not scattered. The value of k (0.08-0.16 d^{-1}) was slightly lower than expected as compared to some literature values in which vigorous mechanical mixing of industrial feedstock was done (0.048 – 0.75 d^{-1}, Andara and Esteban 1999). In this study, mixing was performed by inversion twice per day. More continuous mixing likely would have increased the value of k by distributing the substrate better and minimizing local temperature spikes.

Based on the information generated in this study, an estimate of the amount of additional power generation from commercial food waste or FOG co-digestion was implemented in Palm Beach County. Assuming all of the food waste generated in one-third of Palm Beach County was diverted from the landfill to AD facilities, this would be on the order of 13,173 tons per month based on 9.12 lb per person per day (SWA) and 27.95% of the waste disposed was comprised of food waste (Meeroff and Scarlatos 2008). Currently, an undersized anaerobic digester is located in the east central region of the county's service area. This digestion facility can handle 1.784 million gallons capacity. If 20% of the unused capacity is filled by FOG or meat waste by-products, then the amount of additional methane generated would be on the order of 13,000 – 37,000 m^3 per month, which is equivalent to the amount needed to power 130-360 homes at 10.557 kWh/m^3 and 1081 kWh per household per month (FPL). This value assumes only one digester, which would only require 0.6% of the food waste generated in the service area.

4.2 Recommendations

The main limitations of this study were the variability of seed and feedstock composition from experiment to experiment and also the daily operating conditions of the anaerobic digester like mixing, pH and temperature control, and organic loading, which can lead to changes in composition and characteristics of biogas. Experiments using ratios of 1:2, 1:5 and 1:10 were carried out in a different batch compared to ratios 1:4 and 1:7, so it cannot be certain that all the feedstock concentrations were prepared and tested with the same seed characteristics for both experiments. In order to limit these effects, it is recommended that in further testing, all ratios to be compared need to have the same seed inoculum and feedstock composition in order to find the optimal conditions for maximum methane production using meat and FOG feedstocks. Also, based on our literature review, 1:2-1:10 was considered optimal for anaerobic digestion (Mata-Alvarez et al. 2000; Kabouris et al. 2009; Li et al. 2011; Brown el al. 2012; Komilis et al. 2017). In this study, the findings indicate that 1:10 yielded the highest methane production in 28 days, but since ratios beyond 1:10 were not tested, it is recommended to investigate feedstock ratios > 1:10 for future work to verify the optimal ratio in terms of maximum methane yield. Another challenge was arranging the food waste, meat and FOG from the sources available due to regulatory barriers to food donation, such as insufficient refrigeration or storage at food banks, food safety concerns regarding collection and storage and liability concerns over the food waste.

Ultimate sludge digestibility produced 70-80% more biogas compared to PDAN because in the larger reactors there was constant leaking since the gas lines would not seal properly and biogas bubbles were seen visibly escaping the digester. It is recommended to replace the material with stainless steel or plexiglass with stronger fittings, which would allow more rapid testing to take place. Other improvements to the ultimate sludge digestibility configuration are recommended. Larger sample size (1 L v. 250 mL) with more accurate gas collection measurement would improve

the robustness of the experiment. Temperature control equipment to allow for more close control of thermophilic temperatures for a follow-up experiment is required. To perform anaerobic digestion in the PDAN reactor, proper mixing equipment may be a limitation as compared to the manual mixing (inversion) that was conducted once or twice per day in the ultimate digestibility test. However, proper mixing will facilitate increasing the methane yield and rate. Another issue was that the PDAN reactors were made of glass with very specialized fittings susceptible to breaking after every set of results which led to major delays in setting up the next round of experiments. All of these items can be addressed in a follow-up study.

One common type of system instability is caused by the rapid conversion of the readily degradable organics to volatile fatty acids (VFAs) at an early stage of the digestion process, resulting in a drastic pH drop if insufficient buffering capacity is present. Measuring sludge properties such as alkalinity and VFAs is recommended which becomes important if the pH is not stable enough to support logarithmic microbial growth conditions. Alkalinity plays a vital role in anaerobic digestion. Therefore, it is recommended to measure alklalinty along with pH. A means to continuously monitor pH and predict the impact it has on alkalinity in the digester over time would have eliminated the issue of failure with the first set of samples in the PDAN unit.

Carbon to nitrogen ratio also plays a vital role in characterizing the feedstock. Nitrogen present in the feedstock provides essential nutrients for synthesis of amino acids and proteins that convert to ammonia, which neutralizes some of the volatile acids produced by fermentative bacteria in the digester to maintain favorable pH conditions. For the anaerobic digester microorganisms to grow, C:N (carbon to total nitrogen) ratios higher than 23:1 were found to be unsuitable for optimal digestion, and ratios lower than 10:1 were found to be inhibitory (Hills 1979; Wang et al. 2012; Wang et al. 2014). Thus, it is highly recommended to check the C:N ratio before and during testing.

Finally, further literature review suggests that the comparison between thermophilic and mesophilic would be expected to provide insight in attaining stability and higher methane yield. It is recommended to test ultimate sludge digestibility at elevated temperatures to simulate thermophilic conditions and compare to mesophilic methane production. Although thermophilic AD has an expected rate advantage over mesophilic digestion, a larger initial investment cost is needed to deploy thermophilic systems along with better heating and mixing equipment

5. REFERENCES

1) (2013). Biogas Potential in the United States. National Renewable Energy Laboratory.

2) (2017). Reducing Wasted Food at Home. EPA.

3) (2015). Biogas State Profile: Florida. American Biogas Council.

4) Alvarez, R., & Lidén, G. (2009). Semi-continuous co-digestion of solid slaughterhouse waste, manure, and fruit and vegetable waste. Renewable Energy, 33(4), 726-734.

5) Al Seadi T, Rutz D, Prassl H, Köttner M, Finsterwalder T, Volk S (2008). More about anaerobic digestion (AD). In: Al Seadi T (ed) Biogas handbook. University of Southern Denmark.

6) Andara, A. R., & Esteban, J. L. (1999). Kinetic study of the anaerobic digestion of the solid fraction of piggery slurries. Biomass and Bioenergy, 17(5), 435-443.

7) Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J. L., Guwy, A. J., . . . Lier, J. B. (2009). Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Science & Technology, 59(5), 927.

8) Brown, D., Shi, J., & Li, Y. (2012). Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. Bioresource Technology, 124, 379-386.

9) Bustillo-Lecompte, C. F., & Mehrvar, M. (2017). Treatment of actual slaughterhouse wastewater by combined anaerobic–aerobic processes for biogas generation and removal of organics and nutrients: An optimization study towards a cleaner production in the meat processing industry. Journal of Cleaner Production, 141, 278-289.

10) Campuzano & Gonzalez- Martinez, (2016). Characteristics of the organic fraction of municipal solid waste and methane production; a review. Waste Management., 54 (2), pp. 3-12.

11) Capson-Tojo, G., Rouez, M., Crest, M., Steyer, J., Delgenès, J., & Escudié, R. (2016). Food waste valorization via anaerobic processes: a review. Reviews in Environmental Science and Bio/Technology, 15(3), 499-547.

12) Cioabla, A., Ionel, I., Dumitrel, G., & Popescu, F. (2012). Comparative study on factors affecting anaerobic digestion of agricultural vegetal residues. Biotechnology for Biofuels, 5(1), 39.

13) Clara, M., Kreuzinger, N., Strenn, B., Gans, O., & Kroiss, H. (2005). The solids retention time—a suitable design parameter to evaluate the capacity of wastewater treatment plants to remove micropollutants. Water Research, 39(1), 97-106.

14) Dana Gunders, J. B. (2017). WASTED: HOW AMERICA IS LOSING UP TO 40 PERCENT OF ITS FOOD FROM FARM TO FORK TO LANDFILL. Natural Resources Defense Council.

15) De Baere & Mattheeuws, (2010). Anaerobic Digestion of MSW in Europe BioCycle, 51 (2) (2010), pp. 24-27.

16) Esposito, G. (2012). Bio-Methane Potential Tests To Measure The Biogas Production From The Digestion and Co-Digestion of Complex Organic Substrates. The Open Environmental Engineering Journal, 5(1), 1-8.

17) Fedailaine, M., Moussi, K., Khitous, M., Abada, S., Saber, M., & Tirichine, N. (2015). Modeling of the Anaerobic Digestion of Organic Waste for Biogas Production. Procedia Computer Science, 52, 730-737.

18) Fehrenbach H, Giegrich J, Reinhardt G, Schmitz J, Sayer U, Gretz M, Seizinger E, Lanje K (2008). Criteria for a Sustainable Use of Bioenergy on a Global Scale. Report on behalf of the German Federal Environment Agency. Germany.

19) Ferrer, I., Vazquez, F., Font, X., 2010. Long term operation of a thermophilic anaerobic reactor: Process stability and efficiency at decreasing sludge retention time.101 (9), 2972–2980.

20) Gavala, H. N., Angelidaki, I., & Ahring, B. K. (2003). Kinetics and Modeling of Anaerobic Digestion Process. Advances in Biochemical Engineering / Biotechnology Biomethanation I,57-93.

21) GREET Model (2010) Argonne National Laboratory, U.S Department of Energy. https://greet.es.anl.gov.

22) Gunaseelan, V. (2004). Biochemical methane potential of fruits and vegetable solid waste feedstocks. Biomass and Bioenergy, 26(4), 389-399.

23) He, X., Reyes, F. L., Leming, M. L., Dean, L. O., Lappi, S. E., & Ducoste, J. J. (2013). Mechanisms of Fat, Oil and Grease (FOG) deposit formation in sewer lines. Water Research,47(13), 4451-4459.

24) Hills, D. J. (1979). Effects of carbon: Nitrogen ratio on anaerobic digestion of dairy manure. Agricultural Wastes, 1(4), 267-278.

25) Jiang, J., Zhang, Y., Li, K., Wang, Q., Gong, C., & Li, M. (2013). Volatile fatty acids production from food waste: Effects of pH, temperature, and organic loading rate. Bioresource Technology, 143, 525-530.

26) Jun, D., Yong-Sheng, Z., Mei, H., & Wei-Hong, Z. (2009). Influence of alkalinity on the stabilization of municipal solid waste in anaerobic simulated bioreactor. Journal of Hazardous Materials, 163(2-3), 717-722.

27) Kabouris, J. C., Tezel, U., Pavlostathis, S. G., Engelmann, M., Dulaney, J., Gillette, R. A., & Todd, A. C. (2009). Methane recovery from the anaerobic co-digestion of municipal sludge and FOG. Bioresource Technology, 100(15), 3701-3705.

28) Kabouris, J. C., Tezel, U., Pavlostathis, S. G., Engelmann, M., Dulaney, J. A., Todd, A. C., & Gillette, R. A. (2009). Mesophilic and Thermophilic Anaerobic Digestion of Municipal Sludge and Fat, Oil, and Grease. Water Environment Research, 81(5), 476-485.

29) Kaiser, E.R., (1966). Chemical analyses of refuse compounds. Proceedings of the National Incinerator conference, ASME, New York, IncineratorConference/1966-National-Incinerator-Conference-08.pdf.

30) Kim, M., Ahn, Y.H., Speece, R.E., (2002). Comparative process stability and efficiency of anaerobic digestion; mesophilic vs. thermophilic. Water Resource. 36 (17), 4369–4385.

31) Klass, D. L. (1984). Methane from Anaerobic Fermentation. Science, 223(4640), 1021-1028.

32) Komilis, D., Barrena, R., Grando, R. L., Vogiatzi, V., Sánchez, A., & Font, X. (2017). A state of the art literature review on anaerobic digestion of food waste: influential operating parameters on methane yield. Reviews in Environmental Science and Bio/Technology, 16(2), 347-360.

33) Kuo, J., & Dow, J. (2017). Biogas production from anaerobic digestion of food waste and relevant air quality implications. Journal of the Air & Waste Management Association, 67(9), 1000-1011.

34) Lastella, G., Testa, C., Cornacchia, G., Notornicola, M., Voltasio, F., & Sharma, V. K. (2002). Anaerobic digestion of semi-solid organic waste: Biogas production and its purification. Energy Conversion and Management, 43(1), 63-75.

35) Lepisto, J.A., & Rintala, S.S., (1997). Pilot-scale thermophilic anaerobic treatment of wastewaters from seasonal vegetable processing industry. Water Science and Technology, 36(2-3).

36) Lettinga et al., (1999) High-rate anaerobic treatment of wastewater at low temperatures. Applied Environmental Microbiology, 65(4):1696–1702.

37) Li, C., Champagne, P., & Anderson, B. C. (2011). Evaluating and modeling biogas production from municipal fat, oil, and grease and synthetic kitchen waste in anaerobic co-digestions. Bioresource Technology, 102(20), 9471-9480.

38) Linke, B. (2006). Kinetic study of thermophilic anaerobic digestion of solid wastes from potato processing. Biomass and Bioenergy, 30(10), 892-896.

39) Lin, J., Zuo, J., Gan, L., Li, P., Liu, F., Wang, K., . . . Gan, H. (2011). Effects of mixture ratio on anaerobic co-digestion with fruit and vegetable waste and food waste of China. Journal of Environmental Sciences, 23(8), 1403-1408.

40) Liu and Ghosh (1997) Phase separation during anaerobic fermentation of solid substrates in an innovative plug-flow reactor, Water Science and Technology, 36(6-7).

41) Luc De Baere, B. M. (2010). Anaerobic Digestion Of MSW In Europe. BioCycle-The Organics Recycling Authority.

42) Luste, S., & Luostarinen, S. (2010). Anaerobic co-digestion of meat-processing by-products and sewage sludge – Effect of hygienization and organic loading rate. Bioresource Technology,101(8), 2657-2664.

43) Mantell, C. L. (1975). Solid wastes: Origin, collection, processing, and disposal. New York: Wiley.

44) Mao, C., Feng, Y., Wang, X., & Ren, G. (2016). ChemInform Abstract: Review on Research Achievements of Biogas from Anaerobic Digestion. ChemInform, 47(28).

45) Martín-González, L., et al. (2013) "Alkalinity Ratios to Identify Process Imbalances in Anaerobic Digesters Treating Source-Sorted Organic Fraction of Municipal Wastes." Biochemical Engineering Journal, vol. 76, pp. 1–5.

46) Mata-Alvarez, J., Macé, S., & Llabrés, P. (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresource Technology, 74(1), 3-16.

47) Mckendry, P. (2002). Energy production from biomass (part 1): overview of biomass. Bioresource Technology, 83(1), 37-46.

48) Meeroff, D. M., & Scarlatos, P. D. (2008). Green lodging project phase 4: Green lodging performance measures: Implementation and monitoring. Progress report: Action plan implementation update. Boca Raton, FL: Florida Atlantic University.

49) Motte, J., Trably, E., Escudié, R., Hamelin, J., Steyer, J., Bernet, N., . . . Dumas, C. (2013). Total solids content: a key parameter of metabolic pathways in dry anaerobic digestion. Biotechnology for Biofuels, 6(1), 164.

50) Nandita Ahuja, A. G. (2017). Lessons Learned From Start-Up. FWRJ.

51) Nielsen, H. B., & Ahring, B. K. (2006). Responses of the biogas process to pulses of oleate in reactors treating mixtures of cattle and pig manure. Biotechnology and Bioengineering, 95(1), 96-105.

52) Niessen, W.R. (1977). properties of waste materials, in handbook of solid waste management. (D.J.Wilson , Ed), Van Nostrand Reinholt, New york,1977,pp.10-61.

53) Okeh, O. C., Onwosi, C. O., & Odibo, F. J. (2014). Biogas production from rice husks generated from various rice mills in Ebonyi State, Nigeria. Renewable Energy, 62, 204-208.

54) Owen, W., Stuckey, D., Healy, J., Young, L., & Mccarty, P. (1979). Bioassay for monitoring biochemical methane potential and anaerobic toxicity. Water Research, 13(6), 485-492.

55) Palacios-Ruiz, B., Méndez-Acosta, H., Alcaraz-González, V., González-Álvarez, V., & Pelayo-Ortiz, C. (2008). Regulation of Volatile Fatty Acids and Total Alkalinity in Anaerobic Digesters. IFAC Proceedings Volumes, 41(2), 13611-13616.

56) Paul E, Liu Y (2012). Biological sludge minimization and biomaterials/bioenergy recovery technologies. Wiley, Hoboken, NJ.

57) Pavlostathis, S. G., Tezel, U., Hajaya, M. G., Tandukar, M., Porter, R., Elmendorf, H., . . . Richards, T. (2010). Conversion Strategies and Evaluation of the Transition from Mesophilic to Thermophilic Anaerobic Digestion of Municipal Sludge. Proceedings of the Water Environment Federation, 2010(4), 944-970.

58) Pind, P. F., Angelidaki, I., & Ahring, B. K. (2003). Dynamics of the anaerobic process: Effects of volatile fatty acids. Biotechnology and Bioengineering, 82(7), 791-801.

59) Pilot-scale thermophilic anaerobic treatment of wastewaters from seasonal vegetable processing industry. (1997). Water Science and Technology, 36(2-3).

60) Pisutpaisal, N., Boonyawanich, S., & Saowaluck, H. (2017). Feasibility of Biomethane Production from Banana Peel. Energy Procedia, 50, 782-788.

61) Romano, R. T., & Zhang, R. (2011). Anaerobic digestion of onion residuals using a mesophilic Anaerobic Phased Solids Digester. Biomass and Bioenergy, 35(10), 4174-4179.

62) Raposo, F., Fernández-Cegrí, V., Rubia, M. D., Borja, R., Béline, F., Cavinato, C., . . . Wilde, V. D. (2011). Biochemical methane potential (BMP) of solid organic substrates: evaluation of anaerobic biodegradability using data from an international interlaboratory study. Journal of Chemical Technology & Biotechnology, 86(8), 1088-1098.

63) Rongping, L., Chen, S., & Xiujiu L. (2010). Biogas production from anaerobic co-digestion of food waste with dairy manure in a two-phase digestion system. Applied Biochemistry and Biotechnology, 160(2), 643-654.

64) Safari E, Jalili Ghazizadeh M, Shokouh M, and Nabi Bidhendi Gh. (2011) Anaerobic removal of COD from high strength fresh and partially stabilized leachates and application of multi stage kinetic model. Int. J. Environmental Research, 5(2), 255-270.

65) Samer, M. (2010). A Software Program for Planning and Designing Biogas Plants. Transactions of the ASABE, 53(4), 1277-1285.

66) Scott, R.I., Williams, T.N., & Lloyd, D (1983). Oxygen sensitivity of methanogenesis in rumen and anaerobic digester populations using mass spectrometry. Biotechnology Letters, 5(6), 375-380.

67) Sielaff H. Fleischtechnologie (1996). Hamburg: Behr's Verlag.

68) Tafdrup, S. (1995). Viable energy production and waste recycling from anaerobic digestion of manure and other biomass materials. Biomass and Bioenergy, 9(1-5), 303-314.

69) The role of anaerobic digestion of domestic sewage in closing the water and nutrient cycle at community level. (1999). Water Science and Technology, 39(5).

70) Tu, Q., & Mcdonnell, B. E. (2016). Monte Carlo analysis of life cycle energy consumption and greenhouse gas (GHG) emission for biodiesel production from trap grease. Journal of Cleaner Production, 112, 2674-2683.

71) USEPA methods 1684 (2001). Total, fixed and volatile solids in water, solids and bio-solids. Draft, pp: 11-13.

72) Wang, X., Yang, G., Li, F., Feng, Y., Ren, G., & Han, X. (2013). Evaluation of two statistical methods for optimizing the feeding composition in anaerobic co-digestion: Mixture design and central composite design. Bioresource Technology, 131, 172-178.

73) Wang, X., Lu, X., Li, F., & Yang, G. (2014). Effects of Temperature and Carbon-Nitrogen (C/N) Ratio on the Performance of Anaerobic Co-Digestion of Dairy Manure, Chicken Manure and Rice Straw: Focusing on Ammonia Inhibition. PLoS ONE, 9(5).

74) Wastewater Engineering: Treatment and Reuse. (2003). Boston: McGraw Hill.

75) WEF (1996) operation of wastewater treatment plants, 5 editions, Manual of practice No. 11, Volume 3, chapter 27-33, Water Environment Federation, Alexandria, VA.

76) Yong, Z., Dong, Y., Zhang, X., & Tan, T. (2015). Anaerobic co-digestion of food waste and straw for biogas production. Renewable Energy, 78, 527-530.

77) Zhang, R., Elmashad, H., Hartman, K., Wang, F., Liu, G., Choate, C., & Gamble, P. (2007). Characterization of food waste as feedstock for anaerobic digestion. Bioresource Technology,98(4), 929-935.

78) Zhang, C., Xiao, G., Peng, L., Su, H., & Tan, T. (2013). The anaerobic co-digestion of food waste and cattle manure. Bioresource Technology, 129, 170-176.

79) Zhang, J., & Wang, Q. (2013). Buffering and nutrient effects of white mud from ammonia–soda process on thermophilic hydrogen fermentation from food waste. International Journal of Hydrogen Energy, 38(31), 13564-13571.