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Anaerobic co-digestion of kitchen waste and pig manure with different mixing ratios

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Anaerobic co-digestion of kitchen waste (KW) and pig manure (PM) with seven different PM to KW total solids (TS) ratios of 1:0, 5:1, 3:1, 1:1, 1:3, 1:5 and 0:1 was conducted at mesophilic temperature (35 ± 1°C) to investigate the feasibility and process performance. The co-digestion of PM and KW was found to be an available way to enhance methane production compared with solo-digestion of PM or KW. The ratio of PM to KW of 1:1 got the highest biodegradability (BDA) of 85.03% and a methane yield of 409.5 mL/gVS. For the co-digestion of KW and PM, there was no obvious inhibition of ammonia nitrogen because it was in an acceptable range from 1380 mg/L to 2020 mg/L in the whole process. However, severe methane inhibition and long lag phase due to the accumulation of volatile fatty acids (VFAs) was observed while the KW content was over 50%, and in the lag phase, propionic acid and butyric acid made up the major constituents of the total VFAs. The technical digestion time (T_{80}: the time it takes to produce 80% of the digester's maximum gas production) of the above 7 ratios was 15, 21, 22, 27, 49, 62 and 61 days, respectively. In this study, a mixing ratio of 1:1 for PM and KW was found to maximize BDA and methane yield, provided a short digestion time and stable digestion performance and was therefore recommended for further study and engineering application.

[**Key words:** Anaerobic digestion; Co-digestion; Kitchen waste; Pig manure; Different ratios]

With the rapid economic improvement in recent years in China, kitchen waste (KW) makes up 37–62% of the municipal solid waste (MSW) is a great environmental challenge (1). In China, the amount of MSW was 170 million tons in 2012 which included 80 million tons of KW (2). Due to the high organic matter content in KW (3), it has become an attractive raw material for anaerobic digestion (4). Compared to the traditional landfill and incineration methods, anaerobic digestion is a more promising way for not only solving the environmental problem, but also producing clean energy-biogas (4–7). However, rapid accumulation of volatile fatty acids (VFAs) usually occurs while KW ferments alone which always leads to a great drop of the reactor's pH and, therefore, inhibits the anaerobic digestion process (8,9). Even though KW may contain a certain amount of protein, with the C/N in the range of 14.7–36.4 (4), there were few reports about ammonia nitrogen inhibition. Thus, in previous studies, researchers focused more on taking measures to avoid VFAs inhibition, by a two or three stage system (10–12), adding trace elements as an accelerator for the growth of methanogens (13,14), co-digestion with other materials including press water, algae and cattle manure (15–18). But there was little research on co-digestion of KW and pig manure (PM) with the perspective of improving the fermentation environment.

PM is also a kind of commonly used material for anaerobic digestion which is rich in nitrogen and could reach a high level of ammonia nitrogen in an anaerobic digester (19,20). A high ammonia nitrogen concentration would easily cause an increase of pH over 8.0 and then be an inhibition to methane production, and it was reported mainly because of the free ammonia which was decided by three parameters (total ammonia concentration, temperature and pH) (21). But from another perspective, it can provide a high buffering capacity if digested with material which would cause a pH drop and VFAs accumulation as in KW. Furthermore, free ammonia increases along with the increase of the pH value (22), however, because of the acid-base neutralization in co-digestion, it could lead to a minor amount of free ammonia. Thus, it is supposed to achieve a stable fermentation environment and get the best methane production if KW and PM are used as co-digestion materials in a proper mixing ratio.

The aim of this study was to investigate the feasibility of anaerobic co-digestion of KW and PM with different mixing ratios in terms of methane production and system stability as well as to evaluate the fermentation performance to obtain optimal mixing ratio for future applications.

MATERIALS AND METHODS

Substrates and inoculum The KW used in this study was collected from a canteen at China Agricultural University, Beijing, China. The KW consisted mainly of residual vegetables, meat, rice, and noodles. After picking out some paper napkins and plastic food bags, the KW was ground into particles of 2.0–5.0 mm by a mill and then stored in the freezer at −20°C until use. The fresh PM was obtained from

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TABLE 1. Main properties of substrates and inoculum.

Properties	KW	PM	Inoculum
Total solid (TS) (%w)	18.81 ± 0.12	23.63 ± 0.17	1.38 ± 0.22
Volatile solid (VS) (%w)	17.24 ± 0.08	18.48 ± 0.11	0.77 ± 0.02
VS/TS (%)	91.67 ± 0.24	78.23 ± 0.11	55.97 ± 1.49
pH	–	–	8.09 ± 0.06
Crude protein (%/TS)	14.97 ± 0.35	13.80 ± 0.21	–
Crude fats (%/TS)	30.27 ± 0.21	6.16 ± 0.44	–
Carbohydrate (%/TS)	46.43 ± 0.32	58.27 ± 0.54	–
Crude fibers (%/TS)	17.64 ± 0.52	4.49 ± 0.06	–
Carbon, C (%/TS)	51.83 ± 0.27	44.48 ± 0.12	–
Nitrogen, N (%/TS)	2.75 ± 0.03	4.18 ± 0.06	–
Hydrogen, H (%/TS)	7.50 ± 0.04	6.19 ± 0.06	–
Sulfur, S (%/TS)	0.50 ± 0.04	0.87 ± 0.11	–
C/N ratio	18.88 ± 0.09	10.63 ± 0.15	–

–, no analysis; w, wet base.

Beilangzhong pig farm in Shunyi District, Beijing, China. The inoculated sludge was taken from a 40-L anaerobic digester treating the pig manure. Sludge was domesticated until no more biogas produced prior to use. The properties of the KW, PM and inoculum are shown in Table 1.

Experimental design The batch experiment was carried out using 8 identical 800 mL-conical flasks with the effective volume of 500 mL named digesters A–H. Different mixing ratios were set up as shown in Table 2. The digesters A–G were manually fed at the starting point of the batch experiment with a total solids (TS) concentration of 3% and total material weight of 500 g, which means the initial TS load was 30 g/L. Digester H was the control. The digesters were operated under mesophilic condition at (35 ± 1)°C by a heated water bath (SY-200, Changfeng Instrument and Apparatus Company, Beijing, China). Biogas was collected using gas packs. Each digester was manually mixed twice a day (10:00 and 22:00). All digesters did not adjust the initial pH. The experiment was terminated when there was no obvious gas production. Each treatment was carried out in triplicate and the arithmetic averages were taken for the final analysis.

Analytical methods TS and volatile solids (VS) were measured according to the standard methods (23). Crude protein was estimated by multiplying the total Kjeldahl nitrogen by 6.25, and the total Kjeldahl nitrogen was measured by a Kjeldahl apparatus (K1305A, Sonnen Automated Analysis Instrument Co., Ltd., Shanghai, China). Crude fat was measured by the Soxhlet extraction method. Carbohydrates were calculated by subtracting the amount of protein and fat from volatile solids (24). Crude fibers, which include cellulose, hemicellulose and lignin, were determined by a semi-automatic fiber analyzer (model A220, ANKOM Technology Corporation, NY, USA). Elemental analysis was conducted using an element analyzer (Vario Micro Cube, Elementar Analysensysteme GmbH, Donaustrasse, Germany). The pH was determined by a pH meter (PHS-3C, Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China).

Biogas analysis was performed with a gas chromatograph (1490, Agilent Technologies, USA) with a thermal conductivity detector and a 3 m stainless column packed with Porapak Q (60–80 mesh). The operational temperatures of the injection port, column oven, and detector were 120°C, 150°C and 120°C, respectively. Pure nitrogen was used as the carrier gas at a flow rate of 50 mL/min.

Fermentation liquid samples were centrifuged at 5000 rpm for 10 min at room temperature and then used for the ammonia nitrogen and VFAs concentration analysis, but it should be filtered through a 0.22 μm membrane for latter one (25). Total ammonia nitrogen [TAN: free ammonia ($N-NH_3$) plus ammonium ($N-NH_4^+$)] was measured by the Nessler's reagent spectrophotometry (21). Concentrations of VFAs (including formic, acetic, propionic, butyric, succinic and lactic acid) were analyzed by a high performance liquid chromatography (LC-10A, Shimadzu Corporation, Kyoto, Japan) equipped with an ultraviolet detector at the wavelength of 210 nm. The column temperature of the C18 column (4.6 × 150 mm) was 30°C. H_2SO_4 (5 mM) was used as mobile phase at a flow rate of 0.8 mL/min.

TABLE 2. Experimental design.

Digesters	PM:KW (based on TS)	PM (g)	KW (g)	Water (g)	Inoculum (g)	Total weight (g)
A	1:0	63.48	0	136.52	300	500
B	5:1	52.90	13.29	133.81	300	500
C	3:1	47.61	19.94	132.45	300	500
D	1:1	31.74	39.87	128.39	300	500
E	1:3	15.87	59.81	124.32	300	500
F	1:5	10.58	66.45	122.97	300	500
G	0:1	0	79.74	120.26	300	500
H	–	–	–	–	300	300

–, not adding.

RESULTS AND DISCUSSION

Biogas and methane production From Fig. 1A which exhibits the daily biogas production of each digester, it could be detected that except for digester A (pure PM) which had only one biogas production peak, other digesters had two biogas production peaks. The first biogas peaks happened on the first day in digesters B, C, D, E, F and G of 305 mL, 344 mL, 787 mL, 1175 mL, 1430 mL and 1873 mL, respectively. Through biogas composition analysis, high CO_2 concentration over 50% (v/v) was found in these digesters, besides, in digesters D, E, F and G, hydrogen concentrations were 5%, 20%, 24% and 37%, respectively. The results indicated that acidification occurred at the beginning of the experiment in digesters D–G. On the other hand, biogas production of digesters E, F and G decreased nearly to zero and then resumed normal operation until $NaHCO_3$ was added to adjust the pH value. The higher the ratio of KW, the longer the lag phase of the digestion, and the longest lag phase was nearly 35 days of digester G (pure KW). The phenomenon of two biogas peaks and hydrogen tested in the first three days also occurred in a previous study (26) which was dealing with co-digestion of KW and vegetable waste. Thus, it can be concluded that co-digestion of PM and KW could relieve the acidification inhibition of KW fermenting alone, but there still existed a heavy acidification inhibition when the KW proportion exceeded 50%.

Fig. 1B shows the daily methane production of all digesters except for digester H which only produced nearly 1 mL methane in the first two days. As we can see from Fig. 1B, digester A reached the methane production peak of 304 mL on the 8th day. As the proportion of KW increased, methane production peaks were delayed and the peak time of digesters B, C, D, E, F and G came on the 13th, 17th, 24th, 43th, 48th, and 52th day, respectively. The phenomenon that the production peak was delayed matched the findings of Ye et al. (8). However, because of the high initial substrate concentration (54 g/L) in the experiment of Ye et al. (8), their pure KW treatment failed and never returned back to produce methane even though NaOH and $NaHCO_3$ were added. There were also some studies (5,27) that did not have the phenomenon of a delayed production peak, which could be explained by the low feeding load (≤10 gVS/L) in their experiments. The highest daily methane production occurred in digester D with a methane production of 324 mL, which indicated that co-digestion was helpful in improving the daily methane production compared to the two materials fermented alone.

Fig. 2 gives the total biogas production, total methane production and methane content of all digesters. Biogas production had an obviously rising trend with the increasing ratio of KW. Though it did not appear to be much different from total methane production of digesters D, E, F and G, it was significantly higher than that of digesters A, B and C. Thus, it can be concluded that KW had a better biogas and methane production potential, but there existed two problems: one was the long lag phase for biogas production which prolonged the hydraulic retention time (HRT); another one was the lower methane content and the existence of hydrogen resulting from the VFAs accumulation, and the higher the proportion of KW, the lower methane content (Fig. 2), which could influence the subsequent use of biogas. Compared to KW, biogas and methane production of PM was relatively low but had relatively high methane content. All in all, digester D (1:1) got the highest methane content of 63.47%. Thus, mixing KW and PM at an appropriate ratio not only improved the total methane production compared to PM alone, but also increased methane content compared to KW only.

Biodegradability and technical digestion time Biodegradability (BDA) and technical digestion time (T_{80})