Title
Assessment of anaerobic co-digestion of food waste and wastewater solids for sustainable waste management in Yosemite National Park, USA

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Assessment of anaerobic co-digestion of food waste and wastewater solids for sustainable waste management in Yosemite National Park, USA

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in

Environmental Systems

by

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Abstract

The growing need for sustainable municipal solid waste treatment and energy production has driven the development of new waste management methods like co-digestion. Anaerobic co-digestion of food waste (FW) and wastewater solids (WWS) has been implemented at a few wastewater treatments plants to efficiently treat organic wastes and produce methane-rich biogas as an energy source. Yosemite National Park has an opportunity to design a new co-digestion facility with an upcoming upgrade to their local wastewater treatment plant in El Portal, California. The Park annually produces approximately 5 million tons of primary WWS and 1 million tons of FW waste, with a volatile solid ratio of 70:30 FW to WWS, or 70% FW. Diverted FW is currently sent to the Mariposa County landfill's compost facility. To measure the possible increase in biogas production associated with FW addition to WWS, a biochemical methane potential (BMP) test was done over 35 days under mesophilic conditions with treatment mixing ratios ranging from 0% to 100% FW on a volatile solids basis. Calculated annual methane production increased 3.25 times from 0% FW scenario (WWS only) versus a 70% FW scenario, translating to a potential increase in methane production at the wastewater treatment plant of 28,000 to 91,000 m^3/yr. Results showed that if the wastewater treatment plant also implemented combined heat and power to combust the increased biogas from 70% FW co-digestion, potentially 920,000 kWh/yr could be produced to cover all electricity and heating needs. This research demonstrates that Yosemite National Park could combine FW and WWS to sustainably manage their organic waste in line with their Zero Landfill Initiative, as well as produce enough energy to fully power the El Portal wastewater treatment plant.

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Introduction

A fundamental tenant for developing a sustainable society is summarized in Odum's (2007) first commandment of energy ethics for the survival of humans and nature: thou shall not waste potential energy. A significant source of untapped potential energy is the organic fraction of municipal solid waste (McCarty et al., 2011), the management of which is posing challenges worldwide (Hoornweg and Bhada-Tata, 2012). Global municipal solid waste production rates are accelerating at a faster pace than the rate of urbanization, with the amount of waste expected to nearly double from 1.3 billion tons in 2012 to 2.2 billion tons by 2025 (Hoornweg and Bhada-Tata, 2012).

The conventional approach to managing municipal solid waste in developed countries is landfilling, which stores the waste in highly engineered structures in the ground for hundreds of years (Ferronato and Torretta, 2019). An estimated 30-65% of global municipal solid waste is organic in nature (Ferronato and Torretta, 2019), an enormous source of potential energy that could be harvested via anaerobic digestion to produce methane-rich biogas (Appels et al., 2011). However, the organic fraction of municipal solid waste, which is mostly composed of food waste (FW), can be difficult to anaerobically digest because excessive volatile fatty acids lower the pH and impair the anaerobic digestion process (Nghiem et al., 2017). Co-digestion of organic municipal solid waste with other waste streams that have a buffering capacity has been proposed as a solution to the growing municipal solid waste management challenge (Appels et al., 2011; Braguglia et al., 2018). Mixing co-substrates of varying digestibility can help stabilize the anaerobic digestion process, producing a methane-rich biogas with high energy content while decreasing the mass of solid waste going to landfills.

Since the 1980s, landfills in the US have been engineered and operated to minimize environmental impact of solid waste, but there are still issues that make them unsustainable (Ferronato and Torretta, 2019; Powell et al., 2016). In landfills, the organic component of municipal solid waste rapidly biodegrades and produces methane under anaerobic conditions. Capturing and using landfill gas for energy use poses significant challenges (Powell et al., 2016). Current US regulations require landfills to report greenhouse gas emissions (US 40 CFR Part 98) and landfills built after 1980s are required to capture and manage biogas (New Source Performance Standards and Title V). Compared to biogas from wastewater solids, using landfill gas as a methane source is relatively challenging because of high hydrogen sulfide content (Rasi et al., 2007), which must be scrubbed out of the biogas because it is corrosive to the machinery (McCarty et al., 2011). Lastly, landfilling is costly, not only to municipal solid waste producers who must pay disposal tipping and transportation fees, but also for landfill operators who must manage leachate and greenhouse gas emissions from landfills for decades after closure (Ferronato and Torretta, 2019).

A more sustainable and energy-wise approach to managing the organic fraction of municipal organic solid waste is co-digestion with wastewater solids (WWS) (Appels et al., 2011; Braguglia et al., 2018; F. Xu et al., 2018). WWS typically consist of settleable solids collected early in the wastewater treatment process in a sedimentation basin and termed primary solids. Another source of WWS is microbial biomass, termed secondary solids, that is settled out of the wastewater stream after biological treatment processes such as an aeration basin. These solids are commonly treated using anaerobic digestion to reduce solids and odors, kill pathogens, and improve the solids dewatering, producing methane-rich biogas in the process (Parkin and Owen, 1986). Yet, like most landfills, many wastewater treatment plants (WWTPs) flare their biogas rather than harvesting the energy within the biogas, potentially due to the cost associated with converting biogas into electricity (McCarty et al., 2011; Shen et al., 2015). WWTPs have been deemed the perfect place to introduce co-digestion because many have excess digester capacity previously designed for overestimated, growing populations (Nghiem et al., 2017). In addition, many outdated WWTPs in the US need to be retrofitted (ASCE, 2017), giving waste managers the perfect opportunity to re-design treatment process to more efficiently and sustainably manage our waste products, with the aim to harvest more energy from organic wastes.

Linking organic solid wastes, much of which is made up FW (US EPA, 2018), with WWS via co-digestion provides several benefits and challenges. Previous studies show that FW produces more biogas and methane than other substrate sources like WWS or animal manure (Lisboa and Lansing, 2013; Moody et al., 2011). When captured and used to produce energy, biogas produced from WWS alone can typically offset 25-50% of a WWTP's energy consumption (McCarty et al., 2011; Nghiem et al., 2017). With the addition of organic solid waste, this value can increase to 100% or more, allowing the WWTP to become energy neutral (Nghiem et al., 2017; Shen et al., 2015). Increased gas production is not only the result of increased organic loading, but also a more robust microbial community that tends to develop under co-digestion versus mono-digestion conditions (R. Xu et al., 2018).

A commonly cited, large-scale anaerobic co-digestion project using WWS and municipal organic solid waste was implemented by East Bay Municipal District (EBMUD) in Oakland, California (Nghiem et al., 2017; Shen et al., 2015). The 38,000 m^3/d WWTP collects an estimated 120 metric tons per day of organic municipal waste consisting of restaurant and municipal fats, oils, and grease, vineyard waste, and food processing waste. Because of inert contaminants in restaurant and municipal FW, this waste source was discontinued around 2014, and other more consistent industrial food processing feed stocks were sought out (Carol Weir, personal correspondence; Barillo, 2017). Biogas is cleaned by removing moisture through chilling and siloxanes with activated carbon, and then is combusted and used to power a jet-engine turbine with a capacity of 11 MW. As a result, the plant is one of the first in the US to be energy neutral (Nghiem et al., 2017). Mainly through tipping fees charged to organic waste producers, the co-digestion facility produced $2 million in revenue for EBMUD in the 2012-2013 fiscal year (Shen et al., 2015). Other anaerobic co-digestion facilities also reportedly produce most of their profits through tipping fees (Satchwell et al., 2018; F. Xu et al., 2018).

This study focuses on calculating the potential to implement anaerobic co-digestion of FW and WWS at Yosemite National Park (YNP), a national leader in resource management and sustainability. YNP is implementing a Zero Landfill Initiative that aims to completely divert their solid waste away from landfills over the next decade. In addition, YNP is upgrading its existing 1,900 m^3/d WWTP that treats most of the Park's sewage. In this context, there is a significant opportunity to link the management of organic solid waste and WWS via anaerobic co-digestion. The objective of this study was two-fold. First, we performed a 35-day biochemical methane potential (BMP) test using varying ratios of restaurant FW and WWS from YNP, a key controller of biogas production rates, biogas quality, and anaerobic process stability. The co-digestion process is highly site specific and varies based on the source and quality of waste feeds (Lisboa and Lansing, 2013; Moody et al., 2011). In addition, standardization of BMP assay methods has not been established complicating interpretation of the literature (Montecchio et al., 2019; Raposo et al., 2012). Thus, a site-specific assessment of co-digestion was needed to inform potential co-digestion scenarios at YNP. Second, we critically assessed the mass and quality of WWS and FW produced in YNP to inform potential co-digestion scenarios. Based on the results, we modeled a potential scenario for the co-digestion of FW and WWS at YNP, predicting total methane production and energy production using a combined heat and power (CHP) system.

Methods and Materials

Study Site

YNP is located in the western Sierra Nevada mountains in central California, US and encompasses over 3,000 km^2 wildlands ranging in elevation from 600 to 4000 m. It is one of most popular wilderness destinations in the world, receiving on average 4 to 5 million visitors per year (NPS, 2017). The isolated location and large visiting population make waste management at YNP a challenge.

The Park produces an estimated 2,000 metric tons of landfilled municipal solid waste and diverts 4,200 metric tons of recyclables and organics (NPCA, 2015). This results in a 64% diversion rate close to California's 75% diversion goal for 2025 (California Bill, AB 341). YNP separates its recycling and organics from their landfillable waste and transports it to Mariposa County landfill, which also has a recycling and composting facility, approximately 71 km west of YNP. Currently, YNP produces 1,000 metric tons of FW that could be used for co-digestion (NPCA, 2015). Of that FW, 550 metric tons are sent for composting and are included in the diversion rate, and 450 metric tons are sent for landfilling and not included in the diversion rate.

YNP also produces an estimated 700,000 m^3/yr of sewage, most of which is treated at the El Portal WWTP on the western edge of the Park. The WWTP was designed in the 1960s and has had a few upgrades since it was built. Currently, the WWTP uses primary sedimentation (primary treatment), mixed aeration activated sludge (secondary treatment), sand filtration and ultraviolet disinfection. Another unique feature compared to municipal WWTPs is YNP's outdoor vault toilets. The park regularly pumps out the human waste from the vaults and transports them to the El Portal WWTP.

Precise monitoring of inflow of wastewater and biogas production is limited due to the age of the treatment plant. The WWTP has an average estimated annual inflow of 1,900 m^3/d and a treatment capacity of 3,800 m^3/d. The treatment process produces 5.1 million kg/yr of primary WWS that are first treated via anaerobic digestion, and then centrifuged and sent to a fertilizer facility. Excess secondary solids from secondary treatment is recycled back to the primary treatment process. Currently, biogas produced during anaerobic digestion is flared to the atmosphere with no energy recovery.

Sample Collection and Characterization

WWS from the primary clarifier were collected from El Portal WWTP in 7 L plastic buckets and stored at 4 °C. Inoculum was collected from the WWTP anaerobic digester and stored in the same way as the WWS. FW from YNP restaurants was collected from the Mariposa County landfill, specifically from the compost facility. FW was collected in a 22 L plastic storage bin and stored at 4 °C. FW was mixed in a food processor until a paste-like consistency was achieved. Visually, the FW consisted primarily of sandwich leftovers, melon rinds, and grilled chicken pieces with the bone. Some inorganic contaminants that were found included glass, plastic items, and metal bottle caps. Even though they are considered an organic waste, wax paper cups were also removed from the experimental FW feedstock. The focus of this study was on FW and wax paper cups were deemed outside the scope. Sorted and processed FW was sealed in a 7 L plastic bucket and stored in the refrigerator at 4 °C.

Inoculum, WWS, and FW were analyzed for total solids (TS) and volatile solids (VS) using standard methods one week before BMP test (APHA, 2005). Density for FW was measured by displacement method in a graduated cylinder. Inoculum and WWS pH were measured using a calibrated Mettler Toledo SevenCompact pH meter.

Biochemical Methane Potential (BMP)

BMP assays were performed according to Moody et. al (2011) with a few modifications. Treatments were also designed so that inoculum VS was equivalent to combined FW and WWS VS (1:1 VS ratio). Sleeve stopper septa sealed bottles were placed on an orbital mixer set to 150 RPM and incubated under mesophilic conditions (35 °C). BMP protocol was modified by excluding nutrient medium to balance micro- and macro-nutrients because studies have shown inconsistent BMP results when using nutrient media (Raposo et al., 2012). In addition, nitrogen gas flushing to initially clear the headspace was not used because studies have shown no significant change in BMP results using air compared to flushing with nitrogen gas (Raposo et al., 2011).

BMP tests are useful for comparing and predicting substrate methane potential (Moody et al., 2011; Owen et al., 1979). Experimental design focused on finding an optimal VS ratio of FW and WWS because high FW shows inhibition of methane production (F. Xu et al., 2018). BMP treatments were calculated on a FW:WWS VS ratio basis varying from 0% to 100% FW, while maintaining inoculum to substrate ratio 1:1 VS as stated earlier (Table 1). Treatments were designed with a focus on lower and higher FW to monitor edge effects. An inoculum only treatment was used as the control.

During the BMP assay incubations, biogas was monitored and measured every 1-5 days, depending on biogas production. Gas sampling consisted of collecting 17 mL or less of the biogas using a 30 mL plastic gas sampling syringe and storing it in 12 mL evacuated exetainer glass vials. The rest of the biogas volume was measured using a glass gas syringe with a 50 mL maximum volume. Gas volume of each assay was measured until the glass 50 mL syringe stopped moving, indicating the bottle was back to atmospheric pressure.

Gas composition was measured using a gas chromatography (GC) system (Trace 1300, S/N 119900-0115, Thermo Fishser Scientific) with an injection temperature of 250 ^{o}C, detector temperature of 300 ^{o}C, compressed air and hydrogen as the carrier gases, and a flow rate of 400 mL/min and 150 mL/min respectively. Original biogas samples were diluted 40 times by volume in a crimped 20 mL glass vial designed for the GC autosampler. A series of standard gas samples were prepared using 50% methane gas standard to develop the standard curve.

Data Analysis

Only methane yield was analyzed because methane is the best predictor of larger scale biogas production (Sell et al., 2011). Cumulative methane production was normalized by VS to give specific methane yield (mL CH_4/g VS) and by volume to give volumetric methane yield (mL CH_4/mL substrate added). Researchers normalize results using VS (specific methane yield), which is the most commonly published anaerobic digestion characteristic (Moody et al., 2011). Volumetric methane yield is a unit of measurement that is useful for anaerobic digester managers since they tend to operate digesters based on volumetric loading (Lisboa and Lansing, 2013). To convert FW from mass to volume, FW mass (g) was divided by the lab measured density (g/mL) to get the FW substrate volume (mL).

Based on normalized specific and volumetric methane yields, patterns of methane production were assessed using cumulative production as a function of %FW over the 35-day period. Methane yield as a function of FW:WWS ratio was statistically analyzed using linear regression from the base stats package in R software (version 3.5.2). *p*-values

<0.05 were considered significant. BMP results are reported as averages ± standard error (SE).

Results and Discussion

Waste Characterization

Quality of inoculum and feedstocks (FW and WWS) was characterized by measuring density, TS, and VS. Inoculum, WWS, and FW were similar in density (~1 g/mL) because they are primarily composed of water (Table 2). On a VS basis, FW has an order of magnitude more VS than WWS (0.31 g/g versus 0.029 g/g on a mass basis, 92% versus 75% on a percent basis). This shows that FW is a more potent feedstock than WWS. The experimental YNP FW density (1.10 g/mL) is higher than literature values ranging from 0.4 to 0.8 g/mL (Sundberg et al., 2011). Yosemite FW VS (92%) was within the range of other FW substrate studies which typically report values between 86% to 91% VS (Holliger et al., 2017; Koch et al., 2015).

Even though FW is more heterogeneous than WWS, FW VS do not vary considerably over time. One study looking at changes in restaurant, food market, and commercial FW VS content over one week from Monday through Friday showed no significant change in % VS (85.3 ± 0.65% standard deviation) (Zhang et al., 2007). Another study at two large-scale facilities also showed a small SE from FW samples from 5 different months (91.1 ± 2.0% and 90.7 ± 2.0%) (Holliger et al., 2017). This suggests that though FW was only sampled once for this experiment, and FW is considered heterogeneous, FW VS composition does not vary significantly enough to impact anaerobic digestion.

Annual waste production rate on a mass, TS and VS basis were calculated using annual values provided by El Portal WWTP for 2017 (George Harders, personal correspondence) and a report on YNP solid waste characterization study for 2014 (NPCA, 2015). On a mass basis, there are 5 times more WWS than FW (5,100,000 kg/yr WWS, 1,000,000 kg/yr FW) (Table 2). However, FW is double the WWS VS (320,000 kg/yr VS of FW, 150,000 kg VS of WWS) (Table 2). This shows that on a mass or volume basis, a relatively small volume of FW would be added to the WWTP anaerobic digester. Yet this relatively small volume would increase VS loading substantially and increase the mass of solids to be managed post anaerobic digestion.

Ideal VS ratio of FW and WWS for co-digestion is unknown. At YNP, the VS ratio of FW and WWS is potentially 2.1:1 FW:WWS VS, equivalent to approximately 70% FW. Reported ideal FW:WWS ratios maximize methane volume production and generally have been based on C:N ratio, but mass and volume are also used. Reported values ranging from 20:1 to 30:1 C:N ratios are found in the literature (F. Xu et al., 2018) and government recommendations (AgStar, 2012). A previous study found an ideal ratio of 61.3% pretreated sewage sludge, 28.6% FW, and 10.1% livestock manure, but the basis was not stated (Lee et al., 2019). Some management strategies recommend a VS loading rate, such as EBMUD, with a 3.5 kg VS/m^3·day (EBMUD, 2008), but the mixing ratio of FW:WWS was not stated. Since management of anaerobic digestion for methane production is monitored on a VS or volumetric basis, better reporting on mixing ratios is recommended.

WWS managed at El Portal WWTP and FW produced at YNP are highly dependent on the number of visitors at YNP, but the annual ratio of produced WWS and FW should remain relatively stable. Visitor attendance at the park is seasonal, with a peak season from May to August where monthly visitation is greater than 600,000 visitors/month (Fig. 1). It is interesting that the peak WWS volume is delayed by 1 month. This is most likely caused by the delay of solids flowing through the pipes from YNP to WWTP, following a delay of flowing though the WWTP. In addition, vaults in remote areas of the park are pumped post-peak visitation and trucked to the WWTP. We assumed that FW to WWS VS ratios remain constant throughout the year, and remain constant even day-to-day and month-to-month as supported by the literature (Holliger et al., 2017; Zhang et al., 2007). However volumetrically, based on peak summer visitation, a peak WWS production factor of 2 was calculated.

Biochemical methane potential (BMP)

In order to assess the effectiveness of BMP experimental design, pH and VS treatment efficiency were measured at the beginning and end of the BMP. pH remained unchanged from start to finish across all %FW treatments (Table 3). We define treatment efficiency as the percent reduction in VS. As %FW increased, the treatment efficiency increased slightly (85% to 92.1% reduction in VS) (Table 3).

We examined peak methane production to see if any %FW treatments showed slow rates of specific methane yield, inferring unfavorable conditions for anaerobic digestion. When methane production plateaus, it indicates substantially slower productivity due to microbes consuming all easily available VS. The point of plateau is considered the point of peak methane production. Ratios between 0 to 25% FW peaked after 10 days, followed by 50% FW after approximately 15 days, and then 75% FW after approximately 20 days (Fig. 2A). 90% and 100% FW had the slowest rate of methane production. 90% FW initially plateaued between 17 days and 25 days but continued to increase after and did not reach a peak (Fig. 2A). Similarly, 100% FW did not reach a peak after 35 days continued to produce methane (Fig. 2A). It is important to note that 75% FW produced the most methane during the initial 34 days; on day 35 the 75% and 100% FW treatments reached comparable methane production. This shows that the 90% and 100% FW treatments had some inhibition to produce methane because they had the slowest rate of methane production, but this internal resistance did not prevent them from ultimately reaching high volume of specific methane yield.

Similar patterns can be seen in average methane percent rates as well as peak methane production over the experimental period over the 35 days. High methane percent suggests that biogas quality is higher because it is more combustible and has more energy potential. Initially, 0 to 25% FW lines are higher in methane percent similarly to peak methane production discussed earlier (Fig. 4). After the first 10-days, higher percent methane switched to 75%, 90%, and 100% FW. This shows that quality of methane initially is higher in <50% FW treatments, but switches to >50% FW treatments after 10 days. Slower rates of methane production are seen in both specific methane yield peak rate and the average percent methane, showing an internal resistance to methane production in higher FW treatments, which could be associated with the primary solids inoculum.

Previous FW co-digestion studies have shown that inoculum is an important factor for anaerobic digestion success and can impact biogas production (Elbeshbishy et al., 2012; Raposo et al., 2012). One study compared FW anaerobic digestion using inoculum from a primary solids digester and inoculum from a FW anaerobic digester (Elbeshbishy et al., 2012). Their results showed that inoculum from a FW digester had lower methane yield than inoculum from a primary sludge digester (Elbeshbishy et al., 2012). Based on their results, using primary sludge inoculum did not cause a decrease in methane production for the 90% and 100% FW treatments. Instead of inoculum source, substrate composition is more responsible for the slower methane production.

First, we looked at the individual substrates: WWS (0% FW) and FW (100% FW) (171 ± 9.3 mL CH_4/g VS and 237 ± 16 mL CH_4/g VS respectively) (Table 3). The FW showed an almost 1.5 times specific methane potential compared to WWS. This shows that VS composition of FW produced more methane than the WWS. Literature reviews show similar results, however due to differences in BMP methods, comparing values is challenging. WWS, more specifically primary solids, only had one publication but normalization was done using total chemical oxygen demand (TCOD) (114 mL CH_4/g TCOD) (Elbeshbishy et al., 2012), and therefore cannot be compared to our value. YNP's FW falls within the range of published specific methane yield values ranging from 216 to 380 mL CH_4/g VS (Braguglia et al., 2018; Moody et al., 2011). Reviews of FW anaerobic digestion show that FW methane yield is highly variable when it comes to methane production, especially depending on FW quality such as composition, particle size, mixing, and if any pre-treatment method was used (Raposo et al., 2012; F. Xu et al., 2018).

Recent reviews on BMP methods have reported a lack of consistency among studies. Montecchio et al. (2019), a recent critial review of BMP studies, showed a lack of reporting on alterations to the three current standardized BMP methods (ISO, 1995; Moody et al., 2011; Owen et al., 1979). As previously discussed, mixing ratios in publications were rarely described and often unclear, especially when reporting whether a volumetric or VS basis was used. In addition, standardized BMP methods do not include the use of positive controls such as cellulose, which offer a quality control not only for individual BMPs but also to compare BMPs across experiments. Due to a lack of complete reporting and outdated methods used in many published BMP studies, comparing BMP studies should be done cautiously with these limitations in mind.

To analyze if co-digestion had higher methane production, we performed a linear model of specific methane yield as a function of %FW. Results showed a positive linear relationship with increasing %FW ($r^2 = 0.86$, $p < 0.01$, Fig. 2C). A linear relationship means that methane production using co-digestion is additive and not synergistic. Synergistic results would show a non-linear trend, more specifically showing a peak around 1:1 VS mixing ratio. For example, 50% FW would show a peak, indicating the best methane production was during co-digestion instead of mono-digestion (0% FW and 100% FW). Though it should be noted that those same studies showed synergism for kinetics (Astals et al., 2014; Xie et al., 2017). We see a possible synergism of kinetics in our peak rate results, where 75% FW had the highest peak methane as discussed earlier (Fig. 2A). Increased specific methane yield corresponds to increased %FW.

In addition to analyzing specific methane yield, we also analyzed volumetric methane yield because anaerobic digestion managers often use volume measurements for feedstocks (FW and WWS). 0-25% FW showed similar rates of methane production and overlap each other, peaking at approximately 15 days (Fig. 3A). 50% FW also peaked at approximately 15 days but did not overlap with 0-25% FW. 75% FW peaked at approximately 25 days. 90% FW shows an initial plateau from 17 to 25 days but continues to increase at the end of 35 days. 100% FW shows no plateau and also continues to increase at the end of 35 days. Volumetric peak rates show similar results to specific methane normalization, though the peak times are more delayed for volumetric methane yield. Both volumetric and specific methane yield show that as FW increases, peak rate is delayed, and more methane is produced.

Volumetric methane yield of FW and WWS were compared to see the difference in methane potential of the two substrates. Volumetric methane yield of FW (138 ± 9.6, 100% FW) is approximately 15 times more than WWS (8.30 ± 0.34, 0% FW). This is also close to FW (0.31 ± 0.02 g/g VS) having 10 time more VS than WWS (0.029 g/g VS). Due to high VS, a smaller volume of FW is needed to produce the same yield of methane than WWS.

Linear model of volumetric methane yield required logarithmic transformation of the methane production (y-axis), and also showed a linear increase in biogas production ($r^2 = 0.95$, $p < 0.01$, Fig. 3C). Both exponential and linear relationships show that there is no synergism for methane gas production using co-digestion instead of mono-digestion.

Comparing cumulative volumetric methane yield to cumulative specific methane yield shows similar results but does not show the differences in rates of methane production. Both methods show peak methane production delays as %FW increase. However, volumetric methane yield does not show decrease in quality of methane like specific methane yield and average percent methane show. The main takeaway is that FW is the more potent substrate due to higher VS and produces higher methane yield both specific and volumetric.

One other study used specific methane yield and volumetric methane yield and also showed similar results, though their experimental design was slightly different than the one in this study (Lisboa and Lansing, 2013). Lisboa and Lansing's study also showed that higher VS substrates produced the most methane in both specific and volumetric methane yield, in their case chicken waste. It also showed that acidic waste, in their case cranberry waste, inhibited methane production due to methanogenic toxicity.

Co-Digestion Energy Balance

Currently the El Portal WWTP produces an estimated 28,000 m^3/yr of biogas methane that is flared and lost to the atmosphere. This methane has an energy content of around 280,000 kWh/yr (Fig. 5). Anaerobic digestion facilities include two digesters with volumes of 870 m^3 and 390 m^3, with only the larger digester being used under typical operating conditions. The digesters are heated using electricity and net heating requirements are estimated at around 325,000 kWh/yr. Current electrical use at the plant is around 500,000 kwh/yr for digester heating and 200,000 kWh/yr for other plant operations. The park disposes of an estimated 375,000 kg/yr of biosolids by land application to non-consumable crops.

Waste mass balance indicates that 148,000 kg VS/year of WWS could be coupled with 310,000 kg VS/year of FW, yielding approximately a ratio of 70% FW to WWS. Volumetrically, this is equivalent to an annual average flow of 14 m^3/d of WWS and 2.5 m^3/d of FW. As noted earlier, there is a strong seasonal pattern to waste production that follows the Park visitation trend (Fig. 1) and a monthly peaking factor of 2 (ratio of peak visitors to annual average) was used for preliminary sizing estimates. Together, FW and WWS have an annual loading rate of 1.0 kg VS/$m^3 \cdot$d, or 2.0 kg VS/$m^3 \cdot$d during peak visitation, which is within the suggested loading range (Metcalf & Eddy, 2014).

Preliminary calculations show that the digestor volume required for co-digestion is 350 m^3 on average and 700 m^3 during the peak month when calculated using a 20-d hydraulic retention. Upper range of VS loading rates are around 4.3 kg VS/$m^3 \cdot$d (Metcalf & Eddy, 2014). Based on these estimates, the plant has the existing digester capacity to co-digest FW and WWS during peak months, though an extra 25% backup capacity may be needed. Resulting digester heating needs should correspond to the increase in flow rate and operating volume, which only increases by a factor of 1.25. Thus, net heating needs for the co-digestion scenario is around 410,000 kWh/yr.

Based on our BMP results, and accounting for the fact that BMP assays tend to overestimate methane production (Holliger et al., 2017), we estimate that co-digestion could produce around 91,000 m^3/yr of methane with an energy content of 920,000 kWh/yr (Fig. 5). This is an increase of over 3.3 times compared to current operating conditions. An efficient strategy to harvest energy from biogas is co-generation of heat and electricity from combined heat and power (CHP) technologies (McCarty et al., 2011; Metcalf & Eddy, 2014). A range of CHP systems are available including gas turbines, steam turbines, and reciprocating engines, the most common system in used for natural gas (US DOE, 2017).

For smaller CHP facilities, like WWTPs, micro-turbines or sterling engines are preferred though small reciprocating engines are also used (US EPA, 2014). Each system has a unique electrical efficiency and heat to power ratio. We assumed an average electrical efficiency of 30% and heat to power ratio of 1.5 (US DOE, 2017; US EPA, 2014). Based on an initial 920,000 million kWh, we calculated 70% FW co-digestion could produce 276,000 kWh of electricity and cover electrical use at the plant (200,000 kWh/yr) with an estimated 76,000 kWh/yr of excess energy (Fig. 5), which if converted to electricity could net around $10,000/yr. Current heating needs could be covered by the 441,000 kWh of heating potential, but methods to harness steam and warm water for digester heating is still unclear. Peak summer power production would be on the order of 250 kW suggesting that microturbine CHP or rich-burn reciprocating engine could be an appropriate technology (US EPA, 2014).

Additional Management Considerations

While the proposed scenario would benefit from no longer having to pay for transport and tipping fees for organic FW disposal, several additional issues would need to be assessed during a formal design of a co-digestion process for the El Portal WWTP. Separation of inert material from FW would add a new challenge. To use biogas in a CHP would require pretreatment of the gas to prevent air pollution emissions or damage to the engine. Lastly, there are additional organic sources of waste at the park that could be added to the waste stream as long as it is properly managed.

A significant challenge with organic solid waste is inert impurities (Nghiem et al., 2017). These impurities include glass and plastics that come from bottles and cutlery commonly related with FW, but also include natural FWs like shells and bones. Inert waste must be separated from organic waste because it takes up valuable digester space, decreases biogas potential, increases solids maintenance issues (e.g., increasing digester cleanout frequency), and hampers land application of biosolids which require low amounts of inert materials (Nghiem et al., 2017; Satchwell et al., 2018).

One issue with inert impurities is organic plastics made of biodegradable plastics that are not biodegradable under anaerobic conditions. The Park will need to re-evaluate the use and disposal of polylactic acid (PLA) plastic cups and utensils if it chooses to use anaerobic co-digestion. A preliminary study conducted on PLA dining materials from YNP showed very limited biodegradability over 35 days in replicate anaerobic digestion microcosms (Beutel and Burmistrova, unpublished). This agrees with other studies that have assessed the biodegradability of PLA plastics showing limited biodegradability under anaerobic conditions using BMP methods (Benn and Zitomer, 2018; Krause and Townsend, 2016). Pretreatment of PLA or thermophilic anaerobic digestion increased PLA biodegradability and biogas production, but full biodegradation was not seen in any study (L. F. Vargas et al., 2009). In fact, many of these studies tested landfill conditions and ran their BMP studies for >60 days. This means that even if pretreatment and thermophilic conditions are used, full biodegradability is not possible and pieces of PLA plastic will still be found after anaerobic digestion, negatively impacting digester operations. Some options include removing all plastics to prevent contamination or source separation either at YNP or at the organic waste storage location.

Biogas will also need to undergo pretreatment to remove moisture, sulfides and siloxanes before combustion and energy recovery via CHP (Shen et al., 2015). Moisture is removed using refrigerator cooling. Sulfides are removed using iron sponges. Siloxanes are removed using activated carbon. These methods are effective but need to be included in project development.

Finally, this study did not incorporate other organic wastes produced at YNP including manure, green waste, and kitchen grease for methane yield predictions using co-digestion. Manure (mainly composed of horse manure), green waste and kitchen grease have a specific methane potential of 222 mL CH_4/g VS (Kafle and Chen, 2016), 206 mL CH_4/g VS (Liu et al., 2009), and 650 mL CH_4/g VS (Grosser, 2018; Labatut et al., 2011). It should be noted that grease has an extremely varied specific methane yield in the literature ranging from ~400 mL CH_4/g VS (Labatut et al., 2011) to ~900 mL CH_4/g VS (Grosser, 2018), so a mean value of 650 mL CH_4/g VS was used for calculations. An estimated 550 metric tons of manure produced at YNP annually could produce around 55,000 m^3/yr of additional methane biogas. Green waste has an estimated 385 metric tons and kitchen grease has 28 metric tons, and both could produce 15,000 m^3/yr and 7,000 m^3/yr respectively. That is a total extra 77,000 m^3/yr of methane is possible using these additional organic wastes based on calculations using literature values. That is 2.75 times more biogas production than current conditions. It is safe to assume that these additional substrates will increase methane additively, however rate of methane production would be affected. Pre-testing of such substrate mixtures should still be done to check digestate quality to prevent digester shutdown.

Conclusion

YNP has a window of opportunity during an upcoming WWTP redesign to integrate anaerobic co-digestion to manage organic waste and produce biogas. Co-digesting FW with WWS is beneficial because WWS act as a buffer and FW increases biogas production. Mass balance shows a 70:30 FW:WWS VS ratio that produce 3.3 times more methane volume compared to WWS alone. That translates to a potential 276,000 kWh of electricity by CHP, enough to cover the current electrical usage in excess. Not only could co-digestion make the WWTP energy neutral, it also manages waste in line with the YNP’s Zero Landfill Initiative.

Tables

Table 1

Experimental design of volatile solids (VS) ratios by mass of food waste (FW) to wastewater solids (WWS). Inoculum to substrate ratio was kept consistent on a 1:1 VS volume ratio. Volume of FW and WWS was calculated using density in Table 2. Each ratio was prepared in 250 mL bottles and 150 mL of inoculum and substrate was incubated in triplicate at 35 °C.

Ratio	VS Ratio FW:WWS	Inoculum (ml)	Inoculum VS (g)	FW (g)	FW VS (g)	WWS (g)	WWS VS (g)
100% FW	1:0	143	2.00	6.22	1.93	0.00	0.00
90% FW	9:1	138	1.95	5.40	1.67	6.54	0.19
75% FW	3:1	130	1.84	4.24	1.31	15.41	0.45
50% FW	1:1	119	1.68	2.59	0.80	28.24	0.82
25% FW	1:3	110	1.56	1.20	0.37	39.18	1.14
10% FW	1:9	105	1.48	0.46	0.14	44.90	1.30
0% FW	0:1	102	1.44	0.00	0.00	48.47	1.41
Inoculum Only Control	*NA*	150	2.12	0.00	0.00	0.00	0.00

Table 2
Substrate quality and annual production rate summary. Density, total solids (TS), and volatile solids (VS) were measured in the lab (*n=3*) and averaged ± standard error (SE).

	Units	Inoculum	WWS	FW
Density	(g/mL)	1.01 ± 0.02	1.01 ± 0.17	1.10[b] ± 0.12
TS	(g/g)	0.022[a]	0.038[a]	0.32[a]
VS	(g/g)	0.014[a]	0.029[a]	0.31 ± 0.02
Annual Production	(kg/year)	NA	5,100,000	1,000,000
Annual TS	(kg/year)	NA	194,000	320,000
Annual VS	(kg/year)	NA	148,000	310,000

[a] *SE < 0.01*
[b] *(n=5)*

Table 3
Pre- and post-BMP characterization results including summarizing treatment efficiency and methane production averaged ± standard error (SE).

Ratio (% FW)	Pre-Assay VS (g/g)	Post-assay VS (g/g)	Decrease in VS (%)	Initial pH	Final pH	Cumulative CH_4 (mL CH_4/g VS)[b]	Cumulative CH_4 (mL CH_4/mL added)[b]	CH_4 (%)
0%	0.016	0.012	85.6[a]	7.09 ± 0.03	7.09 ± 0.01	171 ± 9.3	8.30 ± 0.34	54.6 ± 1.8
10%	0.016	0.012	86.0 ± 0.02	7.04 ± 0.01	7.12 ± 0.01	188 ± 7.5	9.88 ± 0.35	55.4 ± 2.0
25%	0.018	0.013	86.5 ± 0.01	7.08 ± 0.02	7.17± 0.02	188 ± 14	11.6 ± 1.0	54.8 ± 2.2
50%	0.020	0.013	88.3[a]	7.20 ± 0.02	7.18± 0.01	213 ± 14	19.7 ± 1.6	53.9 ± 2.6
75%	0.023	0.012	89.2 ± 0.01	7.29 ± 0.01	7.20± 0.01	239 ± 17	40.6 ± 2.8	53.4 ± 3.0
90%	0.025	0.013	90.8 ± 0.01	7.38 ± 0.09	7.31± 0.04	218 ± 29	63.6 ± 8.5	49.0 ± 3.4
100%	0.027	0.013	92.1[a]	7.30 ± 0.01	7.34± 0.10	237 ± 16	138 ± 9.6	50.0 ± 3.5

[a] *SE < 0.01*

[b] Linear regression shows a linear relationship, (p<0.01)

Figures

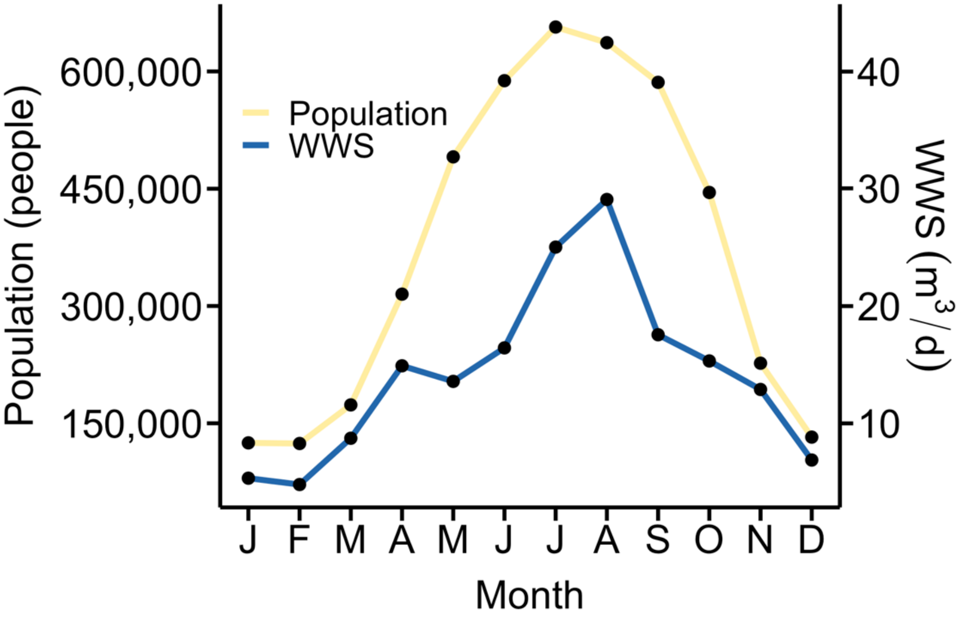

Fig. 1. Yosemite National Park population and El Portal wastewater solids (WWS) sent directly for anaerobic digestion for the year of 2017.

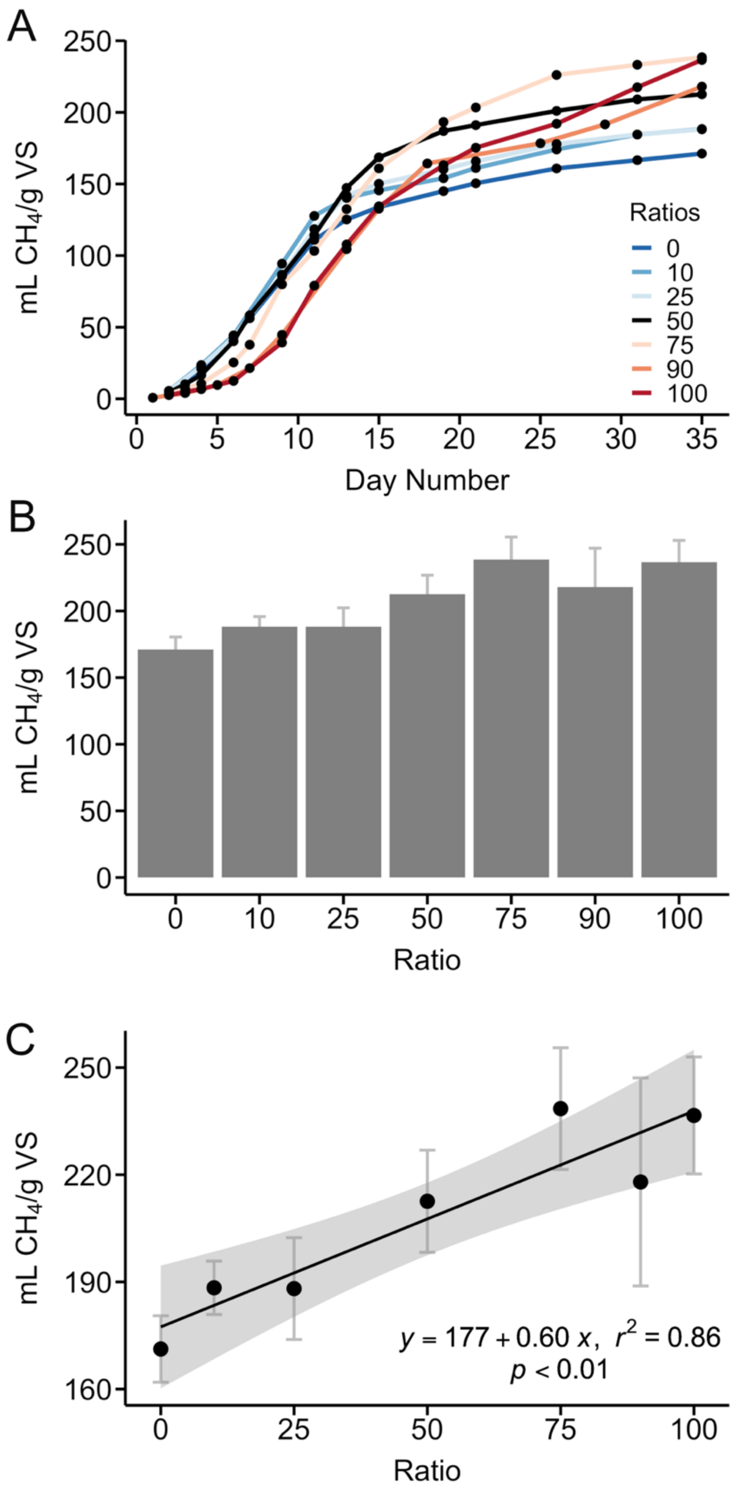

Fig. 2. (A) Cumulative methane volume normalized by substrate VS over 35 days; (B) Cumulative methane production normalized by substrate VS; (C) Linear regression model with cumulative methane production of FW ratios normalized by substrate VS including standard error (SE) ($p < 0.01$). Gray cloud shows 95% confidence interval.

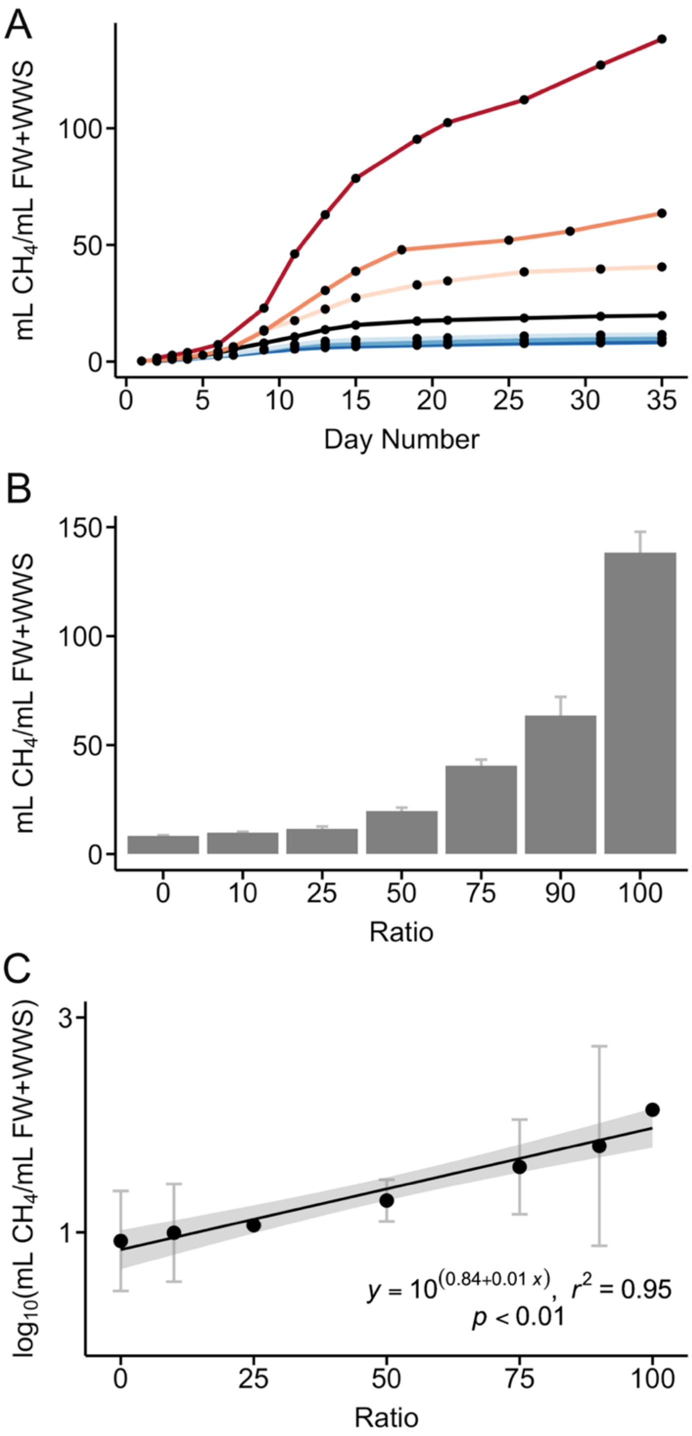

Fig. 3. (A) Cumulative methane volume normalized by substrate volume over 35 days; (B) Cumulative methane production normalized by substrate volume; (C) Linear regression model with cumulative methane production of FW ratios normalized by substrate including standard error (SE) ($p < 0.01$). Gray cloud shows 95% confidence interval.

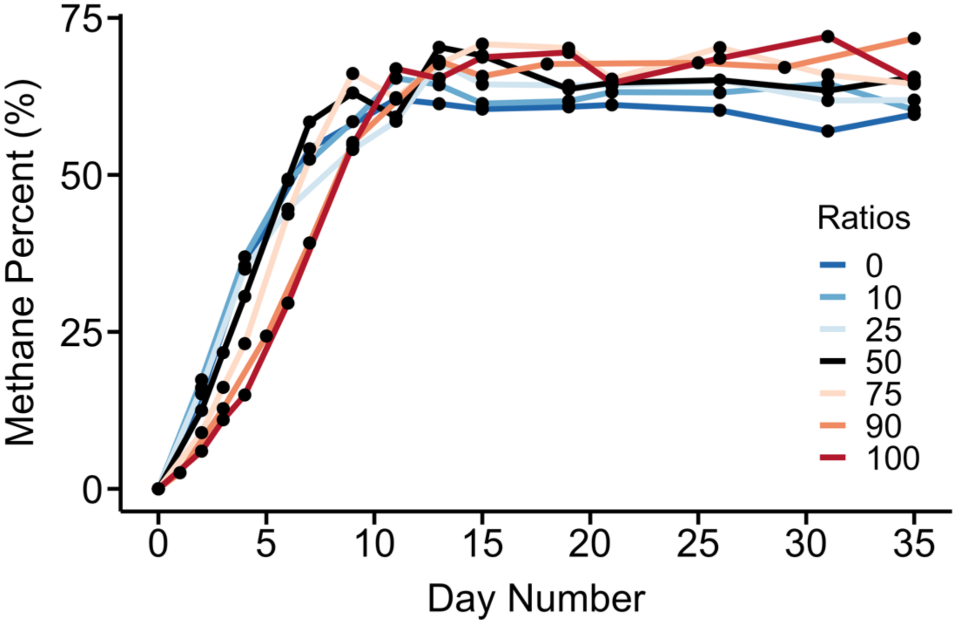

Fig. 4. Average methane percent (*n=3*) for FW ratios 0% to 100% (blue to red) over 35-day BMP.

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Supplemental Tables

Table S1

Summary of collection, processing, and set-up dates for biochemical methane potential test using Yosemite National Park food waste and El Portal wastewater solids and inoculum.

Material	Date Collected	Date Food Processed	Date Digesters Set-Up
Inoculum Wastewater Solids	9/18/18	Not applicable	10/26/18
Food Waste	9/28/18	10/5/18	

Table S2
Summary of ratio of percent food waste (FW) including inoculum only control (IO). Inoculum and WWS volume in each replicate bottle as measured during biochemical methane potential experiment set-up. Inoculum, WWS, and FW mass measured is also included.

Replicate	Ratio (%FW)	Inoculum (mL)	Inoculum (g)	WWS (mL)	WWS (g)	FW (g)
1	IO	150	147.43	0	0	0
2	IO	150	149.98	0	0	0
3	IO	150	149.84	0	0	0
1	100	143	142.5	0	0	6.24
2	100	143	142.49	0	0	6.21
3	100	143	142.1	0	0	6.25
1	90	138	136.26	7	6.67	4.95
2	90	138	136.17	7	6.87	5.21
3	90	138	136.14	7	7.02	5.49
1	75	130	128.85	16	15.59	4.26
2	75	130	128.76	16	15.41	4.24
3	75	130	128.74	15	15.79	4.3
1	50	119	117.21	28	28.68	2.58
2	50	119	117.02	29	28.28	2.56
3	50	119	117.38	31	28.22	2.61
1	25	110	108.92	40	39.24	1.2
2	25	110	108.85	45	39.61	1.24
3	25	110	108.76	39	39.29	1.18
1	10	105	103.33	45	44.96	0.44
2	10	105	102.94	46	45.07	0.45
3	10	105	103.66	45	44.85	0.46
1	0	103	103.93	46	48.46	0
2	0	103	100.04	48	48.53	0
3	0	103	100.01	48	48.79	0

Table S3
Summary of biogas volume sampled and methane percent corresponding for date and for replicate and percent food waste (%FW) treatments, including inoculum only (IO) control.

Replicate	Ratio (%FW)	Date	Day of Experiment	Biogas Volume (mL)	Dilution	Methane GC Value	Methane Percent (%)
1	IO	10/26/18	0	0	NA	NA	NA
1	IO	10/28/18	2	3	20	14.06	0.89
1	IO	10/30/18	4	7	20	67.02	7.45
1	IO	11/6/18	11	31	20	300.36	36.39
1	IO	11/8/18	13	3	20	85.26	9.72
1	IO	11/10/18	15	9	20	288.49	34.92
1	IO	11/14/18	19	9	20	317.15	38.47
1	IO	11/16/18	21	2.5	20	99.72	11.51
1	IO	11/21/18	26	11	40	227.85	27.40
1	IO	11/26/18	31	8	40	201.29	24.10
1	IO	11/30/18	35	12	40	202.28	24.23
2	IO	10/26/18	0	0	NA	NA	NA
2	IO	10/28/18	2	5	NA	NA	NA
2	IO	10/30/18	4	7	20	51.3	5.5
2	IO	11/6/18	11	29	20	299.1	36.2
2	IO	11/8/18	13	3	20	83.9	9.5
2	IO	11/10/18	15	9	20	275.5	33.3
2	IO	11/14/18	19	10	20	342.5	41.6
2	IO	11/16/18	21	2	20	72.0	8.1
2	IO	11/21/18	26	11	40	223.3	26.8
2	IO	11/26/18	31	7	40	170.0	20.2
2	IO	11/30/18	35	8.5	40	213.8	25.7
3	IO	10/26/18	0	0	NA	NA	NA
3	IO	10/28/18	2	5	20	25.79	2.34
3	IO	10/30/18	4	6	20	31.74	3.08
3	IO	11/6/18	11	29	20	298.15	36.11
3	IO	11/8/18	13	3	20	74.73	8.41
3	IO	11/10/18	15	9	20	259.45	31.32
3	IO	11/14/18	19	8	20	140.77	16.60
3	IO	11/16/18	21	2	20	69.86	7.81
3	IO	11/21/18	26	14	40	208.70	25.02
3	IO	11/26/18	31	4.5	40	113.61	13.23

3	IO	11/30/18	35	13.5	40	189.39	22.63
1	100	10/26/18	0	0	NA	NA	NA
1	100	10/28/18	2	167	40	59.06	6.47
1	100	10/29/18	3	79	40	110.30	12.82
1	100	10/30/18	4	56	40	147.40	17.42
1	100	11/1/18	6	86	40	282.84	34.22
1	100	11/4/18	9	204.5	40	477.66	58.37
1	100	11/6/18	11	253.5	40	542.03	66.36
1	100	11/8/18	13	169.5	40	519.39	63.55
1	100	11/10/18	15	162	40	568.36	69.62
1	100	11/14/18	19	148	40	564.74	69.17
1	100	11/16/18	21	66	40	479.33	58.58
1	100	11/21/18	26	98	40	557.41	68.26
1	100	11/26/18	31	175	40	601.37	73.71
1	100	11/30/18	35	86	40	552.57	67.66
2	100	10/26/18	0	0	NA	NA	NA
2	100	10/28/18	2	151.5	40	47.05	4.98
2	100	10/29/18	3	79	40	87.08	9.94
2	100	10/30/18	4	49	40	123.61	14.47
2	100	11/1/18	6	73	40	234.31	28.20
2	100	11/4/18	9	195.5	40	443.96	54.19
2	100	11/6/18	11	230.5	40	544.53	66.67
2	100	11/8/18	13	178	40	541.13	66.24
2	100	11/10/18	15	127	40	565.65	69.28
2	100	11/14/18	19	168.5	40	568.90	69.69
2	100	11/16/18	21	82	40	565.80	69.30
2	100	11/21/18	26	97.5	40	562.25	68.86
2	100	11/26/18	31	135.5	40	581.20	71.21
2	100	11/30/18	35	119	40	566.75	69.42
3	100	10/26/18	0	0	NA	NA	NA
3	100	10/28/18	2	182	40	51.5383	5.5347492
3	100	10/29/18	3	79	40	89.26	10.21
3	100	10/30/18	4	52	40	111.40	12.96
3	100	11/1/18	6	73	40	218.99	26.30
3	100	11/4/18	9	186.5	40	423.89	51.71
3	100	11/6/18	11	230	40	552.72	67.68
3	100	11/8/18	13	181	40	541.02	66.23
3	100	11/10/18	15	178	40	549.55	67.29
3	100	11/14/18	19	179.5	40	568.36	69.62

3	100	11/16/18	21	78	40	538.57	65.93
3	100	11/21/18	26	102	NA	NA	NA
3	100	11/26/18	31	113	40	580.92	71.18
3	100	11/30/18	35	154.5	40	471.05	57.55
1	90	10/26/18	0	0	NA	NA	NA
1	90	11/2/18	1	114	40	25.67	2.33
1	90	11/4/18	3	92	40	106.78	12.39
1	90	11/6/18	5	79.5	40	187.37	22.38
1	90	11/8/18	7	110.5	40	326.06	39.58
1	90	11/10/18	9	127.5	40	451.59	55.14
1	90	11/16/18	15	157	40	541.85	66.33
1	90	11/19/18	18	195.5	40	555.87	68.07
1	90	11/21/18	22	81.5	NA	NA	NA
1	90	11/26/18	25	86.5	40	552.23	67.62
1	90	11/30/18	29	54	40	552.17	67.61
1	90	12/6/18	35	176	40	598.79	73.39
2	90	10/26/18	0	0	NA	NA	NA
2	90	11/2/18	1	106.5	40	31.86	3.09
2	90	11/4/18	3	97	40	121.77	14.24
2	90	11/6/18	5	98	40	240.47	28.96
2	90	11/8/18	7	128	40	348.50	42.36
2	90	11/10/18	9	196.5	40	501.62	61.34
2	90	11/14/18	13	278	40	542.01	66.35
2	90	11/16/18	15	153.5	40	562.51	68.90
2	90	11/19/18	18	152.5	40	545.85	66.83
2	90	11/21/18	22	76	NA	NA	NA
2	90	11/26/18	25	58	40	565.24	69.23
2	90	11/30/18	29	90	40	556.66	68.17
2	90	12/6/18	35	100	40	593.08	72.69
3	90	10/26/18	0	0	NA	NA	NA
3	90	11/2/18	1	121	40	25.12	2.26
3	90	11/4/18	3	91.5	40	101.21	11.69
3	90	11/6/18	5	75.5	40	181.58	21.66
3	90	11/8/18	7	93	40	293.34	35.52
3	90	11/10/18	9	141	40	401.98	48.99
3	90	11/14/18	13	380.5	40	570.53	69.89
3	90	11/16/18	15	169.5	40	505.84	61.87
3	90	11/19/18	18	171	40	555.64	68.04
3	90	11/21/18	22	99.5	NA	NA	NA

3	90	11/26/18	25	88	40	544.66	66.68
3	90	11/30/18	29	75	40	535.53	65.55
3	90	12/6/18	35	132	40	564.03	69.08
1	75	10/26/18	0	0	NA	NA	NA
1	75	10/28/18	2	126	40	80.58	9.14
1	75	10/29/18	3	78.5	40	137.09	16.14
1	75	10/30/18	4	54	40	185.43	22.14
1	75	11/1/18	6	113	40	359.91	43.77
1	75	11/2/18	7	89	40	422.97	51.59
1	75	11/4/18	9	206	40	524.11	64.13
1	75	11/6/18	11	127.5	40	479.40	58.59
1	75	11/8/18	13	151.5	40	568.68	69.66
1	75	11/10/18	15	156.5	40	575.77	70.54
1	75	11/14/18	19	175	40	577.49	70.75
1	75	11/16/18	21	70.5	40	567.11	69.47
1	75	11/21/18	26	92	40	569.59	69.77
1	75	11/26/18	31	30	40	534.01	65.36
1	75	11/30/18	35	34	40	538.30	65.89
2	75	10/26/18	0	0	NA	NA	NA
2	75	10/28/18	2	135	40	83.28	9.47
2	75	10/29/18	3	77	40	143.73	16.97
2	75	10/30/18	4	54	40	205.96	24.68
2	75	11/1/18	6	125.5	40	376.98	45.89
2	75	11/2/18	7	82	40	447.15	54.59
2	75	11/4/18	9	238.5	40	541.44	66.28
2	75	11/6/18	11	130	40	553.80	67.82
2	75	11/8/18	13	153.5	40	542.35	66.40
2	75	11/10/18	15	129	40	567.60	69.53
2	75	11/14/18	19	153	40	579.19	70.96
2	75	11/16/18	21	43	40	509.13	62.28
2	75	11/21/18	26	94.5	40	579.61	71.02
2	75	11/26/18	31	39.5	40	539.12	65.99
2	75	11/30/18	35	25	40	518.68	63.46
3	75	10/26/18	0	0	NA	NA	NA
3	75	10/28/18	2	134	40	73.24	8.23
3	75	10/29/18	3	73.5	40	130.86	15.37
3	75	10/30/18	4	53.5	40	188.64	22.54
3	75	11/1/18	6	113	40	342.25	41.58
3	75	11/2/18	7	74	40	420.37	51.27

3	75	11/4/18	9	217	40	555.37	68.01
3	75	11/6/18	11	132.5	40	494.48	60.46
3	75	11/8/18	13	143	40	546.24	66.88
3	75	11/10/18	15	131.5	40	590.99	72.43
3	75	11/14/18	19	151	40	561.76	68.80
3	75	11/16/18	21	46	40	523.03	64.00
3	75	11/21/18	26	150	40	571.53	70.01
3	75	11/26/18	31	42.5	40	542.68	66.44
3	75	11/30/18	35	26	40	523.42	64.05
1	50	10/26/18	0	0	NA	NA	NA
1	50	10/28/18	2	111	40	112.12	13.05
1	50	10/29/18	3	82	40	186.97	22.33
1	50	10/30/18	4	62.5	40	259.17	31.28
1	50	11/1/18	6	151	40	438.66	53.54
1	50	11/2/18	7	84	NA	NA	NA
1	50	11/4/18	9	141	40	517.14	63.27
1	50	11/6/18	11	145	40	498.91	61.01
1	50	11/8/18	13	149	40	579.66	71.02
1	50	11/10/18	15	89	40	575.07	70.45
1	50	11/14/18	19	71	40	544.45	66.66
1	50	11/16/18	21	18	40	517.29	63.29
1	50	11/21/18	26	48.5	40	532.73	65.20
1	50	11/26/18	31	36	40	533.34	65.28
1	50	11/30/18	35	17	40	544.19	66.62
2	50	10/26/18	0	0	NA	NA	NA
2	50	10/28/18	2	116.5	40	110.43	12.84
2	50	10/29/18	3	80	40	179.58	21.41
2	50	10/30/18	4	60	40	263.32	31.80
2	50	11/1/18	6	139	40	356.41	43.34
2	50	11/2/18	7	93	40	470.28	57.46
2	50	11/4/18	9	128.5	40	512.79	62.73
2	50	11/6/18	11	155	40	479.48	58.60
2	50	11/8/18	13	149.5	40	563.13	68.97
2	50	11/10/18	15	73.6	40	545.91	66.84
2	50	11/14/18	19	86	40	434.87	53.07
2	50	11/16/18	21	18	40	539.07	65.99
2	50	11/21/18	26	42	40	526.32	64.41
2	50	11/26/18	31	39	40	506.04	61.89
2	50	11/30/18	35	15	40	539.14	66.00

3	50	10/26/18	0	0	NA	NA	NA
3	50	10/28/18	2	88.5	40	100.07	11.55
3	50	10/29/18	3	77.5	40	178.84	21.32
3	50	10/30/18	4	63.5	40	239.65	28.86
3	50	11/1/18	6	139.5	40	418.76	51.07
3	50	11/2/18	7	91.5	40	485.80	59.38
3	50	11/4/18	9	121.5	40	516.17	63.15
3	50	11/6/18	11	131	40	474.99	58.04
3	50	11/8/18	13	122.5	40	579.21	70.97
3	50	11/10/18	15	114	40	568.94	69.69
3	50	11/14/18	19	101	40	581.28	71.22
3	50	11/16/18	21	21.5	40	528.95	64.73
3	50	11/21/18	26	46	40	536.20	65.63
3	50	11/26/18	31	39	40	515.23	63.03
3	50	11/30/18	35	16	40	523.60	64.07
1	25	10/26/18	0	0	NA	NA	NA
1	25	10/28/18	2	88	40	129.92	15.25
1	25	10/30/18	4	135.5	40	302.02	36.59
1	25	11/1/18	6	114.5	40	319.54	38.77
1	25	11/4/18	9	224	40	320.37	38.87
1	25	11/6/18	11	143	40	480.45	58.72
1	25	11/8/18	13	98.5	40	562.45	68.89
1	25	11/10/18	15	40	40	527.51	64.56
1	25	11/14/18	19	40	40	510.36	62.43
1	25	11/16/18	21	29.5	40	541.68	66.31
1	25	11/21/18	26	48	40	520.53	63.69
1	25	11/26/18	31	27	40	506.15	61.91
1	25	11/30/18	35	16	40	518.58	63.45
2	25	10/26/18	0	0	NA	NA	NA
2	25	10/28/18	2	90	40	141.10	16.64
2	25	10/30/18	4	121	40	269.81	32.60
2	25	11/1/18	6	132	40	381.57	46.46
2	25	11/4/18	9	207	40	519.19	63.52
2	25	11/6/18	11	146	40	435.28	53.12
2	25	11/8/18	13	83	40	547.45	67.03
2	25	11/10/18	15	36	40	516.02	63.13
2	25	11/14/18	19	44	40	523.62	64.07
2	25	11/16/18	21	18.5	40	514.48	62.94
2	25	11/21/18	26	48	40	540.57	66.17

2	25	11/26/18	31	27	40	492.71	60.24
2	25	11/30/18	35	14.5	40	516.96	63.25
3	25	10/26/18	0	0	NA	NA	NA
3	25	10/28/18	2	86	40	138.94	16.37
3	25	10/30/18	4	128.5	40	295.34	35.77
3	25	11/1/18	6	113.5	40	397.37	48.42
3	25	11/4/18	9	212	40	488.67	59.74
3	25	11/6/18	11	139	40	521.16	63.77
3	25	11/8/18	13	89.5	40	552.78	67.69
3	25	11/10/18	15	26	40	535.70	65.57
3	25	11/14/18	19	39.5	40	541.16	66.25
3	25	11/16/18	21	20	40	518.70	63.46
3	25	11/21/18	26	50	40	534.17	65.38
3	25	11/26/18	31	31	40	517.93	63.37
3	25	11/30/18	35	15	40	482.96	59.03
1	10	10/26/18	0	0	NA	NA	NA
1	10	10/28/18	2	79	40	148.48	17.56
1	10	10/30/18	4	119	40	308.72	37.43
1	10	11/1/18	6	100	40	384.71	46.85
1	10	11/4/18	9	207.5	40	462.98	56.55
1	10	11/6/18	11	119.5	40	510.13	62.40
1	10	11/8/18	13	44.5	40	535.53	65.55
1	10	11/10/18	15	21	40	497.79	60.87
1	10	11/14/18	19	36	40	525.34	64.29
1	10	11/16/18	21	25	40	501.28	61.30
1	10	11/21/18	26	39	40	513.31	62.79
1	10	11/26/18	31	33	40	521.80	63.85
1	10	11/30/18	35	13.5	40	498.91	61.01
2	10	10/26/18	0	0	NA	NA	NA
2	10	10/28/18	2	75.5	40	144.45	17.06
2	10	10/30/18	4	117.5	40	306.24	37.12
2	10	11/1/18	6	100.5	40	411.16	50.13
2	10	11/4/18	9	207	40	496.71	60.74
2	10	11/6/18	11	125	40	540.21	66.13
2	10	11/8/18	13	47	40	520.43	63.68
2	10	11/10/18	15	20	40	492.42	60.20
2	10	11/14/18	19	34	40	508.30	62.17
2	10	11/16/18	21	27	40	515.51	63.07
2	10	11/21/18	26	55.5	40	512.64	62.71

2	10	11/26/18	31	38.5	40	531.13	65.00
2	10	11/30/18	35	16	40	499.39	61.07
3	10	10/26/18	0	0	NA	NA	NA
3	10	10/28/18	2	76	40	145.45	17.18
3	10	10/30/18	4	115	40	299.42	36.27
3	10	11/1/18	6	103.5	40	412.33	50.27
3	10	11/4/18	9	203.5	40	475.72	58.13
3	10	11/6/18	11	120.5	40	528.20	64.64
3	10	11/8/18	13	49	40	521.40	63.80
3	10	11/10/18	15	21	40	514.75	62.97
3	10	11/14/18	19	29	40	480.81	58.76
3	10	11/16/18	21	29	40	532.38	65.16
3	10	11/21/18	26	54	40	521.44	63.80
3	10	11/26/18	31	45	40	528.98	64.74
3	10	11/30/18	35	16.5	40	482.47	58.97
1	0	10/26/18	0	0	NA	NA	NA
1	0	10/28/18	2	56	40	116.27	13.56
1	0	10/30/18	4	114	40	297.69	36.06
1	0	11/2/18	7	147	40	436.49	53.27
1	0	11/6/18	11	196	40	457.78	55.91
1	0	11/8/18	13	49	40	484.08	59.17
1	0	11/10/18	15	31	40	512.40	62.68
1	0	11/14/18	19	41	40	485.77	59.38
1	0	11/16/18	21	20.5	40	507.48	62.07
1	0	11/21/18	26	36.5	40	497.69	60.86
1	0	11/26/18	31	17.5	40	509.95	62.38
1	0	11/30/18	35	19	40	489.53	59.85
2	0	10/26/18	0	0	NA	NA	NA
2	0	10/28/18	2	64	NA	NA	NA
2	0	10/30/18	4	110	40	310.87	37.69
2	0	11/2/18	7	151.5	40	451.67	55.15
2	0	11/6/18	11	211	40	522.51	63.93
2	0	11/8/18	13	55.5	40	502.74	61.48
2	0	11/10/18	15	33	40	488.96	59.78
2	0	11/14/18	19	40.5	40	510.46	62.44
2	0	11/16/18	21	22	40	507.82	62.11
2	0	11/21/18	26	40	40	487.83	59.63
2	0	11/26/18	31	23	40	433.19	52.86
2	0	11/30/18	35	17	40	483.77	59.13

3	0	10/26/18	0	0	NA	NA	NA
3	0	10/28/18	2	60	40	141.37	16.67
3	0	10/30/18	4	110.5	40	270.97	32.74
3	0	11/2/18	7	149	40	442.75	54.04
3	0	11/6/18	11	200	40	541.48	66.29
3	0	11/8/18	13	55	40	517.49	63.31
3	0	11/10/18	15	35	40	482.43	58.96
3	0	11/14/18	19	45	40	496.17	60.67
3	0	11/16/18	21	19	40	484.77	59.26
3	0	11/21/18	26	42	40	493.67	60.36
3	0	11/26/18	31	30	40	456.00	55.69
3	0	11/30/18	35	17	40	489.95	59.90