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ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Green Waste to Renewable Natural Gas by Pyrobiomethane

Anaerobic Codigestion of Pyrolysis Oil and Green Waste Sludge

Gavin Newsom, Governor

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Anaergia Services thanks the Encina Staff for the efforts in the laboratory, operations and management to make this project a success.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

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Green Waste to Renewable Natural Gas by Pyrobiomethane is the final report for the Green Waste to Renewable Natural Gas by Pyrobiomethane project (Contract Number: PIR-12-002) conducted by Anaergia Services, LLC.

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ABSTRACT

Low temperature pyrolysis is an effective approach to convert municipal sludge biosolids from wastewater treatment plants (WWTPs) and green waste into bio-methane for power or fuel production in anaerobic digesters. In this study, anaerobically digested, municipal sludge biosolids and green waste were dried and processed with low temperature pyrolysis to produce biogas; also, the pyrolysis process produces bio-oil and biochar as co-products. The bio-oil was fed to sludge-fed anaerobic digesters, leading to increases in biogas production and volatile solids destruction with no adverse impact on the microbial consortium or digestion process. At a ratio expected at a typical WWTP pyrolyzing indigenous sludge, co-digesting sludge and bio-oil from biosolids resulted in a 25 percent increase in the biogas production rate and a 5-10 percent increase in the volatile solids destruction rate compared to the results from anaerobic digestion of sewage sludge alone. The biochar generated from the pyrolysis process condensed nutrients and reduced the feed to the pyrolyzer by 45-55 percent. Concentration of nutrients and mass reduction enhance the value of the solid end-product and reduce costs associated with transportation and hauling of solid residuals from WWTPs.

Keywords: Pyrolysis, bio-oil, biochar, co-digesting, biosolids, green waste, sludge.

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EXECUTIVE SUMMARY

Introduction

Low temperature pyrolysis is an effective approach to convert municipal biosolids and green waste into bio-methane for power or fuel production in anaerobic digesters. Pyrolysis is a heat treatment of a solid material in an oxygen free environment generating three products: gas, bio-oil and bio-char. In California, green waste accounts for roughly 10-20 percent of the 35 million tons of waste disposed in landfills per year. California's municipal wastewater treatment plants generate 800,000 tons per year of biosolids, of which two thirds are used in land applications and one third are landfilled. Landfilling and land application of these materials is not sustainable. With the expectation that regulations will ban landfilling, measures are already in place to mandate the recycling and recovery for renewable power of these materials. Low temperature pyrolysis is an effective approach to convert biosolids and green waste into renewable fuel and high-value fertilizer.

This process converts dry biosolids and green waste into a high-value fertilizer product called biochar and a liquid called bio-oil. The bio-oil is fed to existing anaerobic digesters to increase biogas production, while the biochar is a nutrient-rich dry fertilizer that can be land applied. Instead, green wastes and biosolids currently landfilled can be dried and processed through low temperature pyrolysis to increase production of renewable biofuel and reduce the residual solids managed at wastewater treatment plants.

Project Purpose

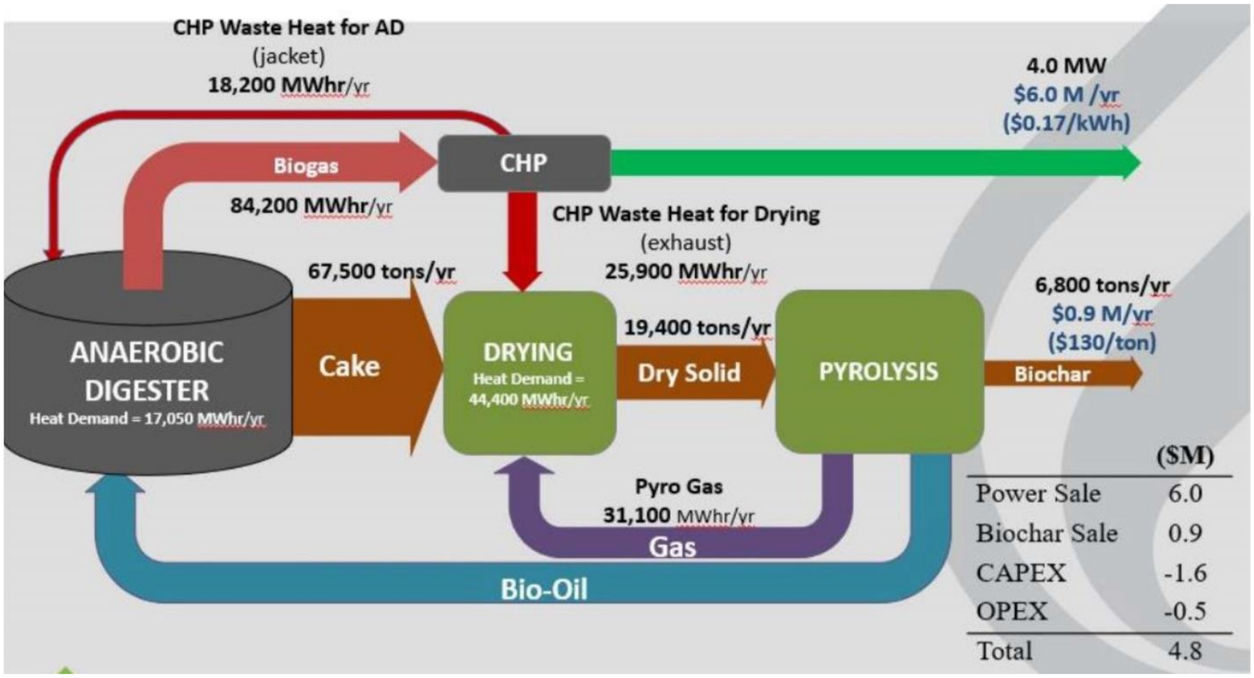
This project demonstrates that oils generated from low temperature pyrolysis of green waste and undigested biosolids from municipal wastewater treatment plants can be readily converted into biogas without adversely impacting the anaerobic digestion process; at the same time, the aforementioned oils produce biogas of equivalent or superior quality when compared to the biogas generated by the sludge alone. The project also demonstrates that condensing the nutrients improves the quality of the residual biochar.

Project Results

Codigesting sewage sludge with bio-oil generated from low temperature pyrolysis of biosolids and green waste enhanced the anaerobic digestion process and increased biogas production and increased volatile solids destruction, as shown in Figure ES-1. Codigestion of sludge and green waste bio-oil resulted in a biogas production rate and volatile solids destruction equivalent to that of the anaerobic digestion of sewage sludge alone, indicating that the biogas production potential of green waste bio-oil is equivalent to that of sludge. Co-digestion of sludge and biosolids bio-oil at a ratio expected at a typical wastewater treatment plant pyrolyzing the indigenous sludge resulted in a 25 percent increase in the biogas production rate and a 5-10 percent increase in volatile solids destruction compared to the anaerobic digestion of sewage sludge alone. This indicates the biogas production potential of biosolids bio-oil is greater than the sludge and offers benefits to anaerobic digestion. The biochar generated from low temperature pyrolysis of dry green waste and dry biosolids concentrated the nutrients resulting in a mass reduction of 45-55 percent of the pyrolizer feed.

Concentration of nutrients and mass reduction enhance the value of the solid end-product and offer savings for transporting and hauling of solid residuals from wastewater treatment plants.

Figure ES-1: Economic Enhancements for a Wastewater Plant by Processing Biosolids



Source: Anaergia Services, LLC

Technology/Knowledge Transfer

The combined digestion and pyrolysis process will produce two new products for potential commercial use. Biomethane produced will likely be used in the same manner as conventional anaerobic digester biomethane, including options such as combustion in an engine for combined heat and power, upgrading to pipeline gas, or even natural gas vehicle fuel. Additionally, pyrolysis converts biosolid waste products into biochar, which contains an ample amount of nutrients and soil-enhancing carbon. Biochar can be sold into agricultural and horticultural market in place of synthetic nutrient fertilizers. Though this project was completed at the Encina Wastewater Authority site, Anaergia will work with additional treatment facilities to identify suitable markets, collect data to enhance the maximum value of the product, and potentially facilitate logistic of the product management. Currently, numerous tours and visitors at the Encina Wastewater Authority site have shown interest in implementing the pyrolysis technology at their respective Wastewater sites, and Anaergia is available to share findings from this project with interested parties.

Benefits to California

Low temperature pyrolysis offers a simple closed loop solution to lowering operating costs and increasing renewable biofuel production in municipal anaerobic digesters. The process offers these benefits:

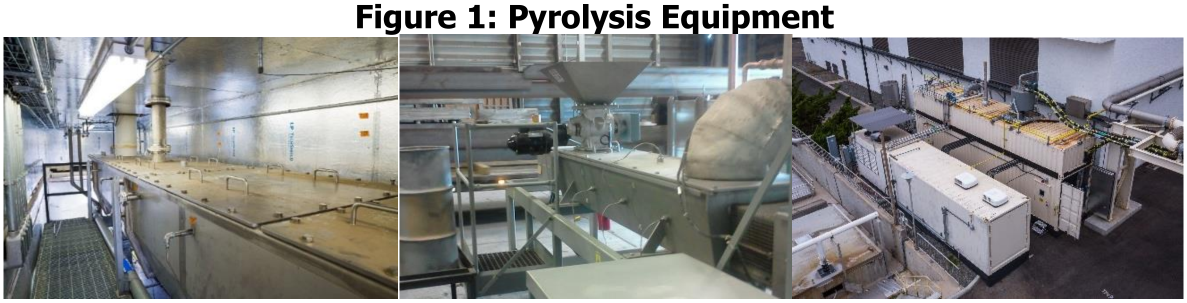
- Increase biogas production in municipal anaerobic digesters by generating a highly digestible oil from feedstocks than can include indigenous undigested biosolids, imported municipal sludge biosolids, and imported green waste.
- Reduce residual solids for disposal at municipal wastewater treatment plants by up to eight-folds by drying dewatered cake for a roughly four-fold reduction in mass followed by low temperature pyrolysis for another two-fold reduction in mass.
- Convert undigested biosolids and green waste into a high value biochar fertilizer that condenses nutrients and improves soil quality.
- Offers a simple and cost-effective packaged solution for wastewater treatment plants that simply dry and heat feedstock at low temperatures to generate a liquid oil and small gas flow. This gas can be introduced into anaerobic digestors untreated and blended with the bulk flow of biogas.

CHAPTER 1: Method

1.1 Pyrolysis Process

Bio-oils from green waste and municipal sludge biosolids were generated in two different pyrolysis machines. A commercial-scale low temperature pyrolysis system operated at the Encina Water Pollution Control Facility (EWPCF) converted dry biosolids pellets (generated on-site) into biochar and bio-oil. The system processed 11 metric tons per day of biosolid pellets, generating, as a fraction of the feed, 45-55 percent char, 35-45 percent bio-oil, and 10-20 percent produced gas. Dry biosolid pellets were stored in a vertical silo and conveyed through a pneumatic transport system into a hopper mounted on the roof of the containerized pyrolysis unit. An air-tight rotating feeder mounted below the hopper continuously fed the electrically heated chamber. Material was conveyed through the chamber by a rotating screw. In the chamber, syngas was released and evacuated through piping into a condenser where condensable liquids (bio-oil) were recovered and stored in an adjacent container to feed to the anaerobic digester. The non-condensed gases were piped into the anaerobic digester and dissolved into the liquid digestate of the digester for bacteria to convert the syngas into biogas and blend with the bulk flow of biogas. The remaining solid material, biochar, that did not vaporize, was discharged from the end of the pyrolysis chamber into a cooling chamber. A screw conveyed the material through an inclined chamber where cooling water, indirectly cooled the char to below 80º Celsius (176º Fahrenheit). The char was discharged into a hopper at the end of the cooling chamber and conveyed into a covered storage bin. For green waste, a pilot-scale system operated off-site was fed dried green waste to generate bio-oil that was shipped and stored at the Encina test site. Figure 1 shows the commercial-scale pyrolyzer installed at EWPCF to process biosolids and the pilot-scale system used to generate green waste bio-oil.

Figure 1: Pyrolysis Equipment



Source: Paul Cockrell, paulcockrellphoto.com

1.2. Codigestion Process

A pilot skid plant consisting of three 150-gal digester skids operated continuously at EWPCF for a 3-month period, one month of start-up and two months of co-digesting sludge with bio-oil. The digesters were operated under the same conditions as the full-scale digesters at the Encina facility: organic loading rate (OLR) of 2.0 kg-VS/m3/d, solids retention time of 20 days, and mesophilic. Digester 1 served as the control and was fed only sludge. Digester 2 was fed a combination of sludge and bio-oil from biosolids. Digester 3 was fed a combination of sludge and bio-oil from green waste.

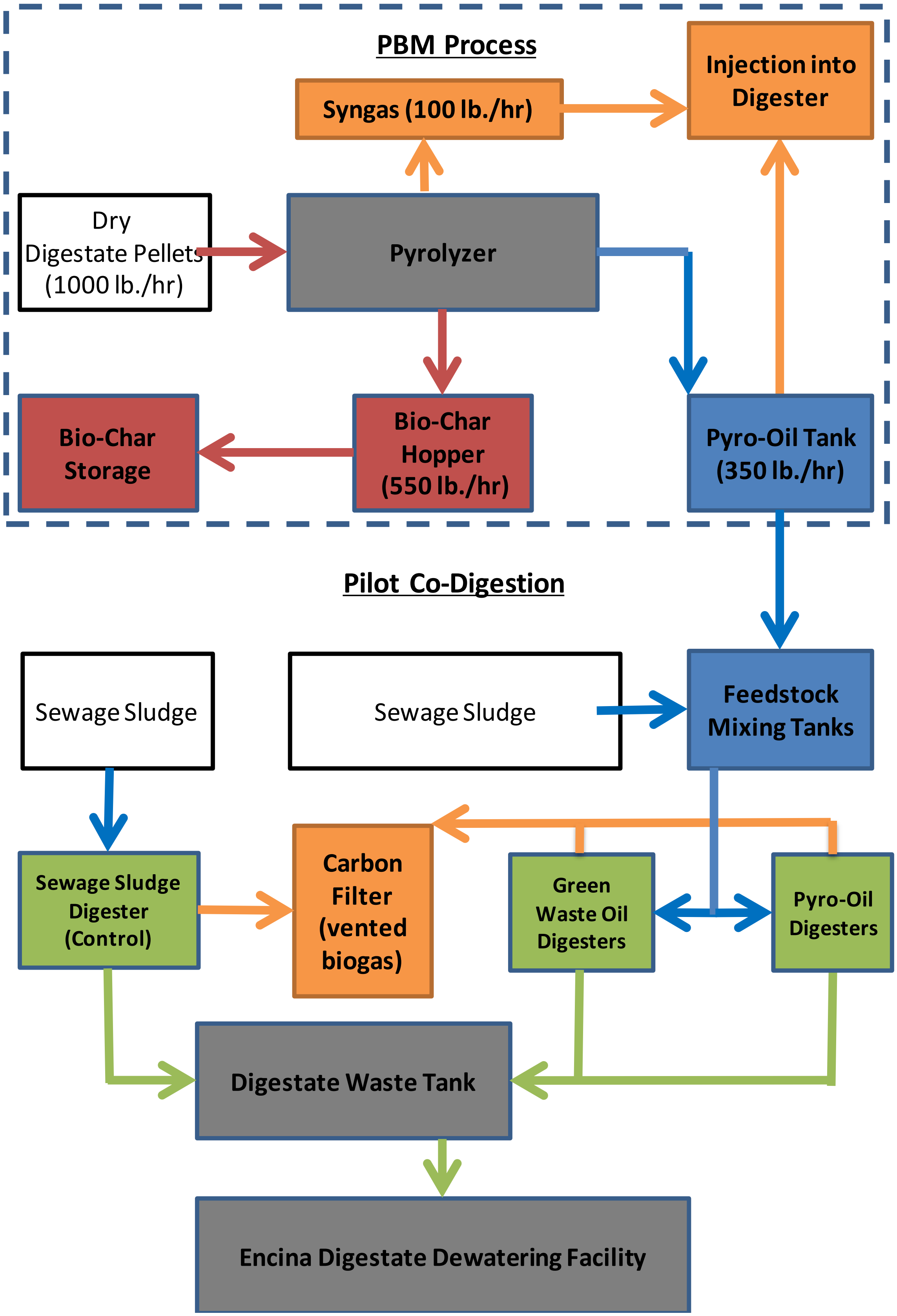
Once the digesters achieved stable operation on sludge only, the study period began and referred to as day "0". On day "0", the sludge feed of digesters 2 and 3 were amended with bio-oil. An applied OLR of 2.0 was maintained and bio-oil was amended to the sludge feed at three loading rates across three periods. In each period, the fraction of the total OLR (sludge + bio-oil) from bio-oil was designed to target 10 percent, 20 percent, and 30 percent corresponding to Periods I, II, and III. These loadings represent a range of bio-oil made by indigenous sludge that municipal sludge digesters could be fed. The solids retention time (SRT) was maintained equal over all digesters to compare the impacts on anaerobic digestion from co-digesting bio-oil and eliminate the effects on biogas production and solids destruction that can result from differences in SRT.

During the study period, the following performance metrics related to anaerobic digestion were monitored:

- Benefits and synergies to biogas production by co-digesting sewage sludge and pyro oil.
- Benefits and synergies to solids destruction by co-digesting sewage sludge and pyro oil.
- Observing stability in digesters fed with bio-oil.

Figure 2 illustrates the process flow of the integrated low temperature pyrolysis system with the oils fed to the test digesters in this study.

Figure 2: Pyro Biomethane Block Flow Diagram



Source: Anaergia Services, LLC

1.3 Digester Sampling and Laboratory Analysis

Performance and operation of the digesters were monitored through feedstock, digestate, and biogas grab samples with on-site analysis by lab technicians at EWPCF. The parameters' monitored and frequency of sampling is summarized in Table 1. Data was recorded on a physical log sheet and transferred to an electronic record each week.

Sampling points used were directly downstream of the digester mixing pumps to obtain an accurate sample of primary effluent and Thickened Waste Activated Sludge (TWAS) entering the digester. Digestate was sampled from a two-gallon reservoir made from a 4" CPVC tube, shown in Table 1. This was located prior to the standpipe overflow elbow, which constantly overflowed at a steady flow rate. The digestate effluent line was drawn from the center of the working volume of the tank to provide a homogenous sample point. From the two-gallon reservoir, a 500 mL bottle was filled and brought to the on-site lab immediately after.

Biogas samples were extracted from gas sampling ports in the headspace via Tedlar gas bags. The Tedlar bag taps were connected to a Dragger tube pump, which drew the gas from the bags and through the sample tube, enabling the analysis of the gas composition.

Table 1: Lab Analysis Schedule

Media	Test	Freq.	Note
Biogas	CO_2% vol. (CH_4% vol. by calculation)	2/wk	Drager Tubes (0-55%)
Biogas	Total Volume and Flow Rate	2/wk	Gas Flow Meter
Digestate	NH_3/NH_4-N & TKN	1/wk	Hach Reagent
Digestate	pH, alkalinity, total volatile acids	1/wk	Meter, Calc Total Vol. Acid
Digestate	TCOD, SCOD	1/wk	Hach Reagent
Digestate	TS & VS (fixed solids, FS by calculation)	1/wk	Standard Methods: 2540 Solids
Feed Stock*	NH_3/NH_4-N & TKN	1/wk	Hach Reagent
Feed Stock*	pH & alkalinity, total volatile acids	1/wk	Meter
Feed Stock*	TCOD & SCOD	1/wk	Hach Reagent
Feed Stock*	TS & VS (fixed solids, FS by calculation)	1/wk	Standard Methods: 2540 Solids

Source: Anaergia Services, LLC

CHAPTER 2: Design Approach

2.1 Codigestion Skid Design Overview

Three pilot digesters were assembled on a skid, each equipped with one 150-gallon anaerobic digester, one 55-gallon feed tank, one feed pump, one set of digestate collection equipment, and one set of biogas metering and collection equipment. Each digester operated at the same organic loading rates and hydraulic retention time under mesophilic conditions to match the operation of the full-scale digester at the Encina plant. The feedstock for each skid was prepared manually in the feed tank, mixed, and then fed to the skid-mounted digester via progressive cavity pump once per day per the feeding schedule. Each digester was equipped with an electrically powered mechanical mixer for continuous mixing. The temperature of each digester was maintained at 35˚C (95˚F) with the heat-tracing element controlled by a resistance temperature detector (RTD) temperature controller. To maintain a constant level of digestate, each digester included an adjustable standpipe to buffer the pressure change inside the digester during sludge feeding and digestate wasting. When the digesters were fed, an equal amount of digestate was discharged from the digester by volumetric displacement through the sandpipe. The digestate from each skid was pooled into a common digestate tank and returned to the plant's dewatering facility. The biogas produced from each skid discharged to two 55-gallon activated carbon scrubbing drums in series, for cleaning. The first drum contained coconut shell GAC that removed 95-99 percent of volatile organic compound (VOC) emissions and the second drum contained KOH-impregnated GAC that removed 95-99 percent H_2S. The scrubbed biogas was vented to the atmosphere.

2.1.1 Digester Tank

Each digester was constructed of 316 stainless steel (SS) with a total volume of 150 gallons (Figure 3). The design working volume was 120 gallons, which places the sludge surface in the middle of the viewing port so that the sludge surface could be monitored for excessive foaming or fouling. Each window was equipped with a cleaning nozzle that sprayed the window to make observation of the sludge surface possible.

Figure 3: 316 Stainless Steel Digester Tanks Before Assembly

Source: Trevor Shackelford, Anaergia Services, LLC

Four 1½" ports on the topside of the tank were used for a view port spray nozzle, gas sampling/feedstock injection, biogas outlet, and a rupture disk in case of overpressure. The top center of the tanks included a 6" ANSI #150 flange to allow for a top mounted electric mixer. On the sidewall of the tank, there were five ports: 2", (2) 1 ½", 1 ¼" and 3". These ports were used for temperature measurement, spare ports, a feedstock injection point, and the effluent standpipe. The bottom side of the tank included a 2" threaded port to allow for draining and cleaning. The tanks were bolted to a 4' x 6' skid painted with blue epoxy that included forklift cutouts for easy placement (Figure 4).

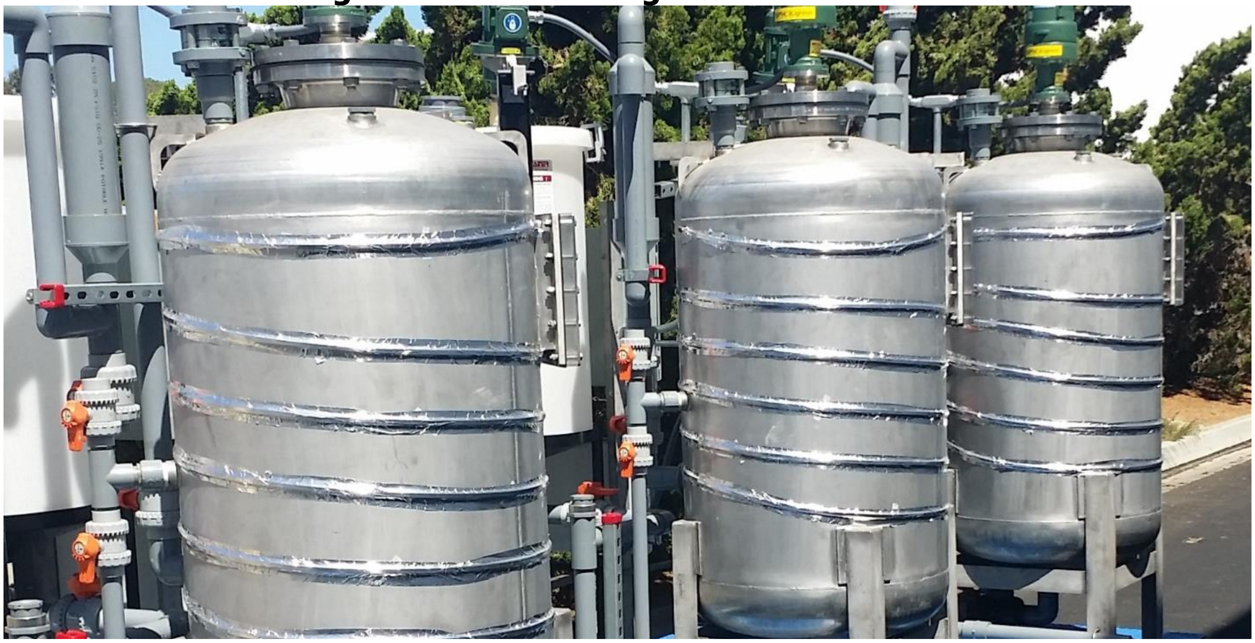
Figure 4: Epoxy Coated Carbon Steel Skid

Source: Trevor Shackelford, Anaergia Services, LLC

2.1.2 Heat Tracing and Controller

A self-regulating, heat-tracing cable was installed on each tank to accurately maintain the setpoint temperature. The heat trace thermometer was installed near the center of the tank to ensure homogenous heating (Figure 5). A separate dial thermometer was used to measure the sludge temperature on the opposite side of the tanks to ensure uniform heating throughout the tank.

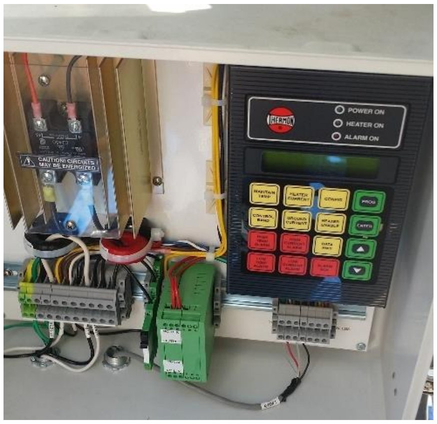
Figure 5: Heat Tracing Before Insulation



Source: Trevor Shackelford, Anaergia Services, LLC

The microprocessor-based, heat trace controller was programmed to keep temperatures at 35 C (+/- 1 C) (Figure 6). The microprocessor provided control and monitoring capabilities via digital information display. The controller stored high and low temperatures readings and provided alarms in the event of major temperature fluctuations. Each controller was housed in a NEMA 4x fiberglass lockable panel. The temperature at the panel was compared with a dial thermometer inserted in the digesters each time a data point was entered to ensure the controller was accurately reporting temperature.

Figure 6: Heat Trace Control Panel



Source: Trevor Shackelford, Anaergia Services, LLC

2.1.3 Feed Tank and Standpipe Overflow

Each digester skid was equipped with a 50-gallon high density polyethylene (HDPE) feed tank with a topside mixer. The feed tanks were filled every 3-4 days with a 60/40 mix of primary sludge and thickened waste-activated sludge (TWAS) to match the sludge ratio fed to the full-scale digesters on-site. Below the feed tanks, a progressive cavity (PC) pump filled feedstock at a typical rate of 7.5 gal/day. The PC pump ran in 30-minute intervals to supply a steady and slow feed rate to the digesters. Feedstock was fed into the digester in the middle of the tank to ensure a homogenous dispersion and mixing. Tank levels were logged to capture the specific feed rate of each digester. The headspace was maintained at a pressure of 8" water column (WC). As the feedstock was pumped the digester, the headspace pressure forced digestate to overflow into the standpipe. The overflow drained into a waste tank that returned to the plant. Figure 7 shows the PC pump, feedstock inlet, and the overflow standpipe. Odor control was also included on the feed tank lid.

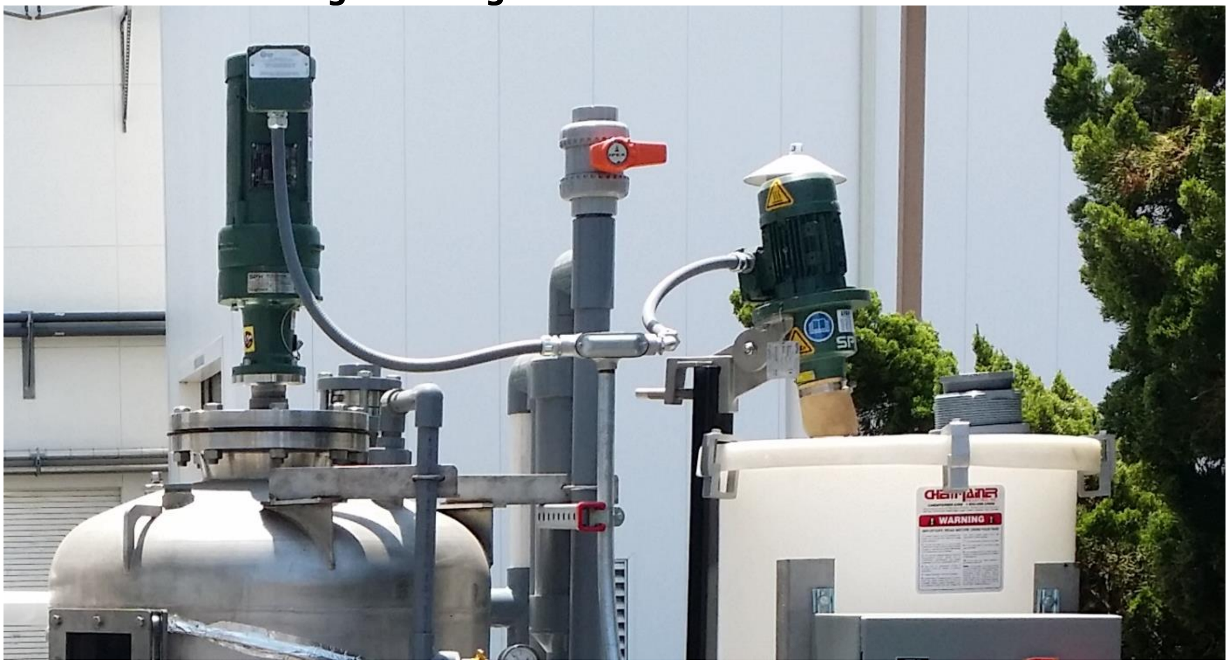
Figure 7: Digester Skid

Source: Trevor Shackelford, Anaergia Services, LLC

2.1.4 Mixers

Both the digesters and feed tanks included topside electric mixers to ensure homogenous digestate and feedstock composition (Figure 8). The mixers ran continuously without downtime throughout the project. Mixer blades and angles were optimized by the vendor to produce the most homogenous mix possible (Figures 9 and 10).

Figure 8: Digester and Feedtank Mixers



Source: Anaergia Services, LLC

Figure 9: Digester Mixer Prop

Source: Trevor Shackelford, Anaergia Services, LLC

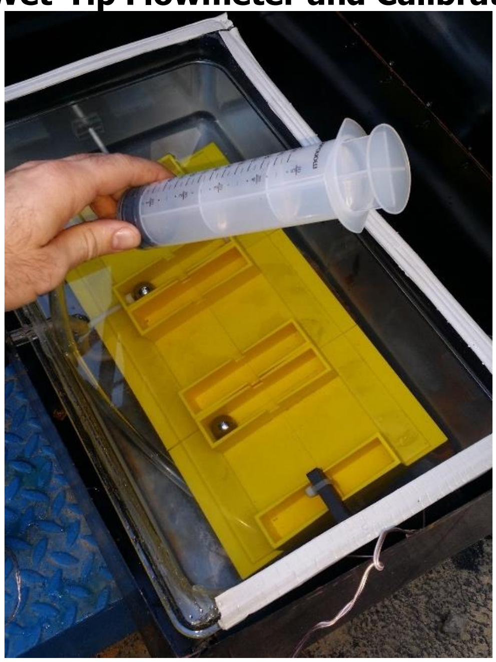
Figure 10: Feed Tank Mixer Prop

Source: Trevor Shackelford, Anaergia Services, LLC

2.1.5 Pressure Regulation and Biogas Flow Meter

The headspace pressure was maintained at 8" of WC via a pressure regulating valve to maintain a constant working volume to allow digestate to overflow during feeding events. From the regulator, biogas was directed to a wet tip gas meter to measure the biogas produced (Figure 11).

Figure 11: Wet-Tip Flowmeter and Calibration Syringe



Source: Trevor Shackelford, Anaergia Services, LLC

The meter filled with a calibrated amount of gas and then tips to the other side passing a totalizer. Each tip represents a specific amount of gas and is logged over time to calculate the cumulative gas flow and gas flow rate.

The biogas was then drawn under a slight vacuum and passed through two carbon vessels for gas cleaning with coconut shell granular activated carbon (GAC) in the first vessel and GAC impregnated with potassium hydroxide in the second vessel (Figure 12).

Figure 1: Dual Carbon Filters

Source: Trevor Shackelford, Anaergia Services, LLC

The overall Pilot Codigestion Project can be seen in Figures 13 and 14.

Figure 13: Overview of the Pilot Codigestion Project

Source: Paul Cockrell, paulcockrellphoto.com

Figure 14: Back Side of Pilot Digesters with Electrical Control Panels and Heat Trace Controllers

Source: Paul Cockrell, paulcockrellphoto.com

CHAPTER 3: Results

3.1 Pyrolysis System Operation

The mass partitioning of the three products (gas, bio-oil, biochar) were quantified as a fraction of the mass fed to the pyrolyzer and are summarized in Table 2. Low temperature pyrolysis reduces the mass of the feed as follows: 45 percent reduction of the biosolids and 55 percent reduction of the green waste. Oil yield is slightly higher for biosolids than green waste. Both feedstocks generate mostly solid and liquid end-products.

Table 2: Mass Balance of Pyrolysis

Product	Unit	Biosolids	GreenWaste
Gas	% of mass fed to pyrolyzer	13	29
Bio-oil	% of mass fed to pyrolyzer	34	27
Bio-char	% of mass fed to pyrolyzer	53	44

Source: Anaergia Services, LLC

3.2 Co-Digestion Results

The results of this study show that the co-digestion of sludge with oil produced from the pyrolysis of biosolids improves digester performance by increasing biogas production and solids destruction. The quality of the residual solid biochar product is improved by concentrating nutrients, and the biochar is safer and easier to handle rather than dry biosolids because the risks of reheating are eliminated.

The results confirm that amending municipal sludge anaerobic digesters with oils generated from low temperature pyrolysis of sludge biosolids or green wastes increases biogas production, increases solids destruction, reduces the quantity of residual solids, and generates an enhanced nutrient-rich solid product.

3.2.1 Loading

Table 3 shows the organic loading rate (OLR) of the three digesters over time. All digesters were fed sludge at the same OLR (2.0 kg/m3/d) with equal solids retention time (20 days); therefore, the equivalently operated digesters were used to compare the benefits of oil co-digestion. All digesters were fed sludge at OLR = 2.0 kg/m3/d which is equivalent to the full-scale digesters on-site. The feed for Digester 2 was amended with pyro-oil from biosolids whereas the feed to Digester 3 was amended with bio-oil from green waste. The fraction of the total OLR from bio-oil was increased in a stepwise fashion with targets of 10 percent, 20 percent, and 30 percent. Actual loading differed slightly and is tabulated in Table 4.

Table 3: Feeding Schedule and the Oil Organic Loading Rate for Each Digester

Period	Day	Dig. 1 (Control)		Dig. 2 (Pyrolysis)		Dig. 3 (Green waste)	
		Sludge OLR*	Oil OLR*	Sludge OLR*	Oil OLR*	Sludge OLR*	Oil OLR*
I	0-14	2.0	0	2.0	0.2	2.0	0.2
II	15-46	2.0	0	2.0	0.4	2.0	0.3
III	47-76	2.0	0	2.0	1.0	2.0	0.6

***(kg VS/m^3/d)**

Source: Anaergia Service, LLC

Table 4: Fraction of Total and Sludge Organic Loading Rates Contributed from Oil

Period	Day	Dig. 2 (Pyrolysis)		Dig. 3 (Green waste)	
		% of Total OLR	% of Sludge OLR	% of Total OLR	% of Sludge OLR
I	0-14	11	13	9	11
II	15-46	20	24	17	20
III	47-76	36	54	25	33

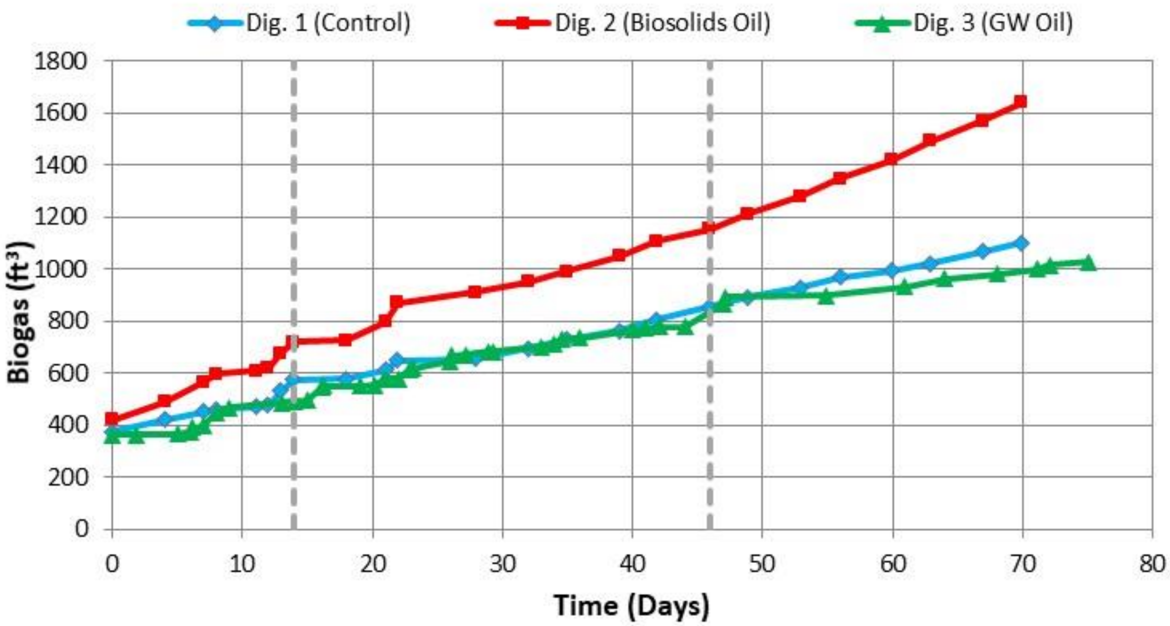
Source: Anaergia Service, LLC

3.2.2 Biogas Production:

Co-digestion of sludge with bio-oil increased specific biogas production. Figure 15 shows cumulative biogas production across the three digesters. A higher cumulative biogas production indicated a higher specific biogas yield. The bio-oil generated from the biosolids resulted in the highest biogas yield, with green waste pyro-oil producing roughly equivalent to the biogas yield of raw sludge.

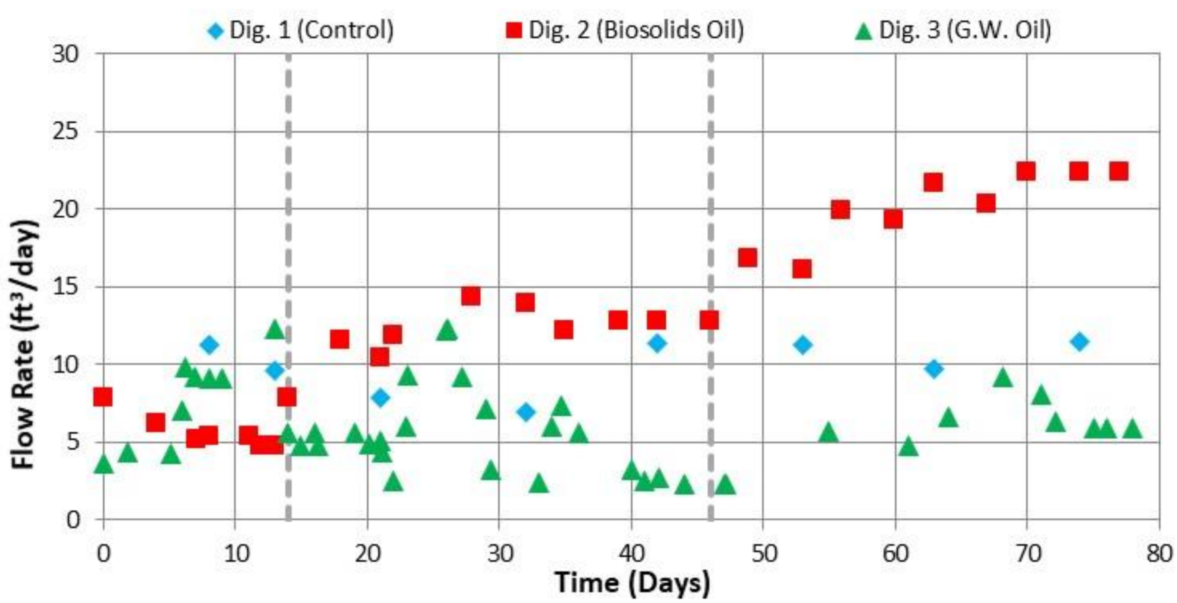
A typical WWTP would generate enough bio-oil from indigenous sludge to amend 10-20% of the OLR in the digester. That is, a typical municipal digester would reflect the phases shown over the period of 0-45 days in Figure 16 and 17. For plants that import external feedstocks such as food, waste, or external sludge, a higher OLR from oil will result, such as the case with the third period. The biogas flow rate shows a 30 percent increase in biogas production when the total digester OLR is roughly 20 percent biosolid bio-oil. Therefore, a typical WWTP could potentially increase biogas production by this amount.

Figure 15: Gas Production for the Digestor Samples



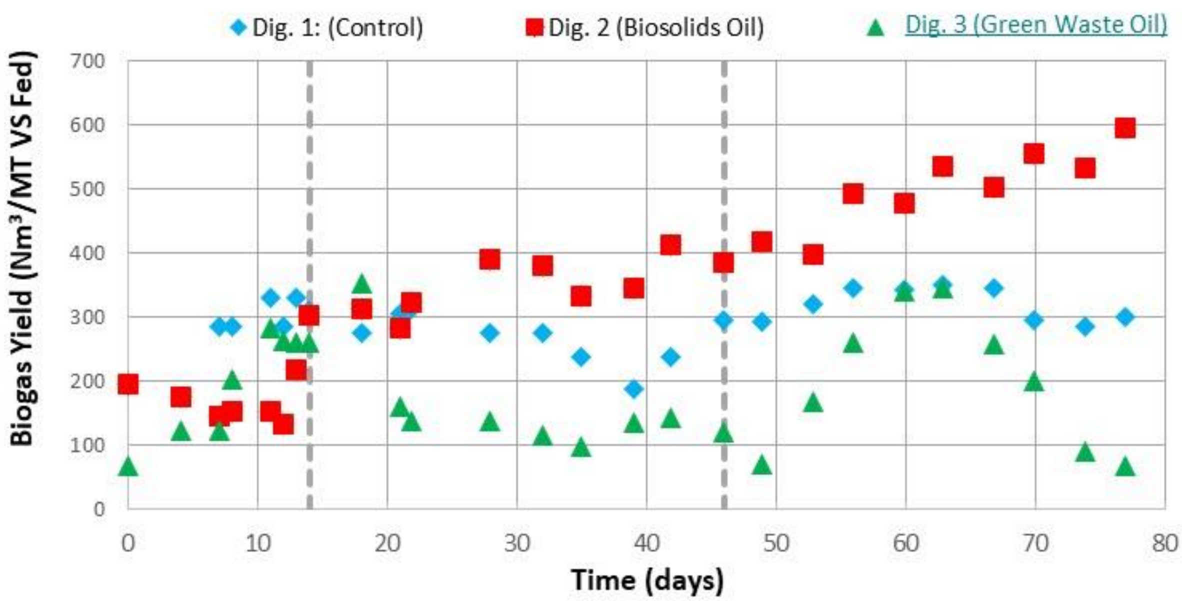
Source: Anaergia Services, LLC

Figure 16: Gas Flow Rate for the Digestor Samples



Source: Anaergia Services, LLC

Figure 17: Biogas Yield for the Digestor Samples

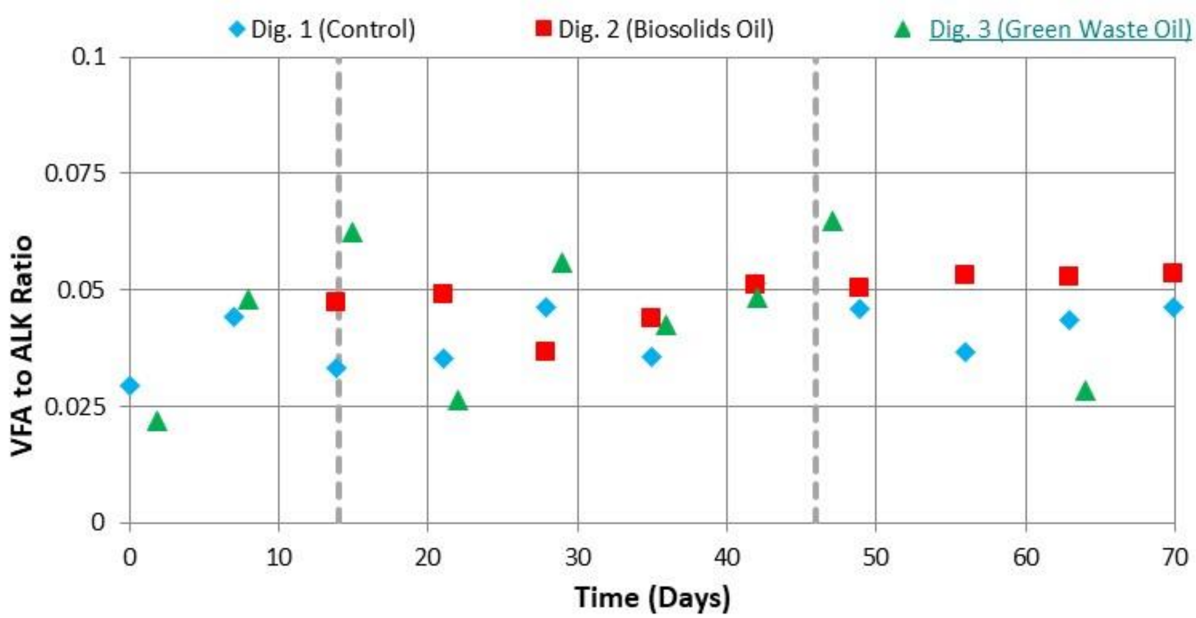


Source: Anaergia Services, LLC

3.2.3 Digester Stability

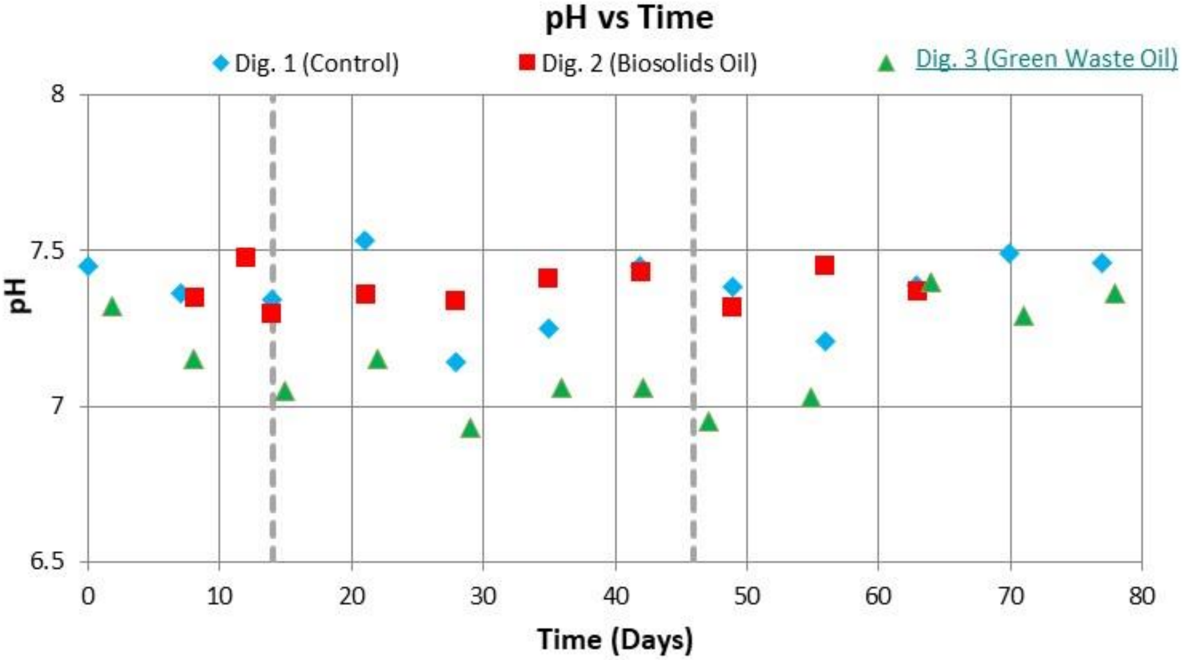
The bio-oil fed into the digesters displayed the same operational stability as the control. The digester stability was monitored by means of the volatile fatty acid (VFA) to alkalinity (ALK) ratio, the pH, and the volatile solids reduction (VSR). Instability in the digester operation is indicated when the VFA:ALK ratios increase, suggesting accumulation of acids that would have converted to methane. This acid accumulation decreases the pH and decreases the VSR indicating reduced biological activity. The VFA:ALK ratio, pH, and VSR metrics were similar in value across the three digesters indicating no measurable difference in digester stability. In fact, the VSR of digester 2 (that is, sludge plus biosolids bio-oil) was higher than digesters 1 and 3 indicating improved digester performance in co-digestion mode as indicated by the greater VSR and biogas production shown in Figures 18-20.

Figure 18: Volatile Fatty Acid to Alkalinity Ratio for the Digestor Samples



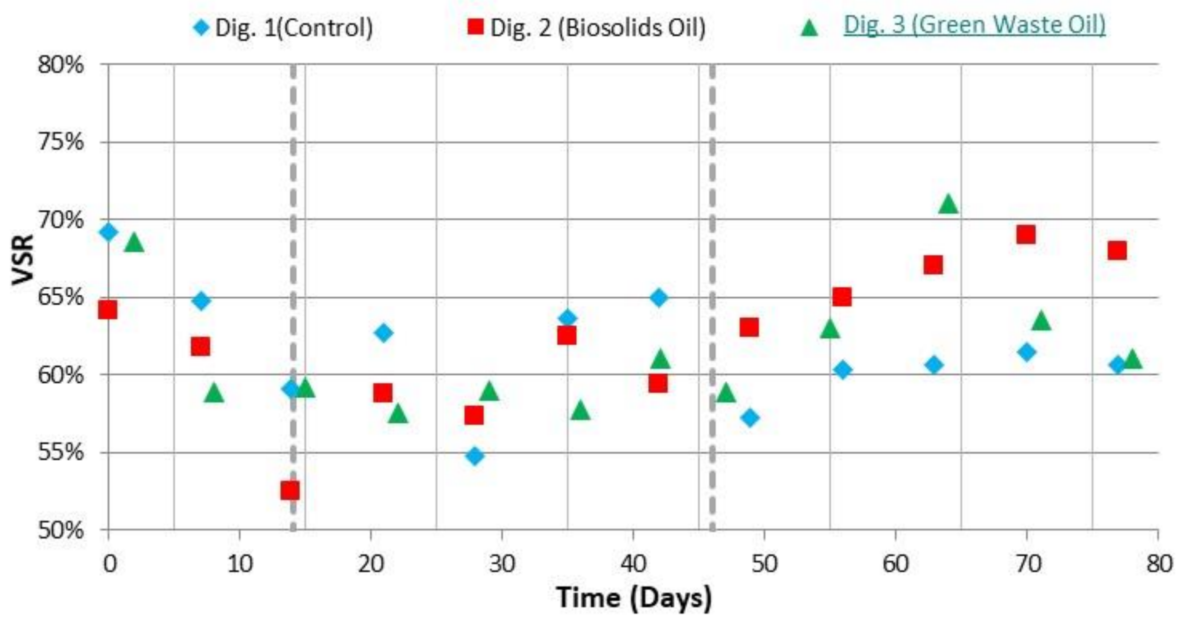
Source: Anaergia Services, LLC

Figure 19: pH of the Digestor Samples



Source: Anaergia Services, LLC

Figure 20: Volatile Solids Reduction for Digestor Samples



Source: Anaergia Services, LLC

3.3 Pyrolysis Oil Analysis and Testing

Chemical characterization of the pyrolysis oils generated from the digested sewage sludge and green waste shows the oils are energy dense and highly digestible (Figure 21). Total solids (TS), volatile solids (VS), and the total solids ratio (VS/TS) are summarized in Table 5. A high TS value indicates an energy dense feedstock, and a high total solids ratio suggests the oils are highly degradable which is consistent with the digestion findings mentioned in the previous section. These values confirm the high biogas potential of the bio-oil.

Table 5: Composition of Pyrolysis Oil

Measurement	Unit	Biosolids Oil	Green Waste Oil
TS	%	88	22
VS/TS	%	98	98

Source: Anaergia Service, LLC

Figure 21: Pyrolysis Oil from Biosolids

Source: Trevor Shackelford, Anaergia Services, LLC

3.4 Biochar Analysis and Testing

The biochar generated from pyrolyzing dry biosolids and green waste reduces the residual mass and increases the value by concentrating nutrients. Tables 6 and 7 summarize the concentration of nitrogen, potassium, and phosphorus resulting from the conversion of the carbonaceous mass of the biosolids and green waste to pyro-gas. Nitrogen did not concentrate as much as the other nutrients because a fraction of the nitrogen volatilized with the gas. However, the biosolids and the char have a similar carbon to nitrogen (C/N) ratio between 6 and 7 which, indicates a nitrogen-rich product. Figures 22 and 23 show different feedstocks before and after the pyrolysis process.

Figure 22: Before and After Biochar from Biosolids

Source: Anaergia Services, LLC

Figure 23: Before and After Biochar from Green Waste

Source: Anaergia Services, LLC

Table 6: Composition of Pyrolysis Biochar from Municipal Digested Biosolids

Metric	Unit	Dry Biosolids	Biochar
Total Nitrogen	% dry mass	6.1	6.3
K_2O	% dry mass	0.3	0.4
P_2O_5	% dry mass	7.0	11.9
S	% dry mass	2.1	1.05
Total Carbon	% dry mass	37.6	42.2
C/N Ratio	-	6.1	7.1

Source: Anaergia Services, LLC

Table 7: Composition of Pyrolysis Biochar From Green Waste

Metric	Unit	Dry Green Waste	Biochar
Total Nitrogen	% dry mass	0.9	1.0
K_2O	% dry mass	0.9	1.6
P_2O_5	% dry mass	0.3	0.6
S	% dry mass	0.2	0.7
Total Carbon	% dry mass	39	16
C/N Ratio	-	47	17

Source: Anaergia Services, LLC

CHAPTER 4: Conclusions

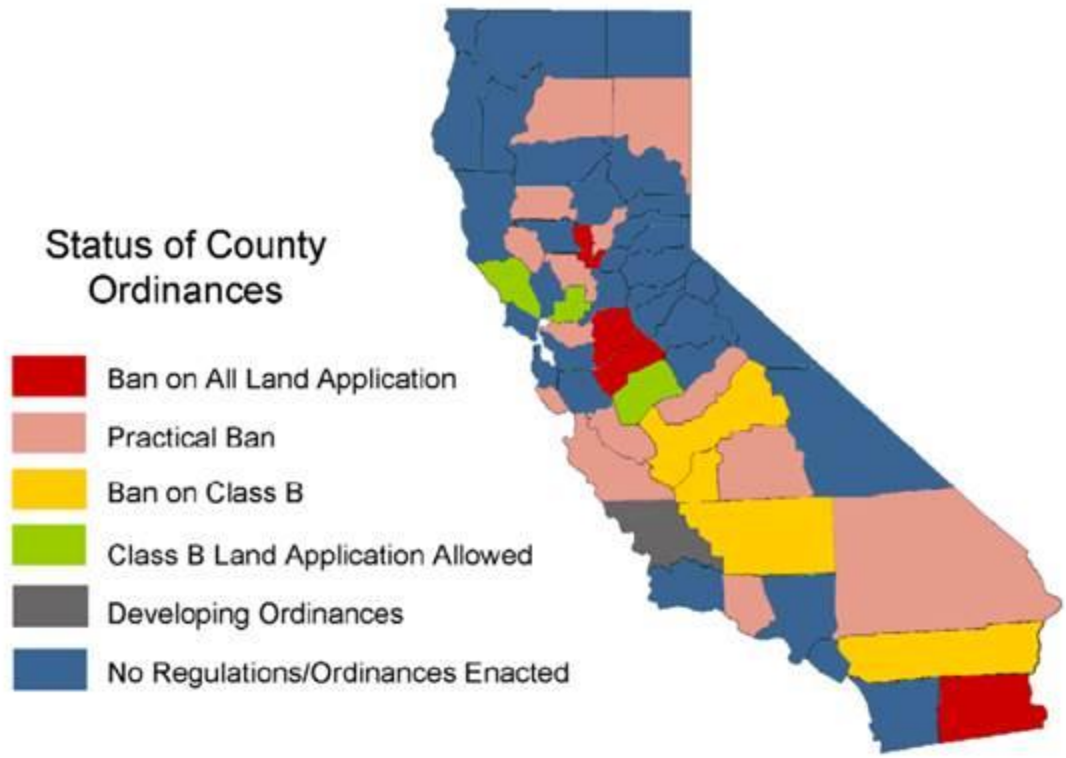
Low temperature pyrolysis is an effective approach to convert municipal biosolids from WWTPs as well as green waste into bio-methane for power or fuel production via anaerobic digestion. This study demonstrated that bio-oils generated from municipal WWTP biosolids and green waste degrade well in anaerobic digesters, increase biogas production, and increase solids destruction. The mass of residual solids following anaerobic digestion can be reduced by up to eight-folds through drying and pyrolysis while the value of the resulting biochar is enhanced through concentration of nutrients, pathogen elimination, and carbon conversion. Low temperature pyrolysis of biosolids and green waste offer the following major benefits to municipal WWTPs: (1) increased biogas production from indigenous biosolids, external green waste, or external biosolids, (2) reduced residual solids up to eight-folds by drying and pyrolyzing the dewatered biosolids cake, (3) improved VS destruction by co-digesting sludge with bio-oil, and (4) increased value of residual solids by producing a biochar product with concentrated nutrients, no pathogens, and converted carbon.

Regulatory pressures in California are driving solutions that sustainably convert biosolids and green waste into renewable fuels and high value products. Converting municipal biosolids and green waste into renewable biogas fuel offers a major opportunity to simultaneously divert material from landfills and convert waste products into renewable fuels that help California achieve regulatory compliance and renewable energy standards. Figure 24 shows ordinances in California, which shows that land application of biosolids is not feasible considering the trend towards regulatory bans or communities classifying land application as an unacceptable practice. Considering the majority of biosolids are currently land applied in California as shown in Figure 25, converting biosolids into renewable fuels will reduce the amount of biosolids that are land applied.

Similar to biosolids, green waste must also avoid being landfilled. Further, recently passed legislation AB 1826 mandates diversion of food waste from landfills and sets a precedent for ambitious organics diversion goals for the state that will inevitably include green waste.

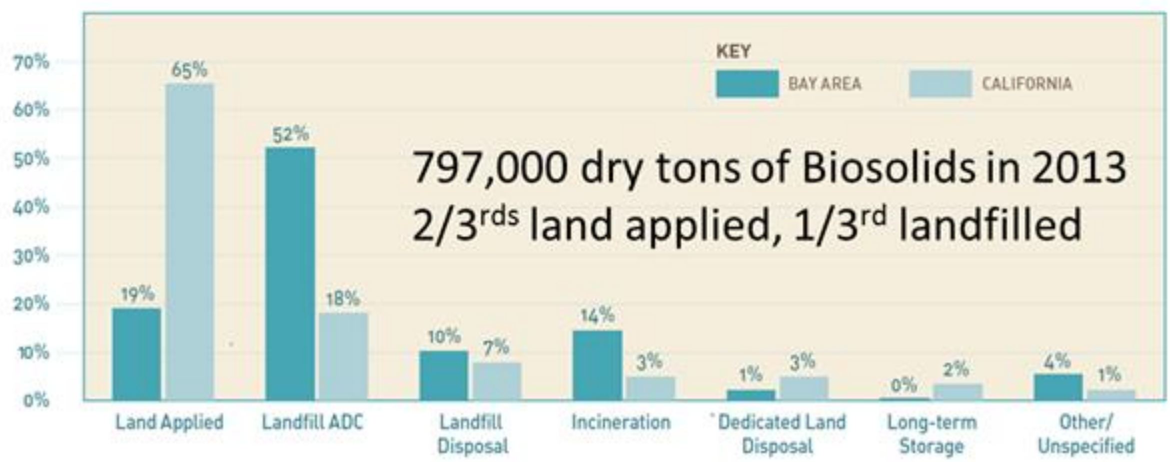
California's renewable portfolio standard also requires utilities to deliver 50 percent of retail electricity from clean, renewable sources from 2030. The California Global Warming Solutions Act: emissions limit, Senate Bill (SB) 32, required a reduction in greenhouse gas emissions to 40 percent below 1990 levels by 2030. Considering biogas is a low-carbon fuel, its use for generating power significantly contributes to the goals set forth in SB 32. Therefore, increasing biogas production from currently disposed products offers benefits for California. Low temperature pyrolysis is an effective approach to convert biosolids and green waste into a renewable fuel and high value fertilizer. The process converts dry biosolids and green waste into a usable gas for heat or power, a high value biochar product, and a liquid called bio-oil. The bio-oil is fed to existing anaerobic digesters to increase biogas production while the biochar is used as a nutrient-rich dry fertilizer suitable for agricultural or horticultural applications. Biosolids and green waste that are currently landfilled can instead be dried and processed through low temperature pyrolysis to increase production of renewable biofuel and reduce the residual solids produced by WWTPs.

Figure 24: Status of Landfill Ordinances in California



Source: Camp Dresser & McKee Inc 2011

Figure 25: California Biosolid Use



Source: Anaergia Services, LLC

Similar to biosolids, green waste must also avoid being landfilled. Further, recently passed legislation AB 1826 mandates diversion of food waste from landfills and sets a precedent for ambitious organics diversion goals for the state that will inevitably include green waste.

CHAPTER 5: Commercial Plan

The project completed at the Encina Wastewater Authority allowed Anaergia to demonstrate the benefits of the integrated digestion and pyrolysis solution and has also offered an opportunity for refinement and improvement of system components and operation. To better enhance the system components, the pyrolysis equipment will be transported off-site for further testing and development elsewhere. However, while on the Encina site, numerous tours and visitors showed interest in implementing the pyrolysis technology at their respective sites. The findings from this study will complement these site visits by demonstrating the resulting energy production and product quality potential from such operations.

5.1 Market Opportunities -Renewable Fuel Production and Waste Diversion

The market for integrated digestion and pyrolysis application is influenced by regulatory bans on residual biosolids and green wastes disposal, increasing incentives and demand for production of renewable energy, increasing demand for sustainable agricultural practices, and the necessity to remove excessive carbon from the atmosphere.

Biosolids and green waste can be interpretated as a resource rather than a waste requiring a cost to dispose. Using biosolids and green waste as a feed, the pyrolysis process produces a high-quality biochar product, a renewable fuel source (bio-oil), and additional biomethane that can be converted to electricity, heat (combined heat and power, CHP), or a natural gas replacement (compressed natural gas, CNG).

5.2 Potential Market Applications and Commercialization Strategies

As mentioned, the combined digestion and pyrolysis process will produce two new products for potential commercial use. First, the additional biomethane produced will likely be used in the same manner as conventional anaerobic digester biomethane. These options include combustion in an engine for CHP, upgrading to pipeline gas, or even CNG vehicle fuel. Through the generation and digestion of the bio-oil, the biomethane production increases. Additionally, the pyrolysis process will convert the biosolids waste product into a biochar product, containing nutrients and soil-enhancing carbon. This biochar can then be sold into the agricultural and horticultural market in place of synthetic nutrient fertilizers (such as nitrogen and phosphorus). Furthermore, the biochar has unique carbon structures that improve soil conditions and can also be used to replace peat and traditional potting soil ingredients. Anaergia will work with the treatment facilities to identify suitable markets, collect data to enhance the maximum value of the product, and potentially facilitate logistics of the product management. Given the requirement for drying of the biosolids prior to treatment with the pyrolysis process, initial efforts for commercialization will focus on sites where drying technologies are already in place, or under evaluation. This is due to the reduction in additional infrastructure required, as well as the local market drivers in biosolids disposal, landfill costs, and agricultural opportunities that drive the evaluation and implementation of drying technologies even without the addition of the pyrolysis process.

5.3 Product Design

Due to the unique nature of the individual projects, assessment of the existing digestion and gas use infrastructure will be required to determine what, if any, modifications are required to accommodate the processing of the bio-oil and resulting biomethane production. Considering that Anaergia has already developed a process to cost-effectively increase conventional anaerobic digester capacity within the existing digester facilities (known commercially as the Omnivore™ process). The pyrolysis configuration is intended to develop a suite of predesigned units of specific capacity that would then be capable of being used together in a "building block" design configuration. As such, custom engineering costs can be minimized while using pre-designed units.

GLOSSARY

Term	Definition
ALK	Alkalinity
Biogas	Gas produced from anaerobic digestion with typical composition of 60% methane and 40% carbon dioxide.
Bio-Methane	Methane produced from biodegradable sources such as sludge, food waste, and biodegradable fats, oils, and grease.
Bio-oil	Biodegradable oils generated from low temperature pyrolysis of biosolids.
Biosolids	Residual solids after anaerobic digestion of primary sludge and waste activated sludge at a municipal wastewater treatment plant.
C/N ratio	Carbon to nitrogen ratio
Cake	A stackable blend of residual solids after anaerobic digestion and water (typically 75 percent water content) that result from dewatering digestate.
CHP	Combined heat and power
CNG	Compressed natural gas
Co-Digestion	Feeding a blend of sewage sludge and external feedstock to an anaerobic digester to produce biogas.
EWPCF	Encina Water Pollution Control Facility
GAC	Granular activated carbon
Green Waste	Discarded plant-based materials such as leaves, grass, branches originating from residential homes and commercial sources such as landscaping, public parks, business, and green frontage.
Green Waste Oil	Biodegradable oils generated from low temperature pyrolysis of green waste.
HDPE	High density polyethylene
kg	Kilogram
m^3	Cubic meters
MWhr	Megawatt-hour
OLR	Organic loading rate
PC	Progressive cavity
Produced Gas	Non-condensible gas produced from low temperature pyrolysis.
Pyrolysis	Thermal treatment of a solid material in an oxygen-free environment that generates three products: produced gas, bio-oil, and biochar.

Term	Definition
RTD	Resistance temperature detector
SRT	Solids retention time
TS	Total solids
TWAS	thickened waste-activated sludge
VFA	Volatile fatty acid
VOC	Volatile organic compound
VS	Volatile solids
VSR	Volatile solids reduction
WC	Water column
WWTP	Wastewater treatment plant.

REFERENCES

Camp Dresser & McKee Inc., *Charting the Future of Biosolids Management: Final Report*, Water Environment Research Federation and National Biosolids Partnership, 2011.