ENERGY INNOVATIONS SMALL GRANT NATURAL GAS PROGRAM

FINAL REPORT

Optimizing Biogas Production from Organic Waste through RNA/DNA Molecular Testing

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Acknowledgement Page

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Abstract

The use of ambient temperature anaerobic digestion of organic wastewater in covered lagoon systems was investigated using biochemical methane potential testing, semi-continuous feed laboratory digesters, and RNA/DNA molecular testing. Six available substrates with COD >5000 mg/l were tested. Biochemical methane potential ranged from 0.22 to 1.07 litersper gram of volatile solids with rank order of winery > beer cider > tomato > fats oil & grease > septage > portable toilet. Five waste mixtures of these substrates were tested in semi-continuous laboratory digesters resulting in 0.12 to 0.51 liters methane per gram volatile solids with the food mixtures performing well while septage and portable toilet waste had the poorest performance. All other indicators of stable digestion were achieved including stable pH and acids, and methane contents from 67 to 73%. Methanogen populations exceeded healthy target ranges from 10^6 to 10^8 per milliliter of sample with largest populations in mixtures demonstrating high methane production. The results indicated that stable and healthy communities of methanogens were developed in the psychrophilic conditions present in covered lagoon digesters. Using a revenue requirements economic model for commercial sized systems, the levelized cost of biogas was estimated at $5.56 to $9.30 per MMBtu and power production at $0.060 to $0.085 per kilowatt-hour, holding a low tipping fee of $0.03 to $0.05 per gallon. The study concludes that there is no technical limitations to developing ambient, unheated covered lagoon digester systems in temperate climates that produce biogas or combined heat and power for costs that are feasible in the current renewable energy marketplace.

Key Words: Anaerobic Digestion, Biogas, Organic Waste, Methanogen, RNA, DNA, Biochemical Methane Potential, Covered Lagoon Digester, Psychrophilic

Executive Summary

Introduction

In California, there are million tons of solids that are diluted into billions of gallons of wastewater that originate from the food processing industry and other sources like septic tanks, portable toilets, and grease traps. The cost for disposing of this wastewater using traditional wastewater treatment is an economic and energy burden for California. However, these solids have the potential to be converted to high-methane biogas using anaerobic digestion, with a potential to produce the equivalent of nearly 2% of commercial natural gas use in California from food processing wastes alone. While conventional high-rate heated digesters are still cost prohibitive for dilute waste streams, ambient temperature covered lagoon digester systems can convert these wastes into renewable biogas while providing a substantially more cost-effective disposal method than long-established wastewater treatment. Some key tools including biochemical methane potential testing and microbial quantification using RNA/DNA analyses can be used to demonstrate conversion of these organic waste substrates in the ambient temperature environment. There is a need to prove that good biogas production and stable communities of methanogens can survive and thrive in an ambient temperature covered lagoon system, unlocking the potential to convert the vast organic waste resource that is available.

Project Objectives

The project had the following technical objectives to achieve the overall goal to determine the feasibility of co-digestion of various organic wastes in ambient temperature covered lagoons:

1. Select at least 6 available domestic and commercial organic waste substrates that are suitable for anaerobic digestion (Targets: Total solids (TS) from 1% to 10%, Volatile solids (VS) at least 80% of TS, Chemical oxygen demand (COD) at least 5000 mg/l, C/N ratio between 20:1 and 40:1, Volatile Fatty Acids (VFA) no more than 5000 mg/l)
2. Determine the laboratory biochemical methane potential (BMP) of individual substrates (Targets: At least 0.25 l/g of VS added, At least 0.25 l/g COD added)
3. Select 5 mixtures of the substrates for optimal digestion conditions and perform continuous feed digestion (Targets: pH between 6.5 and 7.5, VFA no more than 5000 mg/l, Biogas production at least 0.4 l/g VS added and/or 0.4 l/g COD added, Methane content of biogas at least 60%)
4. Measure the methanogienic microbial populations using effluent from the continuous digesters to determine the highest and most diverse populations of the methanogens (Targets: methanogens, Methanosarcina and Methanosaeta, in the range of 1 X 106 to 5 X 106 per milliliter of sample)
5. Determine the technical and economic feasibility of full scale ambient temperature lagoon digesters using the selected waste mixtures (Targets: Biomethane valued at $10/MMBtu, Net costs of treatment no more than $.02/gallon of wastewater and/or $.20/lb VS or COD destroyed, *Added target:* electrical production less than $0.15 per kilowatt-hr)

Project Outcomes

The following actual results were achieved for each objective:

1. Six substrates available in Yolo County including tomato, portable toilet, septage, winery, fats oil & grease, and beer cider wastes were selected because they met the COD criteria of >5000 mg/l. Not all substrates met every other target due to dilution levels and other factors but all demonstrated ample organic matter available to digest and produce biogas.
2. Biochemical methane potential ranged from 1.07 to 0.22 liters/gram of volatile solids with rank order of winery > beer cider > tomato > fats oil & grease > septage > portable toilet.
3. Four food waste mixtures and one human waste mixture (septage and portable toilet) were tested in continuous digesters resulting in 0.27 to 0.51 liters methane/gram volatile solids for the food mixtures and 0.12 liters methane/gram volatile solids for the human. All other performance targets were achieved including stable pH and acids, and methane contents from 67 to 73%.
4. Methanogen populations exceeded the targets ranging from 10^6 to 10^8 per milliliter of sample with larger populations in mixtures demonstrating high methane production. The results indicated that stable and healthy communities of methanogens were developed in the ambient (psychrophilic) conditions present in covered lagoon digesters.
5. The levelized cost of biogas was estimated at $5.56 and $9.30 per MMBtu and power production at $0.060 and $0.085 per kilowatt-hour, with tipping fees in the $0.03 - $0.05 per gallon and analyzing conversion of an existing lined pond facility and a new pond construction respectively.

Conclusions

In conclusion, the study demonstrated the following important results:

- Six important waste and wastewater feedstock used in mixtures are suitable for volatile solids conversion to biogas under psychrophilic digestion conditions experienced in a typical unheated covered lagoon digester.
- Biochemical methane potential assays can be helpful to predict potential biogas production in these systems showing a strong correlation with actual gas production averaging about 60% of measured potential on a volatile solids basis.
- RNA/DNA molecular testing can be used to understand the stable and healthy development of methanogen communities within these lower temperature systems.
- The proposed ambient, unheated covered lagoon digester systems can produce biogas or combined heat and power for costs that are feasible in the current renewable energy marketplace.
- There is no technical limitation to operating covered lagoon digester systems utilizing food waste mixtures in California, as long as there are sustainable options for managing the residual byproducts that are generated.

Recommendations

The research team recommends the following next steps:

- Develop a commercial demonstration system of a covered lagoon digester utilizing food waste mixtures as feedstock.
- Make use of the data generated by this study, the 10+ years of commercial experience from the dairy industry, and tools like BMP assays and RNA/DNA analysis to engineer and develop other commercial anaerobic digester projects in California.
- For the human waste feedstock like septage and portable toilet waste, further analyze the makeup of these wastes, test their co-digestion with other food wastes, and apply tools utilized in this study like BMP assays and RNA/DNA analysis to improve the digestion and secure treatment of these more challenging materials.
- Use the yield results from this study to develop a more complete market analysis for this technology, including potential locations with the most need for organic waste handling, the types and concentrations of available waste, and what existing facilities have the infrastructure and capabilities to site these systems.
- Further study the disposal requirements for residual digester effluent in terms of the sustainability and economics of these systems.

Public Benefits to California

The potential public impact from implementation of this research will be:

- The potential development of a covered lagoon digester demonstration system at Yolo County Integrated Waste Facility that converts 10,000 gallons per day of regionally generated food and grease trap waste into 420,000 kW-h per year of renewable electricity.
- The increased production of renewable biogas from organic wastes with a market potential in California of 9.8 million MMBtu, with a production cost range of $5.5 - $9.5 per MMBtu.
- If this gas was converted to combined heat and power, the market potential is 861,000 MW-hours per year of renewable electricity and up to 3.4 million MMBtu of available heat for commercial utilization at a reasonable production cost from $60 to $85 per MW-h.
- The use of low-cost covered lagoon systems in treating organic wastes could reduce the cost by a factor of four to eight from about $0.20 per gallon for traditional treatment to $0.03 to $0.05/gallon, depending on the disposal costs for the effluent.

Introduction

In California, waste substrates such as septage (septic tank waste) and FOG (fats oil and grease), are generated in large volumes: 237 million gallons of septage per year and 11.5 million gallons of FOG per year (California Wastewater Training and Research Center, 2002). These wastes are typically disposed of at large waste water treatment plants (WWTP) at a fairly low cost, less than $0.05/gallon. However, smaller WWTP's do not have the capability to dispose of these recalcitrant wastes and must haul them some distance and higher cost ($.10 to $0.25/gal) to the large WWPT's (California Wastewater Training and Research Center, 2002). Food processing residues are also an important part of the available organic waste stream in California, amounting to 600,000 dry tons per year of high moisture solids and over 26 billion gallons of wastewater generated by food processing industries containing almost 175,000 tons of BOD (Amon, et al 2012). The handling and treatment of this organic waste is a significant economic and energy burden for California.

However, these waste materials also have the potential to be turned into an energy resource if converted to biogas using anaerobic digestion. Ambient temperature covered lagoon digesters have been used successfully in California and other mild climates to treat dilute wastewaters while producing significant methane-rich biogas. The total annual potential for energy recovery from converting the above substrates to biogas is on the order of 10 million MMBtu, equivalent to about 2% of non-residential natural gas usage in California. The total potential for energy recovery from this biogas fueling combined heat and power (CHP) systems is almost 100 MW of electrical power along with 3.5 million MMBtu of recovered heat. These waste resources are located primarily in rural areas of the state, over 55% from the central valley counties of Fresno, San Joaquin, Madera, Kern Merced and Stanislaus (Amon, et al 2012).

One of the constraints with development of anaerobic digesters is that conventional high-rate systems can be more costly than traditional wastewater treatment. For example, Slaughter (2007) reported that septage could be digested in a high rate digester along with cornstalks to produce biogas for electrical production. The cost of this system required a tipping fee of $0.13/gallon to then have a simple payback of 7 years for the digester system. In another example, Moletta (2007) reported the use of anaerobic digestion to treat winery wastewater in France, utilizing high rate, short retention time digesters such as anaerobic filters and sludge blanket digesters. The equivalent investment and operating cost for this process was reported to be approximately $0.20 per gallon of wastewater treated, and approximately $2.00 per pound of COD treated. These operating costs and tipping fees are in the range of higher prices mentioned above for septage disposal at smaller WWTPs, making them non-feasible from and economic perspective.

The researchers contend that ambient temperature covered lagoon-type digester could be used to treat such wastewaters as septage and winery wastes for less cost than the more complicated heated and mixed digesters cited above. A recent study (Summers and Williams, 2013) of covered lagoon digesters in California have shown that for dairy farms with cheese processing, the covered lagoon system treated the mixture of dairy manure and cheese plant wastewater resulting in a COD reduction of 50%. This system treated an average of 60,000 gallons of wastewater per day containing

5 tons of COD, for a yearly total of 22 million gallons and 1825 tons of COD. The capital cost of this system was $625,000, and the annual investment and operating costs for this system was almost $96,000, which is equivalent to approximately $0.004/gallon of wastewater and about $0.03/ lb of COD treated. These numbers are significantly less than the reported cost of treating septage and winery wastes, and additionally do not include the benefits of utilizing the biogas produced by the digester.

Information on the ideal conversion of these organic substrates within ambient temperature (psychrophilic) digesters is limited. Tools like biochemical methane potential (BMP) assays carried out in psychrophilic conditions can help indicate what potential various substrates have for conversion in a covered lagoon digester system. While these methods have been in use in the anaerobic digestion research community for some time (Owen, et al 1979, Angelidaki, et al 2009), there is little data produced in the lower temperature range because often digesters are heated to mesophilic or thermophilic conditions that are presumably more ideal for digestion as the assumption is that digesters will be heated and mixed.

Methanogen quantification using nucleic acid-based methods (RNA/DNA analysis) can also be helpful in understanding the ability to generate a healthy community of methanogens for high conversion of solids to biogas in a digester system. Methanogens are of great importance in carbon cycling and alternative energy production, but quantitation with culture-based methods is time-consuming and biased against methanogen groups that are difficult to cultivate in a laboratory. Steinberg and Regan (2009) developed a culture-independent molecular techniques that are quicker and easier to replicate in the laboratory and could be useful for understanding lower temperature anaerobic communities.

There is potential to use these tools, BMP testing and RNA/DNA analyses, in the psychrophilic digester environment to demonstrate conversion of various dilute organic waste substrates. There are many typical low solid (less than 5% solids) organic waste streams that are produced by the domestic and commercial sector that can be studied. There is a need to prove that good biogas production and stable communities of methanogens can survive and thrive in these systems with the ample and available organic waste substrates from California.

Project Objectives

Project Goal: The goal of this project was to determine the feasibility of utilizing biochemical methane potential (BMP) testing and molecular biology analyses to increase gas production from the co-digestion of various organic wastes in ambient temperature covered lagoons. In order to achieve this goal, the project had the following objectives with quantifiable performance and cost targets:

1. Select at least 6 available domestic and commercial organic waste substrates that are suitable for anaerobic digestion (Targets: Total solids (TS) from 1% to 10%, Volatile solids (VS) at least 80% of TS, Chemical oxygen demand (COD) at least 5000 mg/l, C/N ratio between 20:1 and 40:1, Volatile Fatty Acids (VFA) no more than 5000 mg/l)
2. Determine the laboratory biochemical methane potential (BMP) of individual substrates (Targets: At least 0.25 l/g of VS added, At least 0.25 l/g COD added)
3. Select 5 mixtures of the substrates for optimal digestion conditions and perform continuous feed digestion (Targets: pH between 6.5 and 7.5, VFA no more than 5000 mg/l, Biogas production at least 0.4 l/g VS added and/or 0.4 l/g COD added, Methane content of biogas at least 60%)
4. Measure the methanogienic microbial populations using effluent from the continuous digesters to determine the highest and most diverse populations of the methanogens (Targets: methanogens, *Methanosarcina* and *Methanosaeta*, in the range of 1×10^6 to 5×10^6 per milliliter of sample)
5. Determine the technical and economic feasibility of full scale ambient temperature lagoon digesters using the selected waste mixtures (Targets: Biomethane valued at $10/MMBtu, Net costs of treatment no more than $.02/gallon of wastewater and/or $.20/lb VS or COD destroyed, ***Added target:*** electrical production less than $0.15 per kilowatt-hr)

During the course of the project, it became clear that some of the targets were more important than others in determining the performance. For the first objective, COD was the most important indicator of a suitable feedstock for producing biogas while other factors tolerated a wider range than first targeted, particularly when mixing substrates for co-digestion. For the second and third objectives, biogas production in terms of VS added proved to be most reliable and predictable in determining performance of substrates and mixtures. For the fourth task, a wider variety of methanogen phylogenetic types than Methanosarcina and Methanosaeta were present in total methanogens. For the final task, an energy cost target was added to address the interest in using biogas directly for renewable electricity and combined heat and power production.

Project Approach

The following tasks were developed to accomplish the project objectives:

1. Selection and characterization of domestic and commercial organic waste substrates
2.A. Laboratory biochemical methane potential testing of individual substrates
2.B. Determination of biogas generation potential for waste mixtures
3. Determination of methanogenic microbial populations by nucleic-acid based analyses
4. Technical and economic feasibility of increased gas production

The approach, methods and materials that were used to accomplish each task are described below.

Task 1 Approach: Selection and characterization of individual substrates

The feedstock used in this project were all generated in Yolo County, California and delivered to the Yolo County Central Landfill near Davis, California. Most substrates were used directly as received by the landfill. Several types of canned tomato waste and salsa (diced tomatoes, whole tomato, green chilies, mild salsa, garlic and cilantro salsa, black bean and corn salsa) were removed from cans and homogenized using a kitchen blender (Ninja Professional-NJ600, USA) and the blended material used as tomato waste substrate. All waste substrate samples were stored in refrigeration at 4 °C after samples were collected and then used for later for BMP analysis or feed for the semi-continuous reactor experiments.

Anaerobically digested cow manure sludge from a dairy manure digester in Galt, CA (Van Warmerdam dairy) was used as inoculum. This covered lagoon anaerobic digester was operated at approximately 25 °C when inoculum samples were collected but this temperature varies somewhat by time of year in these unheated digester systems. Inoculum was analyzed and used for both BMP and digester seeding in the other tasks.

Laboratory chemical analysis of each type of waste and inoculum were performed using standard water and wastewater testing methods by a private laboratory (BC Laboratories, Inc., CA, USA) using the following standard methods: EPA-6010B for total sodium, EPA-300.0 for nitrate as nitrogen and sulfate, EPA-160.4 for volatile solids, EPA-351.2 for Total Kjeldahl Nitrogen (TKN), EPA-350.1 for ammonia as NH_3, EPA-365.4 for total phosphorous, SM17-5210B for Biochemical Oxygen Demand (BOD), and EPA-410.4 for Chemical Oxygen Demand (COD).

Task 2A Approach: Biochemical methane potential of individual substrates

A BMP study was performed in order to obtain preliminary indications of the bio-methane potential from the waste substrates on an individual basis to consider how they could contribute to feeding a continuous digester system. BMP analysis is an efficient and economical method for evaluating the rate and extent of biomass conversion to methane under anaerobic conditions. Angelidaki et. al. 2009 describes the BMP method and the means to insure repeatable results utilized by this study.

Prior to BMP trial setup, the substrates were characterized for total solids (TS), and volatile solids (VS), and chemical oxygen demand (COD). An aliquot of each refrigerated sample were warmed to room temperature (25° C) and placed in a 150 ml septum bottles (Figure 1) with anaerobic inoculum of digester sludge. Digester sludge seed is high in anaerobic bacteria but can also contain some residual biomass feed so it was also run as a control reference to adjust the biogas generated by the other assays. The sealed septum bottles were placed in a water bath (Figure 2) and incubated under a constant psychrophilic temperature of 26.7° C for 30 to 60 days. Each assay was performed in triplicate. Biogas production was monitored daily using a volume displacement method. Biogas composition (O_2, N_2, CH_4, CO_2, and H_2S) was measured after the second week of gas production by supplying a syringe sample to a gas chromatograph (Agilent 2000 Micro GC, Agilent, Inc.) using thermal conductivity detectors (Figure 3). The gas chromatograph was span calibrated with certified reference gases including each of the target gasses prior to use.

Figure 1. BMP septum bottles with substrate

Figure 2. BMP digester setup with water bath temperature control and gas measurement.

Figure 3. Gas sampling (left) and analysis (right) of BMP assays using gas chromatograph

Two sets of BMP trials were started on May 1, 2014 and June 3, 2014 with fresh digester seed collected that same day and temperature acclimated refrigerated waste substrates, with the weight composition of each BMP assay listed in Table 1. For each substrate there were three replications. Chemical analyses were performed on the substrates including TS, VS, COD and nutrients. At the end of the trials, cumulative biogas and methane production per unit of VS and COD added was calculated and reported.

Table 1. Constituents tested in the BMP assays

SUBSTRATE	SEED g	WATER g	SUBSTRATE g	TEMP °C
SEED*	50	50		26.7
TOMATO	80		20	26.7
PORTABLE TOILET	50		50	26.7
WINERY	50		50	26.7
SEPTAGE	50		50	26.7
FOG	80		20	26.7
BEER CIDER	50	30	20	26.7

Task 2B Approach: Determining biogas generation for waste mixtures

Acclimation of active anaerobic inoculum – Sludge from WWTP anaerobic digesters that treat target wastes have been widely used as seed for new digesters. It has been reported that biogas generation could vary due to differences in sludge source or characteristics (Shelton and Tiege 1984, Speece 1988). In this study, dairy manure sludge was used as a source of mesophilic anaerobic microorganisms. However, the microbial populations in this seed were not previously exposed to the wastes targeted in this study (e.g, winery waste). Thus, to accelerate digester start-up and maximize biogas generation, the dairy manure sludge seed first was acclimated to the wastes and temperatures used herein. Two sets of acclimated microbial seeds were developed by running semi-continuous anaerobic digesters for a period of 45 days. One seed was prepared from a mixture of dairy manure sludge and a food waste mixture (FOG, tomato, and winery); the second was prepared from dairy manure and the human waste mixture (septic and portable toilet waste). The acclimated microbial seeds were used to start up the new digesters. Table A2 in Appendix A shows the list of initial parameters tested for the various liquid wastes and the dairy manure sludge. Human wastes were separated from other waste sources because of the presence of pathogens and high sulfate content. Liquid waste mixtures for each set of reactors (3 replications) were tested for various parameters. Tables A3 and A4 in Appendix A shows the initial digester mixture amounts, waste mixture C/N ratios, and organic loading rates.

Experimental Setup – Tests were conducted in triplicate using 50 mL of seed and 50 mL of each liquid waste mixture for co-digestion in 125-mL serum bottles (see Figure 4). Since the densities of all the feedstocks used in this study were close to the density of water, a laboratory scale (PB5001, Mettler Toledo, OH, USA) with accuracy of ± 0.1 g was used to measure the feedstock mixture volume for each digester. The mixture of the inoculum used was 66% dairy manure sludge seed by volume (33 mL) and 34% waste mixture acclimated seed (17 mL). The waste mixture acclimated seed (45 days) was either food waste or human waste. No additional nutrients or trace elements were added to the reactors because it has been reported that a significant amount of nutrients are found in dairy manure (Gustafson, 2000). Triplicate control digesters also were run without any feedstock for each seed type (food waste seed and human waste seed) to measure biogas produced from seed alone. This amount of biogas was deducted from biogas produced in the fed digesters. Controls were prepared using 50 mL seed and 50 mL distilled water mixture.

A controlled ambient environment was set up inside an insulated recycled refrigerator. The temperature inside was controlled using a temperature controller (CN 710, Omega Engineering, CT, USA) connected to a type K thermocouple. The feedback controller with temperature accuracy of ± 0.1 °C was setup to turn on and off a heat strip (BriskHeat, OH, USA) and a fan to keep the temperature at a set point of 26.7 °C. The room temperature was kept below 25 °C; therefore, a cooling hysteresis was unnecessary. Temperature was logged continually using a CN7-A-Process monitor and logger (Version 2.01.00, Omega Engineering, CT, USA).

The pH of the feedstock mixtures was measured before they were added to each digester. After feedstock materials were introduced to the digester, headspace of the digester bottles was purged with nitrogen and sealed immediately with a rubber stopper and aluminum cap. A B-type PTFE magnetic stir bar was left inside each serum bottle, and reactors were stirred daily with the exception of weekends.

Each reactor bottle was opened weekly to remove co-digested waste and seed mixture (17.5 mL), and add the same volume of fresh waste mixture. For the control reactors, distilled water was added. The volume removed and added was based on typical covered lagoon hydraulic retention time of 40 days. A portion of the liquids removed from each reactor was used for chemical analysis, and the rest was shipped to Colorado State University for testing with DNA- and RNA-based assays. Volumetric measurements and additions were done on a mass basis using a laboratory scale (PB5001, Mettler Toledo, OH, USA). The pH of each reactor was checked before and after the addition of feedstock and adjusted with sodium bicarbonate to between 6.5 and 7.5 as required.

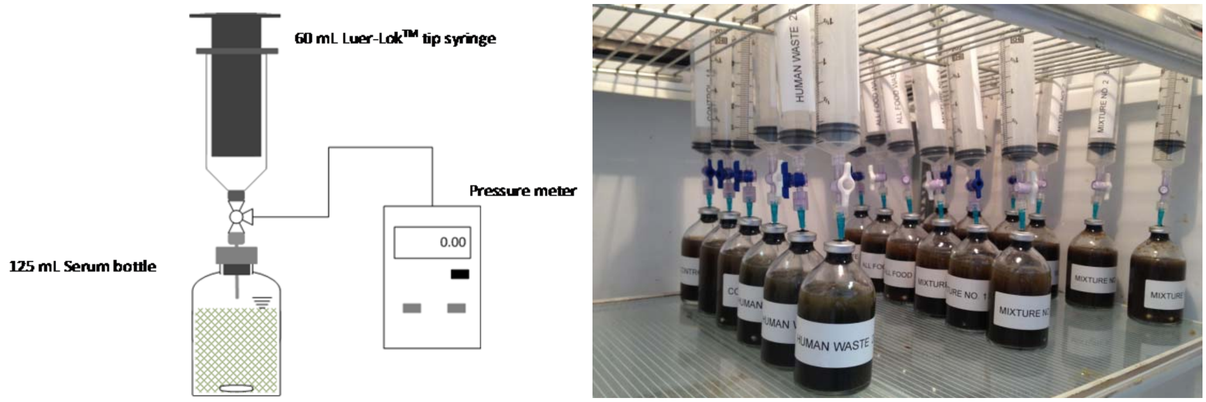


Figure 4. Semi-continuous anaerobic digester setup and gas collection and measurement

Chemical Analyses – Due to limited sample volumes, samples from each triplicate digester were combined for chemical analysis. COD tests instead of BOD test were performed. Chemical analysis of COD, Volatile Acids, sulfate, alkalinity, total phosphorus, and TKN were performed using a a Digital Block Reactor (DRB200, Hach Company, CO USA) and a bench-top Spectrophotometer (DR 3900, Hach Company, CO USA). When necessary, samples were diluted to have results within the range for the Hach kits used. The dilutions ranged between 2 and 100, and no dilution was needed for the control reactors. See Table A5 in Appendix A for kits and test methods used.

Other aqueous chemistry parameters were measured using a portable meter (HQ40d, Hach Company, CO, USA) with various probe attachments. pH was measured with a pH probe (IntelliCALTM PHC10101, Hach Company, CO, USA). Conductivity, Total Dissolved Solids (TDS), salinity, and resistivity were measured using a 4-pole conductivity probe (IntelliCALTM CDC40101, Hach Company, CO, USA). Nitrate as nitrogen (NO_3-N), ammonia as nitrogen (NH_3-N), and sodium (Na^+) were measured with ion selective electrodes (ISEs) (IntelliCALTM ISENO3181, ISENH318101, and ISENa318101, Hach Company, CO, USA). Three-point calibration was performed for every probe and electrode using standard solutions (Hach Company, CO, USA) prior to measurement.

Biogas Composition – Biogas was collected using 60-mL plastic syringes (accuracy of 0.5 mL) connected to valves (Figure 4). Prior to gas volume measurement and removal of the syringes, the pressure inside each reactor was adjusted to atmospheric pressure. To adjust the pressure inside of each reactor, a needle was connected to a hand-held gas pressure sensor (model PDM213, Air Neotronics, Oxford, England) with an accuracy of 0.25 mm of water, and the needle was inserted into the headspace of each reactor through the rubber cap. Then, the volume of the syringe was increased or decreased until the pressure reading was equal to atmospheric pressure (zero gauge pressure). The ideal gas law was used to convert the measured gas volumes to standard temperature and pressure (STP). Saturated vapor pressure was set to 26.1464 mm Hg for the experiment that was operated at 26.7 °C.

Biogas composition (O_2, N_2, CH_4, CO_2, and H_2S) was measured using a micro gas chromatograph (GC) (MTI P200, MTI Analytical Instruments, CA, USA). The micro GC was equipped with dual thermal conductivity detectors (TCD), a 10m MS-5A capillary column (channel A) and an 8m Poraplot U capillary column (channel B). Column temperature was independently controlled to allow simultaneous use of both channels. Either two (O_2 and H_2S) or three point (N_2, CH_4, CO_2) calibration curves were used to calibrate the instrument.

Task 3 Approach: Determination of methanogenic microbial populations by nucleic-acid based analyses

DNA and RNA extraction – 5.1-mL or 1.7-mL digester samples were collected. Week 1 and 3 samples were 5.1 mL, but to accommodate measurement of other parameters, sample volume was reduced to 1.7 mL for subsequent weeks. All samples were centrifuged at 5000g for 3 minutes; supernatant liquid was discarded. Then DNA was extracted from the pelleted digestate material using the PowerMax® Soil DNA Isolation Kit (MoBio Laboratories Inc., Carlsbad, CA) according to the manufacturer's protocol. DNA was stored at -20°C. Digestor samples (1.7-mL) for RNA analysis were frozen with liquid nitrogen upon sampling, put on dry ice for shipping, and then stored at -80°C. RNA was extracted using the RNA PowerMicrobiome™ RNA Isolation Kit (MoBio Laboratories Inc., Carlsbad, CA). Quantity and purity of DNA and RNA were assessed on a NanoDrop™ spectrophotometer. RNA integrity (i.e., lack of sample degradation) was assessed via measuring the intensity and quality of the rRNA bands (23S and 16S) using an Experion™ RNA Analysis Kit (Bio-Rad Laboratories, Hercules, CA) on an Experion™ Automated Electrophoresis System (Bio-Rad Laboratories, Hercules, CA).

Quantitative PCR – Quantitative polymerase chain reaction (qPCR) assays were used to determine the concentration of methanogens in each digester as a function of time via measuring the quantity of *mcrA* genes (gene that encodes an enzyme involved in methanogenesis). The accuracy of specific qPCR assays depends on the types of methanogens present, which can vary. Thus, two published assays developed for application to methanogenic digesters were used; the associated primer sets are shown in
Table 2.

Table 2. Primer sets for qPCR quantification of methanogens

Primer	Sequence (5'-3')	Ref.
mcrA_1035F	GGTGGTGTMGGATTCACACARTAYGCWACAGC	Pereyra et al. (2010)
mcrA_1530R	TTCATTGCRTAGTTWGGRTAGTT	
MLf	GGTGGTGTMGGATTCACACARTAYGCWACAGC	Steinberg and Regan (2009)
MLr	TTCATTGCRTAGTTWGGRTAGTT	

qPCR was conducted with a 7300 real-time PCR system (Applied Biosystems-Life Technologies, Grand Island, NY) as done by Pereyra et al. (2010) with one modification. The qPCR reactions consisted of 12.5 μL of 1 X *Power* SYBR green PCR master mix (Applied Biosystems-Life Technologies, Grand Island, NY), 0.2μM of each primer, 2 μL of DNA or cDNA template, and 7.5 μL of PCR water for a total of 25μL. Additional $Mg(OAc)_2$ was not added (modification to Pereyra et al. (2010)), except for initial assays run to optimize template mass (see text below), because omitting the $Mg(OAc)_2$ was found to increase the amplification efficiency. All assays were run in triplicate. The qPCR system was run with a temperature program of 10 min at 95°C, followed by 40 cycles of 40 sec at 95°C, 30 sec at 56°C, 30 sec at 72°C (Pereyra et al. 2010). Genomic DNA from *Methanococcus maripaludis* (ATCC 43000D) was used to generate standard curves for quantification as described previously (Pereyra et al. 2010); standards ranged from 0.0005-5.0ng/rxn. Results are reported as "Methanogens/mL of Reactor Volume", calculated assuming one copy of the *mcrA* gene/genome (See Appendix B for equation).

Inhibitory substances in DNA extracts from digester samples can reduce qPCR accuracy and lead to underestimation of methanogen quantities (King et al. 2009). To minimize the negative impacts of inhibition, the mass of DNA template per qPCR reaction can be minimized; however, this reduces the limit of detection. To identify the optimal mass of DNA template for the sample matrix present in the reactors studied herein, qPCR assays were run with 0.078-1.250ng of DNA/rxn. DNA extracted from the digesters used for inoculum acclimation (*see Task 2b: Acclimation of active anaerobic inoculum*) was used for these tests. Moderate inhibition was observed for concentrations >0.156ng; however, given that this template mass is lower than what is generally used, we ran all tests at 0.156 and 1.00 ng of DNA/ rxn. Trends were similar for both template masses.

Reverse transcription qPCR (RT-qPCR) – RT-qPCR was used to quantify the concentration of *mcrA* gene transcripts in each reactor. Gene transcripts (RNA copies of genes) are made by cells when they are actively using that gene. Therefore, the quantity of *mcrA* gene transcripts is a measure of methanogen *activity*, while DNA-based assays only definitively indicate *presence*. RNA-based assays are challenging because RNA is highly unstable, and thus, these assays are used infrequently to assess anaerobic digesters. However, RNA analysis at a single time point (week 8) was included herein as an additional basis for comparing the activity of the methanogenic populations in the reactors. To this end, first, complementary DNA (cDNA) was synthesized by mixing 8µl (0.05-1.2µg) of total RNA, 2µL of (10µM) random hexamer primer, and incubating at 70°C for 5 minutes in a PCR machine with the heated lid set at 110°C. Then, 4µL of Invitrogen™ 5X First Strand Buffer (Life Technologies, Grand Island, NY), 2µL of (10mM of each nucleotide) Invitrogen™ dNTP stock, 2µL nuclease-free water, and 2µL of Superscript® Reverse Transcriptase (Life Technologies, Grand Island, NY) was added. These RT reactions were then incubated at 42°C in a PCR machine with heated lid set at 110°C for 1.5 hours. All cDNA was stored at -20°C. The cDNA was used as template in qPCR assays as described in the Quantitative PCR section. RT-qPCR reactions were run with 0.40ng of cDNA/rxn. Negative controls (without reverse transcriptase) were run to verify the absence of genomic DNA contamination. No genomic DNA was detected.

Metagenomic sequencing – To determine the types of methanogens present in each reactor, DNA extracted from samples collected at week 8 was sent to Research and Testing Laboratory in Lubbock, TX for metagenomic sequencing of the archaeal 16S rRNA gene. Archaeal 16S rRNA genes were amplified with primers Arch519F and Arch1017R and sequenced with an Illumina MiSeq sequencer.

Task 4 Approach: Technical and economic feasibility of increased gas production

The results of Tasks 2 and 3 were used to determine the technical and economic feasibility of the ambient –temperature covered lagoon technology to treat the optimal substrate mixtures and the resulting biogas production. Based on the biogas production and treatment parameters determined in Task 2, a full scale facility was sized and the estimated capital, operation and maintenance cost were determined. These capital and operating costs were then input to the UC Davis Biomass Collaborative Energy Cost Calculator (2015) to determine the overall costs of treatment and energy.

The cost was analyzed in terms of bio-methane production cost from the digester in $/MMBtu, net costs to treat wastewater in therms of $/gallon and $/lb of COD or VS, but also in terms of $/kW-hr to produce electricity from combustion of the biomethane in an engine-generator as there is interest in this application for bio-methane with new utility programs for small bio-power facilities.

Project Outcomes

The following outcomes are discussed and related to the quantifiable objectives and targets of the project.

Objective 1 Outcomes: Selection and characterization of individual substrates

Six organic waste substrates that are readily available for delivery and possible disposal at the Yolo County Landfill were characterized for the parameters discussed in the objectives to see if they met the performance target ranges. The selected substrates and characteristics are shown in Table 3, along with the target values. The characteristics of the digester seed material is also shown for reference only. A more complete set of substrate characteristics are shown in Appendix A, Table A1.

Table 3. Chemical and physical analyses of the digester seed and substrates

SUBSTRATE	TS %	VS % of TS	TOTAL N mg/L	C/N RATIO*	BOD mg/L	COD mg/L	VFA* mg/L
TARGETS VALUES	***1 to 10%***	***>80%***	***-***	***20 to 40***	***-***	***>5000***	***<5000***
DIGESTER SEED (Ref)	*2.2%*	*54.5%*	*1200*	0.7	*970*	*2500*	*NA*
TOMATO	7.2%	84.5%	1600	15.0	34000	72000	13200
PORTABLE TOILET	1.0%	49.2%	3300	3.5	4900	35000	10100
SEPTAGE	0.3%	62.0%	450	8.1	3,000	11000	3200
WINERY	0.3%	64.8%	42	50.4	720	6400	1900
FATS, OIL & GREASE	1.3%	73.7%	273	23.1	11000	19000	4700
BEER CIDER	1.75%	89.9%	1300	12.8	22000	50000	11900

*C/N estimated with TOC = (COD -49.2)/3 (Dubber et. al 2010) as total C and TKN as total N, or TOC/TKN; VFA estimated based on concentrations measured within substrate mixtures and allocated by COD

All of these substrates met the project target of having at least 5000 mg/L of COD showing that each had potential for digestion and biogas production. However, they didn't all meet some of the other criteria. These criteria can also be important for digestion, but do not rule out a substrate from being considered suitable feedstock in an acclimated digester, particularly if it can be balanced as part of a mixture. For example, both the septage and winery waste received had total solids below 1% which means they are more dilute that may be desired but with high COD these are still potential digester food. Also, for volatile solids, portable toilet, septage and winery waste appear to have higher non-volatile solids but with high COD these still demonstrate substantial digestible solids. Portable toilet waste and septage had low C/N ratio, largely due to high nitrogen content expected in human waste. The volatile fatty acids estimated for each substrate shows that several are above the target level, but these can readily be balanced by using substrate mixtures and by using an acclimated seed material and stabilized digestion environment as is discussed in the following section.

Objective 2 Outcomes: Biochemical methane potential of individual substrates

The first trial of BMP assays were run for a period of 35 days and the total cumulative biogas was measured. The substrates included tomato processing waste, portable toilet waste, winery wastewater, septage wastewater, and fats, oil and grease (FOG) from restaurants. A second trial was run later for 49 days to capture beer cider waste substrate that was not available for the first run. A set of control assays using digester seed were run during each trial. The seed material was effluent from an unheated dairy manure lagoon digester at an approximate temperature of 20 to 30°C. The results are shown in graphs of cumulative biogas production normalized to g VS added per day. The results for the BMP assays which were held at 26.7°C are shown in Figure 5 for control seeds for trial 1 and 2, tomato waste, portable toilet waste, winery waste, FOG, and beer cider waste. For most of the substrates the gas production increased initially then gradually tailed off so that by the end of the test period, daily biogas production had slowed down to negligible amounts as evidence by the cumulative biogas curve becoming almost horizontal. This observation suggests that essentially all the biogas, and thus methane potential, had been achieved from the substrates in question and the assay is complete.

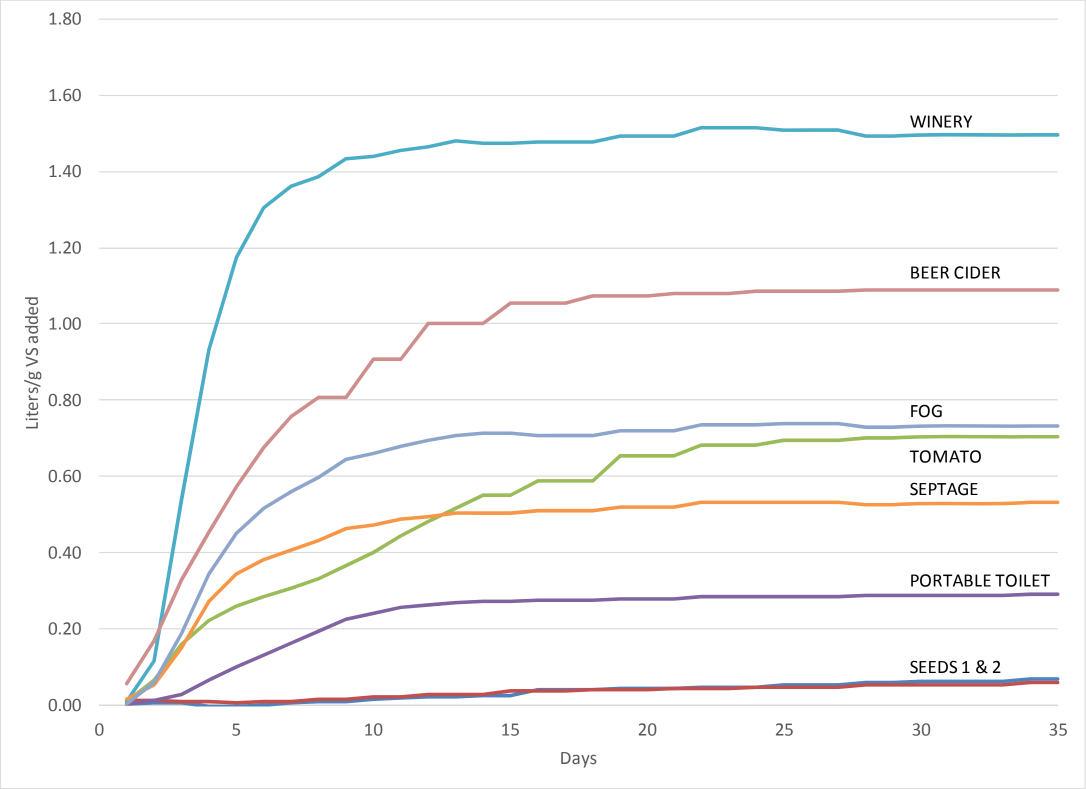


Figure 5. BMP assay results showing average cumulative biogas yield for individual substrates

The accumulated biogas from the BMPs was analyzed after two weeks of production with a gas chromatograph for methane, carbon dioxide and hydrogen sulfide, and the results are shown in Table 4.

Table 4. Gas analysis of biogas from the BMP digesters.

	DRY BIOGAS (N2, O2, H2O free)		
SUBSTRATE	METHANE	CARBON DIOXIDE	HYDROGEN SULFIDE
	%	%	ppm
TOMATO	76.2%	23.8%	12
PORTABLE TOILET	75.3%	24.7%	1209
SEPTAGE	71.5%	28.5%	ND
WINERY	73.3%	26.7%	ND
FATS, OIL & GREASE	72.2%	27.8%	ND
BEER CIDER	76.3%	23.7%	ND

A summary of the final gas yields and Biochemical Methane Potential based on VS and COD for both the first and second set of tests is shown in Table 5.

Table 5. Final results of Biochemical Methane Potential assays of individual substrates

SUBSTRATE	NET BIOGAS, L/g VS ADDED	NET BIOGAS, L/g COD ADDED	CH_4%	NET CH_4, L/g VS ADDED	NET CH_4, L/g COD ADDED
TARGET VALUES				***0.25***	***0.25***
TOMATO	0.71	0.59	76%	0.54	0.45
PORTABLE TOILET	0.29	0.13	75%	0.22	0.10
SEPTAGE	0.53	0.16	73%	0.39	0.12
WINERY	1.50	0.37	72%	1.07	0.27
FATS, OIL & GREASE	0.73	0.46	72%	0.53	0.33
BEER CIDER	1.09	0.34	76%	0.83	0.26

All of the substrates showed methane production and may be viable substrates for co-digestion. In terms of the original target methane production of 0.25 liters per gram VS or COD added, all substrates except for portable toilet waste exceeded this value on VS basis. Both of the human waste substrates, portable toilet and septage, had methane per gram of COD below the threshold. On a volatile solids basis, the order of highest to lowest methane producer were winery > beer cider > tomato > FOG > septage > portable toilet with the lowest being 20% of the highest. On a COD basis, the substrate order of methane productivity was tomato > FOG > winery > beer cider > septage > portable toilet with the lowest 20% of the highest. All of the substrates were moved to the next phase, Subtask 2b, where various mixtures of these substrates were analyzed in semi-continuous digesters. In spite of the lower BMP results for the human waste substrates, there was still significant gas production and sufficient interest in seeing how a mixture of these substrates would perform.

Objective 3 Outcomes: Determining biogas generation for waste mixtures

pH – Initial pH of all substrates and seed mixtures used in the digesters was between 6.5 and 7.5 (see Figure 6). An optimum pH level for anaerobic digestion has been reported to be around 7.0 (Huber *et al.*, 1982, Liu *et al.*, 2008). However, after the first week, the pH of the digesters containing tomato waste mixtures decreased. This drop in pH seems to be directly related to the increase in VFAs (Figure 7) and low methanogen populations (Figure 8). VFAs increased 143% for tomato/FOG /winery/beer and 252% for tomato/FOG mixtures after the first week (see Figure 7). The pH was adjusted using sodium bicarbonate ($NaHCO_3$) and after a week it stabilized to above 7.0. Reducing tomato waste loading rate and increasing the buffering capacity of feedstock was found to improve the pH stability. After the third week, the pH of all reactors was around 7.0. Although, the reactor pH for some of the waste mixtures was slightly above the target pH value of 6.5 to 7.5, this did not negatively impact biogas production. These results are supported by Lee *et al.* (2009) who also found that methanogenesis occurs efficiently at a pH range of 6.5 – 8.2.

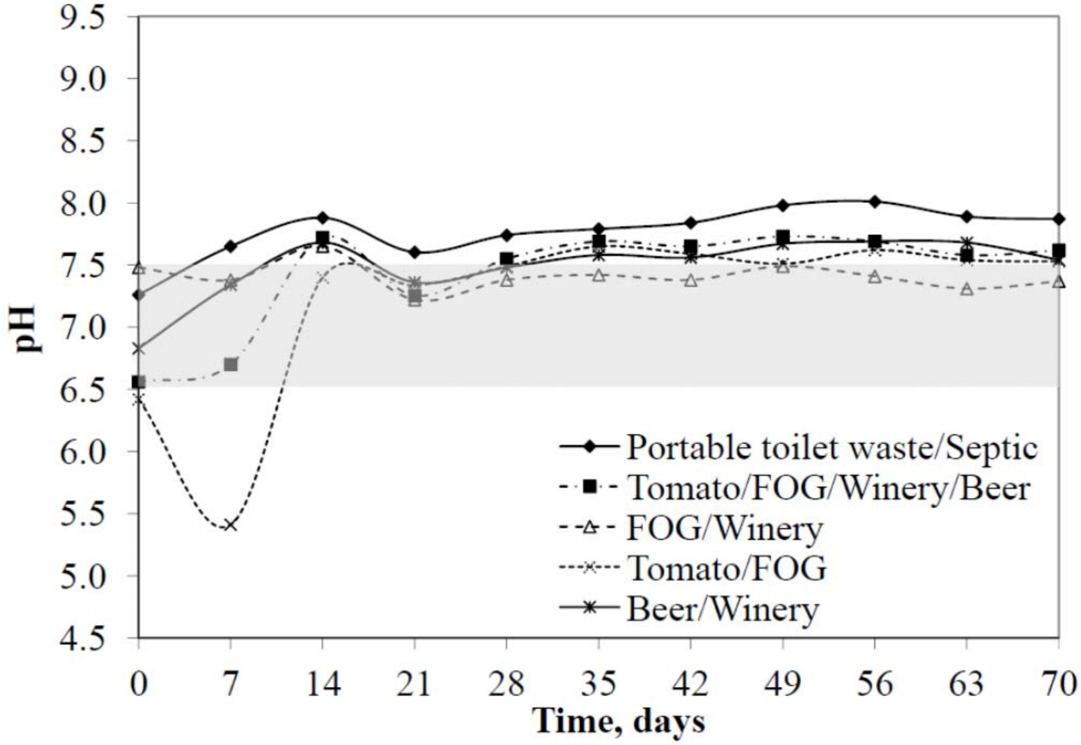


Figure 6. Digester pH trend over time. The gray band indicates the optimum range.

Volatile Fatty Acids – The observed VFA concentrations of digesters with various waste mixtures are shown in Figure 7. Initial VFA concentrations for all reactors were 5,191.33 mg/L or lower (Table A2, Appendix A). This was close to the target value of 5,000 mg/L. However, during the second week, the VFA concentrations for reactors with tomato waste (tomato/FOG/winery/beer and tomato/FOG waste mixtures) increased to 7,402.00 and 10,319.33 mg/L, respectively. This was likely due to hydrolysis of tomato waste and the release of acids as demonstrated by drop in pH (see Figure 6). As shown in Figure 7, after the second week, VFAs dropped and pH increased. The improvement (i.e., reduction) of VFAs is also due to an increase in the growth of methanogens as demonstrated by in Figure 8. The organic loading rates (Table A4, Appendix A) for all waste mixtures, with the exception of the tomato/FOG mixture, were between 1.35 to 2.34 kg VS/m^3.day. The organic loading rate for tomato/FOG mixture was 3.3 kg VS/m^3.day. This indicates that lower organic loading rate are preferable and likely would have reduced VFAs and improved biogas production for the tomato/FOG mixture. All other waste mixtures had VFA values below the target value of 5,000 mg/L.

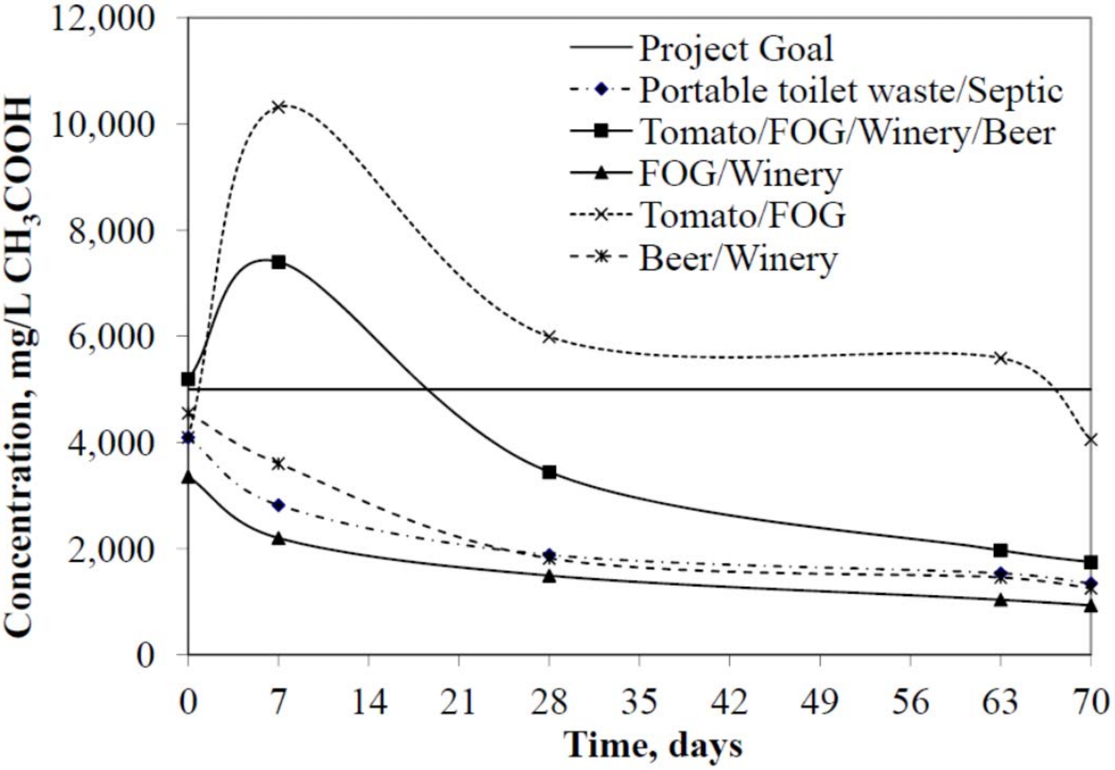


Figure 7. Reactor volatile fatty acids (as acetic acid) trend over time.

Other Digester Constituents – The initial composition of various other digester constituents including nitrogen compounds, sulfur compounds, potassium, sodium, conductivity, alkalinity, etc. are shown in Appendix A, Table A2. The trend for several of these digester constituents over the digestion period is shown in Appendix A, Figures A8-A18. These all indicate stable conditions for anaerobic activity were maintained.

Biogas Production – When considering food waste mixtures, the best biogas yield was from the beer/winery (0.851 L/g VS) and tomato/FOG/winery/beer (0.637 L/g VS) mixtures (Table 6). Biogas produced from other food waste mixtures (tomato/FOG and FOG/Winery) was 39.6 % and 45.4 % lower, respectively. The lowest biogas yield was from the portable toilet /septic waste mixture (0.195 L/g VS), which was 77.1% lower than the best biogas yield. In terms of volatile solids, all of the mixtures met the target of 0.4 L/g of volatile solids added except the portable toilet/septic waste mixture. It is interesting to note that biogas from portable toilet/septic waste also had the highest concentration of hydrogen sulfide (1,209.21 ppm) and the lowest average methane concentration (67.2 %). This could be attributed to potential inhibitory chemicals such as detergents and fragrance mixtures that are added to minimize portable toilet odor. Chemical analysis of the feedstock material for portable toilet waste showed sulfate concentrations of 340 mg/L (Table A1, Appendix A). Sulfate likely was microbially reduced to hydrogen sulfide (see Task 3), thus leading to the high measured sulfide levels. Sulfate reduction is also energetically favorable over methanogenesis, and thus, sulfate-reducing bacteria will outcompete methanogens when sulfate is present, thus inhibiting methane production. None of the mixtures met the COD based criteria for biogas production, but in hindsight this target was set too high as COD concentrations of the substrates were much higher than VS concentrations.

Methane Content – The methane concentration in each semi-continuous anaerobic digester fluctuated weekly as the reactors were opened to add new feedstock and remove degraded waste for testing (Appendix A, Figures A3 – A7). Not including these fluctuations the average methane content for all waste mixtures is presented in Table 6. All digesters had methane content greater than 67% and some had methane content as high as 73% (cider beer /winery waste mixture, and FOG/winery). The target value for methane content for this project was 60%, which is clearly met.

Table 6. Biogas and methane yield, methane and hydrogen sulfide concentration

Parameters	Average biogas yield		Average methane yield		Average methane content	
Waste Mixture	L/g VS	L/g COD	L/g VS	L/g COD	%	± SD[6]
TARGET VALUES	***0.400***	***0.400***			***60.0***	
T/F[1]	0.514	0.319	0.271	0.166	69.3	± 5.2
T/F/W/B[2]	0.637	0.335	0.371	0.195	72.3	± 4.4
B/W[3]	0.851	0.293	0.515	0.177	73.7	± 4.0
F/W[4]	0.465	0.263	0.292	0.169	73.6	± 3.7
P/S[5]	0.195	0.100	0.120	0.062	67.2	± 8.3

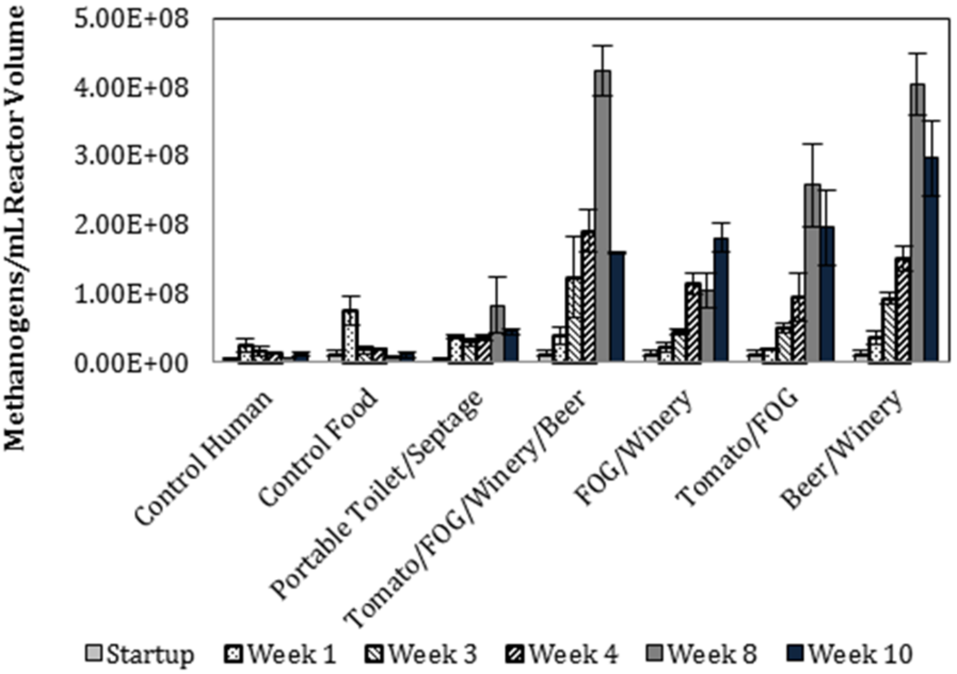
T/F[1] - tomato/FOG waste mixture; T/F/W/B[2]- tomato/FOG/winery/cider beer waste mixture; B/W[3]- cider beer /winery waste mixture; F/W[4]- FOG/winery waste mixture; P/S[5]-portable toilet/septic waste mixture; SD[6] - standard deviation

Objective 4 Outcomes: Determination of methanogenic microbial populations by nucleic-acid based analyses

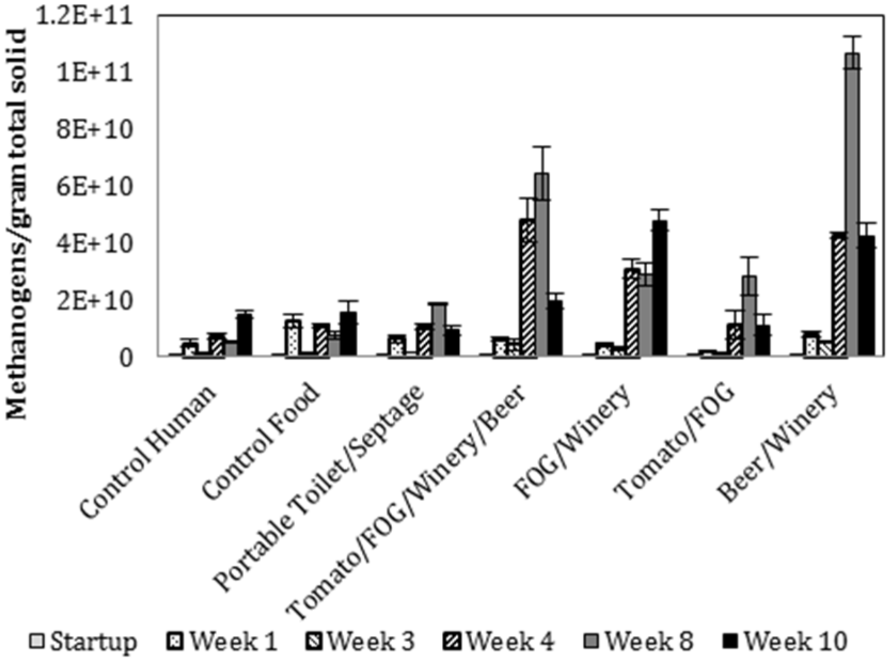
Methanogen population size can be determined by quantifying the *mcrA* gene because this gene is specific to methane-producing organisms (Dubey et al. 2013). For the laboratory digesters, methanogen population sizes were on the order of 10^6 to 10^8 methanogens/ mL of reactor volume (Figure 8A)–similar to population sizes reported by Steinburg and Regan (2009; 2011). Thus, the target of 1 X 10^6 to 5 X 10^6 methanogen/ mL, which was measured using *mcrA* copies per mL of original sample, was clearly met. Control digesters (control human and control food) contained low methanogen populations throughout the study period, which was expected because they were not provided a carbon-source (feedstock). All feedstock combinations tested, with the exception of Portable Toilet/Septage, lead to healthy methanogenic populations with the quantity of methanogens clearly increasing over time. Further, digesters with the highest methanogen populations (Beer/Winery and Tomato/FOG/Winery/Beer) also produced the highest amount of biogas (850.97 mL/g VS and 637.42 mL/g VS) providing multiple lines of evidence that these were some of the best feedstocks tested. Digesters with mid-range methanogen population sizes (Tomato/FOG and FOG/Winery) produced biogas, but at a relatively lower level. The Potable Toilet/Septage digester's methanogen population size was clearly the lowest, and this digester produced little biogas.

Low biogas production in the Potable Toilet/Septage digester suggests that microbial processes in this digester were inhibited. Three microbial processes are required for waste conversion to methane: 1) hydrolysis, 2) acido/acetogenesis, and 3) methanogenesis. First, hydrolyzing bacteria solubilize waste; second, acidogenic and acetogenic bacteria convert soluble material to volatile fatty acids. Lastly, methanogens convert these products to methane. Any, or all, of these processes may have been inhibited in the Portable Toilet/Septage digester. Inhibition may have been caused by inhibitory substances (e.g., certain surfactants) (portable toilet & holding tank deodorizer liquid msds) present in the waste (Jimenez-Gonzalez et al. 2001).

A moderate decrease in methanogen population size was observed at week 10, with the exception of the FOG/Winery reactor. The reason for this decrease is not known and additional tests would be required to determine causes. Interestingly, decreases also were observed at week 10 with primer set mcrA_1035F/mcrA_1530R, but the fractional decreases measured with this primer set were larger. This finding suggests that around week 10, there was a shift in the types of methanogens present with emerging methanogenic groups being less well quantified by the mcrA_1035F/mcrA_1530R primer set than the MLf/MLr primer set. However, given that population sizes during week 8 were still generally as high as during week 4, it is unlikely that the decreased population size at week 8 indicates a longer-term issue.



(A)



(B)

Figure 8. Quantity of methanogens in digesters as a function of time. (A) Methanogens /mL reactor volume. (B) Methanogens per gram total solids (TS).*

***** Data shown is for primer set MLf/MLr with 1.00ng DNA/rxn. Tests with 0.156ng/rxn yielded similar trends (data not shown). Also, trends were similar for primer set mcrA_1035F/mcrA_1530R (Appendix B, Figure B1), although measured populations were higher (2 to 5-fold higher for week 4 & 8) suggesting those primers were more specific for methanogens present in the digesters at those weeks.

Methanogen concentration is a useful indicator of digester health; however, methanogen population sizes can be influenced by the feedstock concentration provided (Yi et al. 2014). Feedstock was provided to all digesters in the same volume; however, the concentration of substrates may have varied between digesters. Thus, methanogen populations per gram of TS (surrogate for feedstock concentration) were also compared (Figure 8B). Similar trends were observed as for methanogen concentrations. Although TS concentrations are an imperfect surrogate for feedstock concentrations, because microorganisms are also measured as TS and feedstock is also present as dissolved organic carbon, these findings indicate that the difference in methanogen population sizes between the digesters is not likely caused by differences in feedstock amounts. Thus, this analysis indicates that low feedstock amount is not responsible for low biogas production in the Portable Toilet/Septage digester.

A more direct measure of the methanogenic population health is the concentration of *mcrA* gene transcripts because transcripts are only produced by active microorganisms. Analysis of *mcrA* gene transcript concentrations indicated that the Tomato/FOG/Winery/Beer, FOG/Winery, Tomato/FOG, and Beer/Winery digesters all contained active methanogen populations, while methanogens present in the control digesters were inactive (Appendix C, Figure C1). Interestingly, transcript levels in the Portable Toilet/Septage digester were significantly higher than in control reactors and were only ~3-fold lower than levels in the Tomato/FOG/Winery/Beer. Given this finding, it is possible that Portable Toilet and Septage waste could be used as digester feedstock if mixed with other feedstocks to dilute out inhibiting compounds. Further studies would be required to test this concept and economics would need to be considered.

Determining the relative abundances of specific types of methanogens in the digesters via metagenome sequencing lead to identification of phylotypes associated with psychrophilic anaerobic digestion (Bialek et al., 2013). Three orders of Archaea dominated all of the digesters that produced high levels of methane: *Methanomicrobiales*, *Methanobacteriales*, and *Methanosarcinales* (Appendix D, Figures D1-D7). These orders of methanogens were all also present in the Potable Toilet/ Septage digester; however, they did not dominate. Rather, this digester was dominated by *Thermoplasmatales*-related Archaea, which are poorly characterized and their ability to generate methane has yet to be fully established (Paul et al.2012), Thus, very few known methanogens were able to survive and grow in the Potable Toilet/ Septage digester. This finding further suggests that substances present were inhibitory for methanogens in the inoculum. Microbial community structures varied amongst digesters fed the other four feedstock combinations, but some common phylotypes emerged. Interestingly, one genus (*Methanocorpusculum*) overwhelmingly dominated the two digesters with the highest biogas production: Beer/ Winery (99% *Methanocorpusculum*), and Tomato/ FOG/Winery/Beer (95% *Methanocorpusculum*). This genus was also present at high levels in the Tomato/FOG digester (38%) and the FOG/Winery digester (34%). *Methanocorpusculum*-like methanogens previously have been reported to dominate psycrophilic digesters (McKeown et al., 2009). The Tomato/FOG digester also contained high levels of *Methanobrevibacter* (41%) and *Methanosarcina* (19%), and the FOG/Winery digester contained low levels of these genera. Phylogenetic histograms are shown in Appendix E. Findings suggest that suitable methanogenic communities for low-temp AD were successfully developed over the course of the study.

Objective 5 Outcomes: Technical and economic feasibility of increased gas production

The results of the technical and economic feasibility of a full sized anaerobic digester to treat the various substrates are presented in this section. The original cost performance targets of this task were as follows:

- Biogas production costs of less than \$10/MMBtu
- Net costs of treatment less than \$.02/gallon of wastewater or \$.20/lb COD/VS destroyed
- Electricity production costs of less than \$0.15 per kWhr (Added Target)

Although several mixtures of the food and human wastes were analyzed in task 2, and it was decided to focus on the food waste mixture labeled T/F/W/B which included tomato waste, FOG, winery waste and beer waste for the full-scale system. This mixture gives the second highest gas production per unit VS as well as the most volume potential for delivery and disposal in Yolo County. The average biogas yield from the T/F/W/B food waste mixture are listed in Table 6 with 0.637 L/g VS at 72.3% methane or a methane yield of 0.371 L/g VS. Converted to U.S. units this corresponds to biogas and methane yields of 10.3 ft^3/lb VS and 7.5 ft^3/lb VS respectively.

The focus of this full-scale study will then be on the food waste mixture, T/F/W/B that includes all the food-based wastes that could possibly come to the Yolo County Integrated Resource Recovery Facility based on past history and anticipated future waste opportunities. The food waste mixture shown in Table 7 and design parameters in Table 8 were assumed for the full-scale digester design. Two digester construction scenarios were considered: Option 1 - A new covered lagoon digester built from the ground up; and Option 2 – Use of an existing lined lagoon at the Yolo County Facility (reducing cost of constructing a new lagoon for the digester). Additional capital expenditures for both options include a can processor for receiving the tomato wastes that come to the facility in discarded cans.

Table 7. Assumptions for food waste quantities for full-scale digester

	VOLUME	MASS	TS		VS		COD	
SUBSTRATE	gal/day	lb/day	%	lb/day	%	lb/day	%	lb/day
BEER CIDER	1,100	9,174						
TOMATO	3,300	27,522						
WINERY	2,000	16,680						
FOG	3,600	30,024						
TOTAL WASTE	10,000	83,400	2.8%	2,335	1.9%	1,585	3.6%	3,036

Based on the biogas and methane yields from the results shown in Table 6, the estimated energy production from the food waste mixture is listed in Table 8. Figure 9 shows the mass and energy flow diagram for the proposed digester system.

Table 8. Design parameters for full-scale digester

DIGESTER PARAMETERS	SI QUANTITY	SI UNITS	US QUANTITY	US UNITS
FOOD WASTE INPUT	36,957	LITERS/DAY	10,000	GALLONS/DAY
VS CONTENT	1.9%		1.9%	
VS INPUT	727	KG/DAY	1618	LB/DAY
BIOGAS YIELD	0.64	M^3/KG VS	10.3	FT^3/LB VS
BIOGAS PRODUCTION	465	M^3/DAY	16,500	FT^3/DAY
METHANE PERCENT	72%		72%	
METHANE PRODUCTION	340	M^3/DAY	12,000	FT^3/DAY

Assuming the quantities in Table 8, a covered lagoon digester can be designed to treat this mix of substrates. This covered lagoon design will be based on dairy manure covered lagoon projects that Williams Engineering has designed and that have been studied by Summers and Williams(2014) in a previous research project·. One of the dairies, #2, was a North Coast Dairy that had an influent quantity of about 60,000 gallons per day at approximately 1.2% VS, or ~ 6000 pounds per day of VS. Although this is 3 times the expected VS from the Food Waste Mixture above, the reason that this digester project was of interest is the size of the lagoon used, about 2.5 million gallons. Option 1 will assume a new covered lagoon and evaporation pond in the costs of the digester system, and Option 2 will assume use of the existing 3-million gallon lined lagoon at the Yolo County Facility as well as existing evaporation pond.

Option 1: New covered lagoon digester system:

The proposed full scale digestion system will consist of the following components:

1. Can processing and handling equipment for tomatoes cans
2. Reception basin/tanks
3. New covered lagoon digester including influent, effluent and sludge removal piping.
4. Gas handling including gas removal piping, H_2S and moisture removal, blower and flare (H_2S reduction is achieved with air injection under the lagoon cover plus a polishing filter.)
5. Electrical generation system including engine-generator set, electrical interface
6. Effluent handling including overflow basin/evaporation pond, and pumping to dispose excess liquids. Since significant solids reduction occurs in the digester, no additional solids separation of the effluent is needed. Also, some evaporation will occur in summer months.

These components are shown in Figure 9 along with the mass and energy flows.

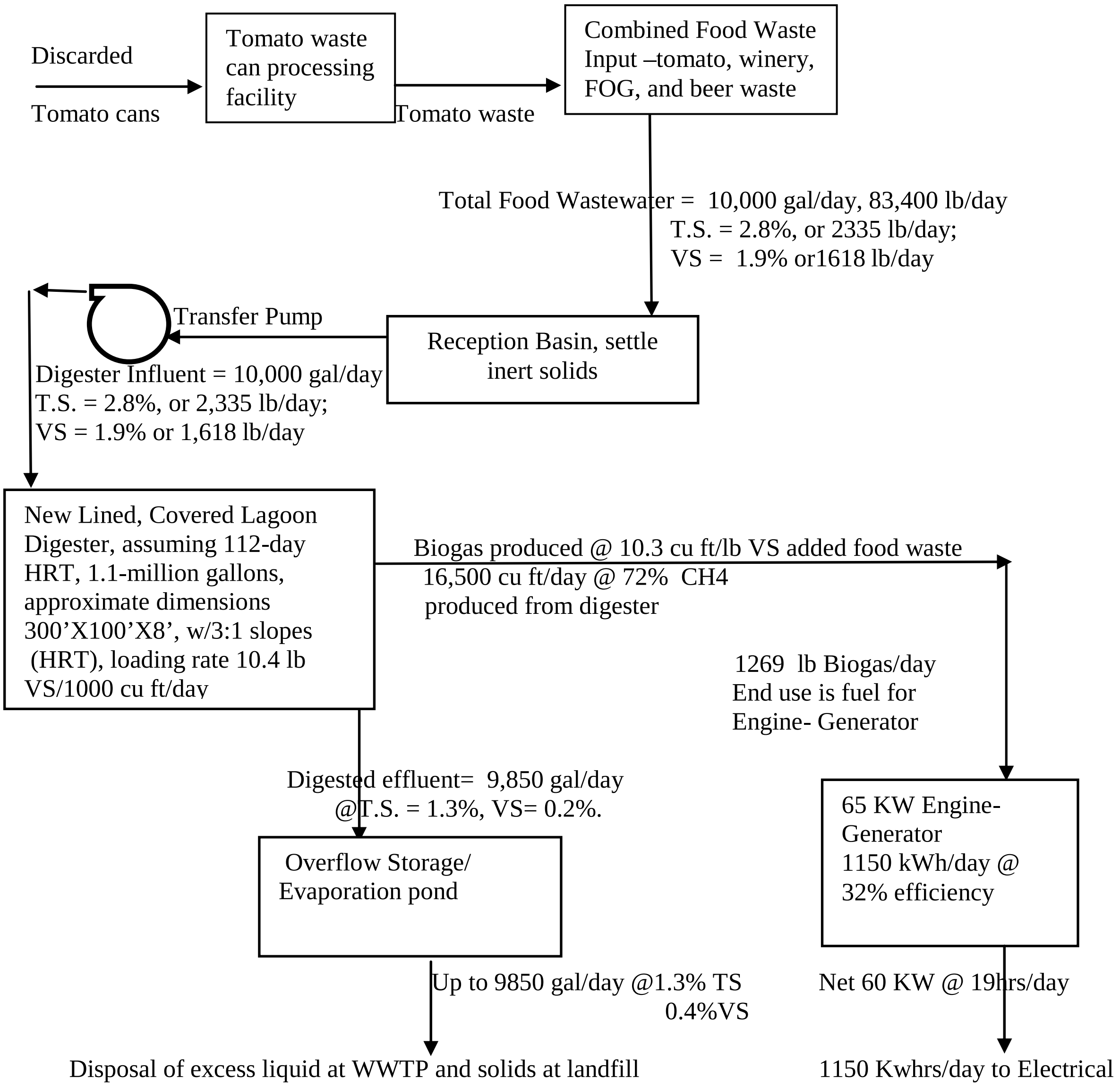


Figure 9: Flow diagram for new lined, covered lagoon digester system

The economics of the new lined, covered lagoon system are summarized in Table 9. The costs of the various components are based in part on the costs of similar dairy covered lagoon digesters described by Summers and Williams (2014) and Summers and Hurley (2014) and the added reception and effluent basins and can processing are based on Yolo county estimates.

Table 9: Estimated costs for new covered lagoon digester system with power generation, Option 1

1. Major Equipment, installed:			**Capital Costs**	**Explanation**
Can processing Equipment			$ 250,000	Yolo county Estimate
Reception basin and influent handling			$ 50,000	Assumed cost of tanks and pumps
Excavation	$ 5.00	per cu yd	$ 28,000	Estimate from Yolo County Landfill
Lagoon Liner/Cover, installed	$ 5.00	per sq. ft	$ 150,000	Liner/Cover cost based on EFI estimate
CHP Engine-Generator	$ 1,500	per kW	$ 90,000	Based on Martin Machinery estimate
Gas Handling	$ 500	per kW	$ 30,000	Piping, H2S scrubber,drier,blower, based on Summers Digester Study
CHP Electrical Interconnect	$ 30,000		$ 30,000	Based on Summers Digester Study
Other Electrical	$ 20,000		$ 20,000	WEA estimate of pumps and blowers electrical
Effluent evaporation basin and effluent handling	$ 120,000		$ 120,000	Assumed cost of effluent evaporation pond, based on Yolo county estimate
2. Total Capital Cost		SUBTOTAL	$ 768,000	
Engineering	10%	% subtotal	$ 76,800	
Contingency	10%	% subtotal	$ 76,800	
Total Installed Capital Cost		TOTAL	$ 921,600	
3. Estimated Operating Cost:				
Annual Electrical Generation			402,157	kW-h per year
Operating Cost per Kwh			$ 0.030	per kW-h
Electrical Generation O&M cost			$ 12,065	
Labor for input material and equipment monitoring			$ 30,000	Yolo county Estimate
Maintenance for can processing, digester and liquids handling			$ 18,432	2% of Capital cost/year
Management/Administration			$ 18,432	2% of Capital cost/year
Insurance/Property Tax			$ 9,216	1 % of Capital cost/year
Electricity consumed by can processing and pumps			$ 10,000	100 hp @ 3 hrs/day
Disposal of excess liquids, assume 50% of effluent			$ 30,000	$0.02/gal disposal at WWTP
Disposal of sludge solids			$ 12,870	Assume 1.3% TS and disposal of 10% of solids annually at $33 per ton
Total Operating Costs			$ 141,015	

These capital costs serve as input to the UC Davis Biomass Collaborative Energy Cost Calculator (2015). The detailed inputs and outputs of this model are in Appendix F, Table F1 and F2 respectively. The summarized results of this analysis for Option 1 are as follows:

- ***Option 1:*** based on the methane yields from the mixture of food waste(tomato, beer, winery and FOG) that are typically received by California municipal solid waste(MSW) recycling facilities, a new covered lagoon methane digester system with electrical generation could be designed and built with the following results:
  - Input: 10,000 gallons/day @ ~2% Volatile Solids
  - Biogas production: 16,500 cu ft/day @ 72% methane
  - Electrical Production: 60 KW net, 1150 kW-h/day
  - Annual electrical production: 415,000 kW-h/year
  - Capital cost: $921,600
  - Operating costs: $141,015/year
  - Tipping fee: $.05/gallon, or $500/day, $182,500/year; assumed to be lower than Yolo county tipping fees for liquid wastes, ranging from $.13to $.15/gallon
  - Life of Project: 20 years
  - ***Cost of electricity: $0.085 / kW-h***

Option 1a was also developed where the output of the digester system was assumed to be the biogas, i.e., the engine-generator was eliminated thus resulting in a lower capital cost; the biogas could then be input for any alternative use such as boiler fuel of input to a gas clean-up skid and then used for vehicle fuel. The cost of this skid is not included in the capital cost, which is summarized in Table 10 along with the operating costs. Note that this could add significantly to the cost of the overall project. The value of the biogas was then determined in $ per MMBtu using UC Davis biomass collaborative model (2015). The detailed inputs and outputs of this model are in Appendix F, Table F3 and F4 respectively. The summarized results of this analysis for Option 1a are as follows:

- ***Option 1a:*** Based on the methane yields from the mixture of food waste(tomato, beer, winery and FOG) that are typically received by California municipal solid waste(MSW) recycling facilities, a new covered lagoon anaerobic digester system where the output is biomethane, can be designed and built with the following results:
  - Input: 10,000 gallons/day @ ~2% Volatile Solids
  - Biogas production: 16,500 cu ft/day @ 72% methane
  - Annual biomethane energy production: 4478 MMBtu/year
  - Capital cost: $777,600
  - Operating costs: $121,750/year
  - Tipping fee: $.04/gallon, or $400/day, $146,000/year; assumed to be lower than Yolo county tipping fees for liquid wastes, ranging from $.13 to $.15/gallon
  - Life of Project: 20 years
  - ***Cost of biomethane: $9.30 / MMBtu plus cost to clean up and compress gas***

Table 10: Estimated costs for new covered lagoon digester system, gas only, Option 1a

1. Major Equipment, installed:			**Capital Costs**	**Explanation**
Can processing Equipment			$ 250,000	Yolo county Estimate
Reception basin and influent handling			$ 50,000	Assumed cost of tanks and pumps
Excavation	$ 5.00	per cu yd	$ 28,000	Estimate from Yolo County Landfill
Lagoon Liner/Cover, installed	$ 5.00	per sq. ft	$ 150,000	Liner/Cover cost based on EFI estimate
Gas Handling	$ 500	per kW	$ 30,000	Piping, H2S scrubber,drier,blower, based on Summers Digester Study
Other Electrical	$ 20,000		$ 20,000	WEA estimate of pumps and blowers electrical
Effluent evaporation basin and effluent handling	$ 120,000		$ 120,000	Assumed cost of effluent evaporation pond, based on Yolo county estimate
2. Total Capital Cost		SUBTOTAL	$ 648,000	
Engineering	10%	% subtotal	$ 64,800	
Contingency	10%	% subtotal	$ 64,800	
Total Installed Capital Cost		TOTAL	$ 777,600	
3. Estimated Operating Cost:				
Labor for input material and equipment monitoring			$ 30,000	Yolo county Estimate
Maintenance for can processing, digester and liquids handling			$ 15,552	2% of Capital cost/year
Management/Administration			$ 15,552	2% of Capital cost/year
Insurance/Property Tax			$ 7,776	1 % of Capital cost/year
Electricity consumed by can processing and pumps			$ 10,000	100 hp @ 3 hrs/day
Disposal of excess liquids, assume 50% of effluent			$ 30,000	$0.02/gal disposal at WWTP
Disposal of sludge solids			$ 12,870	Assume 1.3% TS and disposal of 10% of solids annually at $33 per ton
Total Operating Costs			$ 121,750	

Option 2: Convert existing lined lagoon to covered lagoon digester system at Yolo County
There is an existing lagoon at the Yolo County Integrated Resource Recovery Facility that has a volume of 3.4 million gallons that could be converted to a covered lagoon digester. This unit is one of three Class II surface impoundments that meet Federal Subtitle D standards for lining. The

leachate and condensate collected in these ponds is disposed of through evaporation or as supplemental liquid injected into the bioreactor landfill cells. Since it has already been lined, only a cover would be required and sludge removal pipes would need to be added on the lagoon floor before the cover is installed. Figure 10 shows a plan view of Pond H2 which has dimensions of 360 feet length, 180 feet width and 10 feet total depth, assumed 2 feet freeboard and 8 feet liquid depth, with 3: 1 side slopes. Figure 11 shows a typical installation of a lagoon cover along with the sludge removal pipes. The economics of the covered lagoon system are summarized in Table 11. These costs reflect the use of the existing land fill gas 3 MW electrical generation system, to which the biogas from the covered lagoon will be added. Therefore no additional costs will be incurred for electrical generation capital or operation.

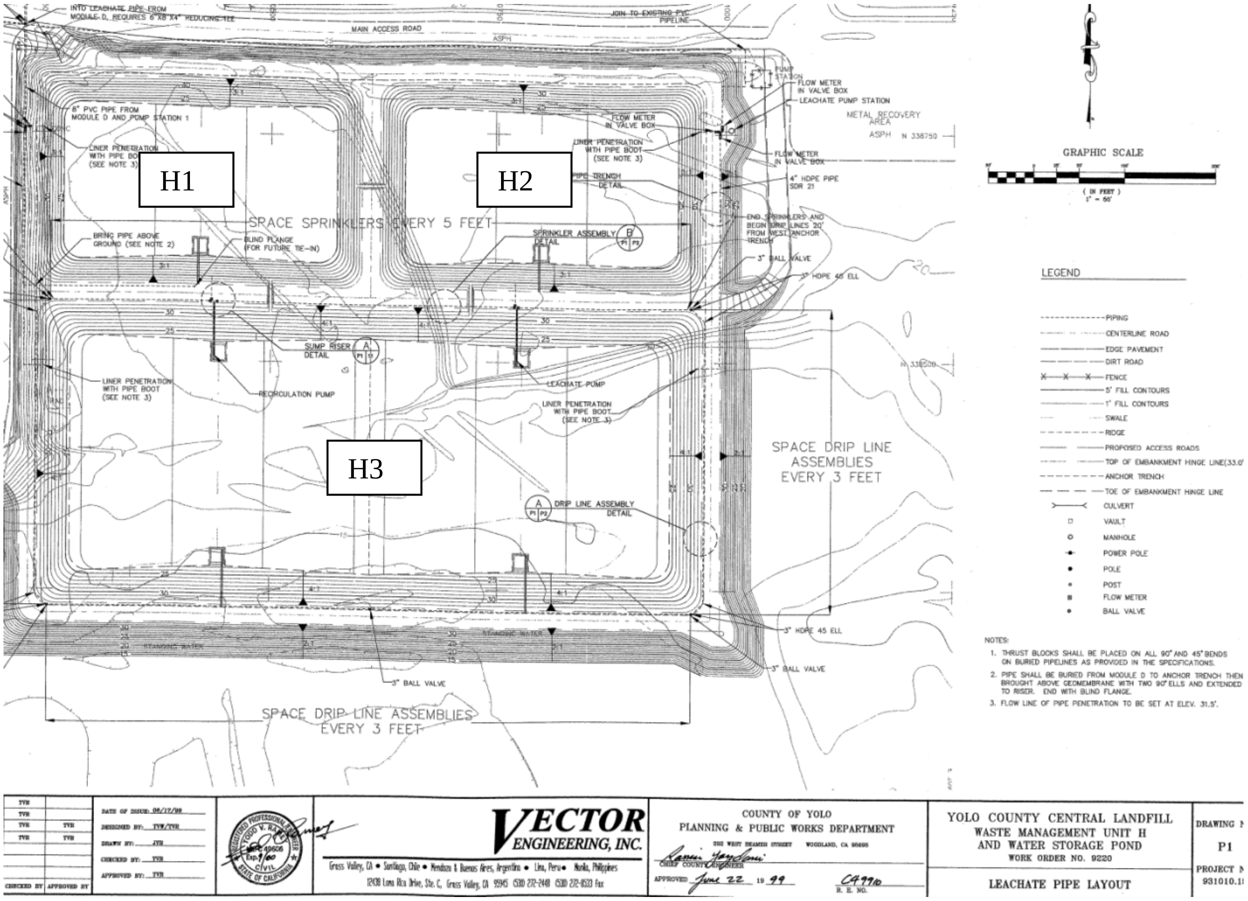


Figure 10. Yolo County Integrated Resource Recovery Facility – existing ponds H1, H2, H3

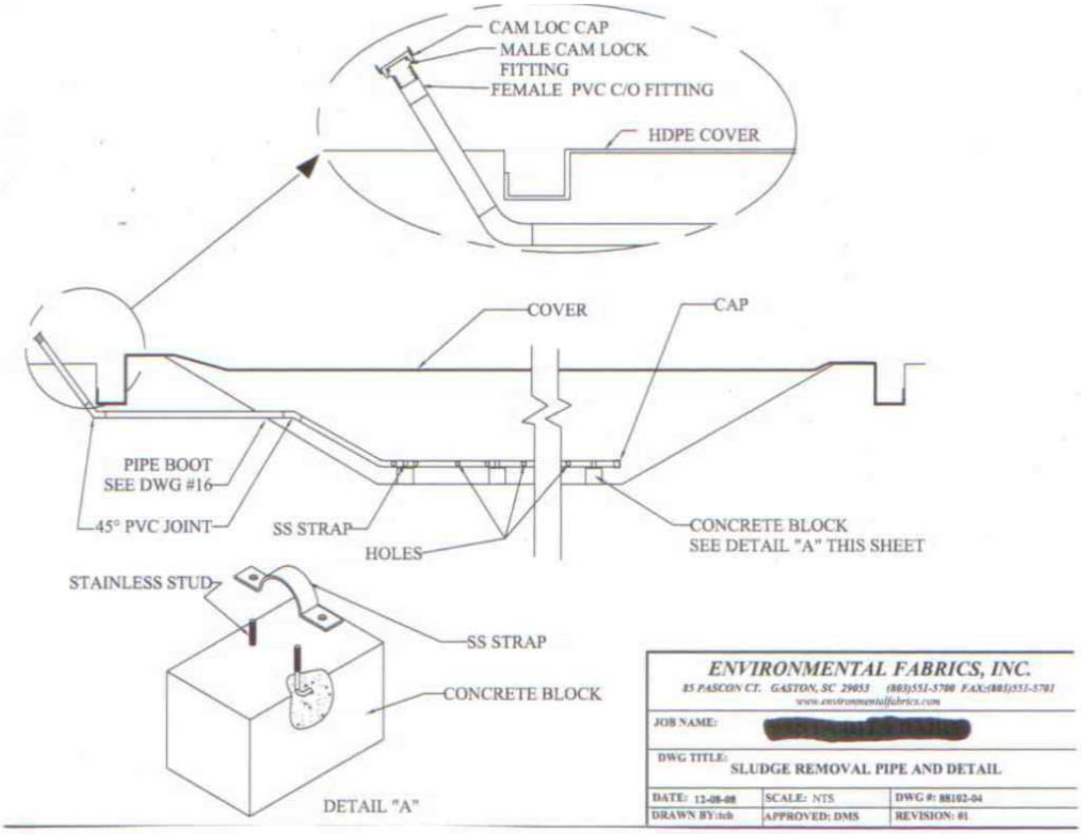


Figure 11. Typical Cross Section of covered lagoon with sludge removal pipes.

Table 11. Estimated costs of converting existing lagoon to digester at Yolo County Facility, Options 2 and 2a

1. Major Equipment, installed:			**Capital Costs**	**Explanation**
Can processing Equipment			$ 250,000	Yolo county Estimate
Reception basin and influent handling			$ 50,000	Assumed cost of tanks and pumps
Cover existing lined lagoon, installed cost	$ 2.00	per sq. ft	$ 129,600	Liner/Cover cost based on EFI estimate
Gas Handling	$ 500	per kW	$ 30,000	Piping, H2S scrubber,drier,blower, based on Summers Digester Study
Other Electrical	$ 20,000		$ 20,000	WEA estimate of pumps and blowers electrical
2. Total Capital Cost		SUBTOTAL	$ 479,600	
Engineering	10%	% subtotal	$ 47,960	
Contingency	10%	% subtotal	$ 47,960	
Total Installed Capital Cost		TOTAL	$ 575,520	

3. Estimated Operating Cost:					
	Annual Electrical Generation			415,000	kW-h per year
	Operating Cost per kW-h			$ -	Use existing Landfill gas Engine-Generator system
	Electrical Generation O&M Cost			$ -	
	Labor for input material and equipment monitoring			$ 30,000	Yolo county Estimate
	Maintenance for can processing, digester and liquids handling			$ 11,510	2% of Capital cost/year
	Management/Administration			$ 11,510	2% of Capital cost/year
	Insurance/Property Tax			$ 5,755	1 % of Capital cost/year
	Electricity consumed by can processing and pumps			$ 10,000	100 hp @ 3 hrs/day
	Disposal of excess liquids, assume 50% of effluent			$ 5,932	$0.02/gal disposal at WWTP
	Disposal of sludge solids			$ 12,870	Assume 1.3% TS and disposal of 10% of solids annually at $33 per ton
	Total Operating Costs			$ 87,577	

These capital costs serve as input to the UC Davis Biomass Collaborative Energy Cost Calculator (2015). The detailed inputs and outputs of this model are in Appendix F, Table F5 and F6 respectively. The summarized results of this analysis for Option 2 are as follows:

- ***Option 2:*** If the existing lined lagoon at the Yolo County Integrated Waste Management Facility is utilized as a digester and the methane used to fuel an engine-generator, and existing onsite facilities such as solids separators are utilized, the following resulting costs and benefits are achieved:
    - Input: 10,000 gallons/day @ ~2% Volatile Solids
    - Biogas production: 16,500 cu ft/day @ 72% methane
    - Electrical Production: 60 KW net, 1150 kW-h/day
    - Capital cost: $575,520
    - Operating costs: $87,577/year
    - Tipping fee: $.03/gallon, or $300/day, $109,500/year, assumed to be lower than Yolo county tipping fees for liquid wastes, ranging from $.13 to $.15/gallon
    - Life of Project: 20 years
    - C*ost of electricity: $0.060/kW-h*

Option 2a was also developed where the output of the digester system was assumed to be the biogas, which could then be input for any alternative use such as boiler fuel of input to a gas clean-up skid and then used for vehicle fuel. The cost of this skid is not included in the capital cost. Table 11 lists the capital and operating cost of Option 2a which are input to the UC Davis Biomass Collaborative Energy Cost Calculator (2015) with the value of the biogas was then determined in $ per MMBtu. The detailed inputs and outputs of this model are in Appendix F, Table F5 and F6 respectively. The summarized results of this analysis for Option 2a are as follows:

- ***Option 2a:*** If the existing lined lagoon at the Yolo County Integrated Waste Management Facility is utilized as a digester, the biomethane produced is the energy output, and existing onsite facilities such as evaporation ponds are utilized, the following resulting costs and benefits are achieved:
    - Input: 10,000 gallons/day @ ~2% Volatile Solids
    - Biogas production: 16,500 cu ft/day @ 72% methane
    - Annual biomethane energy production: 4478 MMBtu/year
    - Capital cost: $575,520
    - Operating costs: $80,557/year
    - Tipping fee: $.03/gallon, or $300/day, $109,500/year, assumed to be lower than Yolo county tipping fees for liquid wastes, ranging from $.13 to $.15/gallon
    - Life of Project: 20 years
    - C***ost of biomethane: $5.56/ MMBtu plus cost to clean up and compress gas***

Summary: With respect to the original cost performance targets of this task given below, the actual results indicated that a higher tipping fee will be required to achieve the electrical and biogas cost objectives:

- Target biogas production costs of less than $10/MMBtu:
  Actual: $5.56 /MMBtu for Yolo County; $9.30/MMBtu for a new installation
- Net costs of treatment less than $.02/gallon of wastewater:
  Actual: $.03/gallon for Yolo County; $.04 and $.05/gallon for a new installation
- Electricity production costs of less than $0.15 per kW/hr (Added Target):
  Actual: $.060/kW-h for Yolo County; $.085/kW-h for new installation

Conclusions

The study demonstrated that six important waste and wastewater feedstock are suitable for volatile solids conversion to biogas in psychrophilic digestion conditions experienced in a typical unheated covered lagoon digester. It showed that tools like biochemical methane potential assays and RNA/DNA molecular testing can be used to understand potential biogas production and methanogen development within these systems. The economic study gave evidence that biogas produced in unheated covered lagoon digester systems could produce biogas or combined heat and power for costs that are feasible in the current renewable energy marketplace.

In terms of analytical tools, both biochemical methane potential assays and RNA/DNA molecular testing results can be further related to the methane yield results obtained in the continuously fed digester systems. The average methane production of the continuous fed digesters can be related to the measured methane potential of the substrates that make up the mixture. Figure 12A shows this in terms of volatile solids conversion and Figure 12B shows this in terms of COD conversion. For each mixture, the average methane production in the continuously fed system was about 50-60% of the measured methane potential. The correlation is strongest ($R^2 = 0.946$) with volatile solids showing a slope of 0.57 between actual methane production and the combined potential of the substrates in the feed mixture. In other words, the actual methane production appeared to be 57% of the measured methane potential. These results indicate that using the individual BMP assay results can be useful to predict performance of a mixture in a real digester. They also show that some amount of the ideal potential conversion may not be realized in a real continuous feed digester system.

A similar comparison of the actual methane production with the methanogen populations measured in the RNA/DNA analysis is shown in Figure 13. The weekly methane yield of the digesters for each mixture were compared with the methanogen populations quantified with the RNA/DNA analysis. While the results show a considerable amount of scatter, there is general trend towards higher gas production with higher measured methanogen population. While the methanogenic community data is not likely to be useful as a predictor of biogas production, it provides evidence about whether communities are likely to flourish over long-term operation. Cultures clearly developed in a low-temperature adapted environment and showed signs of methanogenic community health.

The economic feasibility of implementing the results of this study with commercial covered lagoon digester systems are also demonstrated with this study. New systems for production of biogas using waste feedstocks are shown to produce gas with an energy cost of $9.30 per MMBtu. A system that can take advantage of existing pond infrastructure as is available at Yolo County Integrated Waste Management Facility and possibly other facilities, biogas can be produced at an even lower cost around $5.56 per MMBtu. If the biogas is converted to power, the cost would be $0.085 per kilowatt-hour and $0.060 per kilowatt hour respectively for the new and existing ponds. These costs assume very favorable disposal costs of only $0.03 to $0.05 per gallon, which is considerably below the current treatment costs for many of these feedstocks, but higher than the original target of $0.02 per gallon. These energy costs are near the existing range for fossil energy production for systems using existing infrastructure and new systems have the possibility of qualifying for utility incentive programs for renewable energy like the SB-1122 Utility Feed-In-Tariff for bioenergy.

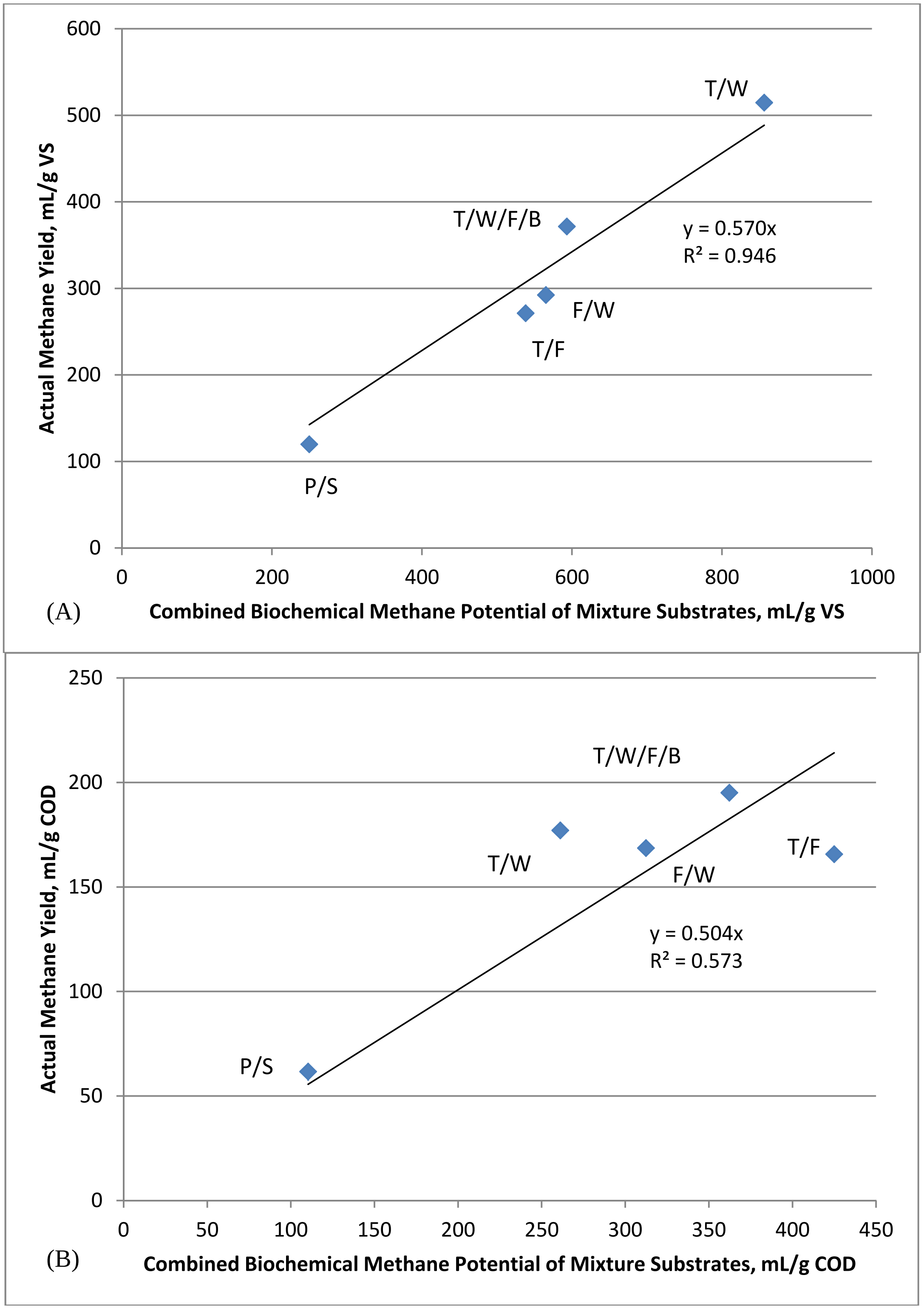


Figure 12. Comparison of the combined biochemical methane potential of the mixture substrates with actual methane yield of the mixtures in continuously fed digesters normalized by A) volatile solids, and B) COD

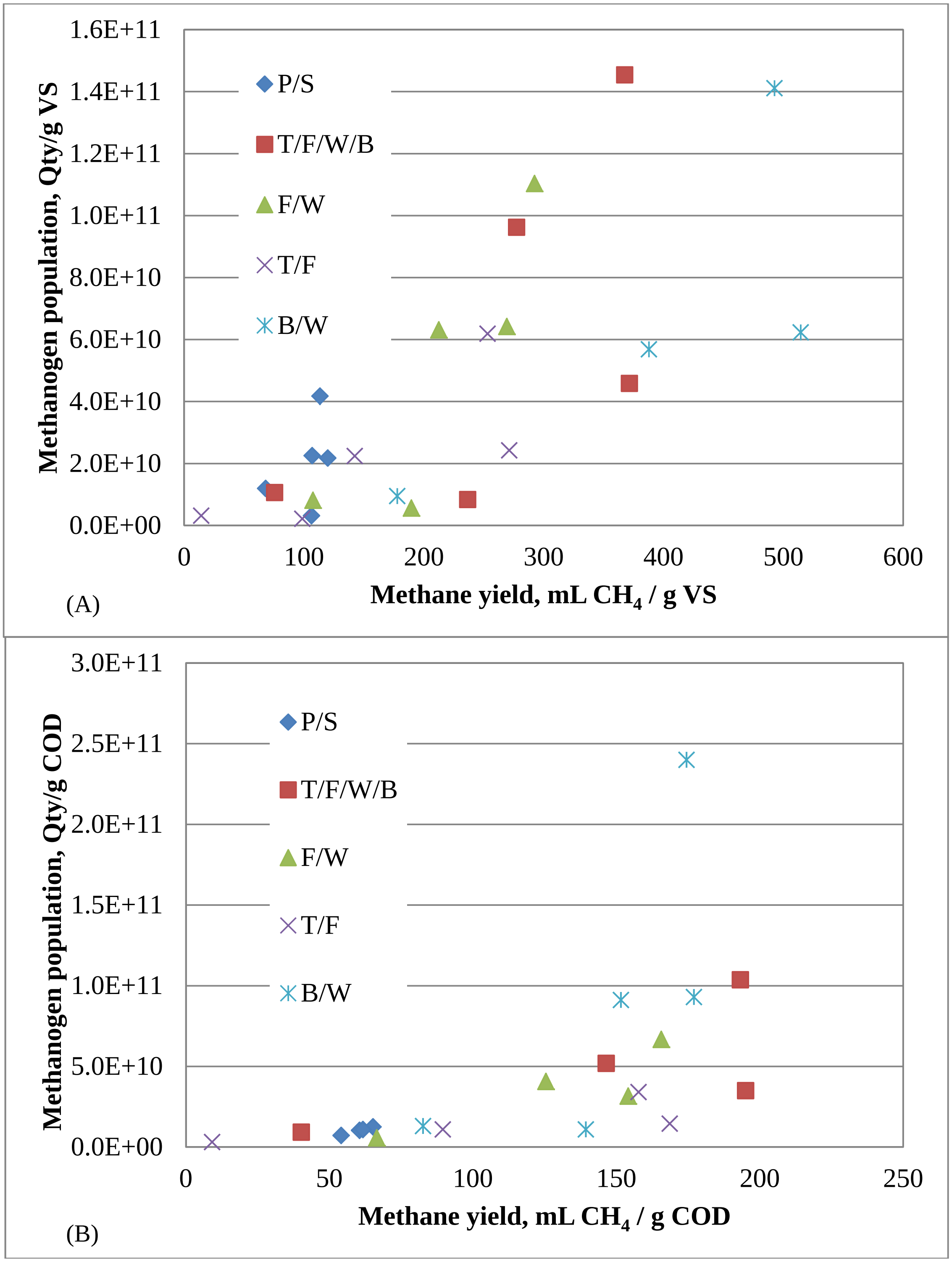


Figure 13. Comparison of methane yield from continuously fed digesters with methanogen population measured with RNA/DNA analysis normalized by A) volatile solids and B) COD.

Recommendations

This project demonstrated that there is potential for widespread implementation of unheated covered lagoon digester systems for conversion of liquid wastes to biogas. The recommended next step is a commercial demonstration system using food wastes, the substrates that had the highest methane potential and least handling issues, potentially at the Yolo County Integrated Waste Management Facility. Developers can make use of the data generated by this study and further utilize tools like BMP assays and RNA/DNA analysis to engineer and develop other commercial anaerobic digester projects in California. The project team sees no technical limitation to the immediate implementation of commercial projects using unheated covered lagoons using food wastes, as the technology already has a number of commercial examples that have been operating for over 10 years in the dairy industry.

For the human waste feedstock like septage and portable toilet waste, there may be more work needed to investigate ways to improve their digestibility. Further study of the makeup of these wastes may indicate why they were less successful in this study over the other organic wastes. Tools developed in this study like BMP assays and RNA/DNA analysis can assist in developing the knowledge about the digestion of these more challenging materials.

The project generated interesting and substantial data on methanogenic populations present in low-temperature anaerobic digestion using a variety of substrates (See Appendix B-E). Because the time period of ten weeks was limited, we recommend extending the data collection on an operating digester system over a longer period to help understand the long-term movement in the populations over time. Also, this DNA/RNA genomics data indicated that methanoginic communities seemed to develop and thrive in these systems, however there is additional opportunity to further derive more actionable information from this method with the goal of optimizing anaerobic digestion process rates and yields. For example, showing that certain methanogenic populations were favored and perpetuated over time with specific feedstocks could be used to better understand implications of co-digestion and changing feedstock in working systems. It could also lead to methods to formulate seed material for the particular feedstock blends to be used in an anaerobic digestion system.

An additional recommendation is to further develop the market analysis for this technology. In particular where in California has the most need for organic waste handling, what are the types and concentrations of the waste, and what are the existing facilities with the infrastructure and capabilities to site these systems. Using the yield results of this current study, a more accurate assessment of potential marketplace for projects could be developed.

Public Benefits to California

The direct impact of this project is that it provides the technical foundation for an AD project using a covered lagoon at the Yolo County Integrated Waste Management Facility that utilizes 10,000 gallons per day of local liquid wastes to produce 16,500 cubic feet per day of biogas at a cost of $5.56 per MMBtu or produces 420,000 kW-h per year of renewable electricity at a cost of $0.060/kW-h in their existing landfill-gas generator equipment.

The potential impact from widespread implementation of this research will be the increased production of renewable biomethane from organic wastes that can then be used in natural gas devices including combined heat and power generation. A very important benefit will be the reduced cost of disposal of these organic wastes as compared with conventional methods as well as reduced transportation costs since the proposed lagoon digesters will be nearer the source of the wastes. Potential recipients would include existing small to medium wastewater and solid waste treatment facilities that could utilize the lower cost covered lagoon technology to treat onsite the organic wastes that were formerly transported to larger treatment facilities at higher costs. The food and winery industry might also benefit by possibly treating their waste onsite instead of incurring high costs of disposal. Finally manure digestion systems that are increasingly being used on California dairies could benefit by co-digesting the available organic wastes along with the manure, thus increasing gas production and revenue through tipping fees.

The total potential for converting wastes to biogas or bio-power in California is estimated using published waste generation data from two studies. The first study (Amon, et al 2012) estimated the amount of organic residues from the food processing in California on an annual basis. They showed wastewater BOD of 175,000 tons per year in 26 billion gallons of wastewater and 575,000 dry tons of high moisture solids generated from various food processing sectors on an annual basis in California. Using the ratios of VS to BOD (1.10) and VS to TS (0.78) for food processing materials from this study, the total amount of volatile solids from these waste streams was estimated. The second study estimated that 237 million gallons of septage per year and 11.5 million gallons of FOG from grease traps per year from a survey of waste handling facilities (California Wastewater Training and Research Center, 2002). Using the wastewater solids concentrations from the published study and converting from TS to VS using the ratios for septage (0.62) and FOG (0.74) from this study, the amount of volatile solids in these waste streams is estimated in Table 12. In all, the waste streams from food processing, grease traps and septage make up an estimated 670,000 dry tons per year of volatile solids potentially available for digestion.

Table 12. California organic residue solids and renewable energy generating potential

Organic Waste Generating Sector	Waste Water Solids	High Moisture Solids	Total Organic Solids	Biogas Potential	Electricity Potential	Installed Power Potential
Units	tons VS/y	tons VS/y	tons VS/y	MMBtu/y	MW-h/y	MW
Fruit/Vegetable Processing[1]	95,378	74,576	169,954	2,520,755	221,801	29.8
Meat Processing[1]	40,659	246,371	287,030	4,257,231	374,594	50.3
Winery[1]	7,429	134,987	142,415	2,112,305	185,862	25.0
Creamery[1]	48,418		48,418	718,130	63,188	8.5
Grease Traps[2]	1,202	-	1,202	12,708	1,118	0.2
Septage[2]	20,833		20,833	162,224	14,274	1.9
Total	213,918	455,933	669,852	9,783,352	860,837	115.6

1. Solids estimates adapted from Amon, et al 2012 as discussed in text. 2. Solids estimates adapted from California Wastewater Training and Research Center, 2002 as discussed in text.

Using the available organic residue data, the renewable biogas and electricity generation potential from implementing the covered lagoon digestion technology investigated in this study is shown in Table 12. The volatile solids conversion factors generated in the study for organic waste mixtures (10.3 ft3 biogas per lb VS) was applied to the food processing wastes and the grease trap and septage were reduced by their lower relative methane potentials of 0.71 and 0.52 respectively relative to the wastes in the mixture. Overall, the potential of about 9.8 million MMBtu per year of biogas could be generated and this is about 2% of the current (2014) non-residential natural gas usage in California. This biogas could be converted to about 861,000 MW-h of renewable electricity in a 30% efficient generator at costs between \$60 to \$85 per MW-h with a reasonable tipping fee in the range of \$0.03 to \$0.05 per gallon. The installed capacity (at 85% availability) required to achieve this would be about 116 MW. The investment required to achieve this potential build-out at \$5000/kW installed would be about \$580 million dollars.

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Glossary

Term or Acronym	Definition
BOD	Biological Oxygen Demand
C	Carbon
C/N Ratio	Carbon to nitrogen ratio
cDNA	Complimentary DNA
COD	Chemical Oxygen Demand
FOG	Fats, Oils and Grease: liquid waste collected from oil and grease traps in wastewater management systems from restaurants and other businesses
N	Nitrogen
qPCR	Quantitative Polymerase Chain Reaction
RT-qPCR	Reverse Transcription Quantitative Polymerase Chain Reaction
TS	Total Solids, amount of solid matter in liquid waste, generally expressed in wt % or concentration, e.g. g/L
VS	Volatile solids: Amount of volatile matter in liquid waste, generally expressed in wt % or concentration, e.g. g/L
WWTP	Wastewater Treatment Plant

APPENDIX A - Supporting data for BMP and semi-continuous digesters

Table A1. Individual waste type, date collected, and test parameter results

	Date sampled	pH	EC	ORP	TDS	Sodium	Nitrate as N	Sulfate	TKN	Ammonia as NH_3	Total P	BOD	COD	TS	VS
			Mhos/cm	mV	mg/L	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg O_2/kg	mg/kg	mg/kg
Dairy Manure (M)	06/03/14	7.37	16,800	-252	0.02	310	N/D	18	1,200	1,100	200	970	2,500	2,2000	1,2000
Tomato mixture waste (T)	04/03/14	3.95	140	91	105	2,500	5.5	140	1,600	320	230	34,000	72,000	69,000	58,000
			Mhos/cm	mV	mg/L	mg/L	Mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	Mg O_2/L	mg/L	mg/L
Portable toilet waste (P)	04/10/14	5.81	1,777	-33	1,273	1,400	N/D	340	2,600	3,300	270	4,900	35,000		16,000
Septic waste (S)	04/01/14	6.58	4,120	-198	3,109	220	N/D	2.4	450	440	57	3,000	11,000		3,400
Winery waste (W)	04/09/14	8.6.	20,350		18,840	99	0.17	30	42	4.2	14	720	6,400		1,600
Fat, Oil, and Grease (FOG) waste	04/10/14	9.05	1,608+	-84	1,135	160	N/D	23	270	53	70	11,000	19,000		12,000
Cider Beer waste (B)	05/05/14	4.77	2,188	-18	1,560	230	N/D	18	1,300	82	240	22,000	50,000		13,000

Table A2. Initial parameters of liquid waste and seeding mixture

Parameter	Unit	Control for human waste	Control for food waste	P/S with seeding mixture	T/W/FOG/B with seeding mixture	FOG/W with seeding mixture	T/FOG with seeding mixture	B/W with seeding mixture
pH		7.56	7.52	7.26	6.56	7.48	6.42	6.83
TS	mg/L	9612.38	11005.06	16168.31	19271.11	15496.52	30818.96	18023.45
VS	mg/L	5130.77	5787.00	9981.79	12768.75	8985.93	19029.76	9650.25
COD	mg/L	5,856.67	3,856.67	12,533.33	23,936.67	14,516.67	29,636.67	20,770.00
Volatile Acids	mg/L	1,526.00	1,963.33	4,093.00	5,191.33	3,356.67	4,094.33	4,552.33
Total N	mg/L	798.00	607.33	1,712.00	1,034.67	692.67	662.33	1,063.00
Nitrate as N	mg/L NO_3^--N	3.99	4.33	11.05	9.30	7.91	12.90	8.44
Nitrite as N	mg/L NO_2^--N	26.26	22.31	29.68	39.97	32.86	33.53	47.96
TKN	mg/L	768.00	580.33	1,671.33	985.67	652.00	615.67	1,006.50
Total Phosphorus	mg/L PO_4^{3-}	143.00	141.00	271.56	272.00	240.89	283.11	276.89
Sulfate	mg/L SO_4^{2-}	1,038.33	1,116.67	1,196.00	1,323.67	1,569.00	1,902.00	2,072.00
Sodium	mg/L Na^+	197.00	555.00	535.00	930.00	665.00	1,180.00	712.50
Conductivity	mS/cm	5.70	6.03	12.50	9.43	7.49	11.12	7.31
TDS	g/L	3.01	3.19	6.91	5.13	4.02	6.11	3.92
Salinity	‰	3.08	3.27	7.17	5.30	4.13	6.32	4.03
Resistivity	Ω·cm	175.50	166.30	79.90	105.80	133.40	89.80	136.80
Alkalinity	mg/L $CaCO_3$	1,702.00	1,667.50	1,985.67	2,425.00	4,486.00	2,725.67	3,968.33

Table A3. Initial reactor seeding and makeup of liquid waste mixtures

Waste Mixture	Reactor Componenets		g
P/S	Seed	Dairy manure	33.00
		Acclimated seed	17.00
	Liquid Waste Mixture	Portable toilet waste	25.00
		Septic	25.00
		SUM	100.0
T/W/FOG/B	Seed	Dairy manure	33.00
		Acclimated seed	17.00
	Liquid Waste Mixture	Tomato	12.50
		Winery	12.50
		FOG	12.50
		Beer	12.50
		SUM	100.0
FOG/W	Seed	Dairy manure	33.00
		Acclimated seed	17.00
	Liquid Waste Mixture	FOG	25.00
		Winery	25.00
		SUM	100.0
T/FOG	Seed	Dairy manure	33.00
		Acclimated seed	17.00
	Liquid Waste Mixture	Tomato	25.00
		FOG	25.00
		SUM	100.0
B/W	Seed	Dairy manure	33.00
		Acclimated seed	17.00
	Liquid Waste Mixture	Beer	25.00
		Winery	25.00
		SUM	100.0

Table A4. Waste mixture C/N ratio and organic loading rate

Waste Mixture	C/N ratio (TOC as total C, TKN as total N)	Organic loading rate (kg VS/m^3·day)
P/S	3.41	1.43
T/W/FOG/B	11.52	2.34
FOG/W	13.98	1.31
T/FOG	16.28	3.33
B/W	14.64	1.35

Table A5. List of parameters and test methods

Parameter	Test Kit (Hach)	Test Method	Measurable
COD	TNT823	10212	$Cr6^+$ / COD
TKN	TNT880	10242	N
Volatile Acids	TNT872	10240	CH_3COOH
Sulfate	TNT865	10227	SO_4^{2-}
Alkalinity	TNT870	10239	$CaCO_3$
Total Phosphorus	TNT845	10209	PO_4^{3-}
Volatile Solids	N/A	EPA 1684	VS
Total Solids	N/A	EPA 1684	TS

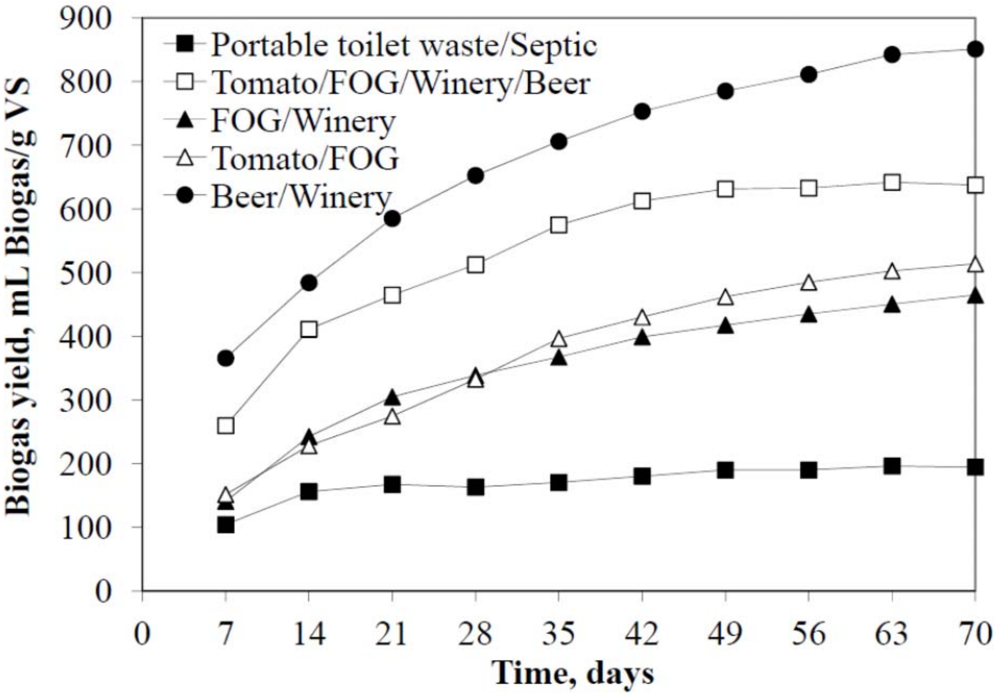

Figure A1. Biogas yield per g VS added over the operation period

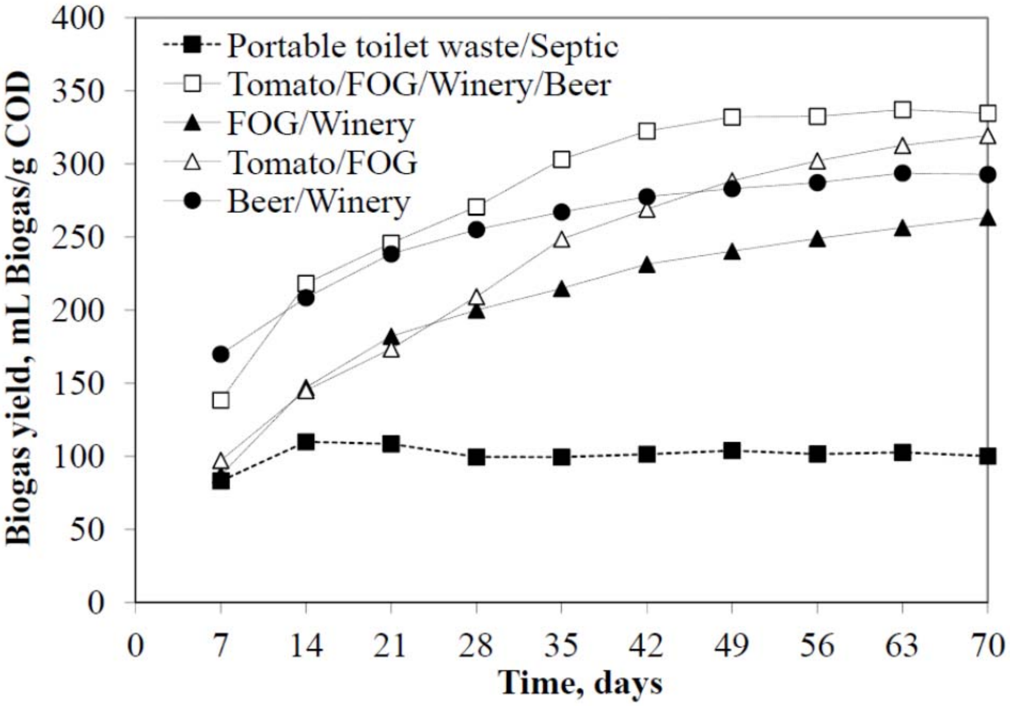

Figure A2. Biogas yield per g COD added over the operation period

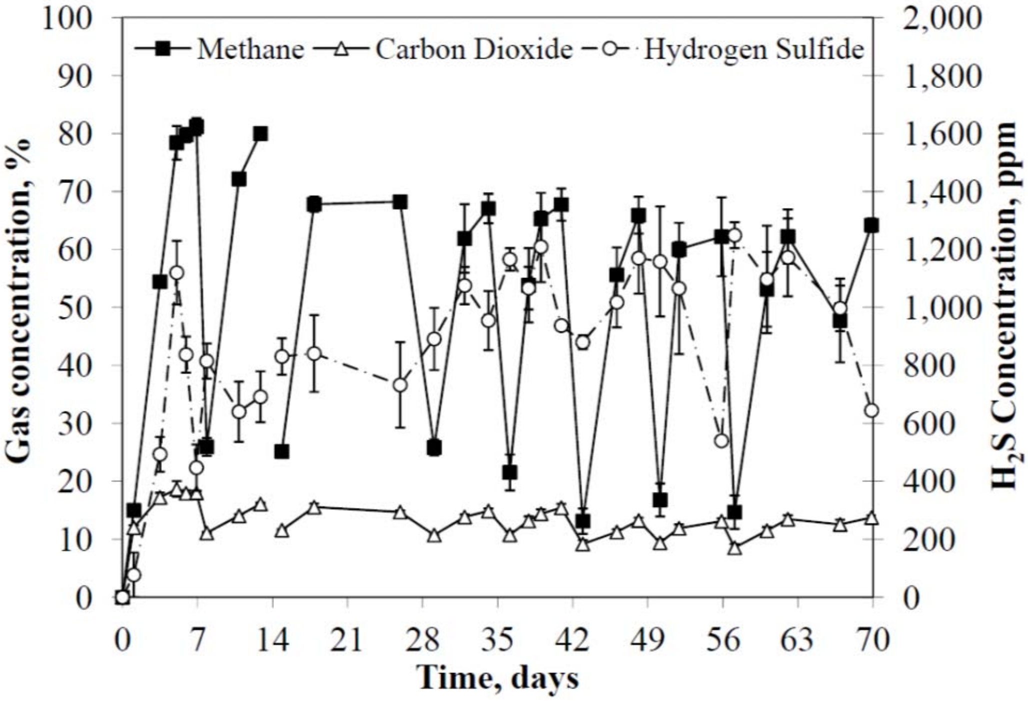

Figure A3. Portable toilet waste/Septic Biogas composition

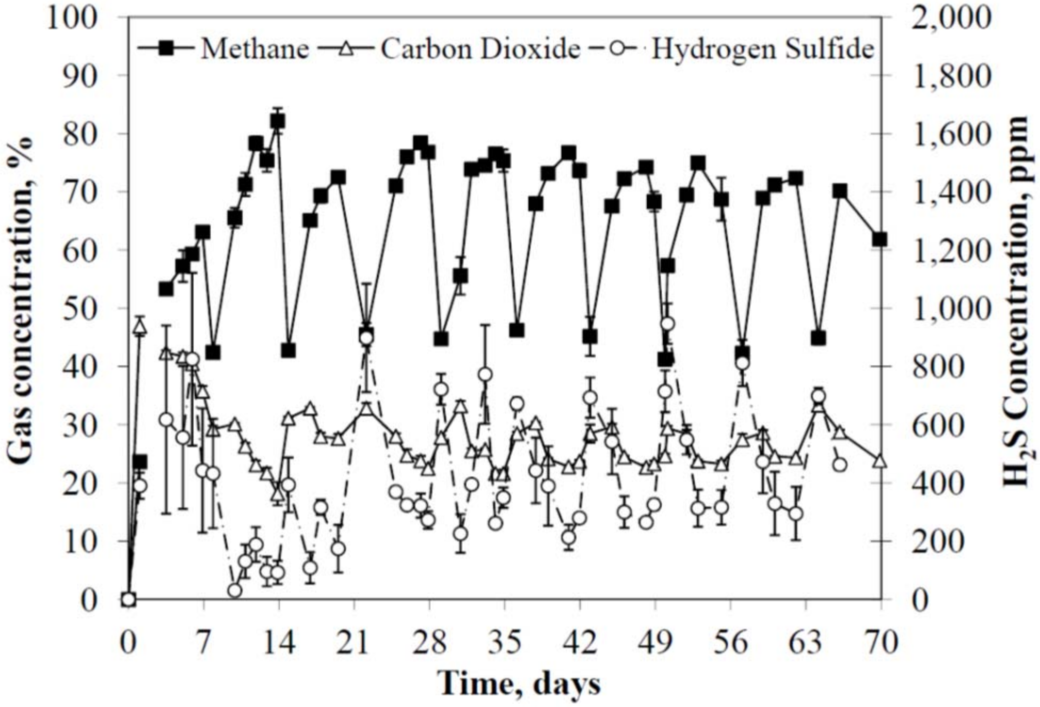

Figure A4. Tomato/FOG/Winery/Beer Biogas composition

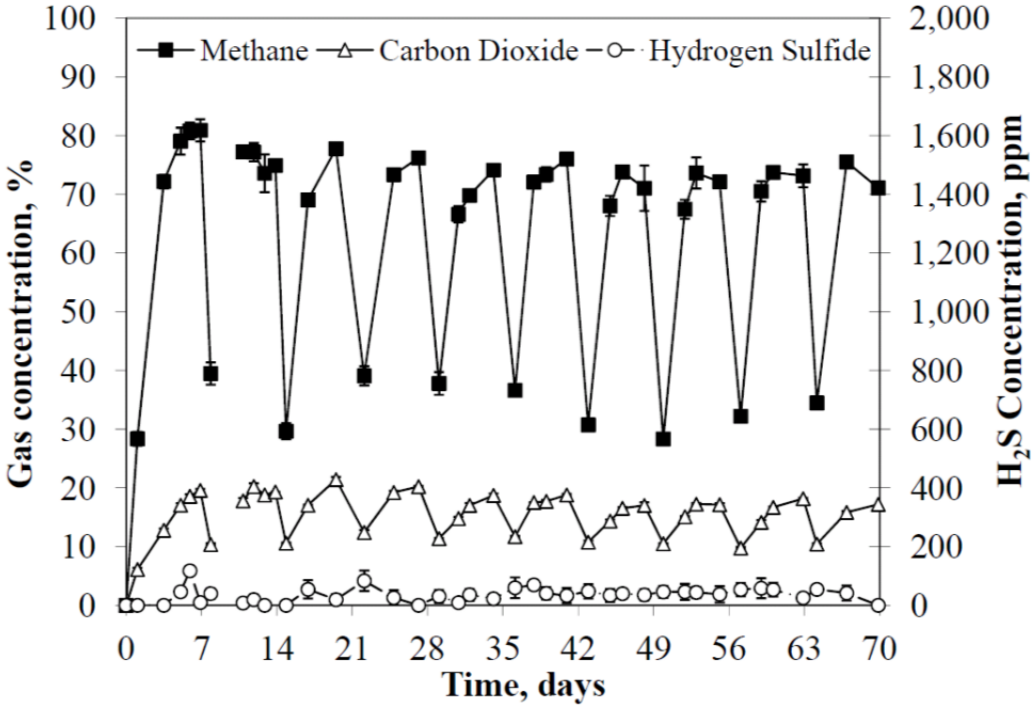

Figure A5. FOG/Winery Biogas composition

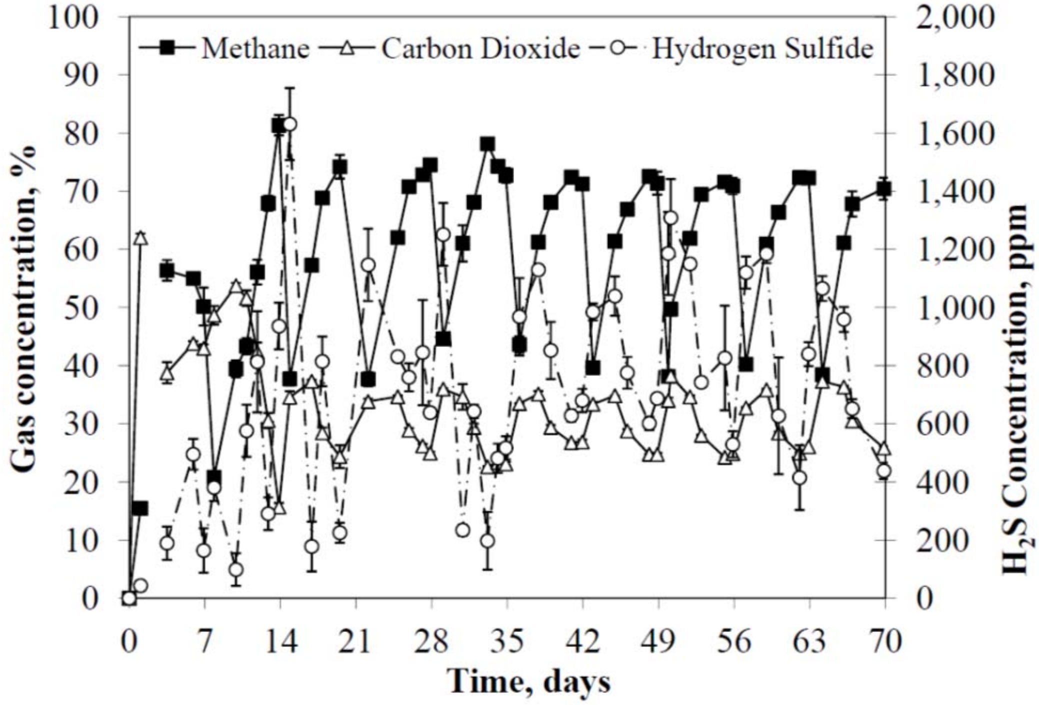

Figure A6. Tomato/FOG Biogas composition

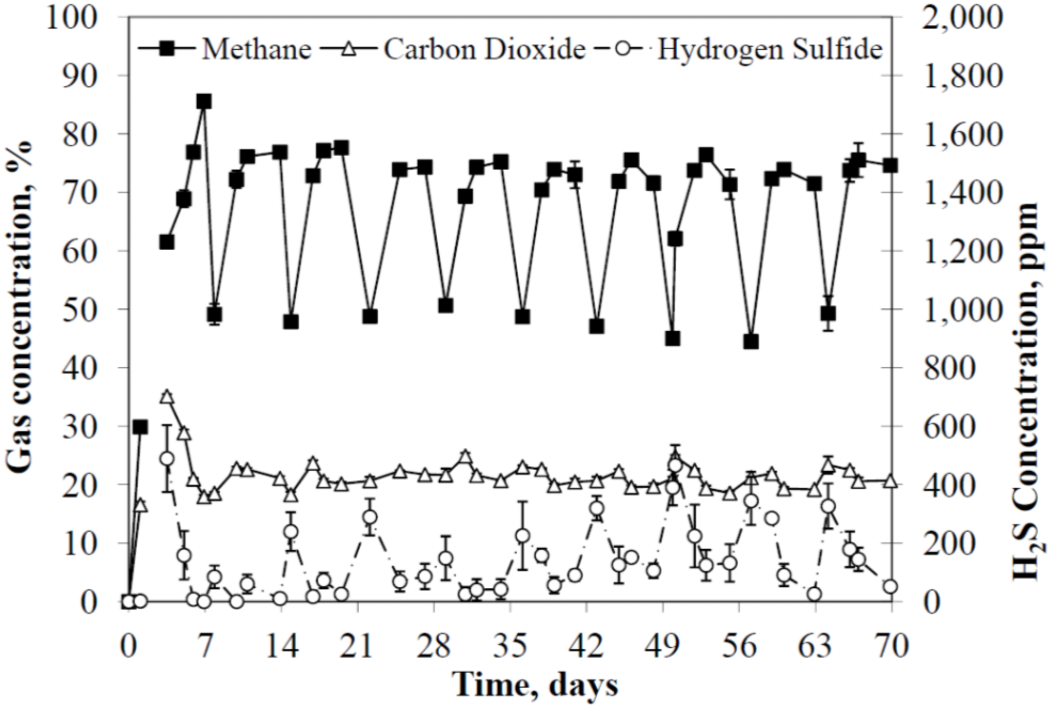

Figure A7. Beer/Winery Biogas composition

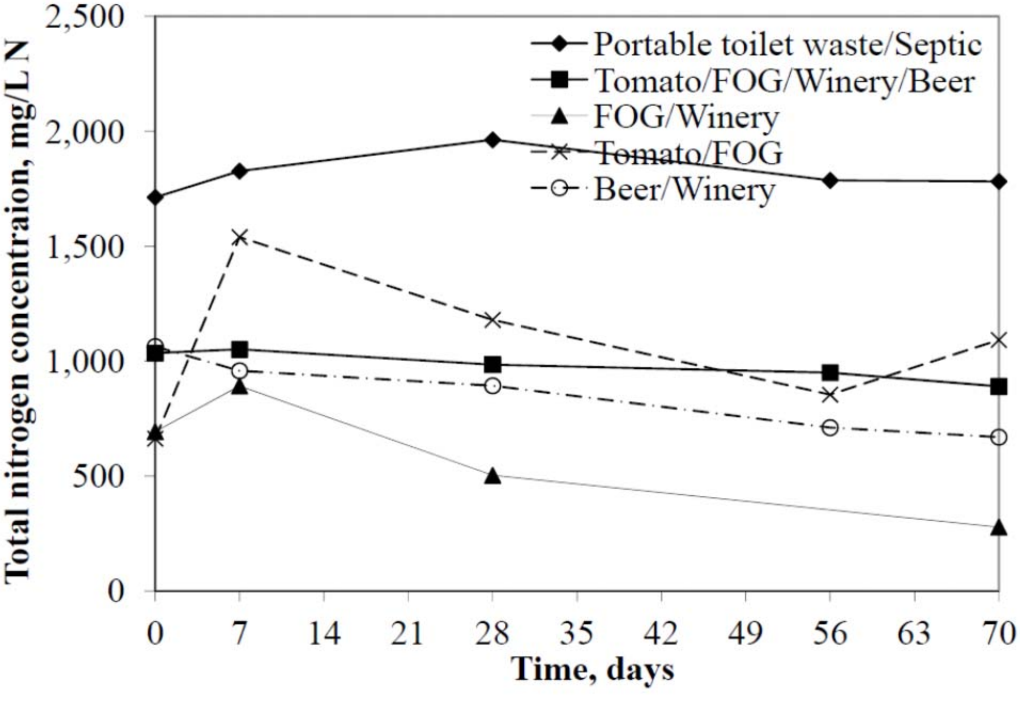

Figure A8. Total nitrogen concentration over operation period

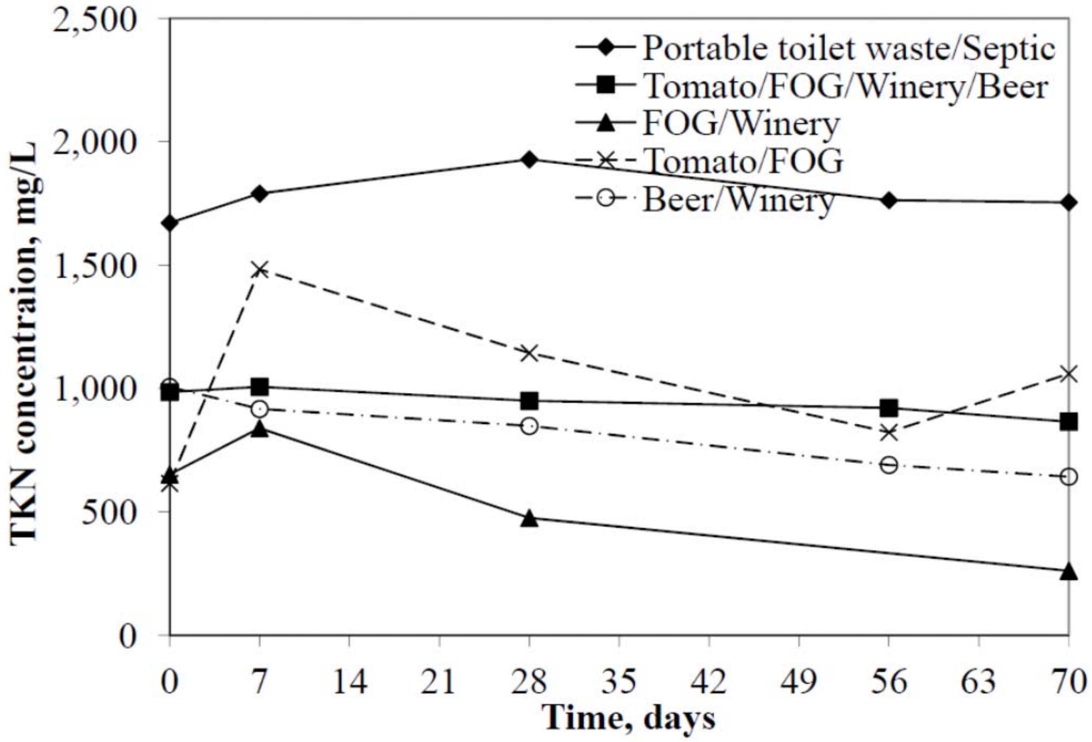

Figure A9. Total Kheldahl nigrogen concentration over the operation period

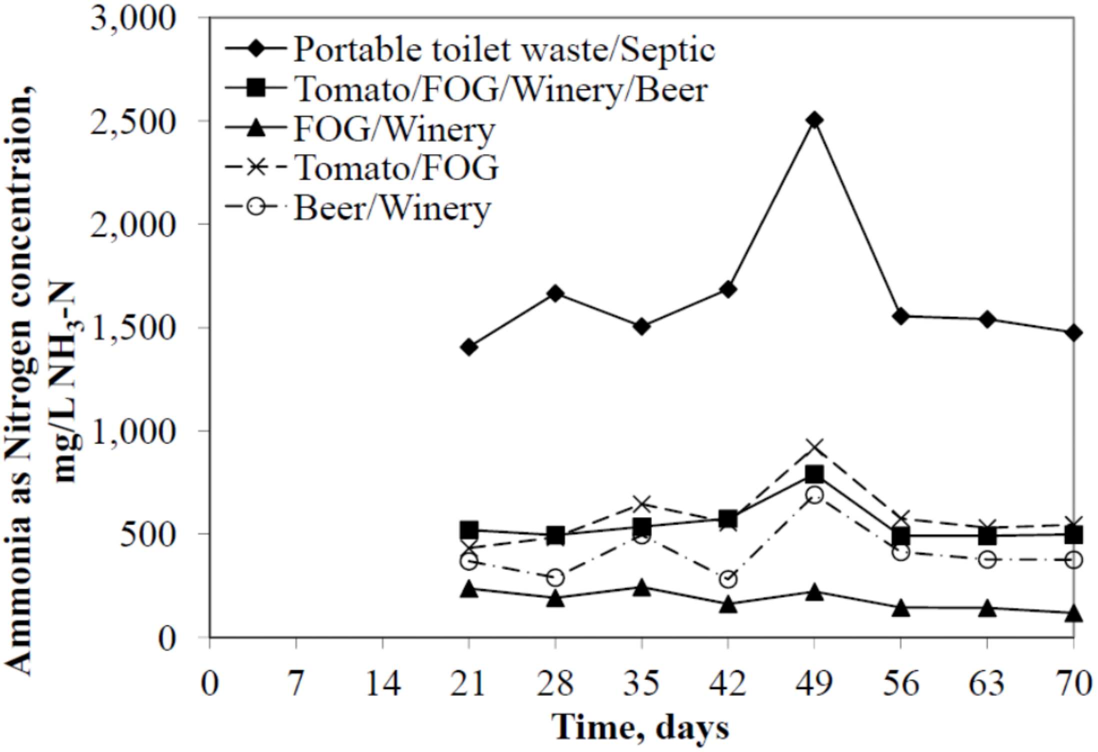

Figure A10. Ammonia nitrogen concentration over the operation period

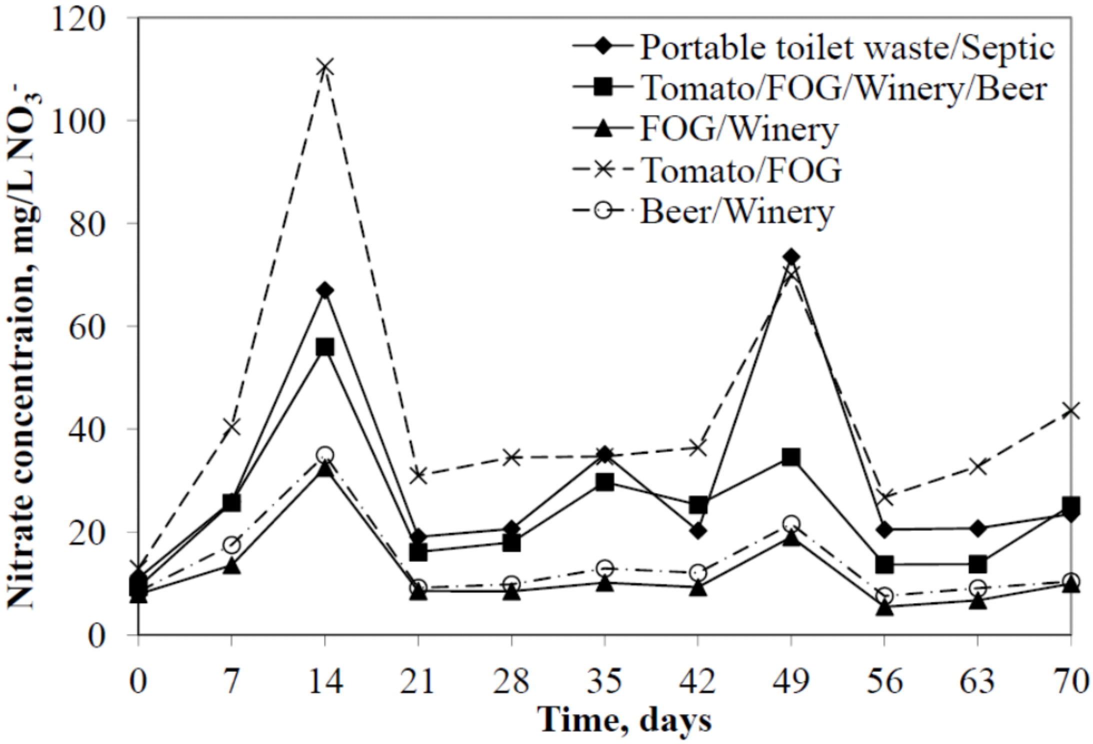

Figure A11. Nitrate concentration over operation period

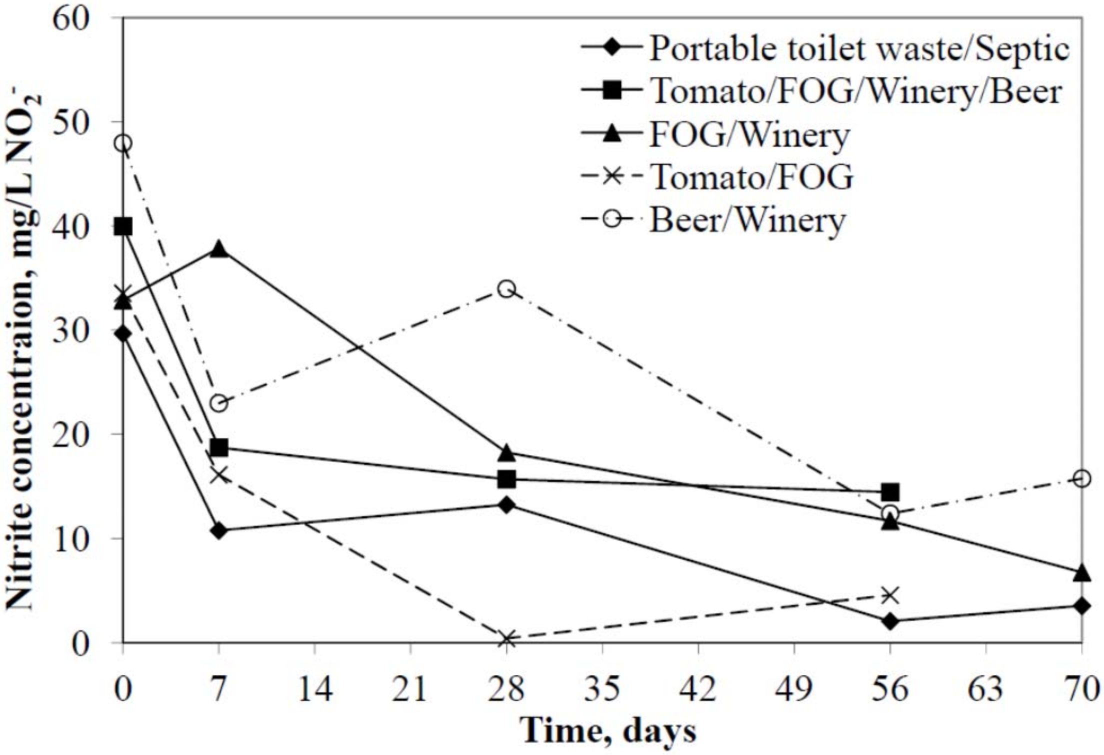

Figure A12. Nitrite concentration over operation period

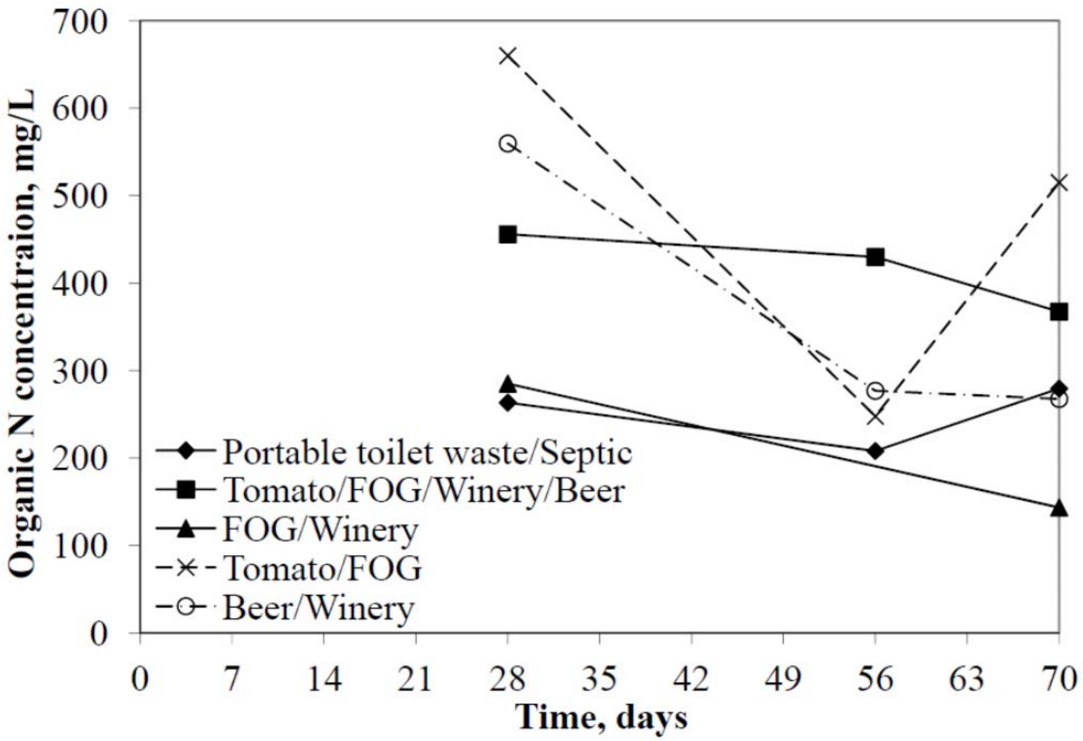

Figure A13. Organic nitrogen concentration over the operation period

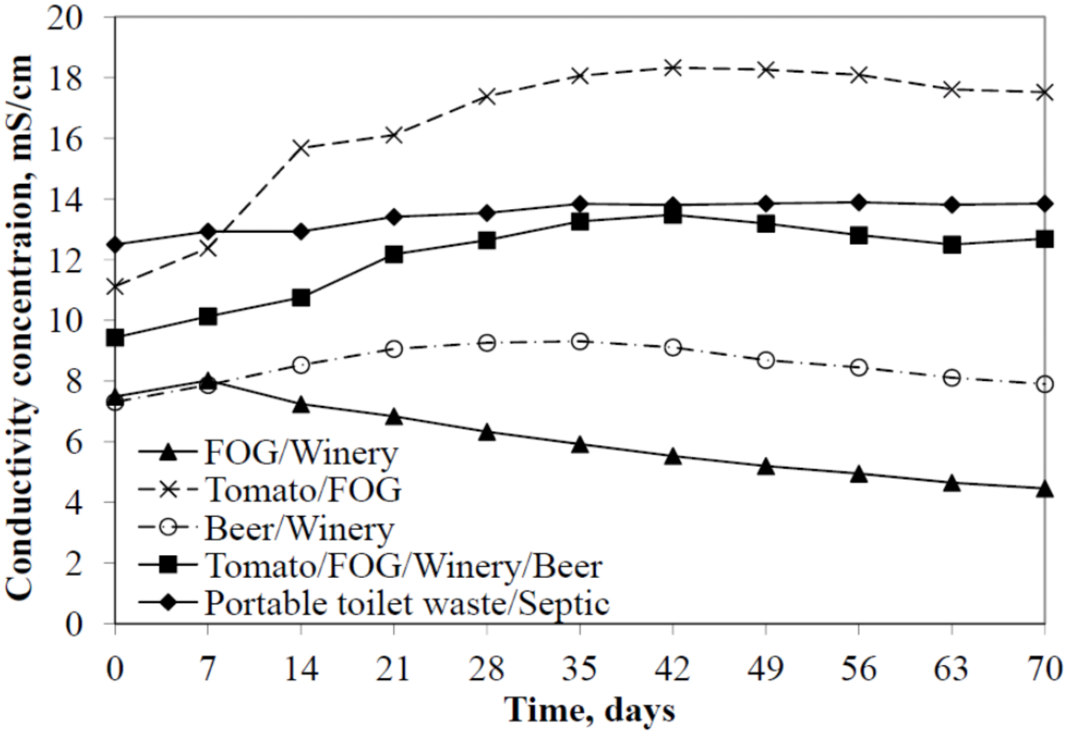

Figure A14. Conductivity trend over the operation period

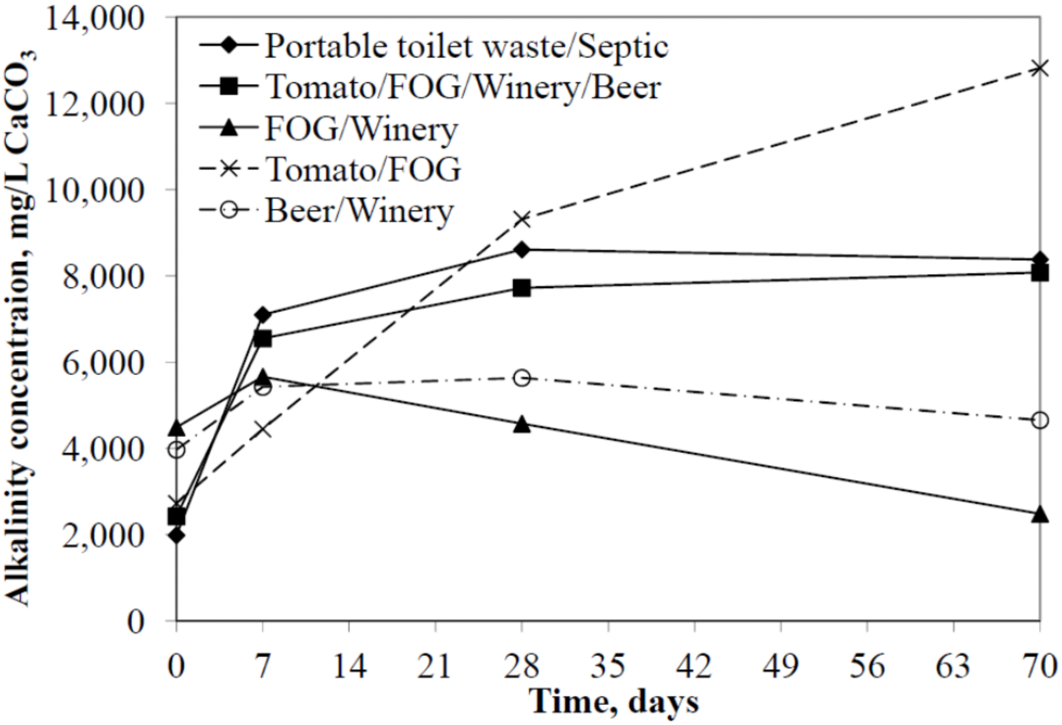

Figure A15. Alkalinity trend over the operation period

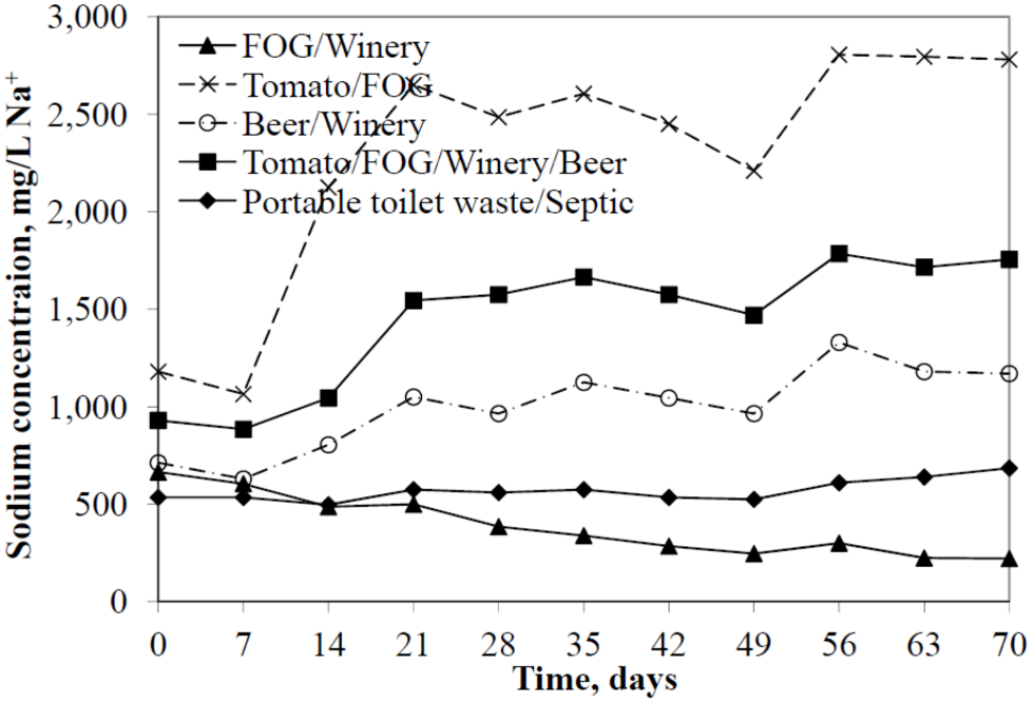

Figure A16. Sodium trend over the operation period

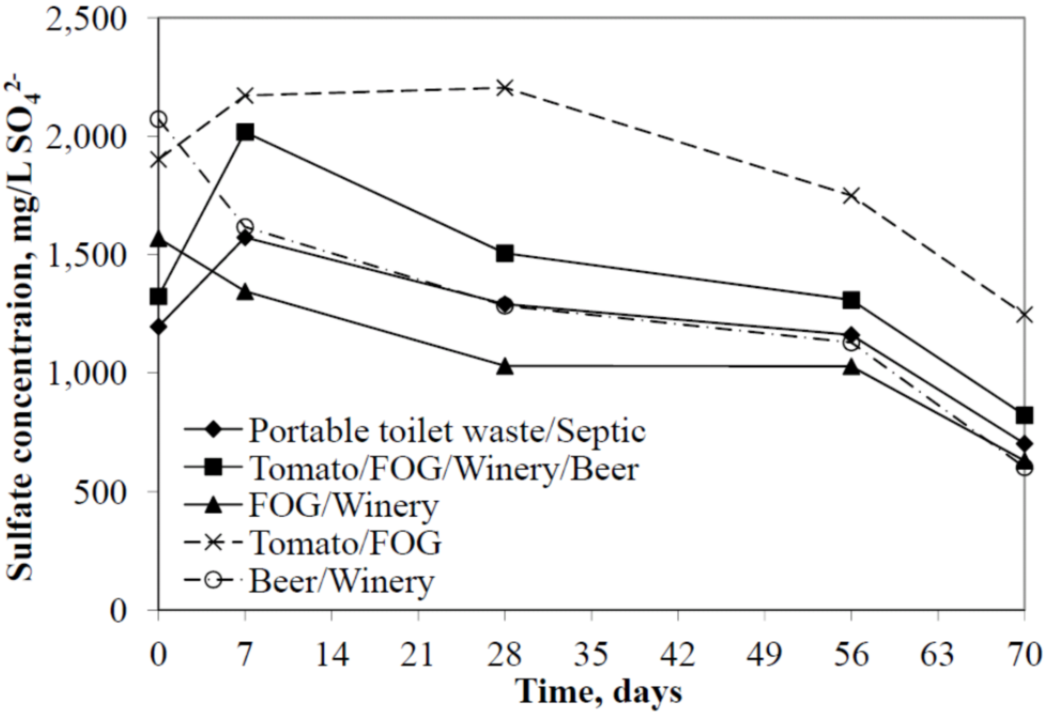

Figure A17. Sulfate trend over the operation period

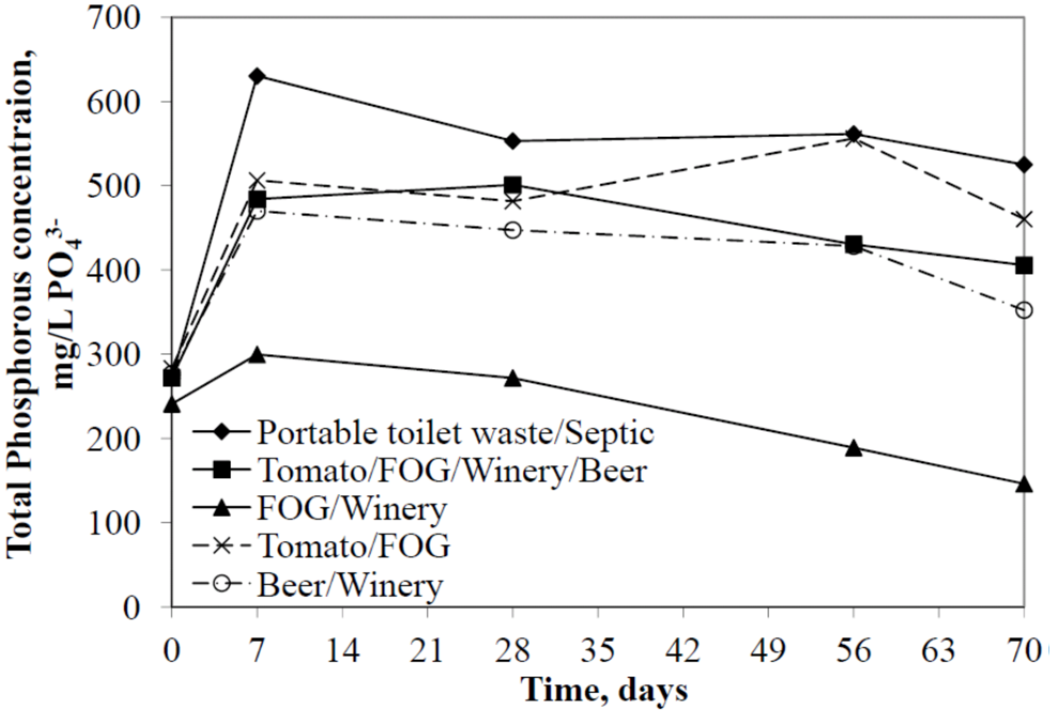

Figure A18. Total phosphorus trend over the operation period

APPENDIX B – Quantification of methanogens

Methanogens/mL was calculated according to the following equation:

$$\frac{\boldsymbol{Methanogens}}{\boldsymbol{mL}} = \frac{\boldsymbol{m * N_A}}{\boldsymbol{b_p * \left(1x10^9 \frac{ng}{g}\right) * m_{DNA} * V}}$$

N_A is Avagadro's number (6.022x10^{23} molecules/mol). V is the volume used in mL. m is the amount of template used in ng. b_p is the genome size of *M. maripaludis* (1,661,137 bp). m_{DNA} is the average mass of a double-stranded DNA base pair (660Da).

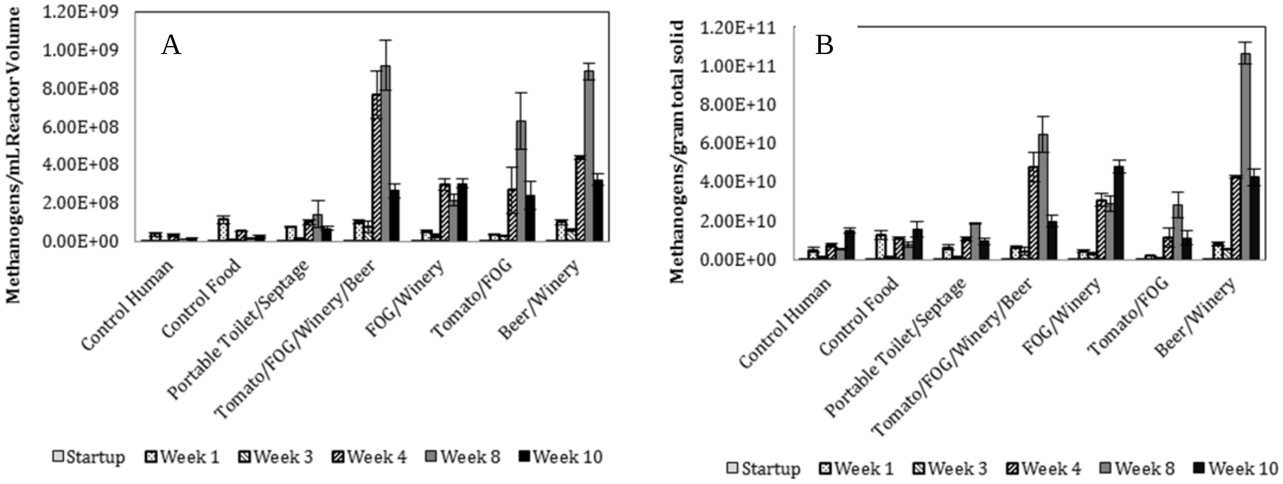

Figure B1. Quantity of methanogens in digesters as a function of time. (A) Methanogens /mL reactor volume. (B) Methanogens per gram total solids (TS). Data shown is for primer set mcrA_1035F/mcrA_1530R with 1.00ng DNA/rxn. Tests with 0.156ng/rxn yielded similar trends (data not shown).

APPENDIX C – Gene transcripts

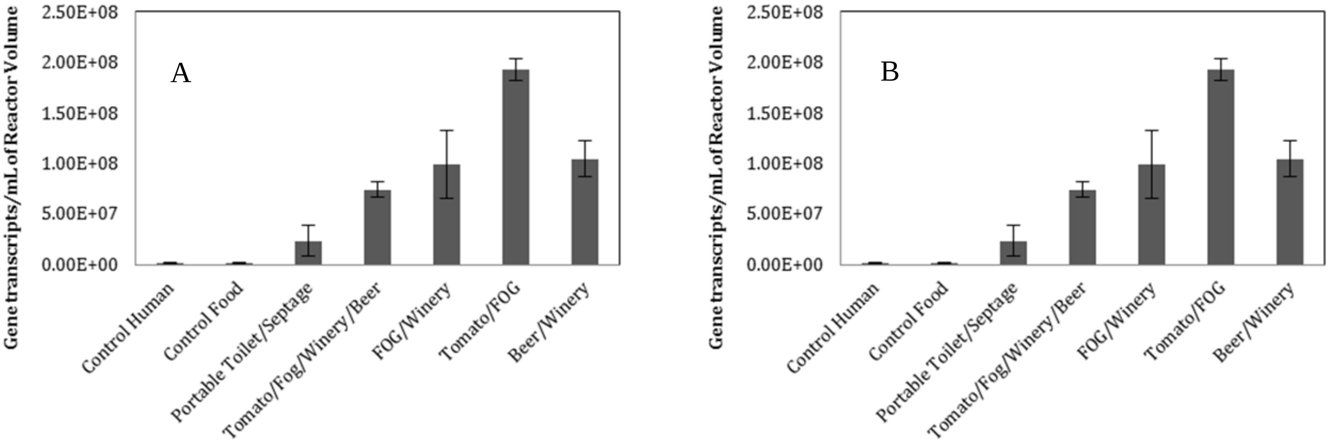

Figure C1. Gene transcripts per mL of reactor volume. (A) Primer set MLf/MLr. (B) Primer set mcrA_1035F/mcrA_1530R. Reactor samples were collected at week 8.

APPENDIX D – Phylogenetic charts

Phylogenetic pie charts were produced for Week 8 based on metagenomic sequencing data. Sequences were clustered into operational taxonomic units and assigned phylogenetic identities with the RDP Classifier. Sequences that could not be identified (i.e., "no hits") were omitted for the purpose of this analysis. The term "unknown" indicates that the confidence value at a particular taxonomic level was below a 51% threshold. This means that the unknown organisms are highly related to multiple organisms in the databases, so it is not possible to determine which organisms were present. In this study, all of the unknown microorganisms were found to be highly related to *Thermoplasmata*, and thus are labeled "*Thermoplasmata*-related" in Appendix E.

Figure D1. Phylogenetic chart for Control Human digester.

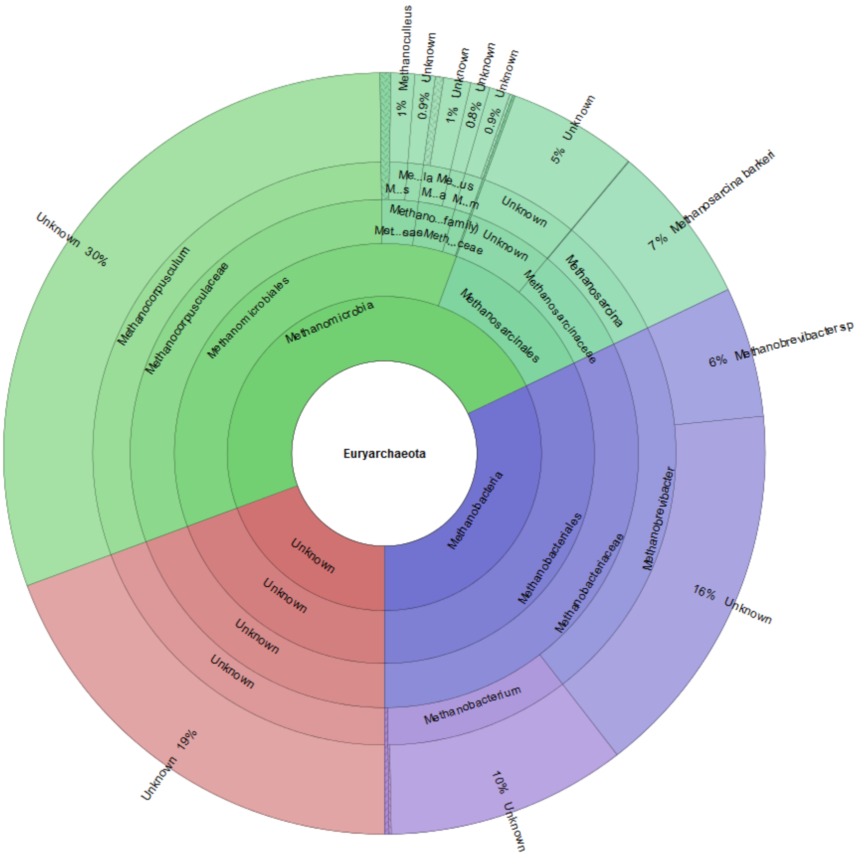

Figure D2. Phylogenetic chart for Control Food digester.

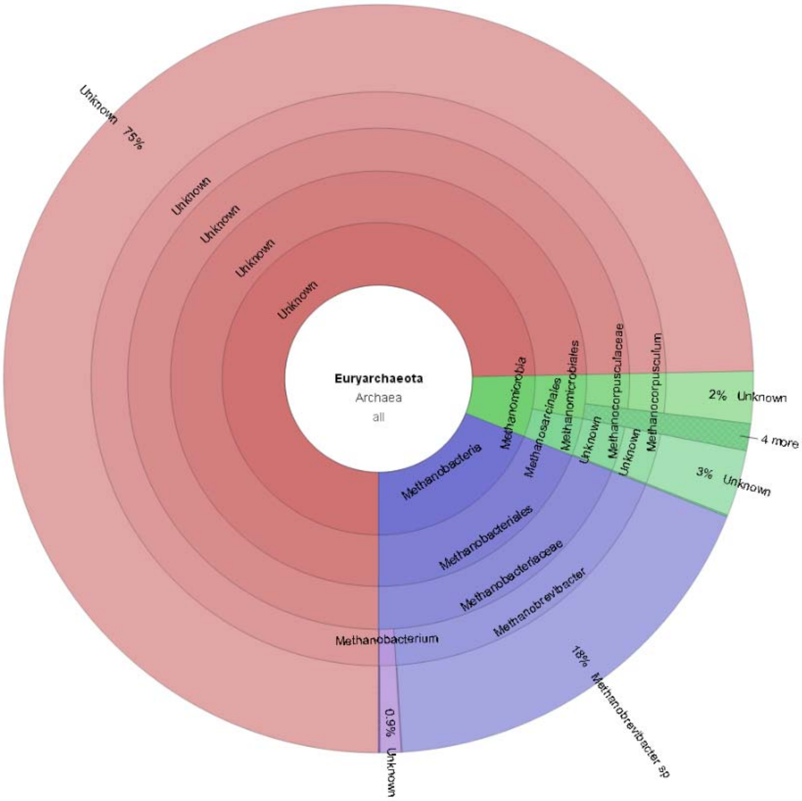

Figure D3. Phylogenetic chart for Portable toilet waste/Septage digester.

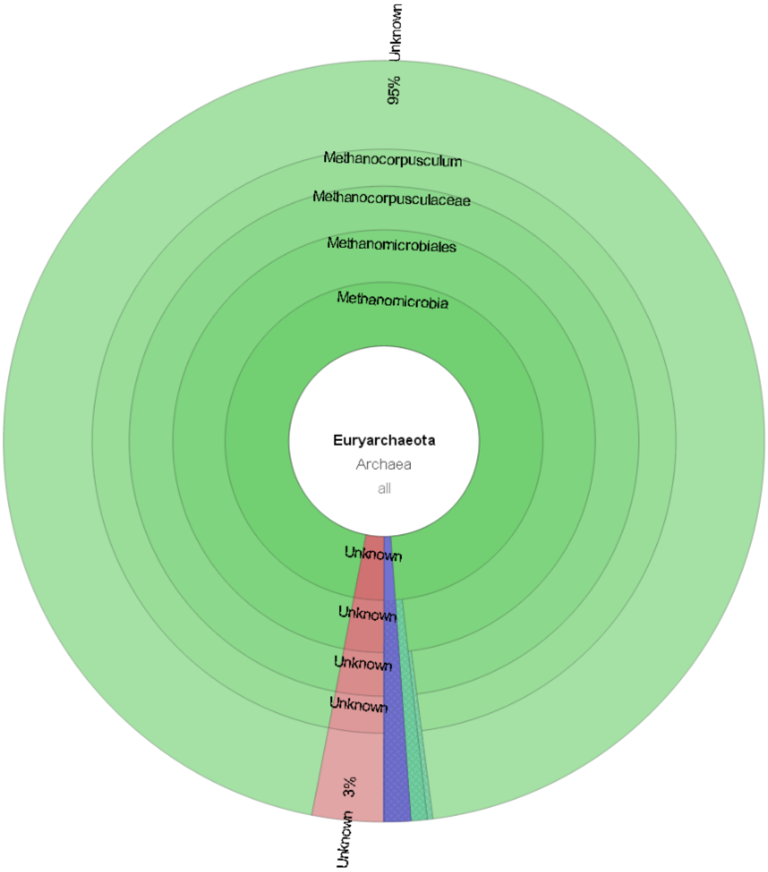

Figure D4. Phylogenetic chart for Tomato/FOG/Winery/Beer digester.

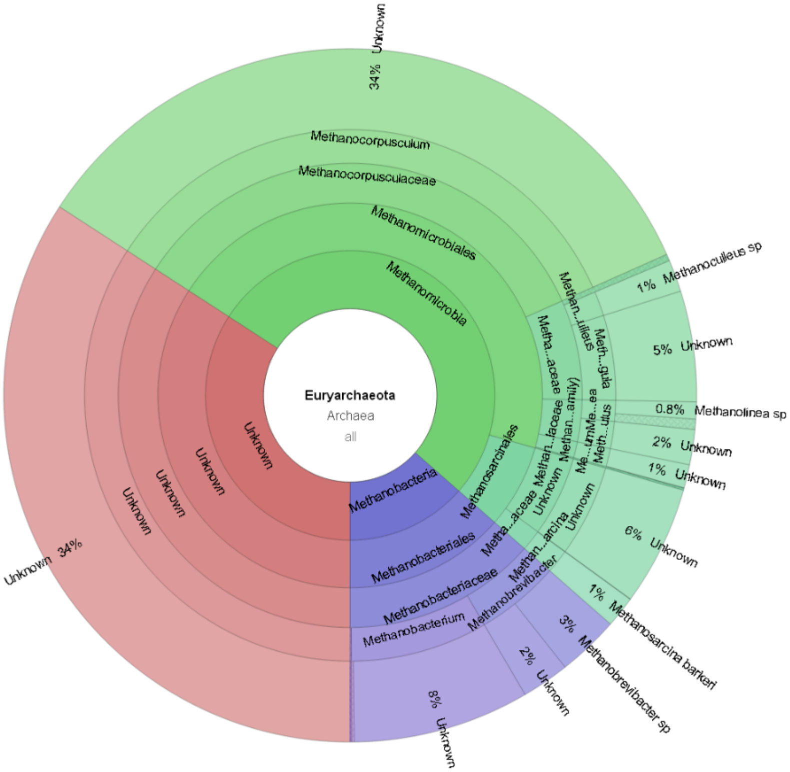

Figure D5. Phylogenetic chart for FOG/Winery digester.

Figure D6. Phylogenetic chart for Tomato/FOG digester.

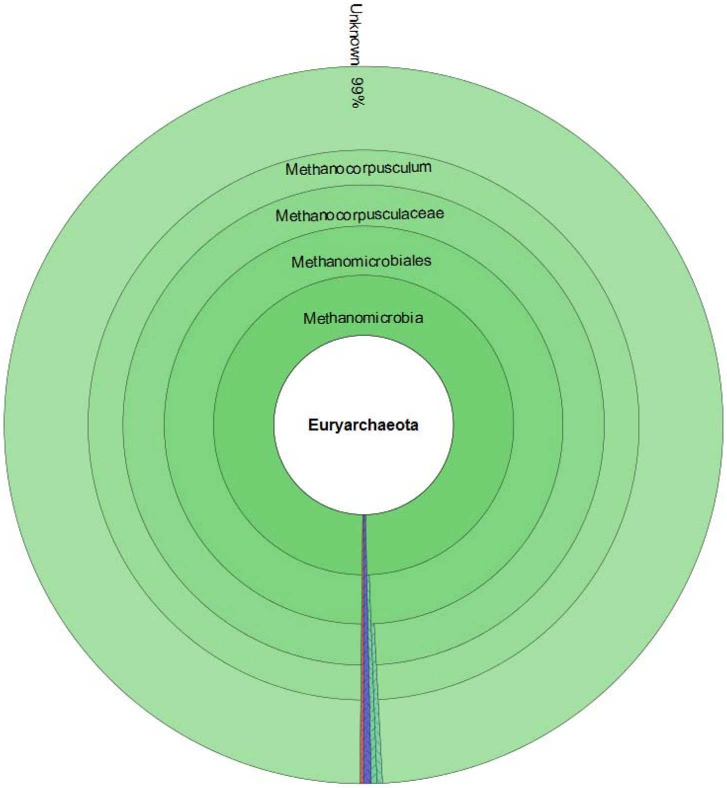

Figure D7. Phylogenetic chart for Beer/Winery digester.

APPENDIX E – Phylogenetic histograms

Histograms were generated to allow for easier comparison of the types of methanogens present in the different reactors at three phylogenetic levels: Order, Family, and Genus. Note that because the data presented in the histograms is based on sequencing, non-methanogenic Archaea may also be shown. *Thermoplasmata* may be part of a recently established order of methanogens, but their ability to generate methane has not been clearly proven (Paul et al., 2012).

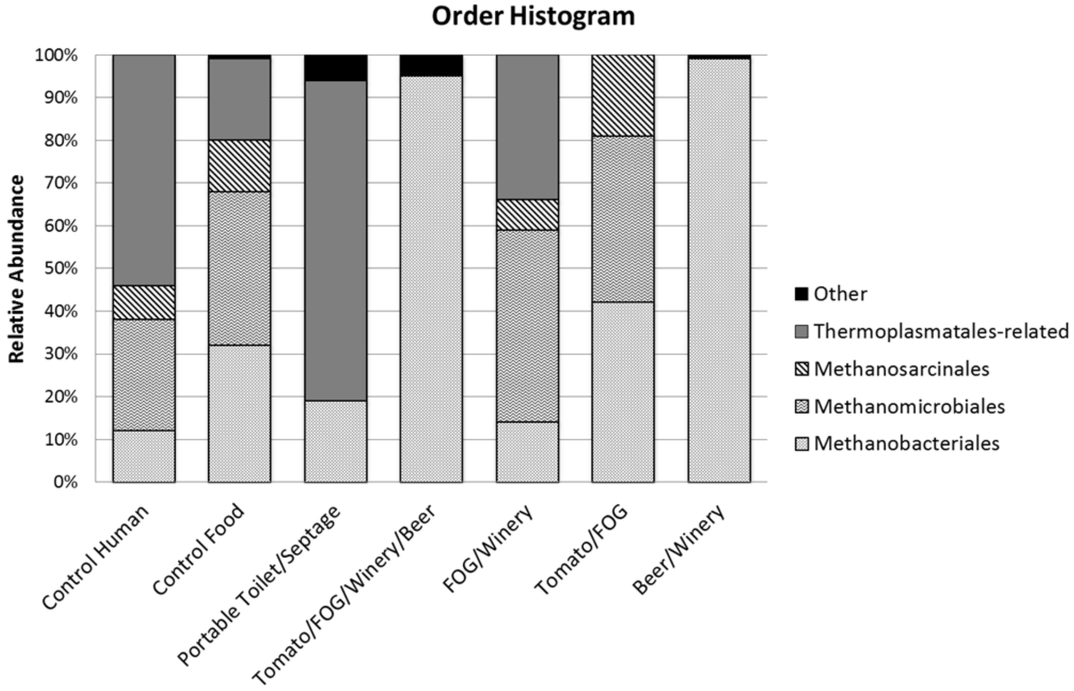

Figure E1. Order histogram for methanogens in digesters

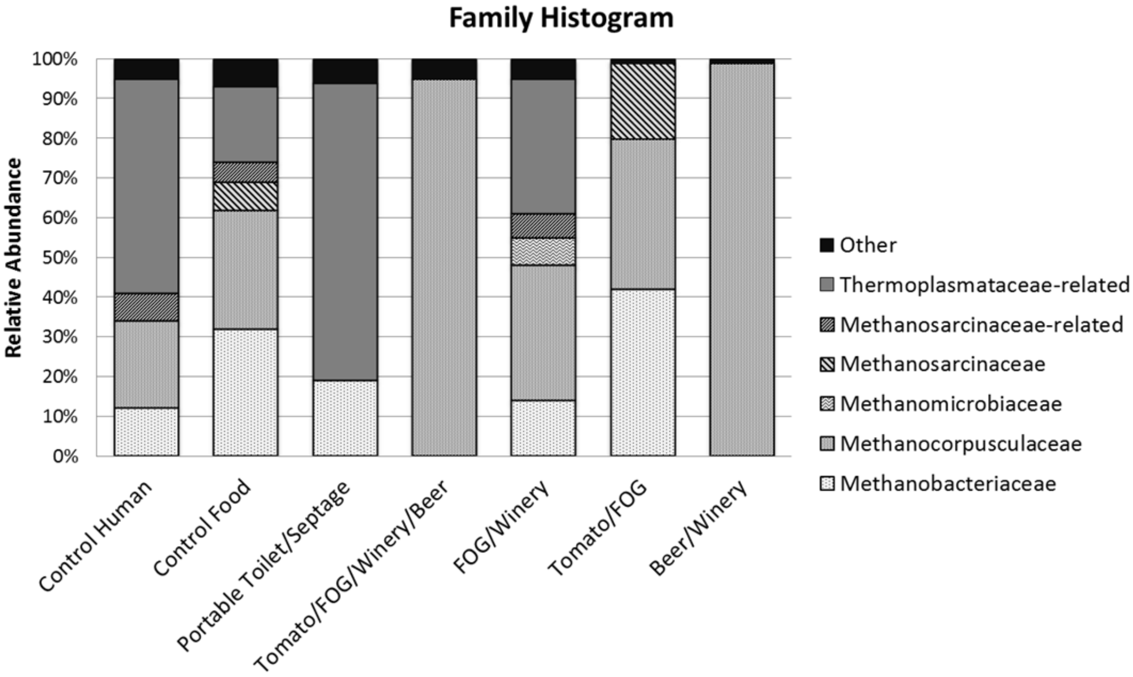

Figure E2. Family histogram for methanogens in digesters

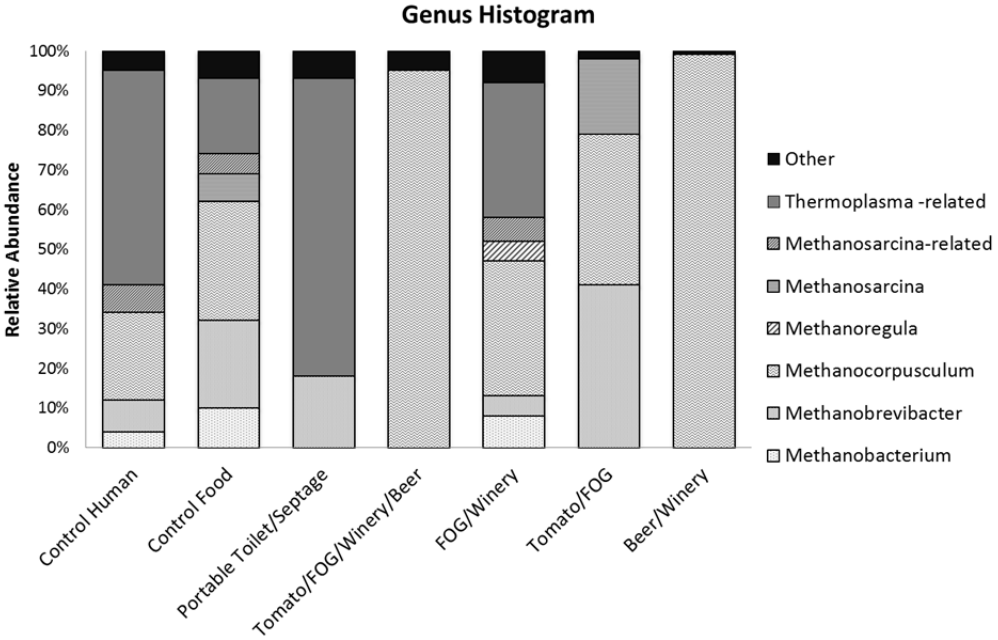

Figure E3. Genus histogram for methanogens in digesters

APPENDIX F – Revenue requirements model worksheets

This appendix gives details on inputs and outputs for the economic calculations made with the revenue requirements model to compute the cost of electricity and biomethane.

OPTION 1: The UC Davis Biomass Collaborative Energy Cost Calculator was used to determine the economic feasibility of each alternative digester system. Table F1 summarizes the results of this model when used to calculate option 1. Option 1 assumes a tipping fee of $.05/gallon. The input for this tipping fee is shown below in the tables as a negative fuel cost of -$470/metric ton of solids. This calculation is as follows: $.05/gallon X 10,000 gal = $500/day. The TS of this material is 2.8% or 2335 pounds/2200 lb/metric ton = 1.06 metric tons/day. Tipping fee is then $500/1.06 dry metric tons = $470 dry metric ton, entered as a negative fuel cost.

Table F1. Revenue requirements model inputs for Option 1, New covered lagoon digester system with electrical production

Capital Cost	($)	($/kWe-net)
Digester and Feedstock Handling System Capital Cost ($)	618,000	10,300
Biogas Cleaning System Capital Cost ($)	30,000	500
Power Generation System Capital Cost ($)	120,000	2,000
Solids Separation	0	0
Engineering @ 10%of eqipment capital cost	76,800	1,280
Contingency @ 10% of equipment capital cost	76,800	1,280
Total Facility Capital Cost ($)	921,600	15,360

Capital Cost: Total installed cost of plant including electrical plus heat recovery and distribution

Electrical and Fuel--base year

Gross Electrical Capacity (kWe)	65
Net Electrical Capacity (kWe)	60
Parasitic Load (kWe)	5
Capacity Factor (%)	79
Annual Hours	6,920
Net Efficiency--Biogas to Electricity (%)	32.0
Methane Concentration in Biogas (% by volume)	72.0
Biogas Density (kg/m^3 at 298K, 1 atm)	0.975
Biogas Heating Value (kJ/kg)	26,818
Biogas Heating Value (kJ/m^3)	26,176
Biogas Consumption Rate (kg/h)	25.2

Gross Electrical Capacity: Total gross generating capacity

Net Electrical Capacity: Net power available for on-site use or grid sales

Parasitic Load: Electrical power used to operate system

Capacity Factor: Annual fraction that rated capacity is available from plant

Fuel Heating Value: Higher heating value (heat of combustion) of fuel.

Biogas Consumption Rate (m^3/h)	25.8	
Power in Biogas (kW)	188	
Gross Efficiency--Biogas to Electricity (%)	34.7	
Annual Net Electricity Generation (kWh)	415,224	
Annual Biogas Consumption (kg/y)	174,181	
Annual Biogas Consumption (m^3/y)	178,651	
Biogas Consumption Per Unit Net Output Power (m^3/kWh)	0.43	
Methane Production (m^3/kg VS destroyed)	0.51	
Biodegradability (kg VS destroyed/kg VS added)	0.90	
Ratio of Volatile Solids to Total Solids in Feedstock (kg/kg)	0.68	
Total Solids Fraction of Wet Feedstock (kg/kg)	0.028	
Methane Production (m3/kg VS added)	0.46	
Methane Production (m^3/kg TS)	0.31	
Methane Production (m^3/kg Wet Feedstock)	0.0087	
Biogas Production (m^3/kg VS destroyed)	0.71	
Biogas Production (m^3/kg VS added)	0.64	
Biogas Production (m^3/kg TS)	0.43	
Biogas Production (m^3/kg Wet Feedstock)	0.012	
Annual Volatile Solids (VS) Consumption (t/y)	280	Volatile solids consumption in metric tons per year
Annual Total Solids (TS) Consumption (t/y)	412	Total solids consumption in metric tons per year
Hourly Total Solids (TS) Consumption (t/h)	0.06	Hourly TS consumption in metric tons per hour
Annual Wet Feedstock Consumption (t/y)	14,718	Total wet feedstock consumption in wet metric tons per year
Hourly Wet Feedstock Consumption (t/h)	2	Hourly wet feedstock consumption in wet metric tons per hour
Annual sludge production (t/y)	238	Approximate annual sludge production in dry metric tons per year

Heat--base year

Total heat production rate (kWth)	123	Total heat production rate equal to fuel power less gross electrical power
Aggregate fraction of heat recovered (%)	50	Fraction of total heat production available for sale
Recovered heat (kWth)	61	Recovered heat production rate
Annual heat sales (kWh/y)	423,875	Total annual heat energy sales
Aggregate sales price for heat ($/kWh)	0.0000	See Heat Sales Price Conversion calculator above for conversion from $/MMBtu
Total income from heat sales ($/y)	0	
Heat income per unit net electrical energy ($/kWh-net)	0.0000	
Overall CHP Efficiency--Gross (%)	67.3	
Overall CHP Efficiency--Net (%)	64.7	

Expenses--base year		($/kWh-net electrical)	
Fuel Cost ($/t)--use negative value for tipping fee	-470.00	-0.4665	Fuel Cost: Cost of fuel in $/dry metric ton of TS, to convert from $/short ton, see calculator above, based on $.05/gallon, 10,000 gal/day
Labor Cost ($/y)	30,000	0.0723	Labor Cost: Cost of labor to operate facility
Maintenance Cost ($/y)	30,497	0.0734	Maintenance Cost: Cost of maintaining the plant
Insurance/Property Tax ($/y)	9,216	0.0222	Insurance/Property Tax: Cost of insurance for the plant plus any property or other local taxes
Utilities ($/y)	10,000	0.0241	Utilities: Purchased utilities including power, gas, water, waste disposal
Management/Administration ($/y)	18,432	0.0444	Management/Administration: Cost for administrative personnel and other administration
Other Operating Expenses ($/y)	42,870	0.1032	Other Operating Expenses: Cost of disposal of excess effluent and sludge
Total Non-Fuel Expenses ($/y)	141,015	0.3396	
Total Expenses Including Fuel ($/y)	-52,678	-0.1269	

Taxes		
Federal Tax Rate (%)	34.00	Federal Tax Rate: For federal tax calculations
State Tax Rate (%)	9.60	State Tax Rate: For state tax calculations
Production Tax Credit ($/kWh)	0.009	Production Tax Credit on Electrical Energy. For Federal PTC, facilities using animal waste must have nameplate rating of 150 kW or above.
Combined Tax Rate (%)	40.34	Combined Tax Rate: combined federal and state tax rate to which project is subject

Income other than energy		
Electricity Capacity Payment ($/kW-y)	0	Capacity Payment: Payment made from power purchaser if plant can guarantee capacity (depends on contract)
Interest Rate on Debt Reserve (%/y)	2.00	Interest Rate on Debt Reserve: Interest income earned on reserve account if financing institution requires security deposit
Sales price for sludge ($/t)	0.00	Value of residuals from digester (sludge, digestate), e.g. as soil amendment, in $/dry metric ton
Annual Capacity Payment ($/y)	0	
Annual Debt Reserve Interest ($/y)	1,331	
Annual Income from Sludge Sales	0	

Escalation/Inflation		
General Inflation (%/y)	2.10	General Inflation: Overall inflation rate used to adjust current dollar result to constant dollars.
Escalation--Fuel (%/y)	2.10	Escalation--Fuel: Rate at which fuel cost escalates over time
Escalation for Production Tax Credit (%/y)	2.10	Escalation--PTC: Specified index for production tax credit
Escalation--Heat sales (%/y)	2.10	Escalation--Sales price of heat: escalation rate applied to heat sales
Escalation--Sludge sales (%/y)	2.10	

Escalation--Other (%/y)	2.10	Escalation--Other: Rate at which other expenses escalate over time

Financing

Debt ratio (%)	90.00	Debt ratio: Fraction of financing covered by debt borrowing
Equity ratio (%)	10.00	Equity ratio: Fraction of financing covered by corporate investment
Interest Rate on Debt (%/y)	5.00	Interest Rate on Debt: Interest rate applied to debt portion of investment
Economic Life (y)	20	Economic Life: Example assumes 20 year economic life
Cost of equity (%/y)	15.00	Cost of Equity: Rate of return on equity portion of investment
Cost of Money (%/y)	6.00	Cost of Money: Weighted cost of investment for full investment including both debt and equity
Total Cost of Plant ($)	921,600	
Total Equity Cost ($)	92,160	
Total Debt Cost ($)	829,440	
Capital Recovery Factor (Equity)	0.1598	Capital Recovery Factor: Factor used to compute level annual cost from present worth
Capital Recovery Factor (Debt)	0.0802	
Annual Equity Recovery ($/y)	14,724	Annual Equity Recovery: Uniform annual revenue required to earn stipulated rate of return on equity
Annual Debt Payment ($/y)	66,556	Annual Debt Payment: Uniform annual payment needed to pay off debt
Debt Reserve ($)	66,556	Debt Reserve: Funds placed in reserve account as security deposit. Sometimes required by financing institution to ensure debt repayment if plant operation is stopped for some period, typically up to one year.

Table F2. Revenue requirements model outputs for Option 1, New covered lagoon digester system with electrical production

Annual Cash Flows

Year	1	2	3	4	5	6	7	8	9	10
Equity Recovery	14,724	14,724	14,724	14,724	14,724	14,724	14,724	14,724	14,724	14,724
Equity Interest	13,824	13,689	13,534	13,355	13,150	12,914	12,643	12,331	11,972	11,559
Equity Principal Paid	900	1,035	1,190	1,368	1,573	1,809	2,081	2,393	2,752	3,165
Equity Principal Remaining	91,260	90,226	89,036	87,668	86,094	84,285	82,204	79,811	77,059	73,894
Debt Recovery	66,556	66,556	66,556	66,556	66,556	66,556	66,556	66,556	66,556	66,556
Debt Interest	41,472	40,218	38,901	37,518	36,066	34,542	32,941	31,260	29,495	27,642
Debt Principal Paid	25,084	26,339	27,656	29,038	30,490	32,015	33,616	35,296	37,061	38,914
Debt Principal Remaining	804,356	778,017	750,361	721,323	690,833	658,818	625,203	589,906	552,845	513,931
Fuel Cost	-193,693	-197,760	-201,913	-206,153	-210,483	-214,903	-219,416	-224,023	-228,728	-233,531
Non-fuel Expenses	141,015	143,976	147,000	150,087	153,239	156,457	159,742	163,097	166,522	170,019
Debt Reserve	66,556	0	0	0	0	0	0	0	0	0
Depreciation	46,080	46,080	46,080	46,080	46,080	46,080	46,080	46,080	46,080	46,080
Income--Capacity	0	0	0	0	0	0	0	0	0	0
Income--Heat	0	0	0	0	0	0	0	0	0	0
Income--Sludge	0	0	0	0	0	0	0	0	0	0
Interest on Debt Reserve	1,331	1,331	1,331	1,331	1,331	1,331	1,331	1,331	1,331	1,331
Taxes w/o credit	40,755	-3,392	-2,502	-1,567	-586	445	1,527	2,664	3,857	5,109
Tax Credit	3,737	3,815	3,896	3,977	4,061	0	0	0	0	0
Taxes	38,229	-5,972	-5,136	-4,256	-3,331	445	1,527	2,664	3,857	5,109
Energy Revenue Required	132,057	20,193	19,900	19,626	19,374	21,948	21,803	21,686	21,600	21,546

Current $ Level Annual Cost (LAC)

Cost of Money	0.1500									
Present Worth (time 0)	114,832	15,269	13,085	11,221	9,632	9,489	8,196	7,089	6,140	5,326
Total Present Worth	220,689									
Capital Recovery Factor (current)	0.1598									
Current $ Level Annual Revenue Requirements ($/y)	35,258									
Current $ LAC of Electrical Energy ($/kWh)	**0.0849**									

Constant $ Level Annual Cost (LAC)

Real Cost of Money (inflation adjusted)	0.1263
Capital Recovery Factor (constant)	0.1392
Constant $ Level Annual Revenue Requirements ($/y)	30,728
Constant $ LAC of Electrical Energy ($/kWh)	**0.0740**

11	12	13	14	15	16	17	18	19	20	Total
14,724	14,724	14,724	14,724	14,724	14,724	14,724	14,724	14,724	14,724	294,472
11,084	10,538	9,910	9,188	8,358	7,403	6,305	5,043	3,590	1,920	202,312
3,639	4,185	4,813	5,535	6,365	7,320	8,418	9,681	11,133	12,803	92,160
70,255	66,070	61,256	55,721	49,356	42,036	33,617	23,936	12,803	0	--
66,556	66,556	66,556	66,556	66,556	66,556	66,556	66,556	66,556	66,556	1,331,128
25,697	23,654	21,508	19,256	16,891	14,408	11,800	9,062	6,188	3,169	501,688
40,860	42,903	45,048	47,300	49,665	52,149	54,756	57,494	60,369	63,387	829,440
473,071	430,168	385,120	337,820	288,154	236,006	181,250	123,756	63,387	0	--
-238,435	-243,442	-248,555	-253,774	-259,104	-264,545	-270,100	-275,772	-281,564	-287,476	-4,753,372
173,589	177,235	180,957	184,757	188,636	192,598	196,642	200,772	204,988	209,293	3,460,619
0	0	0	0	0	0	0	0	0	-66,556	0
46,080	46,080	46,080	46,080	46,080	46,080	46,080	46,080	46,080	46,080	921,600
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
1,331	1,331	1,331	1,331	1,331	1,331	1,331	1,331	1,331	1,331	26,623
6,425	7,806	9,256	10,779	12,378	14,057	15,819	17,670	19,614	-23,341	136,774
0	0	0	0	0	0	0	0	0	0	19,487
6,425	7,806	9,256	10,779	12,378	14,057	15,819	17,670	19,614	-23,341	123,600
21,528	21,547	21,607	21,710	21,860	22,059	22,310	22,619	22,987	-88,132	429,826

4,627	4,027	3,512	3,068	2,686	2,357	2,073	1,828	1,615	-5,385	
										705,151
										705,151

OPTION 1a: The UC Davis Biomass Collaborative Energy Cost Calculator was used to determine the economic feasibility of each alternative digester system. Table F2 summarizes the results of this model when used to calculate option 1a. Option 1 assumes a tipping fee of \$.04/gallon. The input for this tipping fee is shown below in the tables as a negative fuel cost of -\$376/metric ton of solids. This calculation is as follows: \$.04/gallon X 10,000 gal = \$400/day. The TS of this material is 2.8% or 2335 pounds/2200 lb/metric ton = 1.06 metric tons/day. Tipping fee is then \$400/1.06 dry metric tons = \$376/dry metric ton, entered as a negative fuel cost.

Table F3. Revenue requirements model inputs for Option 1a, New covered lagoon digester system with biomethane output

Capital Cost	(\$)	(\$/kWe-net)
Digester and Feedstock Handling System Capital Cost (\$)	618,000	10,300
Biogas Cleaning System Capital Cost (\$)	30,000	500
Power Generation System Capital Cost (\$)	0	0
Solids Separation	0	0
Engineering @ 10%of eqipment capital cost	64,800	1,080
Contingency @ 10% of equipment capital cost	64,800	1,080
Total Facility Capital Cost (\$)	777,600	12,960

Capital Cost: Total installed cost of plant including electrical plus heat recovery and distribution

Electrical and Fuel--base year	
Gross Electrical Capacity (kWe)	65
Net Electrical Capacity (kWe)	60
Parasitic Load (kWe)	5
Capacity Factor (%)	79
Annual Hours	6,920
Net Efficiency--Biogas to Electricity (%)	32.0
Methane Concentration in Biogas (% by volume)	72.0
Biogas Density (kg/m^3 at 298K, 1 atm)	0.975
Biogas Heating Value (kJ/kg)	26,818
Biogas Heating Value (kJ/m^3)	26,176
Biogas Consumption Rate (kg/h)	25.2
Biogas Consumption Rate (m^3/h)	25.8
Power in Biogas (kW)	188
Gross Efficiency--Biogas to Electricity (%)	34.7
Annual Net Electricity Generation (kWh)	415,224
Annual Biogas Consumption (kg/y)	174,181

Gross Electrical Capacity: Total gross generating capacity
Net Electrical Capacity: Net power available for on-site use or grid sales
Parasitic Load: Electrical power used to operate system
Capacity Factor: Annual fraction that rated capacity is available from plant

Fuel Heating Value: Higher heating value (heat of combustion) of fuel.

Annual Biogas Consumption (m^3/y)	178,651	
Biogas Consumption Per Unit Net Output Power (m^3/kWh)	0.43	
Methane Production (m^3/kg VS destroyed)	0.51	
Biodegradability (kg VS destroyed/kg VS added)	0.90	
Ratio of Volatile Solids to Total Solids in Feedstock (kg/kg)	0.68	
Total Solids Fraction of Wet Feedstock (kg/kg)	0.028	
Methane Production (m3/kg VS added)	0.46	
Methane Production (m^3/kg TS)	0.31	
Methane Production (m^3/kg Wet Feedstock)	0.0087	
Biogas Production (m^3/kg VS destroyed)	0.71	
Biogas Production (m^3/kg VS added)	0.64	
Biogas Production (m^3/kg TS)	0.43	
Biogas Production (m^3/kg Wet Feedstock)	0.012	
Annual Volatile Solids (VS) Consumption (t/y)	280	Volatile solids consumption in metric tons per year
Annual Total Solids (TS) Consumption (t/y)	412	Total solids consumption in metric tons per year
Hourly Total Solids (TS) Consumption (t/h)	0.06	Hourly TS consumption in metric tons per hour
Annual Wet Feedstock Consumption (t/y)	14,718	Total wet feedstock consumption in wet metric tons per year
Hourly Wet Feedstock Consumption (t/h)	2	Hourly wet feedstock consumption in wet metric tons per hour
Annual sludge production (t/y)	238	Approximate annual sludge production in dry metric tons per year

Heat--base year

Total heat production rate (kWth)	123	Total heat production rate equal to fuel power less gross electrical power
Aggregate fraction of heat recovered (%)	50	Fraction of total heat production available for sale
Recovered heat (kWth)	61	Recovered heat production rate
Annual heat sales (kWh/y)	423,875	Total annual heat energy sales
Aggregate sales price for heat ($/kWh)	0.0000	See Heat Sales Price Conversion calculator above for conversion from $/MMBtu
Total income from heat sales ($/y)	0	
Heat income per unit net electrical energy ($/kWh-net)	0.0000	
Overall CHP Efficiency--Gross (%)	67.3	
Overall CHP Efficiency--Net (%)	64.7	

Expenses--base year		($/kWh-net electrical)	
Fuel Cost ($/t)--use negative value for tipping fee	-376.00	-0.3732	Fuel Cost: Cost of fuel in $/dry metric ton of TS, to convert from $/short ton, see calculator above, based on $.04/gallon, 10,000 gal/day

Labor Cost ($/y)	30,000	0.0723	Labor Cost: Cost of labor to operate facility
Maintenance Cost ($/y)	15,552	0.0375	Maintenance Cost: Cost of maintaining the plant
Insurance/Property Tax ($/y)	7,776	0.0187	Insurance/Property Tax: Cost of insurance for the plant plus any property or other local taxes
Utilities ($/y)	10,000	0.0241	Utilities: Purchased utilities including power, gas, water, waste disposal
Management/Administration ($/y)	15,552	0.0375	Management/Administration: Cost for administrative personnel and other administration
Other Operating Expenses ($/y)	42,870	0.1032	Other Operating Expenses: Cost of disposal of excess effluent
Total Non-Fuel Expenses ($/y)	121,750	0.2932	
Total Expenses Including Fuel ($/y)	-33,204	-0.0800	

Taxes

Federal Tax Rate (%)	34.00	Federal Tax Rate: For federal tax calculations
State Tax Rate (%)	9.60	State Tax Rate: For state tax calculations
Production Tax Credit ($/kWh)	0.009	Production Tax Credit on Electrical Energy. For Federal PTC, facilities using animal waste must have nameplate rating of 150 kW or above.
Combined Tax Rate (%)	40.34	Combined Tax Rate: combined federal and state tax rate to which project is subject

Income other than energy

Electricity Capacity Payment ($/kW-y)	0	Capacity Payment: Payment made from power purchaser if plant can guarantee capacity (depends on contract)
Interest Rate on Debt Reserve (%/y)	2.00	Interest Rate on Debt Reserve: Interest income earned on reserve account if financing institution requires security deposit
Sales price for sludge ($/t)	0.00	Value of residuals from digester (sludge, digestate), e.g. as soil amendment, in $/dry metric ton
Annual Capacity Payment ($/y)	0	
Annual Debt Reserve Interest ($/y)	1,123	
Annual Income from Sludge Sales	0	

Escalation/Inflation

General Inflation (%/y)	2.10	General Inflation: Overall inflation rate used to adjust current dollar result to constant dollars.
Escalation--Fuel (%/y)	2.10	Escalation--Fuel: Rate at which fuel cost escalates over time
Escalation for Production Tax Credit (%/y)	2.10	Escalation--PTC: Specified index for production tax credit
Escalation--Heat sales (%/y)	2.10	Escalation--Sales price of heat: escalation rate applied to heat sales
Escalation--Sludge sales (%/y)	2.10	
Escalation--Other (%/y)	2.10	Escalation--Other: Rate at which other expenses escalate over time

Financing

Debt ratio (%)	90.00	Debt ratio: Fraction of financing covered by debt borrowing
Equity ratio (%)	10.00	Equity ratio: Fraction of financing covered by corporate investment
Interest Rate on Debt (%/y)	5.00	Interest Rate on Debt: Interest rate applied to debt portion of investment

Economic Life (y)	20	Economic Life: Example assumes 20 year economic life
Cost of equity (%/y)	15.00	Cost of Equity: Rate of return on equity portion of investment
Cost of Money (%/y)	6.00	Cost of Money: Weighted cost of investment for full investment including both debt and equity
Total Cost of Plant ($)	777,600	
Total Equity Cost ($)	77,760	
Total Debt Cost ($)	699,840	
Capital Recovery Factor (Equity)	0.1598	Capital Recovery Factor: Factor used to compute level annual cost from present worth
Capital Recovery Factor (Debt)	0.0802	
Annual Equity Recovery ($/y)	12,423	Annual Equity Recovery: Uniform annual revenue required to earn stipulated rate of return on equity
Annual Debt Payment ($/y)	56,157	Annual Debt Payment: Uniform annual payment needed to pay off debt
Debt Reserve ($)	56,157	Debt Reserve: Funds placed in reserve account as security deposit. Sometimes required by financing institution to ensure debt repayment if plant operation is stopped for some period, typically up to one year.

Table F4. Revenue requirements model outputs for Option 1a, New covered lagoon digester system with biomethane output

Annual Cash Flows										
Year	1	2	3	4	5	6	7	8	9	10
Equity Recovery	12,423	12,423	12,423	12,423	12,423	12,423	12,423	12,423	12,423	12,423
Equity Interest	11,664	11,550	11,419	11,269	11,095	10,896	10,667	10,404	10,101	9,753
Equity Principal Paid	759	873	1,004	1,154	1,328	1,527	1,756	2,019	2,322	2,670
Equity Principal Remaining	77,001	76,128	75,124	73,970	72,642	71,115	69,360	67,341	65,019	62,348
Debt Recovery	56,157	56,157	56,157	56,157	56,157	56,157	56,157	56,157	56,157	56,157
Debt Interest	34,992	33,934	32,823	31,656	30,431	29,145	27,794	26,376	24,887	23,323
Debt Principal Paid	21,165	22,223	23,334	24,501	25,726	27,012	28,363	29,781	31,270	32,834
Debt Principal Remaining	678,675	656,452	633,117	608,616	582,890	555,878	527,515	497,733	466,463	433,629
Fuel Cost	-154,954	-158,208	-161,531	-164,923	-168,386	-171,922	-175,533	-179,219	-182,982	-186,825
Non-fuel Expenses	121,750	124,307	126,917	129,582	132,304	135,082	137,919	140,815	143,772	146,791
Debt Reserve	56,157	0	0	0	0	0	0	0	0	0
Depreciation	38,880	38,880	38,880	38,880	38,880	38,880	38,880	38,880	38,880	38,880
Income--Capacity	0	0	0	0	0	0	0	0	0	0
Income--Heat	0	0	0	0	0	0	0	0	0	0
Income--Sludge	0	0	0	0	0	0	0	0	0	0
Interest on Debt Reserve	1,123	1,123	1,123	1,123	1,123	1,123	1,123	1,123	1,123	1,123
Taxes w/o credit	34,387	-2,862	-2,111	-1,322	-494	376	1,289	2,247	3,254	4,311
Tax Credit	3,737	3,815	3,896	3,977	4,061	0	0	0	0	0
Taxes	31,861	-5,442	-4,745	-4,011	-3,239	376	1,289	2,247	3,254	4,311
Energy Revenue Required	122,271	28,114	28,099	28,105	28,135	30,992	31,132	31,301	31,501	31,734
Current $ Level Annual Cost (LAC)										
Cost of Money	0.1500									
Present Worth (time 0)	106,322	21,258	18,475	16,069	13,988	13,399	11,704	10,232	8,955	7,844
Total Present Worth	263,917									
Capital Recovery Factor (current)	0.1598									
Current $ Level Annual Revenue Requirements ($/y)	42,164									
Current $ LAC of Electrical Energy ($/kWh)	**N/A**									
Current $ LAC of Biomethane ($/MMBtu)	**9.2860**									
Constant $ Level Annual Cost (LAC)										
Real Cost of Money (inflation adjusted)	0.1263									
Capital Recovery Factor (constant)	0.1392									
Constant $ Level Annual Revenue Requirements ($/y)	36,747									
Constant $ LAC of Electrical Energy ($/kWh)	**N/A**									
Constant $ LAC of Biomethane ($/MMBtu)	**8.0931**									

11	12	13	14	15	16	17	18	19	20	Total
12,423	12,423	12,423	12,423	12,423	12,423	12,423	12,423	12,423	12,423	248,461
9,352	8,892	8,362	7,753	7,052	6,247	5,320	4,255	3,029	1,620	170,701
3,071	3,531	4,061	4,670	5,371	6,176	7,103	8,168	9,394	10,803	77,760
59,278	55,746	51,685	47,015	41,644	35,468	28,365	20,196	10,803	0	--
56,157	56,157	56,157	56,157	56,157	56,157	56,157	56,157	56,157	56,157	1,123,139
21,681	19,958	18,148	16,247	14,252	12,157	9,956	7,646	5,221	2,674	423,299
34,476	36,199	38,009	39,910	41,905	44,000	46,200	48,511	50,936	53,483	699,840
399,154	362,954	324,945	285,035	243,130	199,130	152,929	104,419	53,483	0	--
-190,748	-194,754	-198,844	-203,020	-207,283	-211,636	-216,080	-220,618	-225,251	-229,981	-3,802,697
149,874	153,021	156,235	159,516	162,866	166,286	169,778	173,343	176,983	180,700	2,987,841
0	0	0	0	0	0	0	0	0	-56,157	0
38,880	38,880	38,880	38,880	38,880	38,880	38,880	38,880	38,880	38,880	777,600
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
1,123	1,123	1,123	1,123	1,123	1,123	1,123	1,123	1,123	1,123	22,463
5,421	6,586	7,810	9,095	10,444	11,860	13,348	14,909	16,549	-19,694	115,403
0	0	0	0	0	0	0	0	0	0	19,487
5,421	6,586	7,810	9,095	10,444	11,860	13,348	14,909	16,549	-19,694	102,229
32,004	32,311	32,658	33,048	33,483	33,967	34,502	35,091	35,738	-57,675	636,511

6,879	6,039	5,308	4,671	4,115	3,630	3,206	2,836	2,511	-3,524	843,275

OPTIONS 2 and 2a: The UC Davis Biomass Collaborative Energy Cost Calculator was used to determine the economic feasibility of each alternative digester system. Table F2 summarizes the results of this model when used to calculate options 2 and 2a. Options 2 and 2a assume a tipping fee of $.03/gallon. The input for this tipping fee is shown below in the tables as a negative fuel cost of -$282/metric ton of solids. This calculation is as follows: $.03/gallon X 10,000 gal = $300/day. The TS of this material is 2.8% or 2335 pounds/2200 lb/metric ton = 1.06 metric tons/day. Tipping fee is then $300/1.06 dry metric tons = $282/dry metric ton, entered as a negative fuel cost.

Table F5. Revenue requirements model inputs for Options 2 and 2a, Yolo County digester power and biomethane

Capital Cost	($)	($/kWe-net)
Digester and Feedstock Handling System Capital Cost ($)	449,600	7,493
Biogas Cleaning System Capital Cost ($)	30,000	500
Power Generation System Capital Cost ($)	0	0
Solids Separation	0	0
Engineering @ 10%of eqipment capital cost	47,960	799
Contingency @ 10% of equipment capital cost	47,960	799
Total Facility Capital Cost ($)	575,520	9,592

Capital costs shown are for example only. Actual costs may vary.

Capital Cost: Total installed cost of plant including electrical plus heat recovery and distribution

Electrical and Fuel--base year	
Gross Electrical Capacity (kWe)	65
Net Electrical Capacity (kWe)	60
Parasitic Load (kWe)	5
Capacity Factor (%)	79
Annual Hours	6,920
Net Efficiency--Biogas to Electricity (%)	32.0
Methane Concentration in Biogas (% by volume)	73.0
Biogas Density (kg/m^3 at 298K, 1 atm)	0.964
Biogas Heating Value (kJ/kg)	27,514
Biogas Heating Value (kJ/m^3)	26,540
Biogas Consumption Rate (kg/h)	24.5
Biogas Consumption Rate (m^3/h)	25.5
Power in Biogas (kW)	188
Gross Efficiency--Biogas to Electricity (%)	34.7
Annual Net Electricity Generation	415,224

Gross Electrical Capacity: Total gross generating capacity

Net Electrical Capacity: Net power available for on-site use or grid sales

Parasitic Load: Electrical power used to operate system

Capacity Factor: Annual fraction that rated capacity is available from plant

Fuel Heating Value: Higher heating value (heat of combustion) of fuel.

(kWh)		
Annual Biogas Consumption (kg/y)	169,777	
Annual Biogas Consumption (m^3/y)	176,203	
Biogas Consumption Per Unit Net Output Power (m^3/kWh)	0.42	
Methane Production (m^3/kg VS destroyed)	0.51	
Biodegradability (kg VS destroyed/kg VS added)	0.90	
Ratio of Volatile Solids to Total Solids in Feedstock (kg/kg)	0.68	
Total Solids Fraction of Wet Feedstock (kg/kg)	0.028	
Methane Production (m3/kg VS added)	0.46	
Methane Production (m^3/kg TS)	0.31	
Methane Production (m^3/kg Wet Feedstock)	0.0087	
Biogas Production (m^3/kg VS destroyed)	0.70	
Biogas Production (m^3/kg VS added)	0.63	
Biogas Production (m^3/kg TS)	0.43	
Biogas Production (m^3/kg Wet Feedstock)	0.012	
Annual Volatile Solids (VS) Consumption (t/y)	280	Volatile solids consumption in metric tons per year
Annual Total Solids (TS) Consumption (t/y)	412	Total solids consumption in metric tons per year
Hourly Total Solids (TS) Consumption (t/h)	0.06	Hourly TS consumption in metric tons per hour
Annual Wet Feedstock Consumption (t/y)	14,718	Total wet feedstock consumption in wet metric tons per year
Hourly Wet Feedstock Consumption (t/h)	2	Hourly wet feedstock consumption in wet metric tons per hour
Annual sludge production (t/y)	242	Approximate annual sludge production in dry metric tons per year

Heat--base year

Total heat production rate (kWth)	123	Total heat production rate equal to fuel power less gross electrical power
Aggregate fraction of heat recovered (%)	50	Fraction of total heat production available for sale
Recovered heat (kWth)	61	Recovered heat production rate
Annual heat sales (kWh/y)	423,875	Total annual heat energy sales
Aggregate sales price for heat ($/kWh)	0.0000	See Heat Sales Price Conversion calculator above for conversion from $/MMBtu
Total income from heat sales ($/y)	0	
Heat income per unit net electrical energy ($/kWh-net)	0.0000	
Overall CHP Efficiency--Gross (%)	67.3	
Overall CHP Efficiency--Net (%)	64.7	

Expenses--base year

		($/kWh-net electrical)	
Fuel Cost ($/t)--use negative value for tipping fee	-282.00	-0.2799	Fuel Cost: Cost of fuel in $/dry metric ton of TS, to convert from $/short ton, see calculator above, based on $.03/gallon, 10,000 gal/day
Labor Cost ($/y)	30,000	0.0723	Labor Cost: Cost of labor to operate facility
Maintenance Cost ($/y)	11,510	0.0277	Maintenance Cost: Cost of maintaining the plant
Insurance/Property Tax ($/y)	5,755	0.0139	Insurance/Property Tax: Cost of insurance for the plant plus any property or other local taxes
Utilities ($/y)	10,000	0.0241	Utilities: Purchased utilities including power, gas, water, waste disposal
Management/Administration ($/y)	11,510	0.0277	Management/Administration: Cost for administrative personnel and other administration
Other Operating Expenses ($/y)	18,802	0.0453	Other Operating Expenses: cost of disposal of effluent and sludge
Total Non-Fuel Expenses ($/y)	87,577	0.2109	
Total Expenses Including Fuel ($/y)	-28,639	-0.0690	

Taxes

Federal Tax Rate (%)	34.00	Federal Tax Rate: For federal tax calculations
State Tax Rate (%)	9.60	State Tax Rate: For state tax calculations
Production Tax Credit ($/kWh)	0.009	Production Tax Credit on Electrical Energy. For Federal PTC, facilities using animal waste must have nameplate rating of 150 kW or above.
Combined Tax Rate (%)	40.34	Combined Tax Rate: combined federal and state tax rate to which project is subject

Income other than energy

Electricity Capacity Payment ($/kW-y)	0	Capacity Payment: Payment made from power purchaser if plant can guarantee capacity (depends on contract)
Interest Rate on Debt Reserve (%/y)	2.00	Interest Rate on Debt Reserve: Interest income earned on reserve account if financing institution requires security deposit
Sales price for sludge ($/t)	5.00	Value of residuals from digester (sludge, digestate), e.g. as soil amendment, in $/dry metric ton
Annual Capacity Payment ($/y)	0	
Annual Debt Reserve Interest ($/y)	831	
Annual Income from Sludge Sales	1,212	

Escalation/Inflation

General Inflation (%/y)	2.10	General Inflation: Overall inflation rate used to adjust current dollar result to constant dollars.
Escalation--Fuel (%/y)	2.10	Escalation--Fuel: Rate at which fuel cost escalates over time
Escalation for Production Tax Credit (%/y)	2.10	Escalation--PTC: Specified index for production tax credit
Escalation--Heat sales (%/y)	2.10	Escalation--Sales price of heat: escalation rate applied to heat sales
Escalation--Sludge sales (%/y)	2.10	
Escalation--Other (%/y)	2.10	Escalation--Other: Rate at which other expenses escalate over time

Financing

Debt ratio (%)	90.00
Equity ratio (%)	10.00
Interest Rate on Debt (%/y)	5.00
Economic Life (y)	20
Cost of equity (%/y)	15.00
Cost of Money (%/y)	6.00
Total Cost of Plant ($)	575,520
Total Equity Cost ($)	57,552
Total Debt Cost ($)	517,968
Capital Recovery Factor (Equity)	0.1598
Capital Recovery Factor (Debt)	0.0802
Annual Equity Recovery ($/y)	9,195
Annual Debt Payment ($/y)	41,563
Debt Reserve ($)	41,563

Debt ratio: Fraction of financing covered by debt borrowing

Equity ratio: Fraction of financing covered by corporate investment

Interest Rate on Debt: Interest rate applied to debt portion of investment

Economic Life: Example assumes 20 year economic life

Cost of Equity: Rate of return on equity portion of investment

Cost of Money: Weighted cost of investment for full investment including both debt and equity

Capital Recovery Factor: Factor used to compute level annual cost from present worth

Annual Equity Recovery: Uniform annual revenue required to earn stipulated rate of return on equity

Annual Debt Payment: Uniform annual payment needed to pay off debt

Debt Reserve: Funds placed in reserve account as security deposit. Sometimes required by financing institution to ensure debt repayment if plant operation is stopped for some period, typically up to one year.

Table F6. Revenue requirements model outputs for Options 2 and 2a, Yolo County digester power and biomethane

Annual Cash Flows										
Year	1	2	3	4	5	6	7	8	9	10
Equity Recovery	9,195	9,195	9,195	9,195	9,195	9,195	9,195	9,195	9,195	9,195
Equity Interest	8,633	8,549	8,452	8,340	8,212	8,065	7,895	7,700	7,476	7,218
Equity Principal Paid	562	646	743	854	983	1,130	1,299	1,494	1,719	1,976
Equity Principal Remaining	56,990	56,344	55,601	54,747	53,764	52,634	51,335	49,840	48,122	46,146
Debt Recovery	41,563	41,563	41,563	41,563	41,563	41,563	41,563	41,563	41,563	41,563
Debt Interest	25,898	25,115	24,293	23,429	22,523	21,571	20,571	19,521	18,419	17,262
Debt Principal Paid	15,665	16,448	17,270	18,134	19,041	19,993	20,992	22,042	23,144	24,301
Debt Principal Remaining	502,303	485,855	468,585	450,451	431,411	411,418	390,426	368,384	345,240	320,939
Fuel Cost	-116,216	-118,656	-121,148	-123,692	-126,290	-128,942	-131,649	-134,414	-137,237	-140,119
Non-fuel Expenses	87,577	89,416	91,294	93,211	95,168	97,167	99,208	101,291	103,418	105,590
Debt Reserve	41,563	0	0	0	0	0	0	0	0	0
Depreciation	28,776	28,776	28,776	28,776	28,776	28,776	28,776	28,776	28,776	28,776
Income--Capacity	0	0	0	0	0	0	0	0	0	0
Income--Heat	0	0	0	0	0	0	0	0	0	0
Income--Sludge	1,212	1,237	1,263	1,290	1,317	1,344	1,373	1,401	1,431	1,461
Interest on Debt Reserve	831	831	831	831	831	831	831	831	831	831
Taxes w/o credit	25,451	-2,118	-1,562	-979	-366	278	954	1,663	2,408	3,191
Tax Credit	3,737	3,815	3,896	3,977	4,061	0	0	0	0	0
Taxes	22,925	-4,698	-4,196	-3,668	-3,111	278	954	1,663	2,408	3,191
Energy Revenue Required	84,564	14,751	14,613	14,488	14,378	17,085	17,066	17,065	17,085	17,127
Current $ Level Annual Cost (LAC)										
Cost of Money	0.1500									
Present Worth (time 0)	73,534	11,154	9,608	8,284	7,148	7,386	6,416	5,579	4,857	4,234
Total Present Worth	155,943									
Capital Recovery Factor (current)	0.1598									
Current $ Level Annual Revenue Requirements ($/y)	24,914									
Current $ LAC of Electrical Energy ($/kWh)	**0.0600**									
Current $ LAC of Biogas Energy ($/MMBtu)	**5.5631**									
Constant $ Level Annual Cost (LAC)										
Real Cost of Money (inflation adjusted)	0.1263									
Capital Recovery Factor (constant)	0.1392									
Constant $ Level Annual Revenue Requirements ($/y)	21,713									
Constant $ LAC of Electrical Energy ($/kWh)	**0.0523**									

11	12	13	14	15	16	17	18	19	20	Total
9,195	9,195	9,195	9,195	9,195	9,195	9,195	9,195	9,195	9,195	183,892
6,922	6,581	6,189	5,738	5,220	4,623	3,938	3,149	2,242	1,199	126,340
2,273	2,614	3,006	3,457	3,975	4,571	5,257	6,046	6,952	7,995	57,552
43,873	41,259	38,253	34,797	30,822	26,250	20,993	14,948	7,995	0	--
41,563	41,563	41,563	41,563	41,563	41,563	41,563	41,563	41,563	41,563	831,262
16,047	14,771	13,432	12,025	10,548	8,997	7,369	5,659	3,864	1,979	313,294
25,516	26,792	28,132	29,538	31,015	32,566	34,194	35,904	37,699	39,584	517,968
295,423	268,631	240,500	210,961	179,946	147,381	113,187	77,283	39,584	0	--
-143,061	-146,065	-149,133	-152,265	-155,462	-158,727	-162,060	-165,463	-168,938	-172,486	-2,852,023
107,807	110,071	112,383	114,743	117,152	119,612	122,124	124,689	127,307	129,981	2,149,209
0	0	0	0	0	0	0	0	0	-41,563	0
28,776	28,776	28,776	28,776	28,776	28,776	28,776	28,776	28,776	28,776	575,520
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
1,492	1,523	1,555	1,588	1,621	1,655	1,690	1,725	1,761	1,798	29,735
831	831	831	831	831	831	831	831	831	831	16,625
4,012	4,875	5,780	6,731	7,730	8,778	9,879	11,035	12,248	-14,576	85,412
0	0	0	0	0	0	0	0	0	0	19,487
4,012	4,875	5,780	6,731	7,730	8,778	9,879	11,035	12,248	-14,576	72,238
17,193	17,284	17,402	17,548	17,725	17,935	18,180	18,461	18,783	-50,516	338,217

3,696	3,230	2,828	2,480	2,178	1,917	1,689	1,492	1,320	-3,087	
										498,273
										498,273

California Energy Commission
Energy Innovations Small Grant (EISG) Program

PROJECT DEVELOPMENT STATUS

Questionnaire

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Please Identify yourself, and your project: PI Name: Matthew Summers, Summers Consulting, LLC Grant # 13-05G

Overall Status	
Questions	Comments:
Do you consider that this research project proved the feasibility of your concept?	Yes. The biogas production results and methanogen populations were even higher than expected in a lower temperature digestion conditions. All indications are that these feedstock will perform well in ambient covered lagoon digesters.
Do you intend to continue this development effort towards commercialization?	Yes.
Engineering/Technical	
What are the key remaining technical or engineering obstacles that prevent product demonstration?	No.
Have you defined a development path from where you are to product demonstration?	Yes, we are working with Yolo County to develop a demonstration project with food wastes. The digester construction is a known technology
How many years are required to complete product development and demonstration?	1 year.
How much money is required to complete engineering development and demonstration?	$50-100 K. The digester construction is a known technology.
Do you have an engineering requirements specification for your potential product?	Yes. The digester construction is a known technology with a number of qualified vendors with detailed engineering.
Marketing	
What market does your concept serve?	Commercial and industrial – particularly the waste management industry and large producers of organic waste like food processors.
What is the market need?	The market need is established at 26 billion gallons of wastewater and 600,000 tons of high moisture organic wastes (Amon et. al. 2012).
Have you surveyed potential customers for interest in your product?	No. But we worked directly with Yolo Integrated Waste, a potential customer.
Have you performed a market analysis that takes external factors into consideration?	No, but we recommend a statewide analysis of the market.

Have you identified any regulatory, institutional or legal barriers to product acceptance?	We do not believe there are any major barriers other than cost for implementing food waste projects. Covered lagoon digester systems have been accepted by the community as evidenced by a number of dairy projects in the state. Projects using human waste feedstock may require additional regulatory scrutiny.
What is the size of the potential market in California for your proposed technology?	We estimate 10 million MMBtu of biogas production or 100 MW of power production using this biogas in reciprocating engines. This is based on the waste resource identified in Amon et. al. 2012.
Have you clearly identified the technology that can be patented?	Covered lagoon digesters are in the public domain and a number of developers can provide them. We do not believe we have developed any other patentable IP in this project but have perfected know-how in using the tools of BMP assays and RNA/DNA analysis.
Have you performed a patent search?	NA.
Have you applied for patents?	NA
Have you secured any patents?	NA
Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	NA
Commercialization Path	
Can your organization commercialize your product without partnering with another organization?	NO. We would work with existing construction and engineering companies to develop projects.
Has an industrial or commercial company expressed interest in helping you take your technology to the market?	YES. We have talked with developers that are pursuing commercial projects. Each project requires independent funding.
Have you developed a commercialization plan?	NO.
What are the commercialization risks?	We do not believe there are any major risks to utilizing food wastes. Human wastes will require additional research to improve performance and deal with any regulatory hurdles with this feedstock.
Financial Plan	
If you plan to continue development of your concept, do you have a plan for the required funding?	YES. Funding needs to be provided by the developers of each project.
Have you identified funding requirements for each of the development and commercialization phases?	YES. The costs for building the projects for food waste projects.
Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	Not at this time.
What are the go/no-go milestones in your commercialization plan?	NA
How would you assess the financial risk of bringing this product/service to the market?	The risk is based on the economics and success of each project. The tools developed here help reduce the risk by helping improve the performance and predictability of the feedstock used in these systems.

Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	NO.
Public Benefits	
What sectors will receive the greatest benefits as a result of your concept?	Commercial and industrial sectors that process organic wastes.
Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	Generating 10 million MMBtu of renewable biogas could potentially displace up to 2% of the fossil natural gas used in the non-residential sector. Because the biogas generated from organics has a carbon intensity near zero, it would be approximately 2% reduction in carbon intensity of natural gas.
Does the proposed technology reduce emissions from power generation?	NO. As long as sulfur is removed from the gas, combustion equipment would the same emissions that it would on natural gas.
Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	NO. As long as sulfur is removed from the gas, combustion equipment would the same emissions that it would on natural gas. No additional emissions or other negative effects are expected.
Competitive Analysis	
What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	1. Less costly to construct than complete mix, heated digester systems or other treatment options 2. Less costly to operate that complete mix, heated digester systems or other treatment options 3. More robust and forgiving for handling a wide variety and more dilute waste streams The cost factors can be very important to developing projects as return on investment is the biggest hurdle. The flexibility is also very important.
What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	1. Solids buildup can be an issue if not managed properly as system is un-mixed 2. Requires larger land footprint than other systems due to long residence time 3. Startup time to develop methanogen community can be long due to size and cool temperatures For certain feedstock with high settling solids may not be suitable for an un-stirred system. Land footprint may be an issue for some sites only. Startup time is a minor issue as these systems typically run continuously but this is important to consider in planning.
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
If selected, would you be interested in receiving development assistance?	YES. EPIC funding or SB-1122 for projects.