Anaerobic Digestion of FOG for Optimal Methane Production

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Executive Summary

Anaerobic digestion is a biological process that utilizes microorganisms to break down organic matter in the absence of oxygen. Through this process, methane (CH₄) and carbon dioxide (CO₂), together known as biogas, are produced from organic matter fed to the digester. A variety of organic matter may be used in anaerobic digestion, including yard, food, and animal waste, and sewage solids. Anaerobic processes occur both naturally and in controlled environments, such as waste management facilities.

There are four stages to anaerobic digestion, which are carried out by different sets of microorganisms (Figure 1). During the first stage, hydrolysis, bacteria break down organic matter into simple sugars and fatty acids. In stage 2, acidogenic bacteria consume the products of stage one to produce short chain volatile acids (propionic acid (CH₃CH₂COOH) and butyric acid (CH₃CH₂CH₂COOH)) among other products such as alcohols, hydrogen, and CO₂. During stage three, acetogenic bacteria transform the products from both stage 1 and 2 into acetic acid and hydrogen. In methanogenesis, the last stage, methanogenic bacteria convert hydrogen and acetic acid into CH₄ and CO₂.

Figure 1: The four processes of anaerobic digestion.
Methane can be harnessed as a fuel source, though it is often produced in only small amounts from anaerobic digesters. Sewage-fueled anaerobic digesters produce especially small amounts of biogas since sewage contains relatively few nutrients and readily degradable organic matter. Therefore, using sewage as the sole feedstock in a digester is not economically feasible in terms of biogas production. Thus, the feedstock must be supplemented with richer, more readily degradable organic matter. Restaurant waste can be used as a supplement to sewage to increase biogas production.

This project aims to utilize fats, oils, and greases (FOG), also known as restaurant waste, to enhance biogas production in anaerobic digestion. The project is part of a collaboration with the San Elijo Joint Power Authority (SEJPA) to determine the viability of anaerobic treatment to treat FOG and generate energy through produced biogas for SEJPA to use. SEJPA has a stated goal of becoming the FOG collection center for southern California and currently anaerobically digests the organic solids that it produces. However, the biogas produced is not generated in economic quantities and the biogas is flared off on-site rather than captured as an energy source. This project employs bench-scale anaerobic digesters, using sewage as the main feedstock and FOG as a supplement to enhance biogas production.

**Project Objectives**

This project is associated with San Elijo Joint Power Authority, which sits within the Escondido Creek watershed. The project was designed to develop a water treatment system to help the SEJPA to become the regional FOG collection site for southern California. Additionally, this anaerobic treatment system was designed to help the SEJPA become a net producer of energy to the local area. This experience can hopefully be applied to a career in the USDA Forest Service through my hands-on experience with anaerobic digestion and biogas production. Additionally, my lab experience and familiarity with various lab equipment could help me complete tasks in the Forest Service.

The project’s central hypothesis is that the addition of FOG to anaerobic digesters containing SEJPA biological solids and primary effluent wastewater will produce more biogas than digesters not containing FOG. A second hypothesis is that a two-stage anaerobic digester, where the pH is adjusted halfway through the digestion process, will produce more biogas than a single-stage anaerobic digester that does not utilize a pH adjustment scheme.

To test these hypotheses, bench-scale anaerobic digesters, both single and two-stage, were created. The digesters contained primary effluent, thickened waste activated sludge (TWAS), and an anaerobic microbial seed (also known as inoculum) from SEJPA. Treatment digesters were supplemented with FOG. The FOG was collected from Marie Callender’s Restaurant and Bakery. Both cooked and
uncooked FOG was used. The cooked FOG had been cooked in a deep fryer for 1 to 1.5 days. Anaerobic digester conditions, including pH, temperature and nutrients, were previously optimized with the goal of maximizing biogas production.

Biogas and methane productions were measured continuously throughout the experiments to monitor effectiveness of the digesters. Volatile solid concentrations of the sludge were measured to estimate potential biogas production. Measuring volatile solids in the beginning and the end of each 2-week digester experiment provided a guide as to how much biogas would be expected to be produced and how much potential for biogas is left over at the end of the experiment.

**Project Approach**

Throughout the project, seven anaerobic digesters were set up and run for 1 month. The digesters differed in ratios of primary effluent, TWAS, inoculum and FOG. Digester experiments were run to test effectiveness of vegetable oil, uncooked FOG, and cooked FOG. Furthermore, the experiments aimed to test established literature values for the ratio between anaerobic seed and substrate to our own ratio, which was established through experimentation.

**Digester setup:** The experiments were conducted in 155-mL glass bottle batch bioreactors containing a total volume of 100-mL solutions with varying amounts of primary effluent, TWAS and FOG. The bottles were capped using plastic caps with flanged septum and purged with nitrogen gas (N2) for 3 minutes. 20 mL of CO2 were injected into the bottles to create a buffer so that the caps could be quickly removed to allow for addition of inoculum while retaining anaerobic conditions. Inoculum was added to the open bottles using a syringe. The bottles were quickly resealed and underwent purging again using N2 gas for 3 minutes. After purging, the bottles were "burped" to let out the remaining gas inside. The pH of each bottle was measured before securing the caps with parafilm and incubating the digesters in the dark at 30°C where they were shook at 150 rpm.

**Biogas and pH measurement:** Biogas was measured daily using a glass syringe with a 21-gauge needle. The needle was inserted into the septum of the anaerobic digester and the accumulated biogas within the digester pushed the syringe plunger outwards until pressure equilibrium was established. The biogas volume within the syringe was recorded and the biogas was injected into a sealed 155-mL glass bottle containing 155 mL of 10 N NaOH. The mixture was rapidly shaken for 1.5 minutes then left at rest for 30 seconds before measuring the volume of gas produced with the glass syringe. The gas measurement was recorded as the methane (CH4) produced.
**Volatile solids measurement:** Evaporating dishes were cleared of contaminants by heating them at 550°C for 1 hour before being transferred to a desiccator to be cooled then weighed. 5-mL samples from the digesters were transferred into the evaporating dishes using a 20-mL syringe. Once the samples were transferred into the dishes, the dishes were weighed again. The dishes were placed in an oven set to 105°C for 2 hours. After 2 hours, the dishes were placed in the desiccator and then weighed once they had cooled. The difference in weight was used to determine total solid content of the samples.

The dishes were then placed into a furnace set to 550°C for 45 minutes. After 45 minutes, the dishes were removed from the furnace and placed in a desiccator until cool. Once cool, the dishes were weighed. The difference between the final weight and the total solids weight was used to determine volatile solid content.

**Project Outcomes**

In the beginning of this project, experiments were run to determine optimal ratios of digester components. Through these experiments, it was determined that 75 mL primary effluent, 18.75 mL inoculum, 4.68 mL TWAS, and 1.56 mL vegetable oil, uncooked FOG, or cooked FOG should be added to the anaerobic digesters for maximum biogas production. Later, the industry norms ratio was also utilized and compared against that, which was derived from our own experimentation. The literature ratio called for 60% primary effluent and inoculum, 30% TWAS, and 10% oil, which equated to 73.60 mL primary effluent, 24.50 mL inoculum, 1.77 mL TWAS, and 0.13 mL vegetable oil, uncooked FOG, or cooked FOG.

Anaerobic digesters containing the experimentally derived ratio underwent decreases in pH during experiments. The rate of decrease varied minimally between the different FOGs used in experiment. Over a two-week period, experiments containing vegetable oil underwent pH drops from approximately 7.5 to 5.3 (Figure 1). Experiments containing uncooked FOG underwent pH drops from 7.5 to 5.6 and with cooked FOG from 7.5 to 5.7 (Figure 3). This slowed and eventually killed off the bacteria which produce biogas. This can be observed by the decreased rate of biogas production towards the second half of each stage of the experiments (Figure 7-10).

To combat this process, two-stage anaerobic digestion was implemented. Halfway through each experiment (2 weeks) pH was readjusted to pH 8 and the solution was supplemented with new TWAS. Once in second stage, digesters experienced minimal decreases in pH, dropping no lower than pH 7 (Figure 1-3). The pH is more stable during second stage because the organic matter from the FOG and TWAS has already undergone the first three stages of anaerobic digestion (Figure 1). The predominant process taking place during second stage is methanogenesis, which does not produce acid byproducts.
Digesters containing the literature ratio did not experience sharp decreases in pH but were transferred into a second stage after 2 weeks to remain consistent with other experiments. Digesters containing vegetable oil and uncooked FOG underwent decreases from pH 7.5 to 6.5 (Figure 2 & 3). Digesters containing cooked FOG underwent decreases from pH 7.5 to 6.8 (Figure 4). The literature ratio was designed to avoid “crashing” due to high acidity levels so that a two-stage process is not mandatory. This was accomplished by less addition of TWAS and FOG.

**Figure 2:** Two-stage anaerobic digesters containing both the literature ratio (73.60 mL primary effluent, 24.50 mL inoculum, 1.77 mL TWAS, 0.13 mL oil) and experimentally derived ratio (75 mL primary effluent, 18.75 mL inoculum, 4.69 mL TWAS, 1.56 mL), supplemented with vegetable oil.
Figure 3: Two-stage anaerobic digesters containing both the literature ratio (73.60 mL primary effluent, 24.50 mL inoculum, 1.77 mL TWAS, 0.13 mL oil) and experimentally derived ratio (75 mL primary effluent, 18.75 mL inoculum, 4.69 mL TWAS, 1.56 mL), supplemented with uncooked FOG.

Figure 4: Two-stage anaerobic digesters containing both the literature ratio (73.60 mL primary effluent, 24.50 mL inoculum, 1.77 mL TWAS, 0.13 mL oil) and experimentally derived ratio (75 mL primary effluent, 18.75 mL inoculum, 4.69 mL TWAS, 1.56 mL), supplemented with cooked FOG.
Experiments run using the experimentally derived ratio indicate total biogas accumulation of 350 mL using vegetable oil (Figure 5), 384 mL using uncooked FOG (Figure 6), and 280 mL using cooked FOG (Figure 7).

Figure 5: Two-stage anaerobic digesters containing the experimentally derived ratio using vegetable oil.

Figure 6: Two-stage anaerobic digesters containing the experimentally derived ratio using uncooked FOG.
Figure 7: Two-stage anaerobic digesters containing the experimentally derived ratio using cooked FOG.

Experiments run using the literature ratio indicate total biogas accumulation of 321 mL using vegetable oil (Figure 8), 249 mL using uncooked FOG (Figure 9), and 187 mL using cooked FOG (Figure 10).

Figure 8: Two-stage anaerobic digesters containing the literature ratio with vegetable oil.
An experiment was run containing no FOG (Figure 11) to compare against those containing either vegetable oil, uncooked FOG, or cooked FOG. The literature ratio was used and 71.06 mL primary effluent, 24.50 mL inoculum, 4.44 mL TWAS, and 0 mL oil were added to the digesters. The results indicate a total biogas accumulation of 212 mL.
Results from volatile solids (VS) testing of digesters containing the literature ratio supplemented with vegetable oil indicate 4.80 mg/mL VS at the start of the experiment, 31.0 mg/mL VS at the end of the first stage, and 11.7 mg/mL VS at the end of the experiment (Figure 12). Digesters containing the experimentally derived ratio supplemented with vegetable oil indicate 16.9 mg/mL VS at the start of the experiment, 49.0 mg/mL VS at the end of the first stage, and 16.7 mg/mL VS at the end of the experiment (Figure 13).

For digesters containing the literature ratio with uncooked FOG, 4.80 mg/mL VS were present at the beginning of the experiment, 28.5 mg/mL VS at the end of the first stage, and 24.9 mg/mL VS at the end of the experiment (Figure 14). Digesters containing the experimentally derived ratio with uncooked FOG contained 16.9 mg/mL VS at the beginning of the experiment, 40.1 mg/mL VS at the end of the first stage, and 11.4 mg/mL VS at the end of the experiment (Figure 15).
Figure 12: Volatile solids content of two-stage anaerobic digesters containing the literature ratio using vegetable oil.

Volatile Solids in Two-Stage Anaerobic Digesters + Literature Ratio + Vegetable Oil

Figure 13: Volatile solids content of two-stage anaerobic digesters containing the experimentally derived ratio using vegetable oil.

Volatile Solids in Two-Stage Anaerobic Digesters + Experimentally Derived Ratio + Vegetable Oil
Figure 14: Volatile solids content of two-stage anaerobic digesters containing the literature ratio using uncooked FOG.

Volatile Solids in Two-Stage Anaerobic Digesters + Literature Ratio + Uncooked FOG

Figure 15: Volatile solids content of two-stage anaerobic digesters containing the experimentally derived ratio using uncooked FOG.

Volatile Solids in Two-Stage Anaerobic Digester + Experimentally Derived Ratio + Uncooked FOG
Conclusions

The central hypothesis of this project is that the addition of FOG to anaerobic digesters produces more biogas than digesters not containing FOG. This was true for all anaerobic digesters except those containing the literature ratio supplemented with cooked FOG. These digesters accumulate 187 mL biogas during the experiment, which is 12% less yield than digesters containing the literature ratio without FOG supplementation.

Overall, vegetable oil and uncooked FOG supplementation produced the most biogas from anaerobic digesters. Cooked FOG produced the smallest amount of biogas. The reason why cooked FOG is a worse supplement than vegetable oil and uncooked FOG for biogas production is that much of the nutrients have been cooked out of them.

Anaerobic digesters containing the experimentally derived ratio produced more biogas than digesters containing the literature ratio. This was observed for all FOGs used in the project. Total biogas accumulation using vegetable oil reached 321 mL using the literature ratio and 350 mL using the experimentally derived ratio. Biogas accumulation using uncooked FOG reached 249 mL using the literature ratio and 384 mL using the experimentally derived ratio. Biogas accumulation using cooked FOG reached 187 mL using the literature ratio and 280 mL using the experimentally derived ratio.

The experimentally derived ratio performed better than the literature ratio because more readily degradable organic matter was added to the digesters. Adding larger amounts of TWAS led to much larger biogas production and less stability in pH. Using the experimentally derived ratio, the pH can fall too low for digestion to continue, though this is prevented using a two-stage digestion process in which the pH is re-adjusted mid-experiment.

Results from volatile solids testing indicate larger amounts of organic matter being added to digesters when using the experimentally derived ratio. At the end of the experiment, however, roughly equal amounts of organic matter are left over. In the case of uncooked FOG, the amount of organic matter left over at the end of the experiment is even less than in digesters containing the literature ratio. The experimentally derived ratio produced more biogas and did not leave large amounts of organic matter undigested.

Further experiments could investigate the experimentally derived ratio as a valid anaerobic digestion setup to implement into digesters aiming to produce larger amounts of biogas. Additionally, experiments testing the efficiency of biogas production using this ratio would help to further understand FOG supplementation to anaerobic digestion.