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Evaluation of Biogas Production Potential by Dry Anaerobic Digestion of Switchgrass–Animal Manure Mixtures

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Abstract Anaerobic digestion is a biological method used to convert organic wastes into a stable product for land application with reduced environmental impacts. The biogas produced can be used as an alternative renewable energy source. Dry anaerobic digestion [>15% total solid (TS)] has an advantage over wet digestion (<10% TS) because it allows for the use of a smaller volume of reactor and because it reduces wastewater production. In addition, it produces a fertilizer that is easier to transport. Performance of anaerobic digestion of animal manure–switchgrass mixture was evaluated under dry (15% TS) and thermophilic conditions (55 °C). Three different mixtures of animal manure (swine, poultry, and dairy) and switchgrass were digested using batch-operated 1-L reactors. The swine manure test units showed 52.9% volatile solids (VS) removal during the 62-day trial, while dairy and poultry manure test units showed 9.3% and 20.2%, respectively. Over the 62 day digestion, the swine manure test units yielded the highest amount of methane 0.337 L CH_4 /g VS, while the dairy and poultry manure test units showed very poor methane yield 0.028 L CH_4/g VS and 0.002 L CH_4/g VS, respectively. Although dairy and poultry manure performed poorly, they may still have high potential as biomass for dry anaerobic digestion if appropriate designs are developed to prevent significant volatile fatty acid (VFA) accumulation and pH drop.

Keywords Anaerobic · Digestion · Animal manure · Switchgrass · Biogas · Renewable energy

Introduction

Recent increases in fossil fuel prices have increased the demand for biofuel production from crops. The diversion of crops for biofuel production resulted in increased food price and food security concerns. Therefore, research developing alternative biomass for bioenergy has become increasingly important. Animal wastes are good sources of biomass because

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they contain an abundance of organic matter and nutrients. Using animal wastes as biomass offers many advantages for livestock operations by minimizing waste disposal costs and also reducing odors and contaminants [1].

Anaerobic digestion is a biological method used to convert organic wastes into a stable product for application to land without adverse environmental effects. In addition, the biogas produced can be used as an alternative renewable energy source.

Dry anaerobic digestion (>15% TS) has benefits over conventional anaerobic liquid digestion (<10% TS) because it reduces the volume of the reactor and wastewater, as well as producing a more easily transportable fertilizer [2].

Switchgrass (*Panicum virgatum*) has received much attention in recent years and has been a focus of bioenergy research for over a decade [3]. It is a very productive North American native, perennial warm season grass suitable for growth on marginal land [4, 5]. As such, it has great potential as sustainable bioenergy crop. Most past research has focused on switchgrass utilization through combustion, thermochemical conversion, or cellulosic ethanol production [6–9]. However, switchgrass may also have potential for use as a co-digestion substrate in anaerobic digestion by supplementing manure biomass resources and potentially increasing biogas production. Switchgrass cell walls are primarily composed of cellulose and hemicellulose, for example, Dien et al. [9] report switchgrass cellulose concentrations ranging from 273 to 322 g kg^{-1} dry matter (DM) and hemicellulose concentrations ranging from 235 to 279 g kg^{-1} DM depending on the age of the plant material. Hydrolysis of these cell wall components yield sugars which are readily converted to methane during anaerobic digestion. Cellulose hydrolysis has been identified as the rate-limiting step during anaerobic digestion [10], and research is needed to assess the effect of manure and switchgrass co-digestion on biogas production.

In order to develop a suitable dry anaerobic digestion system, appropriate pretreatment and operating strategies need to be employed based on the characteristics of the feedstock. Biogas production depends on many parameters including feedstock composition, operating temperature, and organic loading rate. Although dry anaerobic digestion has many potential advantages, further investigations have been limited. Thus, the aim of this research is to evaluate the biogas production potential of animal manure mixtures with switchgrass during batch operating dry anaerobic digestion. The purpose was to understand the influence of animal manure type (dairy, swine, and poultry manure) on dry anaerobic digestion performance of manure–switchgrass mixtures by investigating the biogas production, composition, substrate removal efficiency, and leachate characteristics.

Materials and Methods

Digester System

Experiments were carried out using laboratory scale digestion bags made of air-impermeable plastic with effective volume of about 1 L (Fig. 1). A fitting that combined a hose barb and septum was mounted on each digestion bag. The hose was used for biogas collection, and the septum was used for leachate sampling. Nine anaerobic digestion bags were filled with manure–switchgrass mixtures, sealed, and placed in a 55 °C incubator to maintain thermophilic conditions. An initial leachate sample was collected for characterization prior to the start of the digestion period. The temperature of the digestion bags was measured using type-T thermocouples. The volume of biogas production was measured with a wet-tip gas meter which is connected to each digestion bag. All temperature and

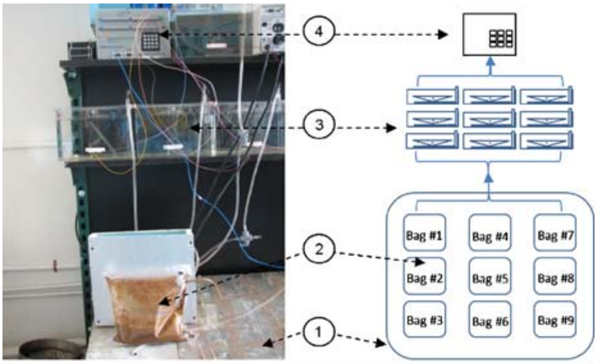


Fig. 1 Schematic diagram and photo of the dry anaerobic digestion system

biogas data were collected every hour by a programmed data acquisition and control system (CR23X, Campbell Scientific, USA). The material inside each digestion bag was mixed manually every other day.

Feed Materials

Three different types of animal manure (dairy, swine, and poultry) in combination with switchgrass were tested in three replications. The dairy, swine, and poultry manures were collected at the USDA-ARS Beltsville Agricultural Research Center (BARC) in Beltsville, Maryland and stored at 5 °C before use. Switchgrass was harvested from production fields at BARC and grounded to average particle size of 2 mm. Each reactor was inoculated by adding digested dairy manure collected from the anaerobic digester at the BARC Dairy Research Facility. Table 1 shows the characteristics of feed materials. The composition of each mixture is shown in Table 2. Total solids of the animal manure and switchgrass mixtures were adjusted to about 15% (Table 3).

Analytical Methods

Moisture content, volatile solids, soluble chemical oxygen demand (SCOD), alkalinity, and NH_4–N of leachate samples were analyzed according to Standard Methods [11]. Total carbon and nitrogen were analyzed by an elemental analyzer (Elementar Vario Max CNS).

Table 1 Characteristics of animal manures, inoculum, and switchgrass (N=3).

	Moisture content (%, w.b.[a])	Volatile solids(%, d.b.[b])	Total C (%, w.b.)	Total N (%, w.b.)
Dairy manure	95.5±0.1	79.1±0.5	2.1±0.1	0.2±0.0
Swine manure	97.0±0.4	74.3±1.9	1.2±0.2	0.2±0.0
Poultry manure	57.1±1.6	78.5±0.1	18.1±1.5	2.1±0.4
Inoculum	97.4±0.0	65.4±1.3	1.1±0.1	0.1±0.0
Switchgrass	4.8±0.3	97.7±0.1	46.0±0.1	0.4±0.0

[a] Wet basis

[b] Dry basis

Table 2 Composition of animal manure and switchgrass mixtures.

	Manure (g)	Switch grass (g)	Inoculum (ml)	Water (ml)
DM[a]	957	200	239	–
SM[b]	856	200	214	–
PM[c]	94.6	200	230	921

[a] Dairy manure test unit

[b] Swine manure test unit

[c] Poultry manure test unit

The pH of leachate samples was measured using a pH meter (AR20 pH/conductivity meter, Accument Research). Volatile fatty acids (VFA) were determined by gas chromatography (Thermo/Finnigan Trace GC Ultra) utilizing a flame ionization detector (FID) and capillary column (Nukol Bonded Free Fatty Acid phase). The column temperature was 250 °C, and the injector/detector temperature was 250 °C. Helium was used as carrier gas with a flow rate of 20 ml/min. Methane was analyzed by gas chromatography (Thermo/Finnigan Trace GC Ultra) with capillary PLOT column and a thermal conductivity detector (TCD). A sample volume of 200 μL, at a split ratio of 1:7 was injected and analyzed under the following conditions: injection temperature: 180 °C; detector temperature: 200 °C; carrier gas: He (flow rate of 3 ml/min).

Results and Discussion

Biogas Production

The average daily and cumulative biogas production is depicted in Fig. 2. All test units showed rapid biogas production for the first 2 days, followed by a rapid decrease in biogas production between days 2 and 4. The high initial biogas production for days 1 and 2 was

Table 3 Characteristics of initial mixtures and leachate (*N*=3).

	DM[a]	SM[b]	PM[c]
Moisture content (%, w.b.)	84.8±0.1	83.5±0.3	84.4±0.6
VS (%, d.b.)	94.5±0.2	95.3±0.6	92.9±0.2
Total C (%, w.b.)	7.1±0.4	7.9±0.2	6.2±0.5
SCOD (g/L)*	14.7±0.3	9.4±0.9	8.8±0.1
Total N (%, w.b.)	0.2±0.0	0.2±0.0	0.2±0.0
C:N ratio	38.3±3.9	41.2±4.4	32.9±2.5
NH_4–N (mg/L)*	283.1±57.6	801.7±313.3	390.5±58.9
pH*	8.0±0.1	7.8±0.1	6.9±0.1
Alkalinity (g/L as $CaCO_3$)[d]	7.4±0.4	9.4±0.8	4.6±0.3

[a] Dairy manure test unit

[b] Swine manure test unit

[c] Poultry manure test unit

[d] leachate

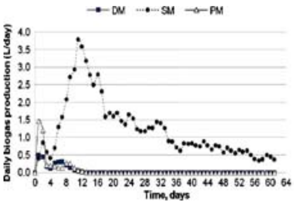


Fig. 2 Average daily and cumulative biogas production

due to the preferential digestion of readily biodegradable organic materials like carbohydrates. The dissipation of the readily degradable materials may have caused temporary biogas production decrease between days 2 and 4 [12, 13].

The swine manure test units showed a steady increase in biogas production starting on day 5. Its biogas production level peaked (3.8 L /day) after 11 days of digestion and then gradually decreased to 0.4 L/day on day 62. Dairy and poultry manure test units showed slight biogas production increases up to 0.3 L/day on days 6 and 8, respectively, after which the biogas production started to decrease and finally ceased on day 14. Figure 3 shows the methane concentration and cumulative methane production. Although rapid biogas production was observed from all three manure–switchgrass mixtures during the first 2 days, there was little methane produced during those 2 days. Maximum methane percentages obtained from the dairy, swine, and poultry manure test units during the first 2 days were about 5%, 5%, and 0%, respectively. Due to dissolved oxygen in the wastewater and also trapped in the pore spaces of the biosolid, most biogas production during the first 2 days came not through anaerobic digestion but aerobic or anoxic degradation.

Between days 6 and 62, the swine manure test units maintained methane content between 40% and 65%. The dairy manure and poultry manure test units reached their peak methane percentage of 24.5% and 8.6% on days 6 and 8, respectively, and subsequently produced no biogas during two additional weeks of digestion.

Substrate Removal in the Leachate

The temporal variations in the SCOD concentrations of the leachate are shown in Fig. 4. The SCOD of the swine manure test units increased rapidly to 33 g/l on day 3, and then decreased to 20 g/l until day 62. The SCOD of the dairy and poultry manure test units increased steeply to approximately 50 g/l for the first 6 days and finally decreased to approximately 40 g/l by the end of the experiment.

Due to the transformation of readily degradable organic materials into their soluble forms through hydrolysis, a rapid increase of soluble COD was observed during the early stages of digestion. The organic materials solubilized by secreted hydrolytic microbial enzymes are generally degraded into intermediary products of anaerobic digestion like VFAs [13, 14]. The swine manure test units maintained a 41% reduction in soluble COD

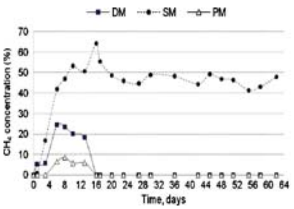


Fig. 3 Methane composition and cumulative methane production

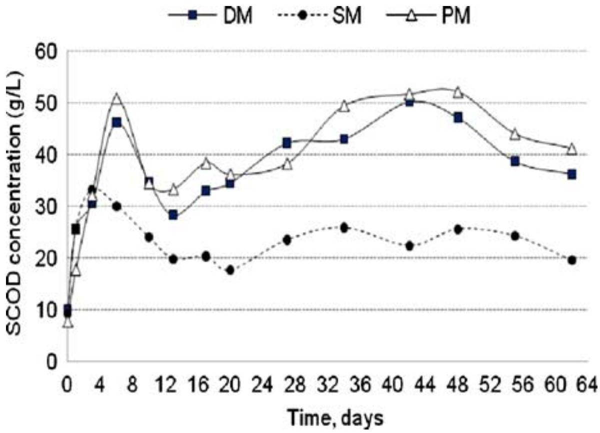


Fig. 4 Temporal variation of soluble chemical oxygen demand (SCOD)

during 62 days of digestion, while the dairy and poultry manure test units showed 19–20% soluble COD reduction. Other researchers have reported stable and active anaerobic microbial activity in swine manure digestion [13, 15]. This may allow for effective digestion of additional substrate, and it may account for the disparity in digester performance observed during this study. The accumulation of VFAs in dairy and poultry manure test units led to irreversible acidification of the digester (pH 5.0–5.5). The low pH reduced hydrolysis rates, slowing further degradation of soluble COD to intermediary anaerobic products in these test units resulting in limited methanogenesis [14, 16].

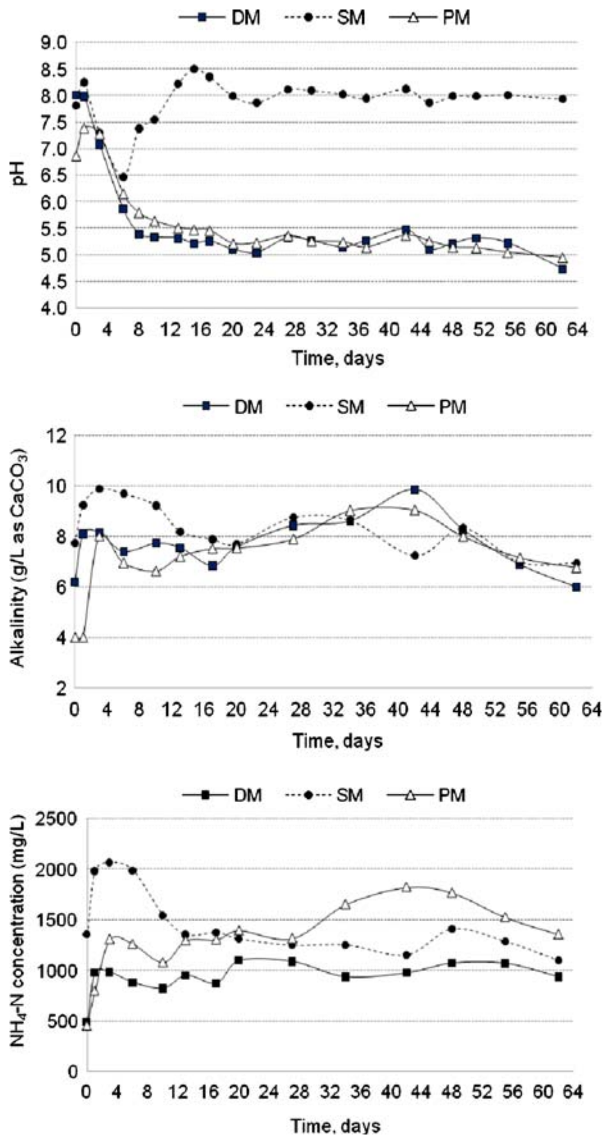
pH, Alkalinity, and Ammonium Nitrogen Variations in the Leachate

Temporal variations in pH, alkalinity, and NH_4–N are presented in Fig. 5. All three manure–switchgrass mixtures showed pH increases during the first 2 days of digestion due to the degradation of urea to ammonia. Subsequently, pH decreased as a result of VFA production by acetogenic bacteria [17, 18]. The swine manure test units reached its minimum pH value (6.5) on day 6, subsequently increasing to approximately pH 7.5 to 8.5 for the remainder of experiment. In contrast, the pH of dairy and poultry manure test units rapidly dropped to between 5.0 and 5.5, a pH that is not favorable to methanogens. The pH of a normal and healthy anaerobic digestion system is generally in the range of 6.5 to 8.5 [19].

In general, pH increase accompanies increasing biogas production because methanogens consume VFAs and generate alkalinity [15]. The pH and alkalinity levels observed during this experiment illustrate that the swine manure test units had a higher buffering capability than either the dairy or poultry manure. The alkalinity of swine manure test units maintained the highest levels of the three manures until day 20, at which point they declined to a level similar to the dairy and poultry manure test units.

Rapid NH_4–N increases were observed from all three manure–switchgrass mixtures during the first 3 days. Throughout the experimental period, the NH_4–N concentration of the poultry and dairy manure test units maintained approximately 1500 mg/L and 1000 mg/L, respectively.. The NH_4-N concentration of the swine manure test units increased to 2100 mg/L on day 3, decreasing to 1100 mg/L after 62 days of digestion. The NH_4-N levels of all three test units were not high enough to have an inhibitory effect on anaerobic digestion performance [20–23]. In general, there is a possible inhibitory effect if NH_4-N concentrations are between 1,500 to 3,000 mg/L, and the pH is above 7.5. If the NH_4–N concentration is above 3,000 mg/L, anaerobic digestion is inhibited regardless of pH level [24].

Fig. 5 Temporal variations of pH, alkalinity, and NH_4–N



VFA Variations in the Leachate

Volatile fatty acids are the intermediary compounds produced during anaerobic conversion of organic materials. Acetic acid, propionic acid, and butyric acid are the major VFAs produced during anaerobic digestion. Ultimately, acetic acid is generated via syntrophic metabolism of propionic and butyric acids. Following acetogenesis, methanogens convert acetic acid to CO_2 and CH_4. Volatile fatty acids are one of the important indicators for measuring anaerobic digestion performance because they are closely related to the changes in pH, alkalinity, and the activity of methanogens [17, 25].

Temporal variations in VFA concentration are depicted in Fig. 6. The swine manure test units showed maximum VFAs concentration (acetic acid, 13 g/L) after 6 days, decreasing to 2 g/L by day 10. The minimum pH value (6.5) was observed when VFA concentrations reached maximum and increased to above 7.5 as VFA concentration decreased to 2 g/L on day 10. Most of the VFAs appeared to be completely consumed by methanogens after 17 days. In contrast to the swine manure test units, dairy and poultry manure slowly

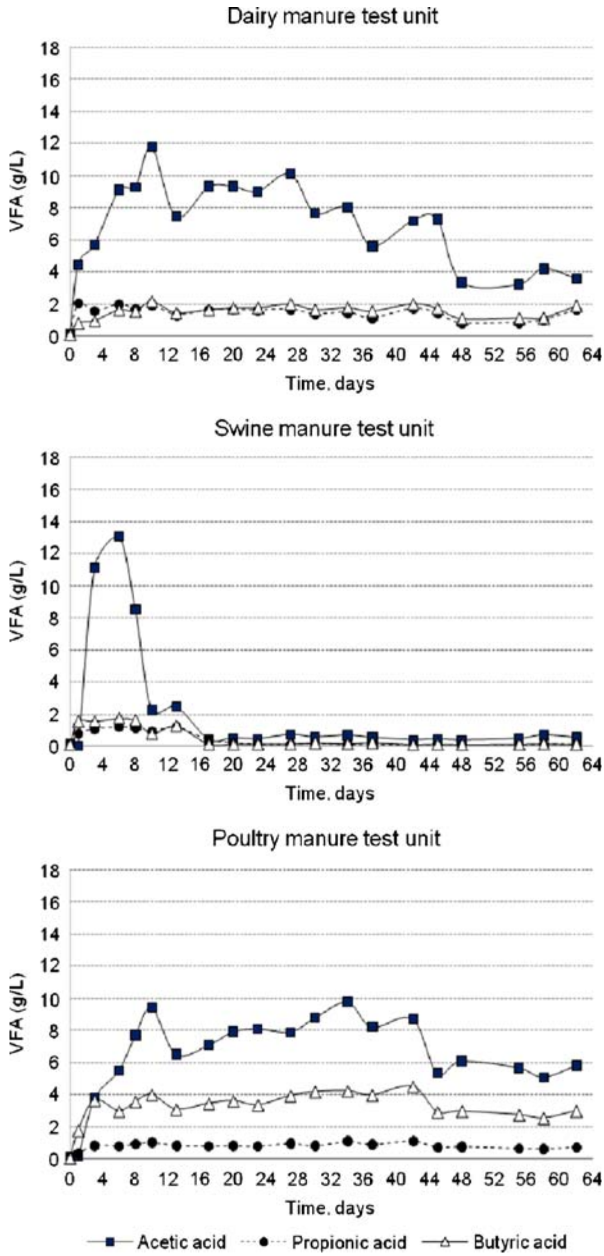


Fig. 6 Temporal variations of VFAs (acetic, propionic, and butyric acids)

reached maximum VFA concentrations (dairy manure, 12 g/L; poultry manure, 9.4 g/L) after 10 days. The dairy and poultry manure test units maintained high VFA concentrations for the rest of the experiment, indicating that there was minimal conversion of VFAs to CH_4 by methanogens. The accumulated VFAs in dairy and poultry manure test units resulted in irreversible digester acidification (pH 5.0–5.5). The low pH inhibited methanogens from converting VFAs to methane.

Comparative Anaerobic Digestion Performance

The swine manure test units showed superior biogas production (72.9 L) compared to the dairy and poultry test units (dairy manure, 2.5 L; poultry manure, 4.3 L). The average methane production from the swine manure test units was 35.6 L, while the other test units each produced less than 1 L of methane throughout the 62-day digestion period (Table 4). The swine manure test units showed 52.9% VS removal over 62 days, while the dairy and poultry manure test units showed 9.3% and 20.2%, respectively. Over the 62-day digestion period, degradation of VS in the swine manure test units yielded the highest amount of methane (0.337 L CH_4/g VS), while the dairy and poultry manure test units showed very poor methane yield of 0.028 L CH_4/g VS and 0.002 L CH_4/g VS, respectively. The irreversible acidification of the system caused by much higher hydrolysis rates relative to methanogenic rates at start-up is the main rate-limiting step in batch-operated dry anaerobic digestion [16]. The anaerobic digestion performance may be improved by separating the acidogenic and methanogenic phases [16, 23].

Effect of the Switchgrass Addition

The effect of switchgrass addition to dairy and poultry manure on anaerobic digestion performance cannot be evaluated due to process failure caused by VFA accumulation and low pH. However, the influence of switchgrass as a co-digestion substrate in combination with swine manure on the biogas production can be assessed.

The mass of VS degraded during 62 days digestion in swine manure test units was 105.3 g (Table 4). Only 22.7 g of VS were supplied by swine manure and inoculum (Tables 1 and 2). Assuming the organic material in swine manure and inoculums was degraded completely, it only contributed 21.5% of the total degraded biomass resulting in the production of 7.6 L of methane. The remaining VS were contributed by the switchgrass resulting in the production of an additional 27.8 L of methane from the swine manure test units. This indicates that switchgrass can be a useful biomass resource as a co-digestion substrate to increase biogas production from swine manure.

Table 4 Methane yield of each test unit for 62 days of digestion (N=3).

	Total biogas production (L)	Total CH_4 production (L)	VS removal (%)	VS removal (g, d.b.)	CH_4 yield (L/g VS)
DM[a]	2.5±0.4	0.39±0.16	9.3±4.3	18.5±8.6	0.028±0.022
SM[b]	72.9±14.7	35.57±7.71	52.9±1.3	105.3±2.4	0.337±0.065
PM[c]	4.3±0.4	0.90±0.83	20.2±0.8	39.6±1.6	0.002±0.002

[a] Dairy manure test unit

[b] Swine manure test unit

[c] Poultry manure test unit

Conclusions

The overall results of anaerobic digestion of animal manure–switchgrass mixtures under dry and thermophilic conditions indicate that the swine manure test units maintained well-balanced conditions resulting in improved digester performance. In contrast, due to high VFA concentrations and low pH, the dairy and poultry manure test units showed poor performances. Of the manure–switchgrass mixtures studied, swine manure test units proved to have the highest biogas production potential (0.337 L CH_4/g VS).

Although dairy and poultry manure performed poorly during this study, they may still have high potential as biomass for dry anaerobic digestion if appropriate designs are developed to prevent significant VFA accumulation and pH drop. Future research into feasible operational conditions to improve biogas production of dairy and poultry manure is necessary. Separation of acidogenic phase and methanogenic phase is one possible approach to prevent VFA accumulation and pH drop. In addition, in order to scale up this technology, a suitable design that minimizes the energy required to maintain reactor temperature needs to be developed. The energy required for heating may be reduced by lowering the digestion temperature or by linking the digester to an economical complementary heat source such as a composting system [26]. Once these obstacles are overcome, at the pilot scale, further research is necessary to implement this technology at the farm scale in the field.

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