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Small-scale Minimal-maintenance Anaerobic Digestion of Food Waste for Solids Reduction and Methane Production: Feasibility Study

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SMALL-SCALE MINIMAL-MAINTENANCE ANAEROBIC DIGESTION OF FOOD WASTE FOR SOLIDS REDUCTION AND METHANE PRODUCTION: FEASIBILITY STUDY

BY

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Lastly, I'd like to thank my research partner Emily Heleva-Ponaski for working countless hours with me on this project through rough days, terrible smells, and even a broken windshield. It wouldn't have been funny without you around.

ABSTRACT

Six gallons of food waste was anaerobically digested for 76 days in two small-scale digesters sitting by a lab window. The main difference, besides waste sources, of these digesters was substrate processing: chopping versus blending. An effort was made to minimize the maintenance of the digesters, however, after 45 days of overly acidic (pH<5) conditions sodium carbonate was added to raise the pH. Both digesters were subsequently seeded with digested sludge from a local wastewater treatment plant, and which time methane production greatly increased. However, by the end of the experiment, total solids reduction, volatile solids reduction, and methane production was greatly lower than values from similar studies. The most likely issue identified was lack of temperature control (too cold) as well as low pH. While the digesters were far from optimized, they did reduce solids, produce methane, and identify ways to avoid similar issues for projects in the future.

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1.0 INTRODUCTION

Cities around the world transport large quantities of waste to landfills at a great expense to their residents, infrastructures, and environments. In America, families discard nearly 25% (by mass) of the food they purchase (Gunders, 2012), not including inedible portions, which in addition to commercial food waste becomes a sizeable portion of total waste. At 6 million tons, food constitutes 15.5% of California's waste (CIWMB, 2008). Food waste then decomposes resulting in up to 23% of America's methane emissions (Gunders, 2012).

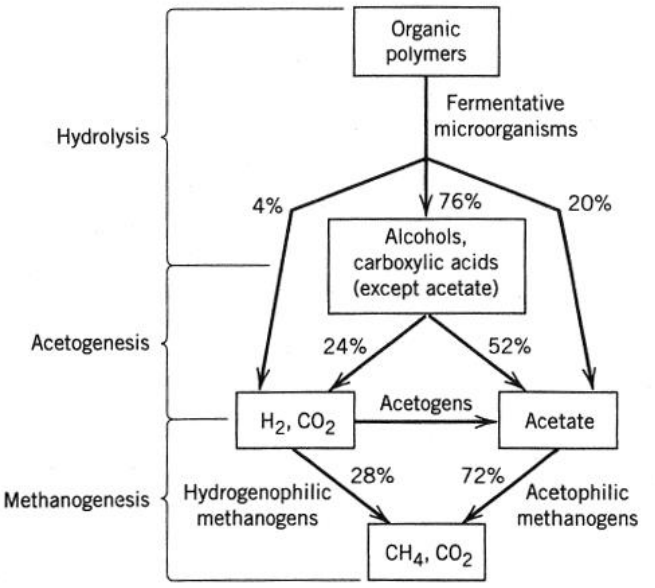

Figure 1: Overview of the anaerobic digestion process, from Zehnder et al. (1982)

Anaerobic digestion is a well-established method for breaking down solids into nutrient-rich liquid fertilizer and methane gas (Gray et al., 2008). While methane is a powerful greenhouse gas, properly collected and stored it can be a useful fuel and therefore a source of renewable energy. While relatively uncommon in the United States, high-solids food waste digestion is becoming increasingly popular in Asia and Europe (De Baere L., 2000). Thus the potential exists for America to reduce greenhouse gas emissions and landfill-bound food waste while generating electricity.

The digestion process consists of four main stages, hydrolysis, fermentation, acetogenesis and methanogenesis as seen in Figure 1. During hydrolysis, complex molecules like proteins,

lipids, and carbohydrates are broken down into simpler molecules by extracellular enzymes (Li et al., 2010).

These amino acids, fatty acids, and sugars are then fermented by bacteria. The products of fermentation vary depending on the types of bacteria present (which is in turn dependent on the pH and temperature). Fermentation produces some amount of acetate, carbon dioxide, and hydrogen, but primarily creates volatile fatty acids used as a substrate during acetogenesis. Acetogenesis continues the creation of acetic acid, carbon dioxide, and hydrogen, which are the primary substrates for methane production (Li et al., 2010). The reaction for glucose (as an example substrate) conversion to acetic acid is:

$$C_6H_{12}O_6 + 2\ H_2O \rightarrow 2\ CH_3COOH + 4\ H_2 + 2\ CO_2$$

(Thompson, 2008).

Methanogenesis is carried out by Archaea, single-celled organisms in their own kingdom separate from bacteria and eukaryotes. These methanogens primarily use acetic acid to produce methane in the overall reaction:

$$CH_3COOH \rightarrow CH_4 + CO_2$$

But methanogens can use a variety of substrates to produce methane, such as hydrogen and carbon dioxide:

$$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$$

(Droste, 1996 and Thompson, 2008).

Common food waste, after processing (e.g. blending) has greater solids content than traditional wastewater digester feedstock at 15% or higher (Li et al., 2010). Food waste also has

a much higher COD (Min et al., 2005), which indicates a greater potential for producing methane (Droste, 1996). Anaerobic digestion of solid waste of all sources (e.g. food, manure) is seen as an important way of treating waste and producing energy in developing countries (Müller, 2007). Operations of any size provide communities with the opportunity to produce fuel or electricity locally. American communities could also localize their food waste disposal, reducing transportation costs and total waste.

Stability of the anaerobic digestion process can be difficult to start and maintain, largely due to the diverse needs and sensitivities of the involved organisms (Chen et al., 2007). Digesters generally require a pH held at neutral and a dedicated heat source. Purely food waste digesters can be especially difficult, lacking the quantity of bacteria present in manure and with more material to be broken down.

Due to the great potential of the technology, a desire exists to create small scale, minimal maintenance anaerobic food waste digesters. Such digesters could use solar radiation as a heat source and ideally would require no pH control or bacterial seeding. The objective of this study was to run an anaerobic food waste digester with minimal interference or maintenance. Additionally, the amount of substrate processing necessary was to be evaluated, comparing chopped waste and blended waste. Upon failure of a digester (defined by low pH, lack of solids reduction, and lack of methane production) appropriate steps were to be taken to recover it, through sodium carbonate (Na_2CO_3) pH control, heating, or reseeding. The high coffee ground content of our food waste supply indicated likely pH control at the very least would be necessary (Kozuchowska & Evison, 1995).

2.0 METHODS

2.1 Digester Apparatus and Operation

Two digesters were run simultaneously, referred to as Chunky and Skinny based on their differences in substrate processing (see below) and resulting solids content. Skinny was started 18 days after Chunky due to issues in substrate acquisition.

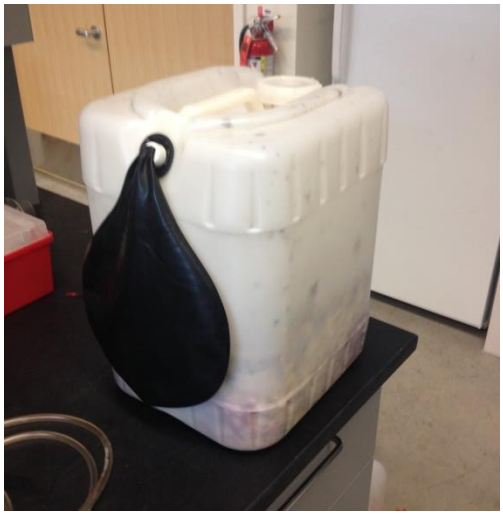

Figure 2: Original digestion container

Both digesters were originally in six-gallon hard-plastic containers (Figure 2) filled with approximately three gallons of substrate. A 36-inch balloon was attached to each digester for gas collection and internal pressure relief via a one-centimeter hole at the top. Initially both digesters were placed in a laboratory flume hood and wrapped with insulation in an attempt to avoid heating them. However without gas production evident the containers were moved to a table near the laboratory windows (Figure 3). The windows faced west, providing afternoon sunlight to the digesters.

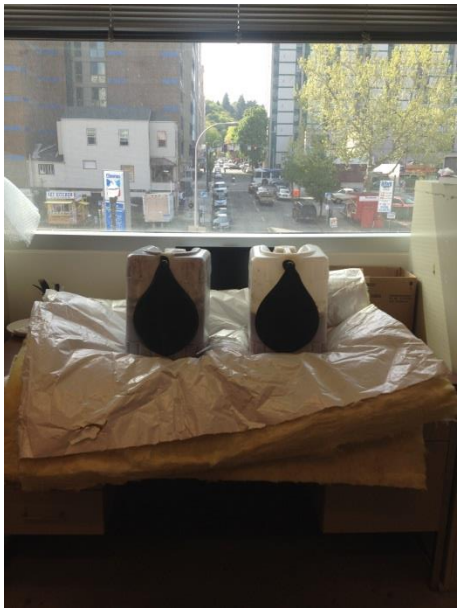

Figure 3: Placement of digesters near laboratory windows

Issues with collecting samples from the containers, along with a transition into a recovery phase for the digesters, prompted transferring both Chunky and Skinny into 20-liter flexible plastic cube containers (Figure 4). Ambient air was forced out of the containers via an attached

Figure 4: Flexible plastic digestion containers

valve, and subsequently the balloons from the first containers were transferred onto the ends of the valves.

A leak in Skinny's container forced an emergency relocation into a smaller flexible container on day 67 of the experiment. This occurred prior to final solids tests.

2.2 Substrates and inoculums

Chunky contained two gallons of vegetarian waste from a Portland State University (PSU) restaurant kitchen, one gallon of vegetarian wood waste from a home kitchen, and approximately half a cup of almond butter. The food waste was chopped into half-inch cubes and mixed by shaking the whole container. On day 18 three liters of tap water were added to the digester.

Skinny contained approximately three gallons of food waste from the PSU Smith Memorial Student Union compost bin and three liters of tap water. Though an effort was made to select vegetarian components, the bin was not explicitly classified as vegetarian. Approximately 50 percent of the substrate was coffee grounds and the remaining portion was dominated by orange and banana peels. Seventy-five percent of the substrate was blended before addition to the digester.

Sodium carbonate (solid) was used to recover the digesters from an acidic (pH < 6.4) state, raising the pH close to neutral. The amount of sodium carbonate necessary was informed by titrations performed on samples from each digester. The pH control was concurrent with the

transfer of the digesters into the flexible plastic containers, effectively creating a two-phase digester operation. After two minutes of mixing the digesters, the pH was measured and additional sodium carbonate was added as necessary. After 48 hours, the pH was verified to be approximately neutral (6.4 – 7.4) and stable.

After pH control, the digesters were each seeded with two liters of digested sludge from the Durham wastewater treatment facility in Tigard, Oregon. The digesters were mixed and the pH was again recorded.

2.3 Sampling and analyses

Titrations were performed using 120mL of sample from each digester. An initial pH a reading was taken. Sodium carbonate (solid) was added in half-gram increments and mixed vigorously until the change in pH was less than 0.1. The pH measurements that were taken at each increment were plotted against the total base addition (Appendix A). This graph was used to calculate the amount of base needed to bring the whole system up to the desired pH.

Total solids (TS) samples and pH measurements were collected an average of every 7.4 days. Approximately 200 mL of substrate was poured into a beaker and mixed. Three to five samples were then processed in accordance with the procedures described in the Methods 1684 from the U.S Environmental Protection Agency. A Orion pH probe was used to measure the pH. Volatile solids (VS) samples were taken once before the digester recovery and again after the digesters had consistently been producing gas. Triplicate samples were taken from each digester both times and processed in accordance with the procedures described in the Methods 1684 from the U.S Environmental Protection Agency.

Gas data was collected on three dates selected based on the pressure buildup within the digesters. Gas volumes produced were estimated based on modeling the air-filled portion of the digester containers as rectangular boxes and the (never fully filled) balloons as cylinders. Volumes were recorded just prior to releasing the gas for methane (CH_4) concentration estimation. The gas was released from the digesters and run past a Hanwei Electronics MQ-4 methane gas sensor under a laboratory fume hood. The resistance of the sensor was read by an Arduino Uno hooked up to a laptop computer continually recording the values. Due to reaching the sensor detection limit of 10,000 ppm CH_4, this data was used only qualitatively and comparatively.

3.0 RESULTS

3.1 Total, Volatile, and Fixed Solids

Solids were reduced in both digesters during the course of the experiment. Chunky saw a 4.89% reduction in TS and Skinny a 5.90% reduction. During the acetogenesis (pre-recovery) phase TS increased slightly, as seen in Figure 5. Although Skinny had higher (19% vs 17%) TS prior to pH control, Chunky retained the higher TS values post recovery (15% vs 13%). The Chunky TS datasets routinely had a larger standard deviation (Figure 6), with an anomaly on 5/15. Skinny's TS levels experienced an unexpected rise during the last day of data collection, after it had been transferred into a new container due to leakage. Prior to that data point, the total TS reduction for Skinny had been 8.17%.

Chunky and Skinny saw a 16.30% and 18.20% reduction in VS, respectively, from pH recovery to the experiment end. As seen in Table 1, Skinny started and ended with a higher VS content along with having the greater reduction. Fixed solids in Chunky and Skinny also saw 16.30% and 18.20% changes, respectively.

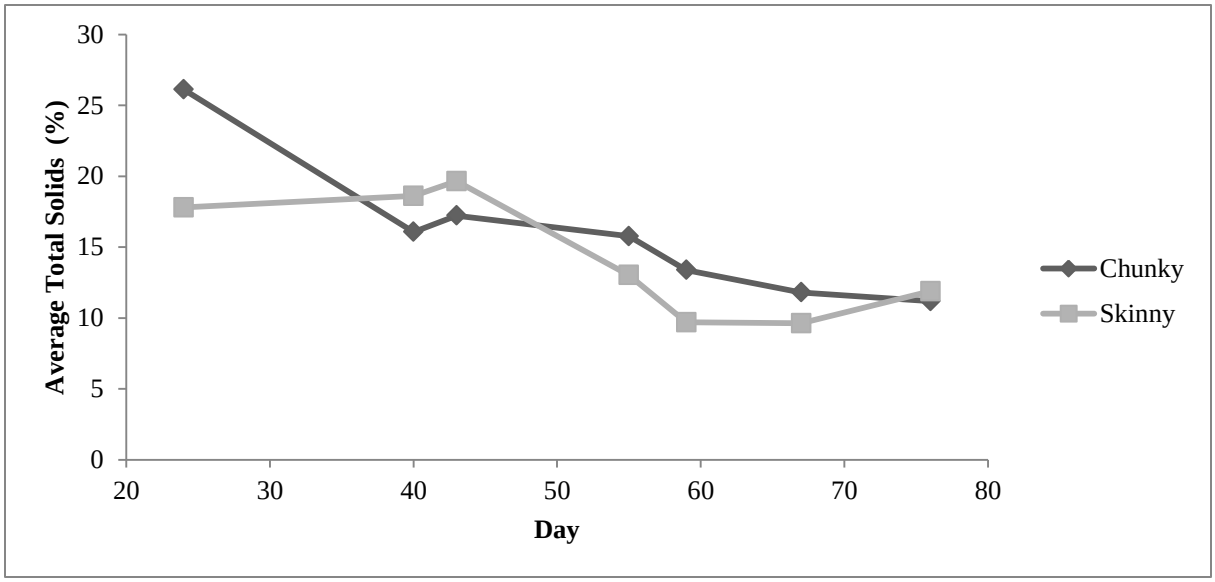

Figure 5: Variation of average total solids with time for the two digesters.

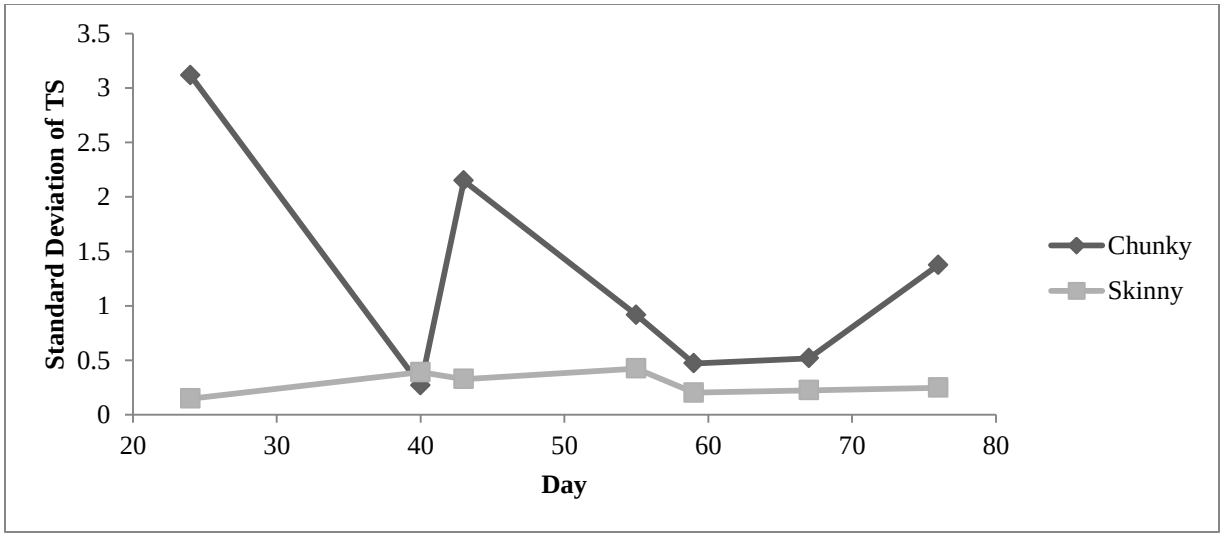

Figure 6: Variation in standard deviation of the total solids samples with time for the two digesters.

Table 1: Change in volatile solids with time for the two digesters.

Digester	Initial VS (%)	Final VS (%)	ΔVS (%)	Initial FS (%)	Final FS (%)	ΔFS (%)
Chunky	85.75	69.45	16.30	14.27	30.57	16.30
Skinny	94.86	76.67	18.20	5.13	23.33	18.20

3.2 pH and Titrations

The pH of Chunky and Skinny were both fairly acidic prior to pH control, averaging around 4.4 and 3.6, respectively. After pH control and seeding (day 47), Chunky and Skinny were at 6.84 and 7.27, respectively. From this point on the pH of both digesters gradually fell over the remaining month of the experiment, with Chunky ending at 6.15 and Skinny at 6.03, below the desired lower-end pH of 6.4.

Titration curve data used to inform the pH control efforts is located in Appendix A.

3.4 Gas Production

Gas production was initially very slow, but accelerated once the digesters were moved from the fume hood to the window. At day 28 of the experiment (day 10 for Skinny), the first gas volumes were estimated from the digesters. As seen in Table 2, Skinny produced more gas than Chunky despite having less time, at 3.76 gallons versus 3.31 gallons. Chunky, however, had exactly double the resistance reading from the methane sensor, at 468 versus 234.

Table 2: Gas production and gas production per day for the two digesters.

	First Collection (4/18)			Second Collection (5/15)			Third Collection (5/17)		
	Days	Gas (gallons)	Gas/day (gal/day)	Days	Gas (gallons)	Gas/day (gal/day)	Days	Gas (gallons)	Gas/day (gal/day)
Chunky	28	3.31	0.118	10	2.38	0.238	-	-	-
Skinny	10	3.76	0.376	10	4.25	0.425	2	4.16	2.078

The second collection dates are post pH control and seeding. The 10-day figure for the second collection is relative to the addition of the digested sludge and not the previous collection time. In the time between the first collection and seeding, gas production was minimal and not recorded or tested. Skinny continued to outperform Chunky, requiring a quick third gas collection after the second. The methane sensor on all second and third collections read a resistance value of 1015, assumed to be the sensor's maximum value.

Gas production continued until the end of the experiment, but no data was collected. Chunky produced a small quantity of gas likely around a gallon. Skinny produced at least twice as much, but the volume was not recorded prior to the leak and subsequent emergency container transfer. More gas was produced after the transfer, but the data was considered suspect due to the high level of contamination and interference introduced.

4.0 DISCUSSION

4.1 Digester Performance

The reduction of solids, largely through the conversion of organic carbon into methane and carbon dioxide, is one of the main goals of anaerobic digestion (Ghaly et al., 2000 and Gray et al., 2008). VS reduction is highly correlated with methane production and thus a useful indicator of digester performance. Chen et al. (2014) saw a 50% VS reduction at with substrate TS values of 15%. Our better performing digester, Skinny, produced a VS reduction of 18.20%, which is just above a third of that value.

Additionally, the results of Chen et al. show methane yields of around 250 mL/g VS for 15% TS. Converting Skinny's total gas production to these units and falsely assuming a 100%

methane concentration, the result is a diminutive 33 mL/g VS (See Appendix B for calculation). This suggests our digesters likely had much greater potential than was properly exploited.

Since pH was controlled in this experiment and the bacterial population was refreshed using seeding, the likely largest culprit for our dismal performance was reactor temperature. While the internal temperature of the digesters was not monitored, the external temperature of the room was nearly always 22 °C. During the transfer of Skinny after its leakage it was noted to "feel very warm," however it was certainly not out of the mesophilic range (about 20-45°C). Mesophilic digesters with high solids content have a history of worse performance (Li et al., 2010) although for normal solids content operations offer some advantages (Thompson, 2008). Ghaly et al. (2000) had success with a mesophilic digester using acid cheese whey as a substrate, but had a temperature control system maintaining their systems at 35.3 °C, a value much closer to body temperature.

Low pH throughout methanogenesis also may have led to reduced performance. While the pH for the digesters was raised to the preferred range of between 6.4 and 7.4, mesophilic operation has actually been optimized at the range of 7.1-7.8 (Liu et al., 2008). Skinny produced the majority of its gas while the pH dropped from 7.27 to 6.92, and the lesser-performing Chunky was below 6.8 for the entirety of post-seeding.

While the methane content of the collected biogas was regrettably not determined, the low values pre-pH control and high (past detection) values after pH control suggest that initially CO_2 was primarily being produced, but after seeding it was primarily methane. This aligns with standard digester biogas production (Droste, 1996).

4.2 Digester Optimization and Control

While difficult to confidently declare due to initial substrate differences, the superior performance of Skinny suggests blending to be preferable to chopping for substrate processing. This is unsurprising considering the reduced size of the food chunks optimizes them for bacterial breakdown. The large standard deviations of Chunky's TS samples likely represents just how non-uniform the solids content was throughout the digester, as compared to Skinny's consistent low standard deviation.

The acid-forming stage is generally optimized around a pH of 4.5-6 (Demirel & Yenigün, 2002), contrasting with common digester operation at a neutral pH. Chunky began in this range, while Skinny began below it, suggesting a high level of acid already present. This was likely due its higher content of coffee grounds (Kozuchowska & Evison, 1995), though present in both digesters. While acidification was likely hampered due to the low temperatures, the net reduction in pH suggests acids were being produced. However, the excessively low (<4) pH of Skinny may suggest ethanol fermentation was occurring (Demirel & Yenigün, 2002). Alcohols are not conducive to anaerobic digester processes (Chen et al., 2007). The acidity problems with the digesters may suggest that VFA content was not a limiting factor for methanogenesis.

The low initial pH and during acid formation, however, did necessitate pH control to move onto the methanogenesis phase. Ghaly et al. (2000) had only CO_2 production after pH control without bacterial seeding, which informed the decision to seed the digesters with digested sludge. The low pH in both Chunky and Skinny had likely reduced the presence of methanogens, if present initially at all.

Digester operation likely could have been further optimized by continued pH control, keeping the digesters in the (as discussed in section 4.2) 7.1 to 7.8 range. The additional sodium

carbonate would have raised the fixed solids content (Ghaly et al., 2000) but could have sustained methane production. The pH slightly falling after pH control likely indicates low alkalinity in the digesters and continued acid production at a rate greater than the methanogen conversion of the acids into methane. A simple way to add alkalinity would have been more egg shells in the substrate.

5.0 Conclusion

The effects of minimal interference and maintenance on a small-scale anaerobic food waste digester were investigated. Without substrate processing, pH control, reseeding, and incoming sunlight for heat, the project likely would have been a complete failure, suggesting that control over these variables is important. However, our results of our study also show the potential for each variable to be controlled in a simple manner, suggesting a low-maintenance digester could be feasible. A digester with blended food waste, a higher eggshell content for alkalinity, with a small amount of manure, left out in a warm climate would likely perform quite well. Additionally, forgoing coffee grounds may reduce acidity as well as lingering lignin (Pujol et al., 2013). Informed by this study's discoveries, further studies should be done further optimizing the feasibility of low-maintenance food waste digesters. Chunky and Skinny were far from models of perfection, but they did manage to reduce solids and generate methane.

Research could also be done on existing food waste digestion projects abroad that have been quite successful. For example, household food waste digesters used for gas production in Pune, India function quite easily as long as the initial substrate contains cattle manure, the feedstock is blended, and the digester is not over-fed (Muller, 2007).

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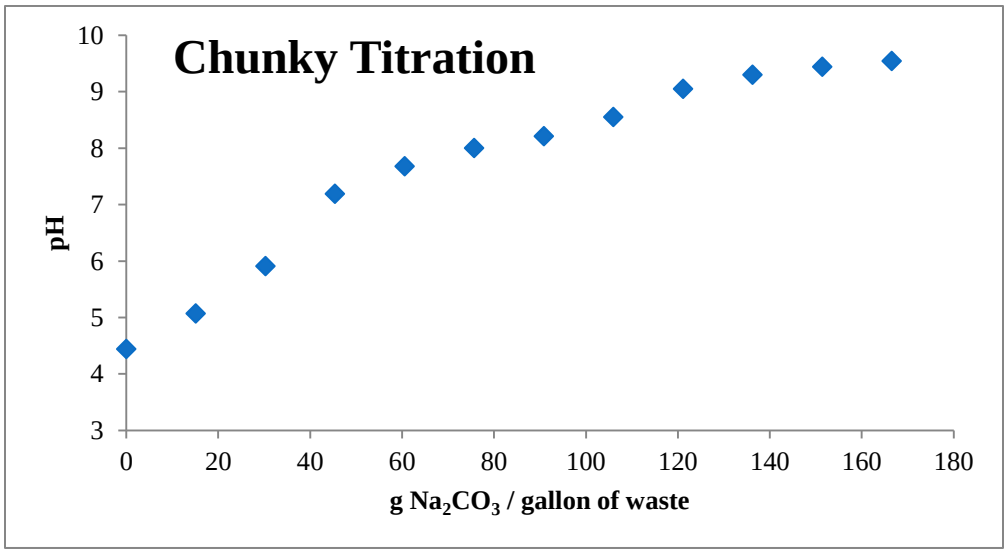
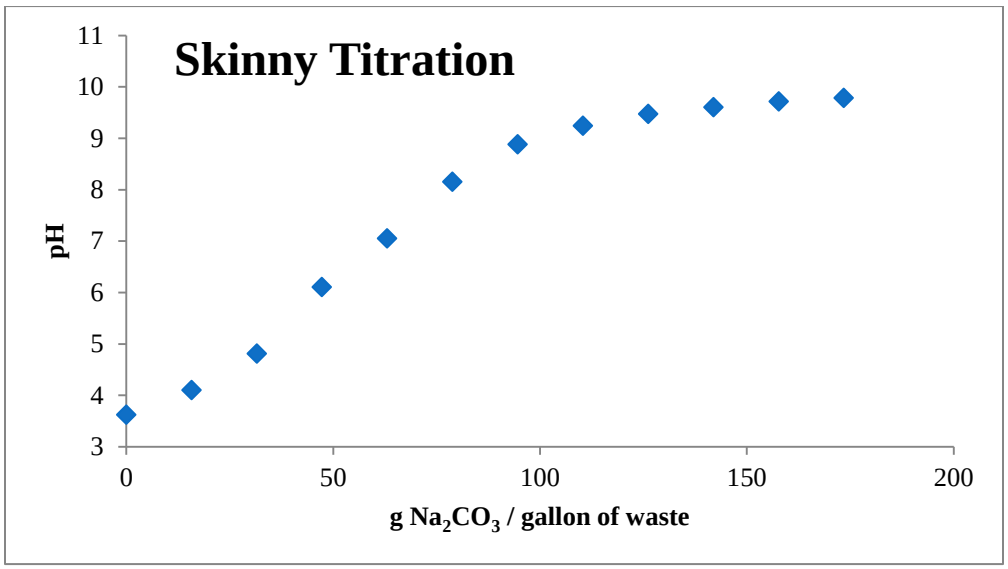
7.0 APPENDICES

Appendix A – Titration Data

Below are the titration curves for Chunky and Skinny. Each was done with approximately 120 mL of sample from the digesters. Sodium carbonate was used as the strong base and was added until the change in pH was < 0.1. Note the horizontal axis denotes the weight of sodium carbonate required per each gallon of food waste.





Appendix B – Skinny Methane Production (mL/g VS)

In order to compare Skinny's methane production to the results of other studies, the total recorded volume (in gallons) was converted to mL/g VS. Below is a quick rundown of the calculation.

Assumptions: 100% of gas produced is methane. Skinny substrate density equivalent to water

Total gas production: 12.17 gallons. Pre-methanogenesis VS: 94.86% TS: 13%

$$12.17\ gal\ \times \frac{3785\ mL}{1\ gal} = 46060\ mL$$

$$3\ gal\ \times 94.86\% \times 13\% \times \frac{3785\ mL}{1\ gal} \times \frac{1\ gram}{1\ mL} = 1400\ grams$$

$$\frac{46060\ mL\ CH_4}{1400\ g\ VS} = 33\ mL/g$$