Evaluation of anaerobic digestion of food residue at Dickinson College

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Abstract. — The objective of this study was to establish and operational protocol and evaluate the performance of a pilot-scale anaerobic digester at the Dickinson College Farm. A secondary goal was to consider the feasibility of implementing an anaerobic digester on Bucknell University's campus. Such evaluation was conducted through the analysis of Dickinson College Farm's digester which is located within the Susquehanna Valley River Basin. Analytical results indicated that the Dickinson digester achieved over 50% solids destruction, over 95% chemical oxygen demand (COD) removal, consistent gas production averaging 7.5 m^3 per feeding, and a methane content of 65%. Based upon laboratory analysis, it was projected that over 54 MWh of electricity could be generated and over 21,000 kg CO_2 equivalent greenhouse gas emissions could be voided at Dickinson College pending installation of digestion capacity for the entirety of food residue at the College. A similar projection indicated that over 200 MWh of electricity could be produced and over 83,000 kg CO_2 equivalent greenhouse gas emissions could be avoided at Bucknell University through full-scale anaerobic digestion of food residue.

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1. Introduction

With more than 37 million tons of food residue being generated in 2013 in America alone, the disposal of organic waste is significant issue in need of more sustainable alternatives. According to the Environmental Protection Agency (EPA), food residue is the largest component of municipal solid waste (MSW), accounting for over 21% of the waste stream in the United States [2]. Although landfills have the potential to generate energy from the methane gas produced by decomposed food residue, their relatively low biodegradation rates and high potential for gas loss make landfills a less preferred alternative for food residue management. A better, more sustainable alternative to landfill disposal is anaerobic digestion in engineered reactors.

Anaerobic digestion is a biochemical process that utilizes microbes to degrade biomass and convert it into biogas. This biogas typically consists of around 60% methane and 40% carbon dioxide, making it a valuable source of renewable energy. Unlike other sustainable methods of waste disposal, such as composting, anaerobic digestion requires no oxygen to biodegrade food residue, and exerts no net energy requirements. This absence of oxygen demand makes the process a net energy producer and also limits microbial growth, yielding a high degree of waste stabilization and low production of excess microbes. In addition to the biogas produced, anaerobic digestion produces another useful product; the solid/liquid residue, known as digestate, remaining after the degradation of food residue can be used as a soil conditioner. Overall, food residue is better served if treated in an anaerobic process, where it can be converted into a valuable form of energy and soil amendment, rather than unsustainably disposed in a landfill.

Currently, the majority of Dickinson College food residue is composted at the College Farm. Shifting food residue from composting to anaerobic digestion at Dickinson would reduce on-site energy consumption and reduce greenhouse gas (GHG) emissions. Because Bucknell University's food residue is transported to the Lycoming County Landfill, even greater reduction in energy consumption and GHG emissions could be realized by full-scale anaerobic digestion. By potentially implementing a small-scale anaerobic digester on campus, the University could begin to reduce its food residue transportation and landfill tipping costs, decreasing its carbon footprint and contribution of nutrient-rich leachate to Lycoming Landfill. The university could also begin to produce useful biogas, which could be converted into heat and electricity. This electricity could be used to reduce power costs, either by supplying power to regions of campus or being sold to the utility grid.

A local model of how Bucknell could begin small-scale anaerobic digestion of food residue exists at Dickinson College Farm in Carlisle, Pennsylvania. Dickinson College, which is also located in the Susquehanna River watershed, started a pilot-scale anaerobic digester in the summer of 2016, with guidance and assistance from Bucknell. Dickinson's digester takes a portion of the college's food residue to produce biogas and a valuable soil amendment. Through this pilot-scale digester, Dickinson is assessing the potential benefits of full-scale anaerobic digestion of food residue.

Bucknell's assistance in the assessment of Dickinson's digester was vital, due to significant expertise in anaerobic biodegradation and the Environmental Engineering & Science Laboratory. To complete this collaborative effort between Bucknell and Dickinson, on-site digester feeding, monitoring, sample collection, and shipment were completed by Dickinson staff and students, whereas Bucknell assumed responsibility for sample analysis, data management, and assessment of digester performance. Also, Bucknell employed digester performance data to project potential benefits of full-scale implementation of anaerobic digestion at Dickinson, and Bucknell. This report is the result of our evaluation of digester performance and full-scale projections.

2. Methods

2.1. Reactor configuration

Figures 1 and 2 are photographs of the Dickinson College Farm digester and the greenhouse it is contained in, respectively. Figure 3 is a photograph of the solar panel used to heat the digester, along with natural heating from the sun and ambient air.

Figure 1. Photograph of the Dickinson College Farm digester

Figure 2. Greenhouse containing the Dickinson College Farm

Figure 3. Solar panel used to heat the digester

The Dickinson digester is a 23-foot-long cylindrical tube with a diameter of 3 feet and a working volume of 132 cubic feet (or 988 gallons). The tube is constructed of 65 mil reinforced EPDM roofing membrane, and the two end caps are made from polypropylene. The end caps are attached to the digester tube with stainless steel straps, caulked with water cutoff mastic. Located inside one of the farm's greenhouses, the digester is heated by sunlight, with help from solar panels[1]. The Dickinson digester is characterized as a plug flow reactor, since the microbes travel through the reactor with the feed, continually breaking down the organics in the food residue and converting them into biogas.

2.2. Operation of the anaerobic digester

Over the course of the study, the digester was operated by Matt Steiman, the Dickinson College Farm Director, and two Dickinson College physics students, Sean Jones and Emily Whitaker. The digester was routinely fed around 8 a.m. on Sundays, Tuesdays, and Thursdays.

Figure 4 is a photograph of the tank where food waste is added, diluted with tap water, and mixed before being fed to the digester. Figure 5 is a photograph of the discharge end of the digester, where effluent is released and the recirculation pump moves microbes to the influent end of the digester to inoculate recently-added food waste.

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[1] Heating of the digester via this solar panel is currently under evaluation

Figure 4. Food waste slurry (in white tank) is piped to digester

Figure 5. Discharge of effluent (PVC tube) and recycle pump (right)

The feeding protocol was as follows: First, 50 kilograms of food residue (as received from the dining facilities) was weighed in buckets, using a hanging scale. This feed was then dumped into an elevated tank located outside the greenhouse. Tap water was then added via garden hose to prepare a slurry of 77 gallons. After the feed was mixed and homogenized with a paint mixer connected to a power drill, a plug, located a few inches above the base of the tank, was removed and the feed flowed by gravity through PVC piping into the digester. Ball valves on the input and output ends of the digester were opened to enable feed to enter and digestate to leave the digester, respectively. While the new feedstock was added, effluent was allowed to flow from the digester freely at the effluent end. Once the fresh feed was added, a recirculating pump was run for a total of two minutes to move anaerobic microbes to the influent end of the digester, and thus inoculate the freshly added food residue to initiate biodegradation.

2.3. Sampling and Analysis

This study was conducted for 9 weeks from the first week of June through the first week of August 2016. Samples were collected during feeding events on Sundays, Tuesdays, and Thursdays, iced, and shipped to Bucknell University for analysis on Tuesdays, Wednesdays, and Fridays, respectively. Samples analyzed at Bucknell included feed slurry, digestate, recycle, and biogas, as shown in Figure 6.

Figure 6. Samples collected for analysis: feed (left), digestate (middle), recycle (right), gas (front)

The samples were collected as follows: The feed slurry sample was obtained from the feed tank immediately after mixing with the drill as completed. Before digestate exited the digester, the effluent pit was pumped down to a set level, denoted when the top of the effluent pit pump was exposed. As feedstock was added, digestate was allowed to stream from the digester freely. After all feed was added and digestate discharge ceased, the effluent tank was mixed and a digestate sample was simultaneously pulled from the tank. Following feeding, the recirculation pump was run for two minutes. The recirculation sample valve was flushed and the first sample was dumped before taking a sample within this two minute period. Finally, the gas sample was taken downstream of an H_2S scrubber, moisture trap, and gas meter. Before taking the sample, the valve on the gas manifold was opened and the adapter tubing was flushed. After some gas was allowed to flow out, a gas sample bag was connected to the tubing and filled with biogas.

The analysis of the digester included both operational and laboratory data. Gas production, as well as digester, greenhouse, and ambient temperatures were recorded daily at Dickinson Farm. The digester operators also recorded feed added (mass and volume) and performed titrations to determine pH, alkalinity and volatile acid/partial alkalinity (VA/PA) ratios on the days of feedings. At Bucknell University, the samples were further analyzed to determine other characteristics. The feed was characterized by total solids (TS), volatile solids (VS), chemical oxygen demand (COD), and total Kjeldahl nitrogen (TKN). Digestate and recycle samples were evaluated for total suspended solids (TSS), volatile suspended solids (VSS), soluble chemical oxygen demand (sCOD), and volatile fatty acids (VFAs). Finally, the analysis of the gas samples yielded the percentage of hydrogen, carbon dioxide, and methane present in the mixture.

Solids, COD, and TKN analyses were completed according to *Standard Methods for the Examination of Water and Wastewater*. Volatile fatty acids (VFAs) and methane content in biogas were determined via gas chromatography.

3. Results and discussion

3.1. Overview of the Dickinson College digester's performance

Table 1 provides a performance overview of the Dickinson College Farm's digester, including characteristics of the biogas, feedstock, and digestate samples.

Table 1. Overview of digester performance

	Average	**Standard Deviation**	**90% Confidence Interval**
Biogas			
m^3 Biogas/kg FR	0.146	0.022	0.010
% CH_4	65.0	1.41	0.472
m^3 CH_4/kg FR	0.096	0.016	0.008
Feedstock			
g TS/g FR	0.111	0.028	0.009
g VS/g FR	0.101	0.027	0.009
g COD/g FR	0.217	0.066	0.022
mg TKN/L FR	886	285	121
Digestate			
g TSS/g FR	0.056	0.081	0.027
g VSS/g FR	0.037	0.051	0.017
g sCOD/g FR	0.005	0.002	0.001
% COD removal	97.6	0.919	0.309
Note: FR refers to food residue			

3.2. Operation

Figure 7 shows the operational parameters of the digester, including pH, organic loading rate (OLR), VA/PA ratio, and bicarbonate alkalinity.

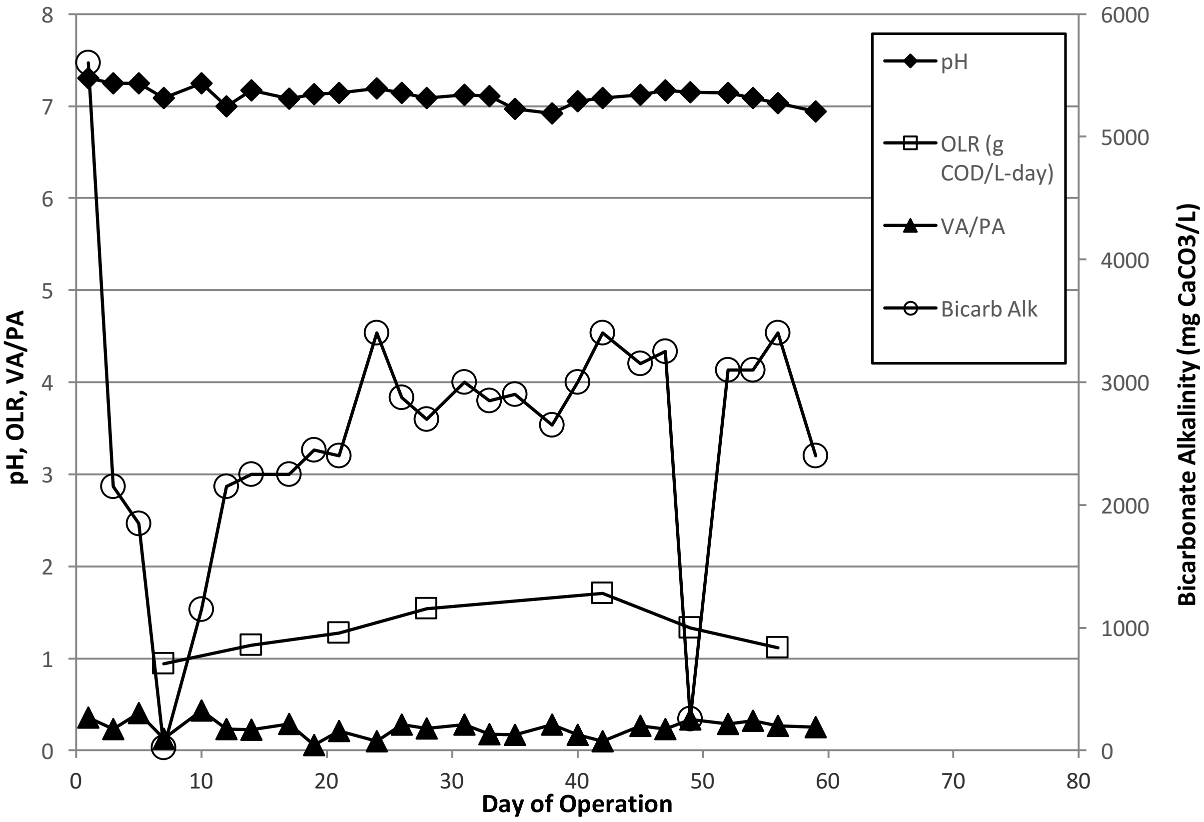

Figure 7. Operation parameters

Except the initial two weeks of the project, the hydraulic retention (HRT) was maintained at 29.9 days. This ensured that food residue remained in the digester long enough for biodegradation of organics into biogas.

The average organic loading rate (OLR) during the study period was 1.3 g COD/L-day. Based on experience with other full-scale digestion system, OLR of 1-2 g/L-day is considered typical of a low-rate anaerobic digestion process. Low-rate systems are often employed for biodegradation of particulate organic matter, which requires increased time for hydrolysis of non-soluble organics. Given a consistent feeding regimen and similar feedstock characteristics, organic loading rate is expected to remain constant. Since the amount of food residue fed to the digester remained fairly constant at 50 kg, the minor variations in OLR over the course of the study were due to variations in COD content of daily food residue from campus dining facilities.

Figure 7 also demonstrates increasing alkalinity and stable VA/PA ratios over the course of the study. Alkalinity is a measure of buffering capacity, or ability to resist changes in pH. Therefore, the digester's ability to resist decreases in pH progressively improved over the period of operation, most likely due to biodegradation of proteins in the digester. The VA/PA ratio remained consistently under 1. This means that volatile acids did not noticeably increase in comparison to alkalinity, and that the digester still had plenty of buffering capacity to resist pH changes. VA/PA is typically employed on-site to monitor the operation of a digester. The steady-state value is a function of feed type, OLR, and reactor configuration. In general, a low VA/PA is desirable and preferably well below 1.

Although bicarbonate alkalinity increased over the course of the study, a gradual decline in pH was observed. During the process of anaerobic digestion, organic matter is initially hydrolyzed and converted into volatile fatty acids by acidogenic bacteria. These acids are then converted into compounds which can be used by methanogenic microbes to produce renewable biogas. A decrease in pH is an indicator that acidogenic bacteria are producing acids faster than methanogenic bacteria can convert them into biogas. While a continued decrease in pH below 7.0 may be troublesome, the drop observed in pH in the Dickinson College Farm digester did not seem to negatively affect performance. There was no indication of an increase in specific volatile fatty acids (acetic, propionic, and butyric), and the digester's pH was still in an optimum neutral interval. However, at the end of the study, the pH eventually dropped below 7.0. According to O'Flaherty et al., the optimum operating range for anaerobic digestion is at pH 7.0-7.5 [1]. Above and below this pH range, inhibition of microbial growth may occur. Therefore, it would be problematic if the decreasing pH trend in the Dickinson digester continued. If this were to happen, it would be best to temporarily suspend feeding until the digester pH stabilized above 7.0.

3.3. Feedstock characteristics

Figure 8 shows values for total solids (TS), volatile solids (VS), and chemical oxygen demand (COD) in the feedstock throughout the study period.

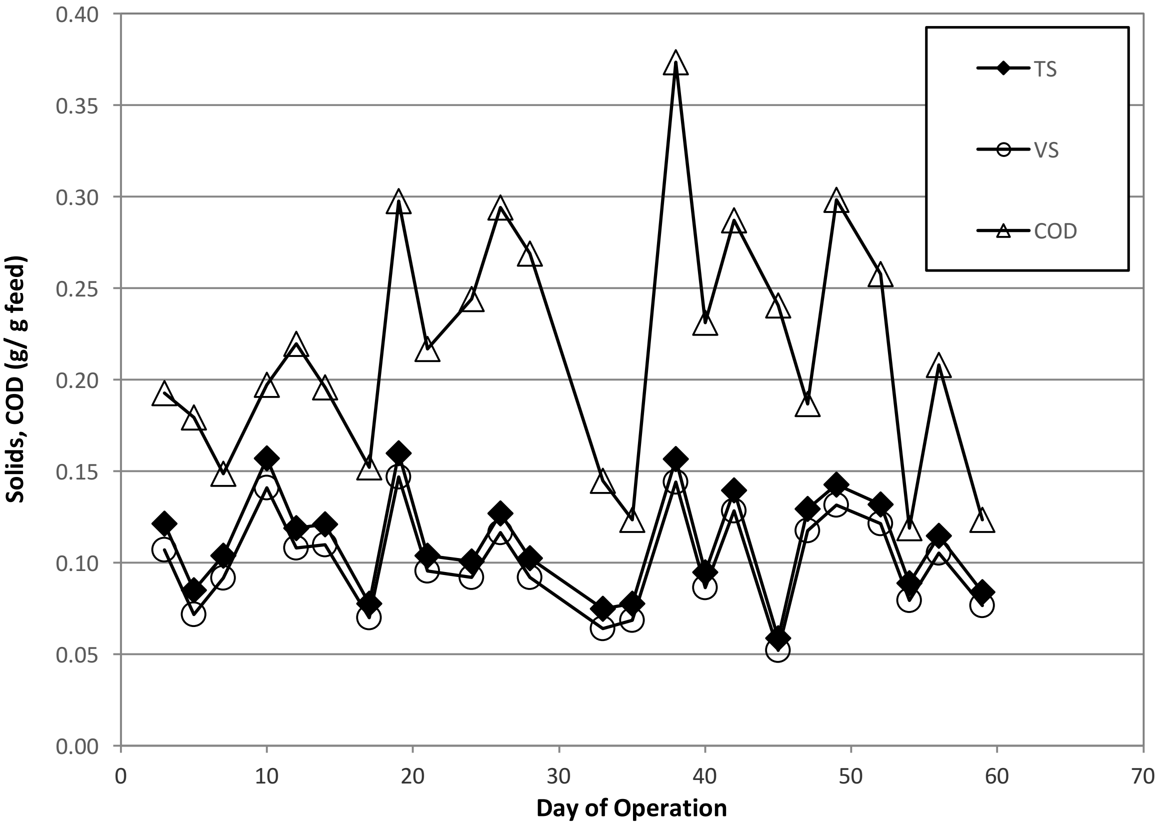

Figure 8. Solids and COD content in feedstock

Values for all three variables remained consistent over the operation period, with a total solids average of 0.11 g/g feed, a volatile solids average of 0.10 g/g feed, and a chemical oxygen demand average of 0.22 g/g feed. The slight variability seen in solids and COD is mostly the result of differences in the feedstock provided from Dickinson College. For example, food residue composed mainly of vegetables is likely to have different characteristics than residue composed primarily of meats or pastas. Figure 8 also shows that the feedstock had a high content of volatile solids, averaging 90% of total solids. Since the microbes break down volatile solids to produce biogas, a high VS content in the feed indicates a high potential for its conversion into methane.

The average total Kjeldahl nitrogen (TKN) in the feed was 886 mg/L, while the average total nitrogen in the feed was 911 mg/L. Total Kjeldahl nitrogen is the sum of nitrogen in ammonia and organically-bound forms, whereas total nitrogen includes TKN as well as nitrogen found in nitrite and nitrate forms. This means that essentially all of the nitrogen present in the feedstock existed in an organic form. In the digester, all organic N is typically converted to ammonium. Digestate (effluent from the digestate) is expected to contain only slightly less ammonia-N than the input food slurry, due to some microbial growth within the digester.

3.4. Digestate characteristics

Values for total suspended solids (TSS), volatile suspended solids (VSS), and soluble chemical oxygen demand (sCOD) in the digestate are shown in Figure 9.

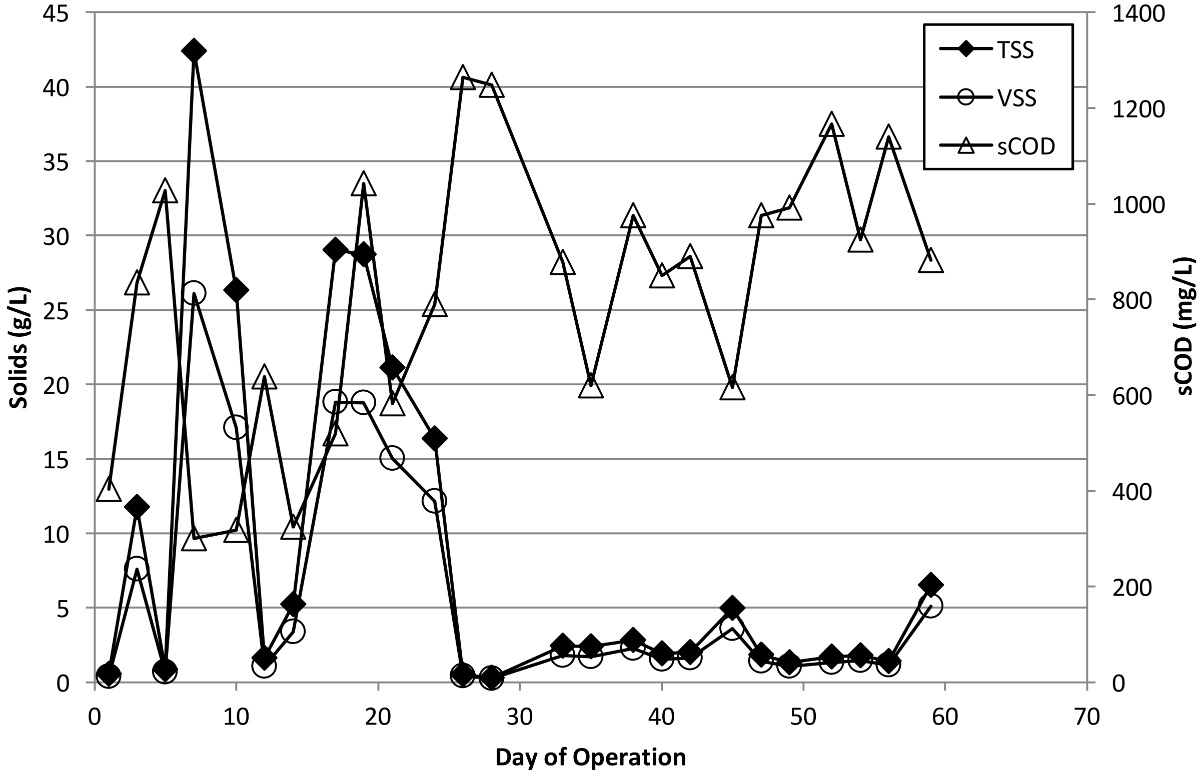

Figure 9. Solids and sCOD content in digestate

The average solids content in the digestate samples was 0.06 g TSS/g feed and 0.04 g VSS/g feed. The average sCOD was 808 mg sCOD/L digestate.

Over the first month of operation, significant variability in the digestate characteristics is evident. Since the operational HRT of the reactor was almost 30 days, the first month of digestate samples are characteristic of feedings prior to this study. Prior to the commencement of this study, no feeding routine had been enacted; the reactor was fed a couple buckets of feedstock every few days. There was inconsistency in mass and volume of feed added, frequency of feedings, and operational protocol. This irregularity likely contributed to this variation in digestate quality.

However, after the first month, the solids content of the digestate was very consistent. This is representative of more consistent lab analysis, operation, and sampling, and also indicative of the reactor approaching steady state performance. Since anaerobic digestion relies on the breakdown of solids to produce biogas, consistently low solids content in the effluent (digestate) represents the steady breakdown or organic matter by microorganisms. On average, the reactor destroyed 50% of solids. This reduction of solids content from feedstock to digestate is another indicator of good digester performance.

Figure 10 shows chemical oxygen demand in the feed, soluble chemical oxygen demand in the digestate and recycle, and percent COD removal from anaerobic digestion.

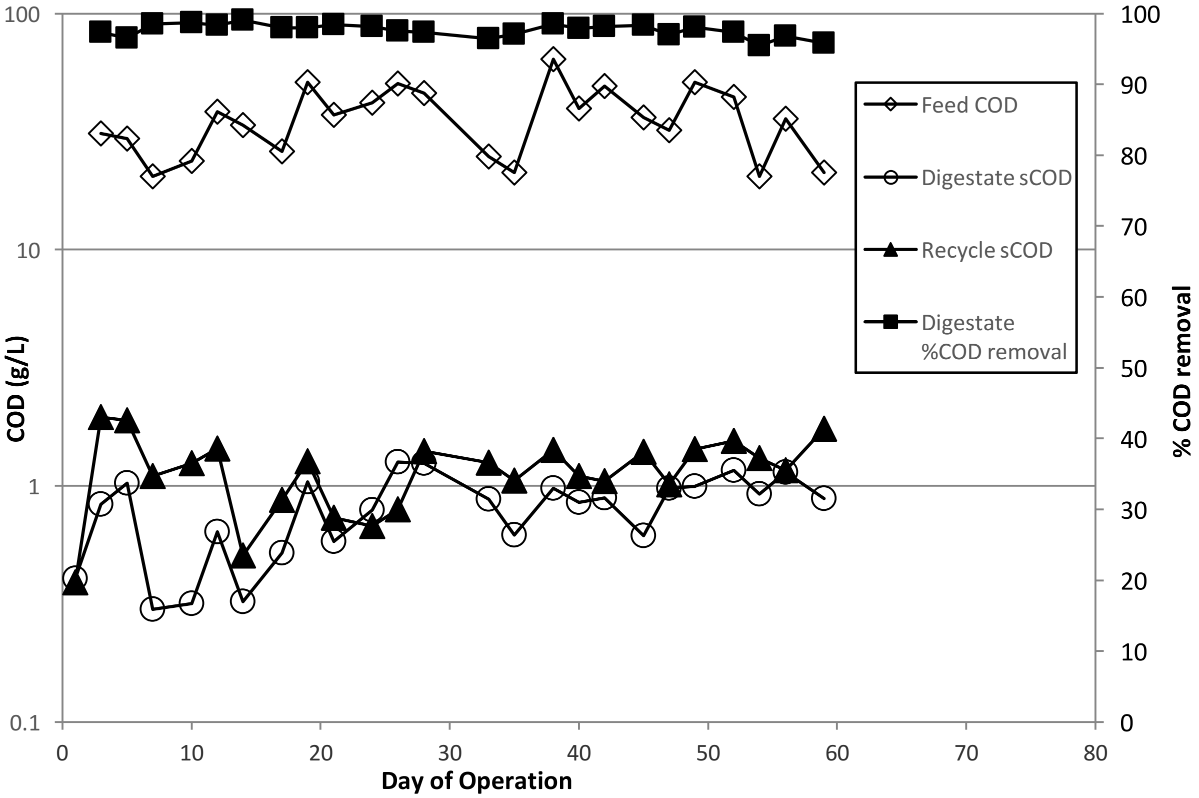

Figure 10. Chemical oxygen demand

While solids remained fairly constant after steady-state conditions were approached, sCOD in the digestate approached 1 g/L. However, COD in the feed appeared to increase slightly. Most importantly, even though chemical oxygen demand values differed in the feed and digestate samples, COD removal remained consistently above 95%. COD is a surrogate indicator of biodegradable organics, so high removal denotes significant conversion of organics to methane by the digester. Overall, over 95% COD removal by the digester indicates excellent performance.

3.5. Gas production

Figure 11 shows the biogas and methane produced per feeding, in addition to average percent methane.

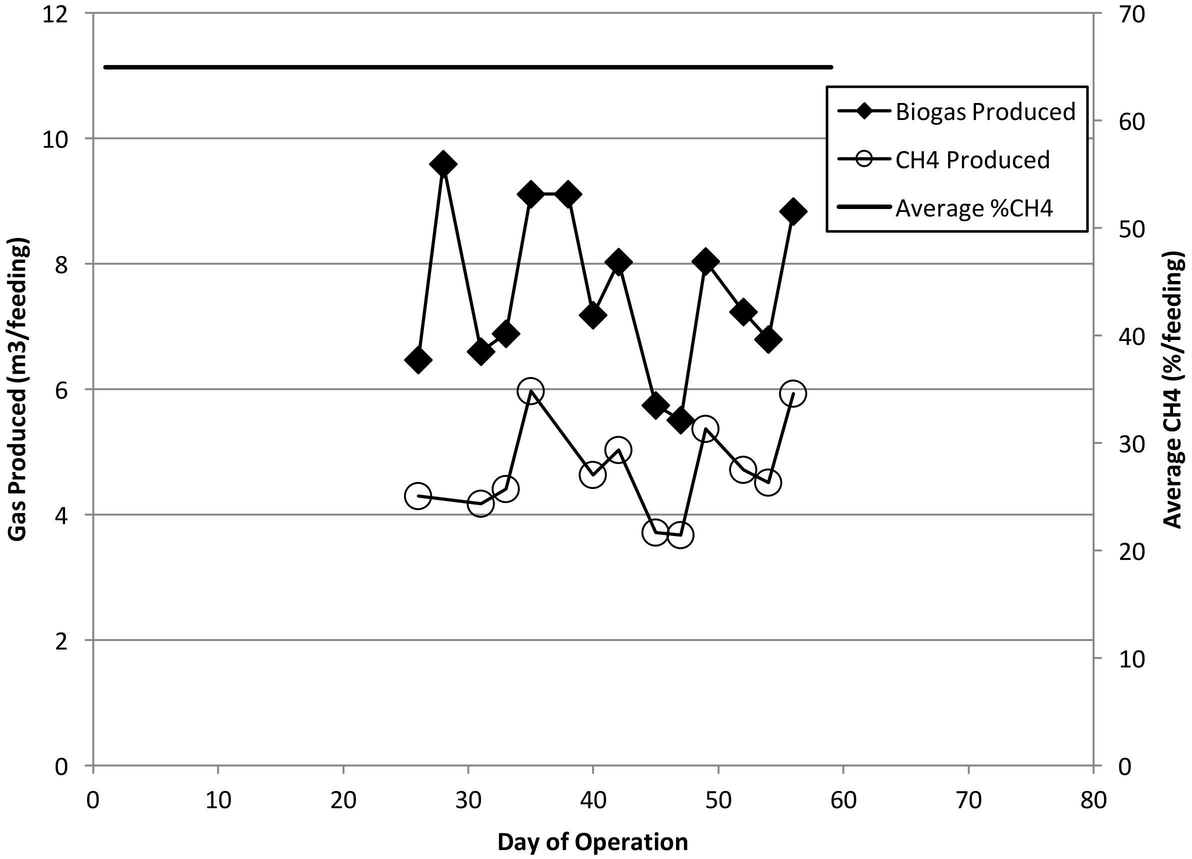

Figure 11. Gas production per feeding

Once the gas meter was installed (day 25), gas production was observed to be very consistent around 7.5 m^3 per feeding on average. Steady gas production illustrates that the system is more or less being operated under a steady environment (temperature, feeding, pH).

In addition to stable gas production, the gas samples exhibited respectable levels of methane; on average, the methane content in the resultant biogas was 65%. This methane content signifies typical methanogenic activity and conversion of organic matter into methane.

3.6. Effect of temperature

The Dickinson College Farm digester was operated in the mesophilic range, working at temperatures typically between 30-35ºC. Operating at such a range produces stable conditions for effective microbial function. In general, the digester operated at uniform temperature, only varying a few degrees from the average temperature of 32.8ºC. Temperature inside the digester affects microbial reaction rates. Thus, a consistent temperature range relates to stable conversion of feedstock into biogas. The consistent temperatures displayed by the Dickinson digester are an added indicator of efficient operation and digester performance. Furthermore, the minor deviations in temperature did not directly affect gas production or COD removal.

3.7. Dickinson College and Bucknell University Projections

Table 2 shows the projections for feed and digestate characteristics, gas and electricity production, and indirect greenhouse gas reductions if Dickinson College treated all of campus food residue via anaerobic digestion. Digester performance data was also employed to project potential full-scale food residue treatment at Bucknell University, for future consideration. These projections are based upon total annual food residue production estimates for both schools, as well as CHP (combined heat and power) efficiency and emission rates [3,5] and fossil fuel emission factors [6,7] provided by the Environmental Protection Agency (EPA). It was also assumed that the Bucknell food residue demonstrated the same characteristics as the Dickinson food residue. Since Bucknell University is a larger institution, it produces more food residue in a year, and thus has more potential to produce electricity and lower its carbon footprint. However, anaerobic digestion provides both schools with an opportunity to treat their food residue in a more sustainable way.

Using small-scale anaerobic digesters to treat all of their food residue would also give Dickinson and Bucknell opportunities to generate energy, which could be used on-site or sold to the grid. One of the significant end products in anaerobic digestion is biogas, which contains a high percentage of methane, typically gaging around 60%. Pure methane has a high heating value, which signifies a large quantity of energy released upon combustion. This energy is then utilized by CHP systems and turned into thermal and electrical energy, at an efficiency around 33% [5]. If anaerobic digestion is fully implemented at both schools, and Dickinson College obtains the capacity to generate power, electricity would be produced on-site. This production would reduce demands from local power plants to supply electricity, thereby reducing fossil fuel consumption. Therefore, greenhouse gas emissions avoided by Dickinson and Bucknell are deemed as "indirect."

Not only can Bucknell University and Dickinson College harvest energy from anaerobic digestion, but they can do so to a considerable extent. According to the U.S. Energy Information Administration (EIA) [4], the annual electricity consumption in the average U.S. home in 2014 was 10,932 kWh. That means that if Bucknell University treated all of its food residue through anaerobic digestion, it would produce enough electricity to power over two homes annually. Similarly, Dickinson College would produce enough electricity to power over one home annually. While not enough energy would be produced to meet the institutions' energy demands, the biogas produced would still substantially alleviate landfill tipping, transportation, and electricity costs.

Table 2. Dickinson College and Bucknell University Projections

	Dickinson	**Bucknell**
Annual Food Residue (kg)	77,318	303,907
Feed COD (kg/yr)	16,741	65,803
Gas (m^3/yr)	11,279	44,333
CH_4 (m^3/yr)	7,406	29,108
Digestate TSS (kg/yr)	4,312	16,950
Digestate VSS (kg/yr)	2,893	11,371
Digestate sCOD (kg/yr)	370	1,456
Electricity Produced (kWh/yr)^~	25,571	100,512
GHG reduced (kg CO_2 eq/yr)	10,006*	23,200`
^Assuming 33% CHP electricity efficiency [5]		
~Assuming composite high heating value of methane of 1,014.6 BTU/ft^3 [7]		
*Assuming total greenhouse gas emission rate of 862.68 lb. CO_2e/MWh, based on the total output emission rate of greenhouse gases in the RFCE eGRID subregion in 2012 [6]		
`Assuming greenhouse gas emission rate of 0.23 kg CO_2e/kWh from natural gas combustion [3]		

4. Conclusion

This study showed that the anaerobic digester operated at Dickinson College Farm demonstrates typical performance. The Dickinson digester demonstrated satisfactory solids destruction, high chemical oxygen demand removal, consistent temperatures and pH, typical methane content, and consistent gas production. If anaerobic digestion were implemented full-scale at both Dickinson College and Bucknell University, at this observed level of efficiency, many benefits would ensue, including a reduction in indirect greenhouse gas emissions, production of renewable energy, and reduction of landfill tipping (Bucknell) and transportation costs. From this analysis, implementation of such a pilot-scale digester at Bucknell University would be a worthwhile endeavor to further evaluate management of the University's food residue.

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