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Pilot-scale biogas production in a temperate climate using variable food waste

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ABSTRACT

Low-input, household-scale anaerobic digestion (AD) is practical for rural energy generation, but the heating and maintenance of such systems has prevented the use of this technology in temperate climates. This study quantified the temporal variation of fuel production from an unheated, pilot-scale (2 m^3) anaerobic digester in southeastern Ohio, USA. The feedstock for the digester consisted of ground, mixed pre- and post-consumer food waste collected daily and diluted to 10% solids with rainwater collected on site. Fuel production varied from 7.96×10^{-6} to 8.45×10^{-2} m^3 CH_4 $kgVS^{-1}_{added}$ following three separate inoculations over the course of two years. The positive relationship between ambient air temperature, biogas yield, and biomethane production rates for both years was a dominant driver affecting fuel quantity and quality. Biogas quality produced from variable feedstocks in these conditions was poor, with an average volumetric methane (CH_4) content of 20% and an average CO_2:CH_4 ratio of 7.8. Methane yields did reach 50% during the warm seasons, but this yield was not consistently maintained. Despite low energy yields that resulted from the wide range of ambient temperatures (−18 °C–33 °C) and variable feedstocks, we achieved a moderate energy return on investment relative to previously published results describing AD system energy requirements. Pilot-scale, unheated AD systems using mixed food waste can be effective in temperate regions, but the systems should be managed to compensate for seasonal temperature changes and feedstock chemistry.

1. Introduction

Anaerobic digestion (AD) is a waste management technology used to recycle organic waste materials and produce methane-rich biogas. Biogas from AD is a renewable fuel generated from a variety of organic substrates (feedstocks), and is thus an important technology for both the treatment and recycling of growing solid waste streams. Purified biogas is a drop-in fuel that can replace natural gas, an increasingly important fossil fuel for the global energy supply [1]. Previous literature investigates potential biogas production from homogenous waste materials [2], as well as mixtures of materials (i.e., codigestion) [2–5]. We currently know much less about the feasibility and expected ranges of biogas production using mixed, non-uniform and temporally variable feedstocks in pilot-scale systems and temperate climates, as most studies investigating the effects of variability still focus on characterizing performance outcomes under sets of stable conditions [6,7]. Overall, the literature emphasizes maximizing potential digestion outcomes via various forms of controls on the process and/or the feedstock(s), while the effect of a variable feedstock (such as food waste streams encountered in practice at the community or household scale) and process instability have been relegated to a category of 'things to avoid'. In this study, we determine the biogas production rates from a pilot-scale, unheated anaerobic digestion system using unsorted variable food waste, and assess the response of this system to the ambient temperature changes that characterize a temperate climate.

AD is comprised of a series of concurrent biological processes all conducted by microbial populations with individual physical and biological preferences [2,8,9]. There are four key stages of anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The initial step of hydrolysis is often considered rate limiting to biogas production and has been repeatedly tied to the hydraulic retention time, pH, moisture content and particle size of the digestion substrate

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[10–13]. Intermediate chemical by-products can also inhibit the different microbial communities and hinder optimal biogas yields. It is well established that excess buildup of lipid degradation products like fatty acids and nitrogen compounds like ammonia, and the concomitant alteration of the pH, inhibit the function and viability of the hydrolytic and methanogenic communities in particular [4,11,14]. This is especially true when digesting high nitrogen content feedstocks like food waste [13,15].

The process of AD can be manipulated to increase organics conversion via changes in digester designs, operating temperatures, codigestion and substrate pre-treatments, and/or organic loading rate and hydraulic retention times [9,16], yet all changes are a balance of the factors affecting the key microbial populations involved, not all changes are easily made to extant systems, and the monitoring of any effects is generally expensive and time consuming. The microbial activity that facilitates each stage of anaerobic digestion is also temperature-dependent, and highly variable temperatures have the potential to disrupt the stages in AD [8,17,18]. The rate and total amount of products yielded from the microbial community in an AD system is therefore likely to decline with frequent temperature changes; however, the thermal inertia of material within a digester, as well as the ability of the microbial populations to retain metabolic capacity as temperatures vary, could mitigate declines in biogas production rates associated with ambient temperature fluctuations [19].

Food waste, both pre- and post-consumer, is a high quality organic material for biogas production because the molecular composition is biologically compatible with the microbial communities that facilitate AD [20,21]. Food waste is also readily available - the United States generated 37.1 and 38.4 million tons of compostable food waste in 2013, and 2014, respectively [22,23]. Despite the potential for recycling, food waste had the smallest reported rate of diversion from landfilling relative to other municipal solid wastes, with only 4.8%, 5.0%, and 5.1% recovered and composted in 2012, 2013 and 2014, respectively [22,23]. This is a substantial waste stream available for diversion, recovery and reuse in AD systems. While food waste is an excellent source of easily digestible compounds and thus a good feedstock for enhancing biogas yield in AD systems [24], the performance dynamics of pilot-scale, unheated AD systems that depend on mixed and unsorted food waste is still uncertain. Pilot-scale systems designed for distributed energy production and organic waste diversion could have a significant impact on the organic fraction of municipal solid waste in low-income, rural US communities, but issues with biogas quality and quantity need to be resolved before widespread adoption can be considered.

Previous research on food-based AD has shown that the high nitrogen content of most food waste mixtures predispose digesters towards nitrogen inhibition, ammonia accumulation and low pH, and souring, necessitating low organic loading rates and other remediation strategies to manage the carbon to nitrogen (C:N) imbalance within the digesters [2,14,15]. Another strategy is to manage inhibition and souring using codigestion with materials like animal waste or energy crops that balance the C:N of the primary feedstock (in this case food waste), although published optimums for C:N ratios in food waste vary from 12 to 70 [4]. Such a wide optimum C:N ratio provides theoretical flexibility for the use of unsorted food waste as a feedstock, but the wide range also indicates a need for further refining the optimum C:N for feedstocks, particularly for use in systems with variable environmental conditions. The design of the digesters, the timing of the stages of digestion, and the choice and handling of feedstocks used in AD systems all affect biogas production, with methanogenic activity typically maximized when environmental conditions remain relatively stable [25].

We know that AD systems perform optimally when temperatures are consistent, as the majority of methanogenic microbes are meso- and thermophiles with growth temperature ranges between 35 °C and 91 °C [25]. Thus, the minimum temperature optimums for biomethane production present a challenge for low energy input AD systems in temperate climates [26,27]. The sustainability of AD systems requires minimizing the energy inputs for heating, sorting and pre-treating the waste feedstock, while simultaneously increasing the biogas quantity and quality. Predictable energy balances on a scale commensurate with the available waste stream and environmental conditions are essential for realizing this technology.

In this study, we resolved biogas yields resulting from variable inputs and seasonal temperatures in an AD system operated inside a passively heated greenhouse in Athens, Ohio, USA. Our primary goal with this research was to understand biogas yields from a low-input, passively heated system with variable, unsorted food waste as a feedstock. We designed the small-scale system to operate off-grid in a greenhouse with on-site rainwater collection to reduce energy inputs. We quantified the variability in biogas yield over the course of two years, sampling through seasonal temperature shifts. This study evaluated the effect of variable ambient temperatures on fuel yields from a pilot-scale anaerobic digester, filling an important gap in knowledge needed to advance the potential application of AD technology in temperate climates and rural areas [28].

2. Materials and methods

2.1. Site description and climate

The experimental AD facility is located within a small greenhouse structure immediately adjacent to a Class 2 composting facility on The Ridges in Athens, Ohio. Outside air temperature data were collected from the OHIO weather station located 2 km northeast of the AD facility, which recorded meteorological conditions every hour. HOBO dataloggers inside the greenhouse enclosure, one situated at ground level and another installed 1.2 m above ground level, record the air temperature and light intensity every 30 min, beginning in April 2016. Weather data used for analysis in this study were the daily average, minimum, and maximum day and night (as defined by sunrise and sunset) temperatures recorded from the OHIO weather station (2015 and 2016) and from within the greenhouse (2016 only).

Athens, Ohio (39.32° N 82.1° W, elevation 226 m) is located in the plant hardiness zone 6, with an average annual (winter) minimum temperature range of −23.3°C to −20.6°C (USDA Plant Hardiness Zone, 2012, http://planthardiness.ars.usda.gov/PHZMWeb/). The OHIO weather station recorded average temperatures of 22.2°C for summer 2015, and 23.6°C and 2.2°C for summer 2016 and winter 2016, respectively. Seasonal differences described in the remainder of this text refer to the equinox and solstice dates of March 21, June 21, September 21, and December 21.

2.2. Digester

The pilot-scale AD system was built in the spring of 2015, tested and optimized during the months of June and July, and consistent data collection began in August of 2015. The system included a cylindrical geomembrane digestion vessel made from 1 mm flexible polyvinyl chloride (PVC) that contained approximately 2 m^3 of liquid material with an equivalent area of headspace (Viogaz Inc., Costa Rica). The digester was installed partially belowground with the liquid level inside the digester flush with ground level. The digester had one, 7.6 cm diameter PVC inlet connected to a hopper suspended 1.2 m above ground level, which was controlled with a ball valve on the digester end and a gate valve immediately underneath the hopper. The two valves ensured a consistent air seal during substrate additions. There were three outlets on the digester: 1) a 7.6 cm outlet at ground level, including a ball valve followed by a 50 cm deep passive siphon with a pressure relief port in the event of excess gas accumulation; 2) a 10 cm sludge port that drains from the bottom of the digester, sealed with a ball valve; and 3) a 5 cm gas outlet at the top of the vessel (Fig. 1).

The digester occupied a 1.8 × 2.7 m area in the corner of a 3.7 × 7.3 m greenhouse constructed with an aluminum frame and 6 mm twin wall

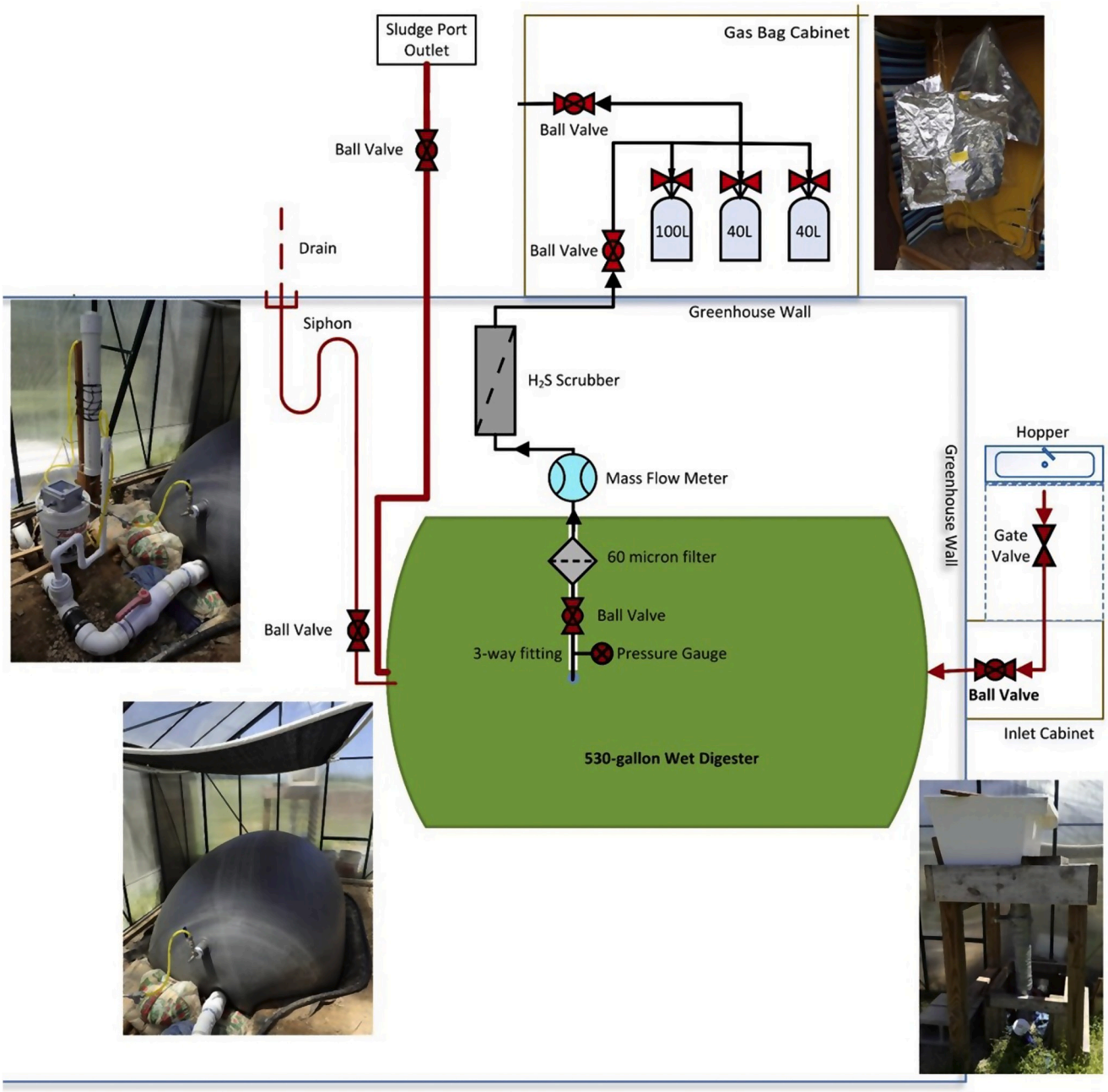

Fig. 1. Schematic of the pilot-scale anaerobic digester, with red lines representing PVC plumbing and fittings, and black lines representing stainless steel plumbing and fittings. Pictures of the features are overlaid adjacent to their counterparts within the schematic drawing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

polycarbonate panels (Juliana Gardner 21.4 Greenhouse, International Greenhouse Company). A 1.8 × 2.4 m shade panel (Shatex 90% black, Wellco Industries, Corona, CA, USA) was suspended 1 m above the top of the digester to protect the digester from UV damage. The inlet and outlets were plumbed to originate/terminate outside of the greenhouse structure so that all material handling occurs outside of the enclosed greenhouse space.

2.3. Inoculum

Initial inoculations of the digester were accomplished with healthy reactor digestate from nearby industrial AD facilities (Quasar Energy Group; Independence, OH); the digester was subsequently operated as a plug flow system with discrete daily inputs. Due to several minor modifications of the system design (to allow more efficient gas sampling), the digestion vessel was replaced twice, resulting in three distinct inoculation events. Inoculation material was collected from commercial digestion units operated by Quasar in Columbus, OH (typically digesting 33% food waste, 33% grease waste, and 33% biosolids) and in Wooster, OH (digesting wastewater). We installed and inoculated the first digester on June 16, 2015 with approximately 760 L of healthy effluent from the Quasar Columbus, Ohio plant (pH 7.96, VFA/TIC 0.57) and 190 L of rainwater collected at our experimental facility. We halted operations for the winter at the end of November 2015.

A new digester unit with an improved sludge port (for sampling solids from the bottom of the vessel) was installed in May 2016 with an initial inoculation of approximately 950 L of healthy effluent from the Quasar Wooster, Ohio plant (pH 7.9, VFA/TIC 0.21). One 38 L addition

of pig manure was added to supplement microbial AD activities upon startup on May 24, 2016. The pig manure was collected from a local farmer in Athens, Ohio. As gas production rates accelerated in early summer, resistance in the gas line resulted in an irreparable rupture of the digester on June 25, 2016. We replaced this digester with an identical unit (and a gas out line with a larger diameter), which was installed and inoculated on September 30, 2016 with approximately 950 L of healthy effluent from the Quasar Columbus, Ohio plant (pH 8.14, VFA/TIC 0.4).

2.4. Feedstock

We fed the digester once every day with a feedstock comprised of unsorted food wastes collected from the Ohio University Athens campus and rainwater collected on site. Ohio University collects pre- and post-consumer food waste from all of its dining halls and food preparation locations on the Athens campus for in-vessel composting. For this study, we collected 8 L daily of fresh food waste from the commercial mixer at the university composting facility after the entirety of the daily food waste intake was mixed, ensuring that the material fed to our experimental digester represented a truly mixed sample of unsorted university food waste. The food waste was then ground using one of two grinding machines: a commercial meat grinder with a 4.5 mm steel plate sieve (Weston PRO Series #22, 750 W, 1HP), or a custom commercial paper shredding unit modified for processing wet materials equipped with 5/32-inch wide blades. The material processed with either machine was functionally equivalent in size. Between July and November 2015, we added approximately 57 L weekly (in three, 19 L batches spaced throughout the week) of post-fermentation brewery waste (i.e., trub) from Athens, OH microbreweries.

In total, daily inputs to our AD system amounted to an average of 20.7 L (±10.6 L) at an average moisture content of 10% solids (±5%). For the study period we had an average organic loading rate of 1.1 $kgVS_{added}\ m^{-3}\ d^{-1}$ (±0.5 $kgVS_{added}\ m^{-3}\ d^{-1}$) and an average hydraulic retention time of 116 days (±12 days). Prior to the daily feeding, we adjusted the substrate moisture content to approximately 90% using rainwater collected on site, and the pH to between 6.5 and 8 using sodium bicarbonate.

Samples of influent (raw food, brewery waste, and pig manure) and effluent digestate were periodically collected and analyzed throughout the 2015 and 2016 measurement campaigns. Liquid samples of all materials were homogenized with a food processor and diluted to 1% solutions for detection of total nitrogen, total phosphorus, and chemical oxygen demand (COD) via digestions and HACH spectrophotometric methods 10072, 10127, and 8000 respectively (HACH, https://www.hach.com/). To assess moisture and nutrient contents, samples were dried in a 105°C oven for 24 h [29]. After drying, samples were ground to powder and analyzed for carbon (C) and nitrogen (N) content using a Costech ECS 4010 CHNSO analyzer equipped with a 3 m HAYESEP Q 80/100 MESH column and a TCD (Costech Analytical Technologies, Inc., Valencia, CA). Ash content was determined by combustion at 550°C for 24 h [29]. Average characteristics of digestion materials are described in Table 1.

2.5. Biogas capture, storage, and analysis

Biogas produced from the digester filtered through a 1 m gastight length of 10 cm (4 inch) diameter PVC pipe packed with iron sponge (Connelly-GPM, Inc., Chicago, IL, USA) to remove hydrogen sulfide. The biogas then passively filled 40 L and 100 L ALTEF gas collection bags with polypropylene valves and septum fittings for sampling (Restek Corporation, Bellefonte, PA, USA). Biogas bags were closed when they reached their known-volume capacity. Rates were calculated from the final volume and the time it took the bag to fill. Gas samples were collected from each full bag to determine the composition of carbon dioxide (CO_2) and CH_4 in the biogas. Gas samples were stored with positive pressure in 10 mL serum vials fitted with crimped, gastight 20 mm butyl rubber septa; sample vials were stored in refrigeration (2.8°C) and analyzed within 2 weeks of collection. Biogas samples were analyzed with a gas chromatograph using FID and TCD detectors for the simultaneous determination of CH_4 and CO_2, respectively (Bruker Daltonics, Billerica, MA, USA); gas production rates were normalized to standard temperature and pressure and reported as volumetric content.

2.6. Analysis and statistics

Volumes of food waste were converted to mass using a conversion factor of 3.8 pounds per gallon (i.e., 1.72 kg per 3.79 L) as defined for "food waste – university" by EPA [30]. We determined ash content in a time series of 20 subsamples of mixed food waste via combustion at 550°C and then used the average ash content (5.3% ash) to calculate volatile solids (VS) contents. Average moisture content and ash content were also calculated for each feedstock separately (Table 1) to determine dry mass and grams of volatile solids for all individual inputs.

Immediately following digester installations and inoculation events (i.e., stabilization periods), biogas would regularly contain negligible concentrations of methane before methanogens became productive. During these discrete start-up periods (lasting no longer than 14 days), any measurements with <1% CH_4 in the biogas were excluded from statistical analyses. Relationships between the mass and percentage of CH_4 and outside air temperature were determined with correlation analysis. Differences in CH_4 generated during different seasons were determined using analysis of variance (ANOVA) and Tukey's honest significant difference (Tukey's HSD) tests. All statistics were performed with R version 3.4.1 [31].

Table 1
Analytical analysis of inputs and outputs for the pilot-scale anaerobic digester during the 2015 and 2016 field seasons; averages are shown.

Content Type	Total Solids (%)	Carbon (%)	Nitrogen (%)	C:N[a]	Total Nitrogen (mg N L^{-1})[b]	Total Phosphorus (mg P L^{-1})[b]	Chemical Oxygen Demand (mg L^{-1})[b]
Inoculum							
Quasar (N = 4)[c]	6.7	28	4	7.6	12700	5870	
Pig manure (N = 2)	26.5	29	2	12.6	5550	6945	
Feedstock Inputs							
Food waste (N = 60)	27.9	53	6	17.2	1900	300	76500
Brewery waste (N = 29)	10.4	69	9	8.8	6641	2808	218966
Digester Output (N = 17)	5.2	36	2	21.2	3629	999	94386

[a] Average of the ratios calculated for individual samples taken during the 2015–2016 field seasons.
[b] Determined using a test tube digestion and spectrophotometric method.
[c] Average of material from Columbus (6/16/2015) and Wooster (5/24/2016).

3. Results

3.1. Biogas production rates and CH_4 content

Overall, the biodigester produced an average of only 0.136 m^3 CH_4 $kgVS_{added}^{-1}$ over the course of the study period with an average volumetric CH_4 content of only 20%. Biogas production rates and maximum daily temperature were significantly correlated in both 2015 and 2016 ($p < 0.001$). There was also a significant relationship between the CH_4 content of the biogas and the maximum daily temperature for both years (Fig. 2; $p < 0.001$, $R^2 = 0.3182$), as well as the season ($p < 0.01$, not shown).

Average seasonal temperatures for summer and fall did not vary significantly by year but were associated with significantly different CH_4 contents of the biogas ($p < 0.05$). Post-hoc Tukey HSD tests were used to resolve significant differences between CH_4 content of the biogas by season regardless of year ($p < 0.05$, Table 2), with average temperatures of 28°C, 28°C, and 16°C corresponding with CH_4 percentages of 10.7%, 27%, and 23% in the spring, summer, and fall seasons, respectively. The mean CO_2:CH_4 ratio of the biogas was similar in both years and remained similar across seasons in 2015. There was a strong contrast between seasons in 2016, when mean seasonal CO_2:CH_4 ratios were at least 10-fold higher in fall than in spring or summer ($p < 0.001$; Table 2).

3.2. Energy production dynamics

Total energy production, as measured in megajoules (MJ), was positively related to outside air temperature, but with significantly different slopes in the relationship observed in 2015 ($p < 0.001$, $R^2 = 0.1632$) than in 2016 ($p < 0.001$, $R^2 = 0.3277$), as shown in Fig. 3. Energy produced was positively correlated to the proportional CH_4 content of the biogas ($p < 0.001$, $R^2 = 0.4177$). The amount of chemical energy produced per unit of VS added was significantly related to the day of year ($p < 0.001$, $R^2 = 0.5687$) and did not vary between years (Fig. 4). The relationship between outside air temperature and day of year shown for both years in Fig. 4 was best expressed by a second-order polynomial ($R^2 = 0.7194$, $p < 0.001$). Day of year serves as a metric for the time since inoculation, and the rising temperature during this period was an important factor affecting AD.

Gas samples collected in the first 14 days of digestion that yielded <1% CH_4 were excluded from both the visualization and the statistical analyses, but a trend with time since inoculation persisted throughout the sampling. Fig. 5 shows the chemical energy yield per unit VS added as it relates to the day since an inoculation event. Energy production increased significantly with time since an inoculation ($p < 0.01$). The inoculation event in May of 2016 (period 2, Quasar Wooster material) yielded a unique pattern of gas production, with positive biogas production starting at day 8 as opposed to days 16 and 30 for inoculation periods 1 and 3 (both Quasar Columbus material), respectively, and a greater positive slope ($p < 0.01$) than the other two inoculation periods. However, overall average CH_4 production per unit VS added was not significantly different between inoculation periods 1 and 2 according to a post-hoc Tukey's HSD test ($p < 0.01$), with overall rates in periods 1 and 2 averaging over 5-fold greater than the average from period 3. Periods 1, 2, and 3 lasted 160, 32, and 83 days, respectively.

4. Discussion

Energy yield from the AD system tested in this study was variable, but most strongly correlated with ambient outside temperatures. The source of inoculum also appeared to influence biomethane production, but this response was confounded with temperature effects. In order to assess energy cost and production, we calculated an energy return on investment (EROI) metric by balancing the energy required to operate our system and the energy produced by the system. Despite the suboptimal CH_4 percentages in the biogas produced, and the low levels of biogas produced relative to theoretical potentials, the EROI was relatively high due to the extremely low energy inputs required for the AD system design. Given this result, we posit that pilot-scale, unheated systems thus have potential value in temperate regions with a variable feedstock.

The pilot-scale AD system yielded very low levels of biogas and biomethane relative to theoretical estimates. The low fuel yields were most likely due to: 1) the frequent changes in system temperature, 2) the lack of system mixing leading to issues with inhibition and souring, 3) variation in inoculum quality, and 4) our reliance on post-hoc

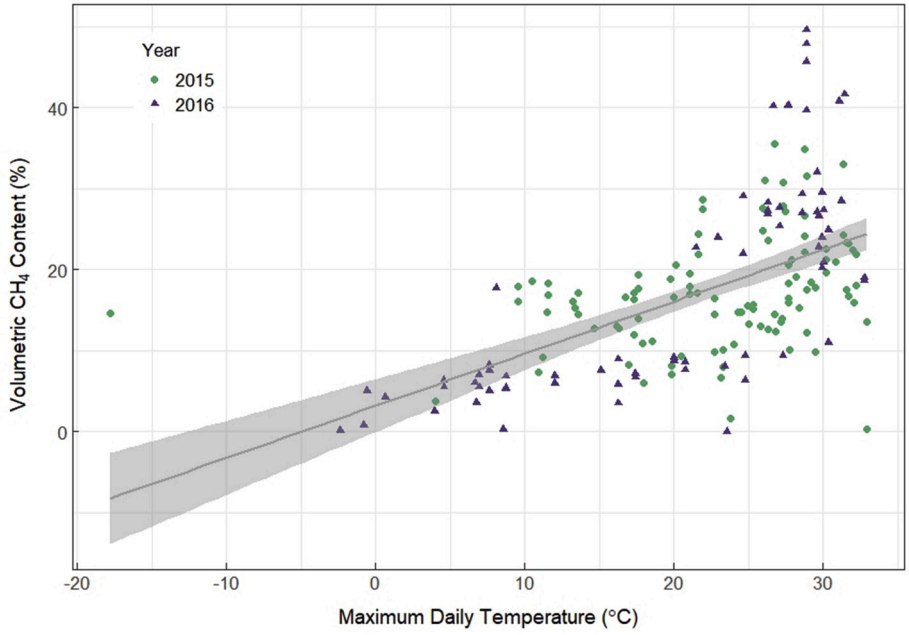

Fig. 2. Linear regression of volumetric CH_4 content by maximum daily temperature and year, with green circles representing 2015 measurements and purple triangles representing 2016 measurements, and a linear, least-squares fit regression line for all data including a 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Annual and seasonal biogas production and chemical characteristics.

	Maximum Daily Temperature (°C)[a]	Biogas Flow Rate (L hr^{-1})[a]	Volumetric CH_4 Content (%)[a]	Chemical Energy Produced (MJ)[b]	Chemical Energy Production Rate (MJ hr^{-1})[a]	CO_2: CH_4 Ratio[a]	Digester Input Volume (kg VS_{added})[b]	Energy Return (MJ $kgVS^{-1}_{added}$)[a]	pH Digester Output[a]	Temperature Digester Output (°C)[a]
2015	23.0	9	17.2	56	0.053	9	92	0.65	6.9	23.0
Summer	28.2	10	13.9	36	0.067	8	56	0.74	6.6	28.5
Fall	18.3	8	20.8	20	0.039	10	37	0.57	7.1	20.5
2016	19.9	6	17.2	19	0.029	11	74	0.34	6.0	12.0
Spring	28.4	6	6.2	12	0.041	2	29	0.39	7.7	18.6
Summer	29.4	2	27.0	4	0.028	1	2	1.73	7.9	11.9
Fall	12.3	7	44.9	4	0.020	19	42	0.10	5.8	11.4

[a] Average.
[b] Total sum.

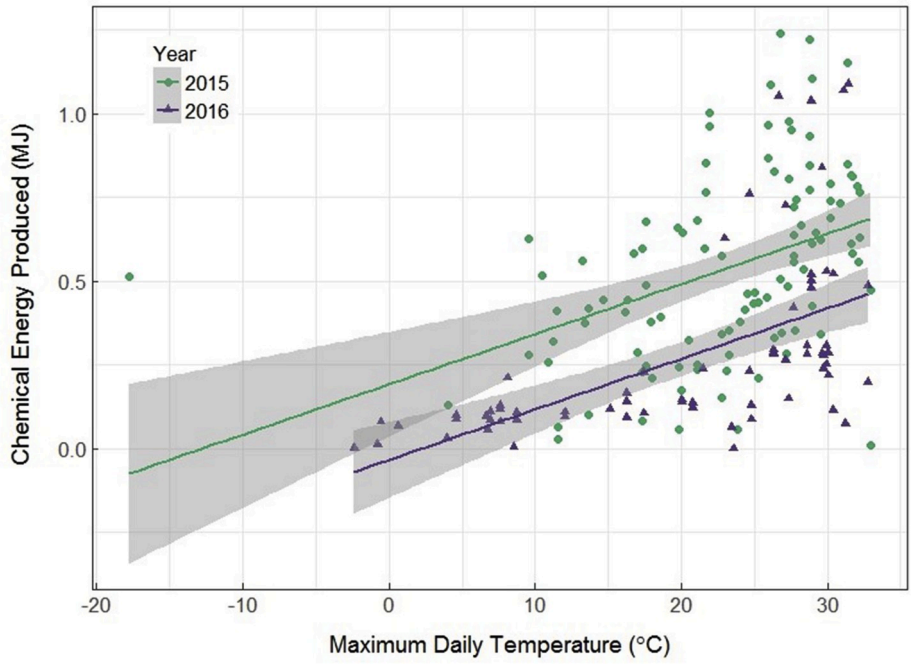

Fig. 3. Chemical energy produced as related to maximum daily temperature with green circles representing 2015 measurements and purple triangles representing 2016 measurements, including a linear regression fit line and 95% confidence interval for each year. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observations of digester health metrics rather than real-time monitoring. One of the initial objectives of our research into unheated, pilot-scale AD systems was to determine the feasibility for distributed biofuel production in rural areas in temperate regions. Off-grid systems like the one we built are meaningfully different from commercial systems in both scope and potential. Here, we sought to understand the baseline energy production of a system operated with highly variable conditions.

In our temperate climate, decreasing temperatures in the fall and early winter corresponded to a significant decrease in the chemical energy yield produced by the digester, regardless of the time since inoculation. This is not surprising, as the relationships between digester health, CH_4 yield, and temperature are well established in both small and large-scale AD systems [2,5,11]. In the future, it might be worthwhile to re-inoculate during seasonal shifts with more cold- or warm-adapted microbial communities, including active methanogens, to determine any interactive effects of temperature and inoculation [34,35]. In this study, we relied on the thermal insulation provided by the greenhouse and the ground trench that held the liquid portion of the digester, and the thermal entropy of the digestion material itself to buffer against any drastic or abrupt changes in digester temperatures. Still, it is evident that even gradual temperature changes affected the biogas quality and quantity from the system.

4.1. Annual patterns

At the times when the digester was warmest and consistently yielding biogas (i.e., not during a startup period), the biomethane production was commensurate with a typical AD system customized to a consistent feedstock chemistry, approaching 50% CH_4. However, the overall average biomethane yield across all temperatures was much lower (17%). The EROI (Table 3), however, does suggest that an unheated AD system with unsorted mixed food waste as the primary feedstock can be feasible in a temperate climate. Despite arrested digestion on multiple occasions due to cold temperatures, digester souring, and updating the digester input and output plumbing, there was a persistent positive relationship between biogas, biomethane production, and outside temperature (Figs. 2 and 3). With close monitoring and adjustments to the organic loading rate and pH of the system in order to prevent organic acid buildup and souring, CH_4 production gradually continued to increase over time.

The least productive season of the study period was fall 2016, which had the lowest energy yield per unit feedstock input (MJ $kgVS^{-1}_{added}$), the

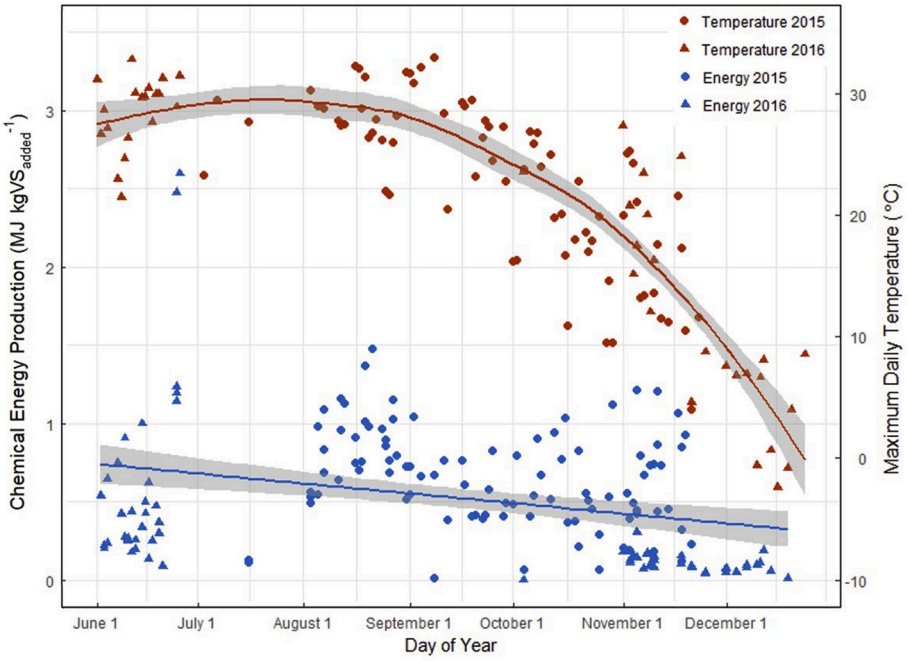

Fig. 4. Chemical energy yield per unit volatile solids added (blue) and maximum daily temperature (red) by day of year in 2015 (circles) and 2016 (triangles). Each factor shown includes a least-squares regression line for all the data (linear for chemical energy production, quadratic for maximum daily temperature) with a 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

lowest MJ yield per hour, the lowest digester output pH, the lowest average outside air temperature, and the highest CO_2:CH_4 ratio in the biogas produced (Table 2). Interestingly, the biogas production rate during this period was not statistically different from any other season in either year, and in fact, had a slightly higher average biogas flow rate as compared to other 2016 seasons (6.8 L h^{-1} versus 5.6 and 2.4 L h^{-1} for spring and summer, respectively; Table 2). The combination of the markedly higher CO_2:CH_4 ratio with the steady biogas production rate indicates a mismatch in the functionality of the different microbial communities, namely that there was an inhibition of the methanogenic stage, leading to higher proportions of fermentative gas (i.e., CO_2) production.

Fall 2016 was also the measurement period that followed inoculation period 3, when we used the same source industrial AD operation as inoculation period 1. Retrospectively, when compared to the other measurement periods, the digester was clearly in distress following inoculation 3. There are a few possible explanations. One possibility is that the microbial community in the AD vessel was changing - a condition that would lead to a temporary reduction in biomethane production - at the same time that cooler temperatures arrived, which disrupted the transition in the microbial community. A second possibility is that the inoculum had a lower density of methanogenic bacteria relative to the previous inoculum, and the rate of feedstock input was too high relative to the inoculum volume, leading to inhibitions and decreased productivity. A third possibility is that the lower biomethane was simply the result of temperatures declining at a faster rate during the fall 2016 measurement period than in the previous year. In temperate conditions, the differential kinetics and temperature sensitivities of the microbial processes may lead to less predictable chemical energy yields from methanogenesis than would typically be expected in warmer climates [2,17,32].

One of the research objectives of this project was to determine the potential for biogas production when operating a small, passively heated AD systems year-round in a temperate region. Given the temperatures we measured inside the greenhouse structure and of the digester output over the first two years of the project (Table 2), it is likely that the dominant microbial communities shift in response to seasonal temperatures. It is unclear how long a temperature-related microbial shift might take, but previous studies suggest that generating a shift between temperature-reared communities may take anywhere between two and nine months [33,34], with high inoculum-substrate ratios required during that period to maintain community balance and health [35].

In controlled conditions, it would be possible to use gradual, stepwise temperature changes to induce a shift to/from a psychrophilic community and maintain community balance and function. In a passively heated system that relies on the thermal entropy and mass of material, there is less temperature control, particularly in smaller-volume systems. If a shift between psychrophilic and mesophilic communities leaves the microbial community sensitive to other changes, as has been suggested by other work [34], the potential for year-round operation of an unheated system with variable inputs is greatly reduced. It may be possible to alleviate the risk of digester functional decline during seasonal temperature changes with systematic inoculations of psychrophilic or mesophilic microbes, but the efficacy of such treatment protocols is currently unresolved. In addition, while temperatures were related to day of year and season, throughout the study we experienced multiple, episodic periods of temperature fluctuations within a season. These alternating cold and warm periods showed that system productivity could respond relatively quickly to temperature changes, and that brief exposure to cold temperatures did not greatly inhibit AD functionality. The ability of a system to recover biogas production when warmer temperatures occur could support the feasibility of pilot-scale AD in temperate locales [19].

4.2. *Differences among inoculation periods*

There were three discrete inoculation periods that occurred throughout this experiment: July 2015, May 2016, and September 2016. After each of these inoculation events, there was at least a 7-day delay in biogas production, but the subsequent indicators of functional AD activity were not consistent in all startup phases. After inoculation period 2, a rapid rise in biogas production rate and CH_4 concentrations occurred, contrasting the slower and more steady increase in biogas

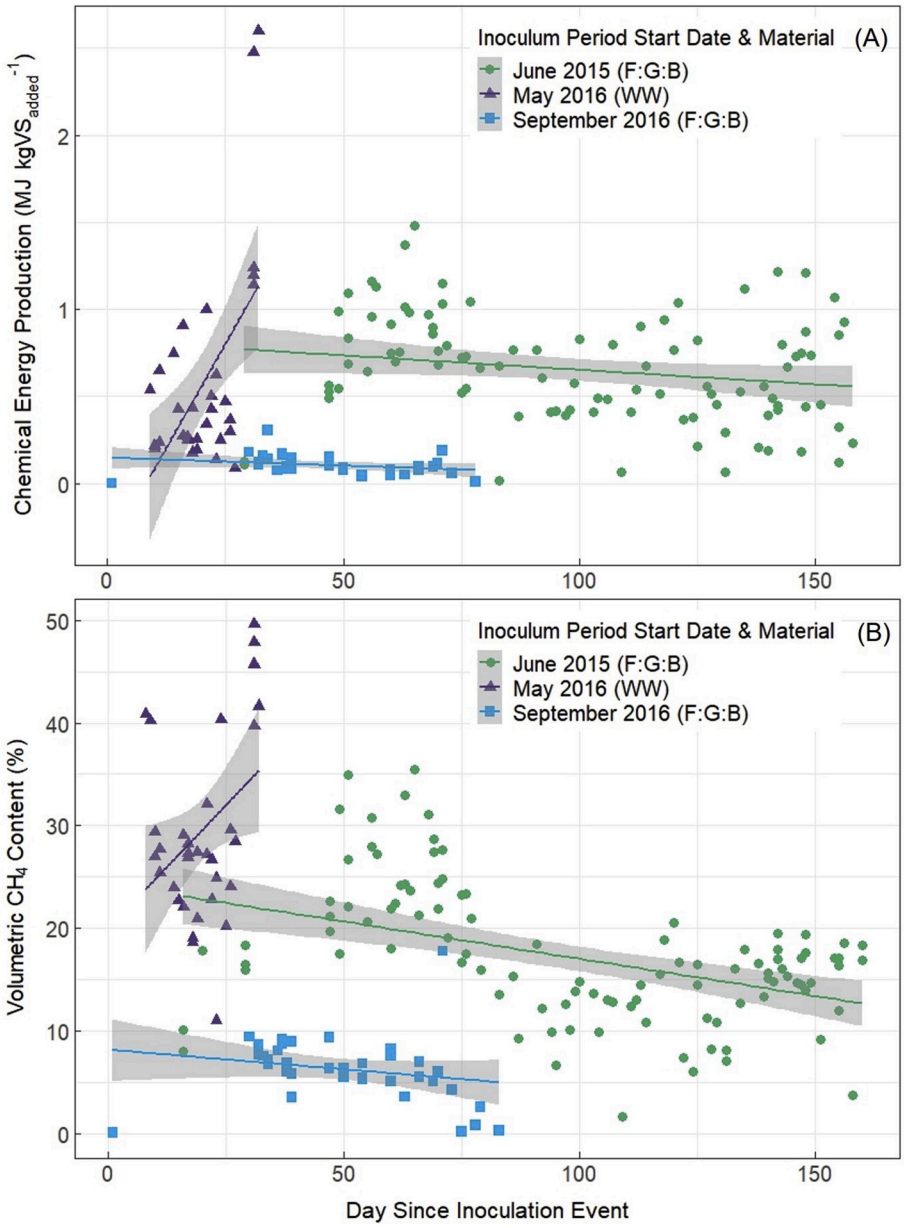

Fig. 5. Chemical energy yield (A) and volumetric CH_4 content (B) by inoculation event and day since inoculating, with inoculation period 1 as green circles, period 2 as purple triangles, and period 3 as blue squares. The material digested at the source digester for each inoculation is listed by period in the figure legend (F:G:B for approximately equal parts food waste, grease waste, and biosolids; WW for wastewater). Each inoculation period includes a linear, least-squares regression fit line with a 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

production that occurred after inoculation periods 1 and 3 (Fig. 5). Inoculation periods 1 and 3, both using Quasar Columbus material, did not result in measurable CH_4 in the biogas until days 16 and 30, respectively.

Given the marked difference in the startup timing and rate of biomethane production between inoculation events, it is likely that the source material (obtained from industrial AD systems) had an impact on the recovery rate immediately following an inoculation event [36]. The material from Quasar in Columbus, which we used for inoculations 1 and 3, was most similar to the food waste feedstock used for the subsequent daily feeding of the AD system. Contrarily, inoculation period 2, which resulted in the fastest and most dramatically positive recovery in terms of energy yields, had inoculum from the industrial AD system processing only wastewater (Quasar Wooster).

We used the pH of the digester output, the concentration of CH_4 in the biogas, and the C and N content of the substrate and waste materials as indicators of digester microbial health (Table 2). With the timing and values of these metrics over the course of the study period, we speculate that the suboptimal C:N of the feedstock was frequently the cause of low biogas and low biomethane production. The observed lags in biomethane productivity throughout the multi-year study period belies a singularly dominant effect of temperature because fluctuations in biogas quality were more likely also due to the inconsistency in the feedstock quality. Measurements of inhibition products like fatty acids and ammonia, usually standard in commercial-scale AD operations, will be important to monitor if the AD system studied here were adopted for energy production.

4.3. Energy balance

The system studied here was exceptional for its extreme low energy input, as we did not perform any powered biogas collection or cleaning, and the digester was not stirred, heated, fed, or monitored with any electrical equipment. In short, the vast majority of energy demand for our system came from the grinding of the feedstock, which amounted to an average of 2.5 min of grinding per gallon of feedstock at 456 Watts, so 0.038 kWh for approximately 5 min a day. The system included dataloggers powered via solar panels, but the dataloggers were used

Table 3
Energy yield of different feedstocks used in anaerobic digestion systems as reported in previous literature.

Feedstock type	# of studies	Source (s)	EROI	kWh Mg^{-1}	MJ Mg^{-1}	GJ Mg^{-1}
Crop residue	3	1,2,3	4.8	2424	8726	8.7
Dedicated crop	7	1,2,4-8	7.1	2788	10037	10
Food waste	6	2,9-13	5	815	2935	2.9
Food waste	*1*	*this study*	*3.7*	*121*	*437*	*0.4*
Grease	1	1	7.7	6111	22000	22
Livestock waste	3	1,2,14	3.1	1457	5244	5.2
Municipal waste	7	1,2,15-19	1.9	626	2252	2.3
Co-digestion	4	19,20-22	2.7	434	1564	1.6

Sources: 1. Berglund & Borjesson 2006; 2. Borjesson & Berglund 2006; 3. Chevalier & Meunier 2005; 4. Barbanti et al., 2014; 5. Bauer et al., 2010; 6. Gerin et al., 2008; 7. Navickas et al., 2011; 8. Navickas et al., 2012; 9. Banks et al., 2011; 10. Bernstad & la Coeur Jansen 2011; 11. Bernstad & la Coeur Jansen 2012; 12. Eriksson & Spangberg 2017; 13. Khoo et al., 2010; 14.Zhang et al., 2015; 15. Belbloom et al., 2013; 16. Chai et al., 2015; 17. Colón et al., 2012; 18. DiStephano & Belenky 2009; 19. Edwards et al., 2017; 20. Lubken et al., 2011; 21. Torquati et al., 2014; 22. Zhang et al., 2013.

exclusively for research purposes and thus not included in the calculated energy requirements of the system. When compared to the energy production potentials of AD systems using a variety of feedstocks (Table 3), it is evident that the low energy demands of our small-scale system allowed for a positive EROI even with our low biomethane yields. Importantly, our energy inputs do not include the energy for waste production, collection, and transport, as our mixed food waste feedstock was available on-site. Such recovery costs would be avoided if an AD system is co-located with a facility that already aggregates appropriate organic wastes for another purpose.

In addition to the upstream waste management, downstream wastes from AD systems can be utilized as a soil amendment and fertilizer product, or as a material included in composting activities, both capable of eliciting additional energy savings. During this study, the digestate waste material was primarily used as an amendment to composting activities occurring on-site – the material was dumped on windrows of immature compost to provide both moisture and compostable solids. We also used the digestate waste stream as a soil amendment/fertilizer material in experimental field plots of fallow soils and bioenergy crops located approximately a mile away from the digester site. Assessment of the impacts of land applications are forthcoming and not within the scope of this study, but could be an important economic aspect supporting implementation of distributed, pilot-scale AD in rural America [37].

5. Conclusions

Due to the low energy requirements, a pilot-scale, low-solids AD system operating off-grid and year-round within a temperate climate with unsorted food waste as the primary feedstock has promise for biomethane production. Maintaining biogas production year-round with significant seasonal changes is feasible, but careful monitoring is necessary to avoid negative energy balances in the winter months. Inoculum source affects the potential fuel yield, but further analysis of this response is needed to understand the interaction between inoculation events and seasonal temperature shifts. Further experimentation is also needed to resolve the importance of psychrophilic or mesophilic microbial communities during seasonal temperature shifts. With the low energy inputs of an off-grid system that is integrated with existing waste collection, positive energy balances can be expected even with non-uniform waste feedstocks in suboptimal environmental conditions, making pilot-scale, unheated AD a viable candidate for distributed waste-to-fuel systems in rural America.

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Declarations of competing interest

None.

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