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Evaluating Methane Production from Anaerobic Mono- and Co-digestion of Kitchen Waste, Corn Stover, and Chicken Manure

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ABSTRACT: Anaerobic mono- and co-digestion of kitchen waste (KW), corn stover (CS), and chicken manure (CM) under mesophilic (37 °C) conditions were conducted in batch mode with the aim of investigating the biomethane potential (BMP), biodegradability, methane production performance, and stability of the process. An initial volatile solid concentration of 3 g VS L^{-1} with a substrate-to-inoculum (S/I) ratio of 0.5 was first tested, and two S/I ratios of 1.5 and 3.0 were evaluated subsequently. The modified Gompertz equation was used to assist in the interpretation of the conclusions. The results showed that BMP and specific methane yields were 725 and 683 mL g^{-1} VS_{added} for KW, 470 and 214 mL g^{-1} VS_{added} for CS, and 617 and 291 mL g^{-1} VS_{added} for CM, respectively. Therefore, KW had the highest biodegradability of 94% as compared with CS (45%) or CM (47%). For KW mono- and co-digestion with CS, CM, or their mixture, methane production performance was better at an S/I ratio of 1.5 than that of 3.0. For CS, CM, and their mixture, S/I ratios of both 1.5 and 3.0 were suitable. A synergistic effect was found in the co-digestion process, which was mainly attributed to a proper carbon-to-nitrogen ratio and the reduced total volatile fatty acids-to-total alkalinity ratio, thus providing better buffering capacity and supporting more microorganisms for efficient digestion.

INTRODUCTION

Anaerobic digestion (AD) is a complicated process in which anaerobic microorganisms convert organic matter into methane and carbon dioxide in an oxygen-free environment. This technology has been used throughout the U.S. and many European countries to treat organic waste, over the past decade.[1]

Traditionally, around the world, animal manure has been used as a monosubstrate for most of the digesters to produce biogas.[2] However, because of the inherent deficiency of carbon and low biodegradability and methane yield, the economics of manure digesters are not favorable. Besides, in many places, limited availability of animal manure is another problem.[3] Thus, feedstock alternatives and multifeedstock digestion need to be developed. Recently, co-digestion of animal manure with crop straw or food residues shows a continued growth trend.[4,5] Co-digestion may produce a synergistic effect because of the contribution of nutrients or the balance of the carbon-to-nitrogen (C/N) ratio.[6,7]

Kitchen waste (KW), corn stover (CS), and chicken manure (CM) are three typical organic solid wastes with a huge amount of production in China. About 60 million tons of KW, 300 million tons of CS, and 400 million tons of CM are produced every year.[8,9] KW has a low buffer capacity, and therefore, digestate can be prone to low pH. CS contains a high percentage of lignocelluloses, which cannot be effectively digested by anaerobic bacteria and leads to low biogas yield and long digestion time. CM has a low C/N ratio, which also leads to low AD performance. Thus, mono-digestion of KW, CS, or CM is always not desirable.[2,5,7] Co-digestion of these substrates with a certain proportion may improve the methane production performance.[2,10] However, little information is available about co-digestion of these three substrates and synergistic effects evaluation.

Besides the characteristics and proportions of substrates, the amount of inoculum is another important factor that directly affects the methane production performance.[11] The amount of inoculum and substrates is always connected and defined as the substrate-to-inoculum (S/I) ratio. The S/I ratio is especially important when operating a large-scale batch reactor and when estimating the biomethane potential (BMP) of a feedstock.[12] Liu et al. found that, under thermophilic conditions, methane yields of food waste were declined from 510 to 252 mL g^{-1} VS_{added} with the S/I ratio increased from 1.6 to 5.0.[13] Thus, investigating the proper S/I ratio and AD performance of mono- and co-digestion of KW, CS, and CM to conduct efficient methane production is necessary.

The objectives of this research were (1) to evaluate the biomethane potential and biodegradability of KW, CS, and CM, (2) to describe the methane yields and demonstrate the synergistic effects of co-digestion of KW, CS, and CM by using kinetic model and composition analysis of feedstocks and digestate, and (3) to investigate the effect of S/I ratio on methane production from anaerobic mono- and co-digestion of KW, CS, CM, and their mixture. The results of this work can provide useful information for the application of the biomethane potential method and anaerobic co-digestion technique.

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■ MATERIALS AND METHODS

Substrates and Inoculum. KW, CS, CM, and inoculum used in this study were collected from the Yanqing District of Beijing City, China. KW, which was collected from a restaurant, was smashed, homogenized, and frozen at −20 °C to prevent biological decomposition. CS was collected from a corn field and was ground to 40 mesh (0.422 mm) by a mill (KINGSLH, China). CM was collected from a hennery and was kept at −20 °C for later use. Inoculum was obtained from the effluent of an anaerobic digester treating chicken manure. The sludge was collected and stored at 4 °C for no more than 3 days before utilization. The characteristics of KW, CS, CM, and inoculum are presented in Table 1. Each data point presented was the average of triplicate measurements of the same feedstock.

Table 1. Characteristics of KW, CS, CM, and Inoculum

characteristics[a]	KW[a]	CS[a]	CM[a]	inoculum
TS (%)	26.3	84.9	29.9	8.8
VS (%)	22.7	76.9	19.0	4.0
FS (%)	3.6	8.0	10.9	4.8
VS/TS (%)	86.3	90.6	63.5	45.5
pH	4.7	ND	9.0	8.2
TVFA (g L^{-1})	8.4	ND	1.1	ND
TA (g $CaCO_3$ L^{-1})	1.2	ND	9.2	ND
C (%TS)	52.9	43.2	35.9	23
H (%TS)	7.9	5.9	5.0	0.3
O (%TS)	26.0	44.4	29.8	ND
N (%TS)	2.6	0.8	3.3	0.9
C/N	20.3	54.0	10.9	25.5
protein (%TS)	16.2	5.0	21.0	ND
lipids (%TS)	0.4	0.0	0.0	ND
cellulose (%TS)	15.2	42.3	20.0	ND
hemicellulose (%TS)	9.2	29.8	23.2	ND
lignin (%TS)	4.4	8.3	1.6	ND

[a]ND, not determined; KW, kitchen waste; CS, corn stover; CM, chicken manure; TS, total solids; VS, volatile solids; FS, fixed solids; TVFA, total volatile fatty acids; TA, total alkalinity.

Biomethane Potential Evaluation. To evaluate the ultimate methane potential and biodegradability of KW, CS, and CM, biomethane potential (BMP) assays were carried out in 1 L glass bottles with a working volume of 500 mL. The initial volatile solid (VS) concentration of organic substrates was 3 g VS L^{-1}. The corresponding S/I ratio was 0.5 according to Chynoweth et al.[14] After adding and mixing the needed amounts of substrates and inoculum in the reactors, tap water was added to fill up the working volumes. All digesters were tightly closed with rubber stoppers and screw caps. The headspace of each digester was purged with nitrogen gas for 2 min. Solutions were kept in an incubator (YIHENG, China) maintained at a mesophilic temperature (37 °C). No additional nutrient solution was added to BMP tests. The BMP of substrates was evaluated based on their specific methane yield (SMY, mL g^{-1} VS_{added}). All the digesters were performed in triplicate and manually shaken twice a day for about 1 min. Biogas production from three blank digesters that contained the same amount of inoculum and water was also measured.

Biogas samples were taken every day during the first 7 days of digestion and once every 2 or 3 days thereafter. Daily biogas production was calculated from the measurement of pressure in the headspace of each reactor and was converted to volume by application of the ideal gas law.[5]

Effect of Substrate-to-Inoculum Ratio and Synergism on Methane Production. According to Liu et al. and zhou et al.,[13,15] when the S/I ratio is higher than 3.0, mono-digestion of a given substrate usually shows lower methane yield. However, good methane production performance could be found at an S/I ratio of 1.5 in most mono-digesters. Therefore, in this study, to evaluate and compare the difference and synergistic effects of KW, CS, CM, and their mixture in mono- and co-digesters, two S/I ratios of 1.5 and 3.0 were used. The corresponding initial VS concentrations were 9 and 18 g VS L^{-1}, respectively. The mixture ratios of KW + CS, KW + CM, CS + CM, and KW + CS + CM were 1:1, 1:1, 1:1, and 1:1:1, based on VS. All the tests were carried out in duplicate. Other conditions were the same as those of the BMP assay.

Analytical Methods. Total solids (TS), volatile solids (VS), fixed solids (FS), and total alkalinity were measured according to the standard methods.[16] The pressure in the headspace of each reactor was measured using a 3151 WAL-BMP-Test system pressure gauge (WAL Mess-and Regelsysteme GmbH, Germany).[5] The pH value was determined by a pH meter (METTLER, Switzerland). Crude protein content was calculated by determining total organic nitrogen and multiplying by a factor of 6.25.[17] Lipids content was determined by Soxhlet extraction using diethyl ether as solvent.[18] Organic element (CHNS) was measured by an organic elemental analyzer (Vario EL cube, Germany). Element "O" was estimated by assuming C + H + N + O = 99.5% on a VS basis.[19] Cellulose, hemicellulose, and lignin contents were estimated by analysis of neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL)[20] in ground samples using an AMKOM 2000 Fiber analyzer (AMKOM, USA).

Biogas samples were analyzed by using a 7890A gas chromatograph (Agilent, USA) equipped with a thermal conductivity detector, and helium was the carrier biogas. A 2 m × 3 mm stainless steel column packed with TDX-01 (JK, China) was used. The temperatures of the oven, injector port, and detector were 120, 150, and 150 °C. Volatile fatty acids (VFAs) were measured using the GC-7890A equipped with a flame ionization detector, and nitrogen was the carrier gas. A DB-wax capillary column (Agilent Technologies, USA) with a length of 30 m and an inside diameter of 530 μm was used. The temperatures of the initial oven, injector port, and detector were 40, 200, and 210 °C, respectively. The temperature programming of the oven was as follows: Hold for 1 min at 40 °C, ramp to 65 °C at 5 °C/min, hold for 1 min, ramp to 160 °C at 25 °C/min, hold for 8 min.

Theoretical Methane Yield. The theoretical methane potential (TMP) of organic substrates can be estimated by the Buswell formula[21] based on elemental composition, as shown in eqs 1 and 2. All TMP data were converted assuming biogas at standard temperature and pressure (STP).

$$C_nH_aO_bN_c + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right)CO_2 + cNH_3 \quad (1)$$

$$\mathrm{TMP}\left(\frac{\mathrm{mL\ CH_4}}{\mathrm{g\ VS}}\right) = \frac{22.4 \times 1000 \times \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)}{12n + a + 16b + 14c} \quad (2)$$

Data Analysis. The values of VS removal were calculated based on direct measurements of the reactors' VS contents before and after the digestion tests. The weighted average methane content was calculated as described in detail by El-Mashad et al.[5] The significance of variance tests were determined using analysis of variance (ANOVA) with a significance level of 0.01 and 0.05.[22] Data analysis was completed by PASW statistics 18 for Windows (IBM, USA). Graph and data processing were completed by OriginPro 8.0 (OriginLab, USA).

The modified Gompertz model (eq 3), which can accurately describe and predict cumulative methane yield through the entire AD process, has been widely applied in modeling methane production.[23,24]

$$B = B_0 \exp\left\{-\exp\left[\frac{\mu_m e}{B_0}(\lambda - t) + 1\right]\right\} \quad (3)$$

where B represents the cumulative methane yield (mL g^{-1} VS_{added}), B_0 is the maximum methane yield (mL g^{-1} VS_{added}), μ_m stands for the maximum methane production rate (mL g^{-1} VS_{added} d^{-1}), λ refers to the lag phase time (day), t means the incubation time (day), and e is equal to 2.72.

■ RESULTS AND DISCUSSION

Characteristics of Substrates. Characteristics of KW, CS, and CM samples and the inoculum are shown in Table 1. Based on a total weight basis, KW and CS contained higher VS, but lower FS, than that of CM. The VS/TS ratio was 86.3, 90.6, and 63.5% for KW, CS, and CM, respectively. A higher VS/TS ratio means a higher organic content, which is desirable for biogas and methane production. However, organic element analysis showed that CS had a C/N ratio of 54.0, which might be unsuitable for anaerobic digestion since the proper C/N ratio is usually ranged from 13.0 to 28.0.[25,26] CM also had an unsuitable C/N ratio of nearly 11.0. On the other hand, Table 1 shows that both CS and CM contained a lot of fiber, which consists of cellulose and hemicellulose. About 72% (dry basis) and 43% (dry basis) fiber were found in CS and CM, respectively. Organic substrates that contain abundant lignocelluloses always lead to low biogas yield and long digestion time.[27] Therefore, among the three organic substrates, KW has good potential for AD.

Biomethane Potential of KW, CS, and CM. Biomethane potential (BMP) is essential to evaluate the methane production of a given organic substrate during its anaerobic decomposition.[28] After digestion for 28 days, biogas and methane yields of KW, CS, and CM in BMP assays are shown in Table 2. For KW, CS, and CM, the specific biogas yields (SBYs) were 1142, 417, and 496 mL g^{-1} VS, respectively; the weighted average methane content (WAMC) was 60, 51, and 59%, respectively; and the specific methane yields (SMY) were 683, 214, and 291 mL g^{-1} VS, respectively. Statistical analysis showed that the SBY and SMY of KW were significantly higher ($p < 0.01$) than those of CS or CM. It is apparent that KW, which contains more substrates available to be digested by anaerobic microorganisms, had the highest WAMC, SMY, and SBY. On the other hand, CS, which contains a high percentage of lignin, showed the lowest SMY and SBY. He et al. reported that complex structures of lignin and other cell wall polysaccharides made lignocellulosic waste materials hard to be biodegraded and used by anaerobic microorganisms and thus caused a low digestion rate and biogas production.[27]

Table 2. Biogas and Methane Yields of Different Substrates in Biomethane Potential Assays

parameter	KW[a]	CS[a]	CM[a]
specific biogas yield (mL g^{-1} VS_{added})	1142	417	496
specific methane yield (mL g^{-1} VS_{added})	683	214	291
theoretical methane potential (mL g^{-1} VS_{added})	725	470	617
biodegradability (%)	94	45	47
weighted average methane content (%)	60	51	59
initial pH	8.0	8.2	8.2
final pH	7.4	7.4	7.5
VS removal (%)	87	54	62

[a]KW, kitchen waste; CS, corn stover; CM, chicken manure.

Theoretical methane potential (TMP) calculation results showed that KW (TMP = 725 mL g^{-1} VS_{added}) had a higher TMP than CS (TMP = 470 mL g^{-1} VS_{added}) or CM (TMP = 617 mL g^{-1} VS_{added}). Therefore, KW had the highest biodegradability (SMY/TMP, %) of 94% as compared to CS (45%) or CM (47%), indicating that KW is a desirable feedstock for AD. The final pH values of KW, CS, and CM reactor were 7.4, 7.4, and 7.5, which are within a stable neutral range of 7.2–7.8.[25,26]

For different substrates, the daily biogas yields, cumulative biogas yields, and methane content are shown in Figure 1. Similar trends of daily biogas production were observed for all substrates. Biogas production started immediately after innoculating, kept increasing until reaching the peak, and then began to decline (Figure 1A). KW, which contains a high initial TVFA concentration (Table 1), showed a long start-up time and long maximal biogas production rate occurred time. As shown in Figure 1B, after 20 days of digestion, almost 90% of the final biogas yields were obtained. Therefore, a hydraulic retention time (HRT) of 20 days is suitable for a continuous digester to treat each substrate, which is similar to the data reported by El-Mashad et al.[5] The methane content of biogas increased from an average of 27% to a relatively constant level of approximately 58% after about 11 days (Figure 1C).

To sum up, KW, which contains higher energy density and more substrates available by microorganisms, had the highest biogas and methane yields as compared to CS or CM. Neutral pH, lower start-up time, and higher methane content collectively showed that the reactors performed well.[29]

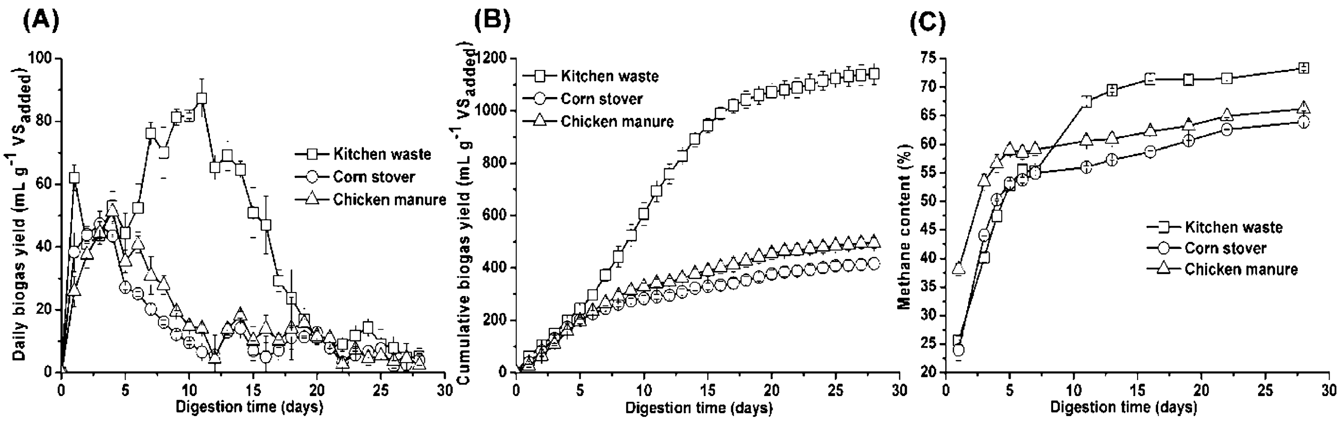


Figure 1. Daily biogas yields (A), cumulative biogas yields (B), and methane content (C) of three wastes in biomethane potential assays. Error bars were obtained based on three replicates.

Effect of S/I Ratio on Methane Yield. To investigate the effects of substrate-to-inoculum (S/I) ratio on methane production performance, two S/I ratios of 1.5 and 3.0 were conducted. As shown in Figure 2, at an S/I ratio of 1.5, all digesters had good methane production performance. The digester that was fed with KW alone showed the highest specific methane yield (SMY), which was 670 mL g^{-1} VS_{added}. CS or CM co-digestion with KW could increase the SMY from 210 mL g^{-1} VS_{added} (CS alone) to 414 mL g^{-1} VS_{added} (CS + KW, 1:1 on a VS basis), and from 309 mL g^{-1} VS_{added} (CM alone) to 491 mL g^{-1} VS_{added} (CM + KW, 1:1 on a VS basis). At an S/I ratio of 3.0, all reactors, except for the KW digester, showed good methane production performance. Co-digestion could enhance the methane production for a certain substrate. The specific methane yields of KW, CS, CM, KW + CS, KW + CM, and KW + CS + CM were 176, 220, 302, 300, 405, 302, and 432 mL g^{-1} VS_{added}, respectively.

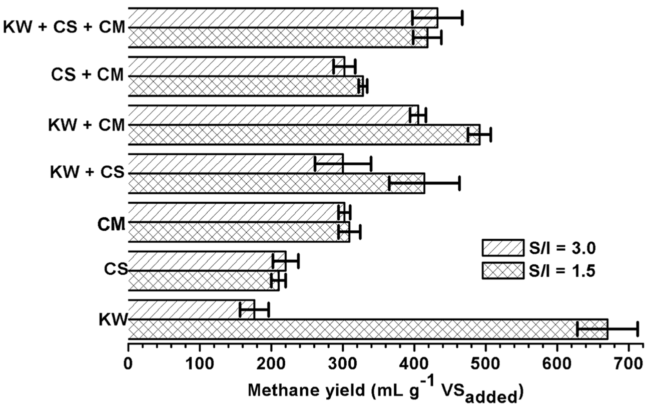
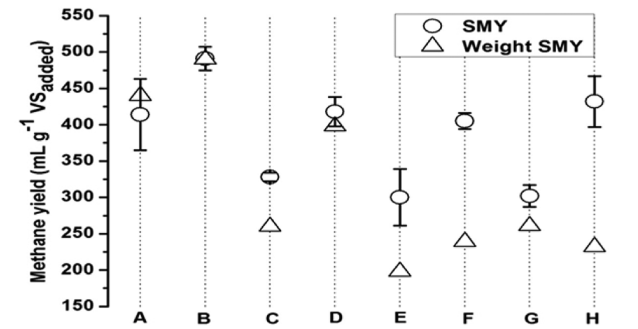


Figure 2. Effect of substrate-to-inoculum (S/I) ratio on methane production of different substrates. KW, kitchen waste; CS, corn stover; CM, chicken maure. The mixture ratios of KW + CS, KW + CM, CS + CM, and KW + CS + CM were 1:1, 1:1, 1:1, and 1:1:1, based on VS. Error bars were obtained based on two replicates.

The above results indicated that co-digestion with substrates that have a high methane production potential (such as KW) is a good way to increase the methane production performance for agricultural wastes. Xu and Li[18] reported that CS co-digestion with dog food (DF) could increase the methane yield from 92.5 mL g^{-1} VS_{added} (CS alone) to 304.4 mL g^{-1} VS_{added} (CS + DF, 1:1 on a VS basis). Besides, co-digestion of CS with dog food could reduce the start-up time and volatile fatty acid accumulation. The SMY of mono-digestion of KW at an S/I ratio of 3.0 was 74% lower than that of 1.5. KW has a low buffer capacity and is easy to acidify. The higher the S/I ratio, the more serious acidification occurs, thus leading to low biogas production. Co-digestion of KW with other substrates is one of the efficient ways to solve such problems. At an S/I ratio of 3.0, co-digestion of KW with CS or CM significantly improved the methane production potential. The increase rate was up to 51% (co-digestion of KW with CS), 69% (co-digestion of KW with CM), and 86% (co-digestion of KW with a mixture of CS and CM), respectively.

Statistical analysis showed that the SMYs of KW and KW co-digestion with CS or CM at an S/I ratio of 3.0 were significantly lower ($p < 0.01$) than that of 1.5. However, for CS, CM, and their mixture, the SMY at an S/I ratio of 3.0 had no significant difference ($p > 0.05$) with that of 1.5. These results indicated that, for KW mono- and co-digestion with CS, CM, or their mixture, methane production performance was better at an S/I ratio of 1.5 than that of 3.0; for CS, CM, and their mixture, S/I ratios of both 1.5 and 3.0 were suitable for initializing a new batch reactor.

Evaluation of Synergistic Effect. To investigate the synergistic effect with co-digestion of two or more substrates in the same digester at S/I ratios of 1.5 and 3.0, the modified Gompertz model and composition analysis of feedstocks and digestate were used. As can be seen from Figure 3, synergistic effects are found in most of the co-digesters. Synergism could be seen as an additional methane yield for co-digestion substrates over the weighted average of the individual substrates' methane yield, namely, the weighted specific methane yield (Weighted SMY).[7] If the value of positive differential (SMY − Weighted SMY, mL g^{-1} VS_{added}) is greater than the value of the standard deviation (SD) of SMY, it is concluded that there is a synergistic effect existing in the experiment.[7] For example, the Weighted SMY and the SMY of co-digestion of CS and CM at an S/I ratio of 1.5 was 260 mL g^{-1} VS_{added} and 328 mL g^{-1} VS_{added}, respectively. The positive differential of 68 mL g^{-1} VS_{added} was greater than its standard deviation of 6 mL g^{-1} VS_{added}, so it was clear that the difference was indeed the result of a synergistic effect. It can be seen from Table 3, that the corresponding C/N ratio of co-digestion of CS and CM was adjusted to 16.8, which was in the range of the proper C/N ratio of 13−28. As noted earlier, co-digestion may adjust the C/N ratio; thus it may be one of the reasons why a synergistic effect occurred. For co-digestion of KW with CS, CM, and their mixture, a synergistic effect was not obvious at the low S/I ratio of 1.5, while a synergistic effect was found at the high S/I ratio of 3.0 (Figure 3).



Sample	Differential	SD of SMY	Synergistic effect
A: KW + CS, S/I = 1.5	-26	49	not clear
B: KW + CM, S/I = 1.5	1	16	not clear
C: CS + CM, S/I = 1.5	68	6	synergistic
D: KW + CS + CM, S/I = 1.5	19	20	not clear
E: KW + CS, S/I = 3.0	102	39	synergistic
F: KW + CM, S/I = 3.0	166	11	synergistic
G: CS + CM, S/I = 3.0	41	15	synergistic
H: KW + CS + CM, S/I = 3.0	200	35	synergistic

Figure 3. Synergistic effects analysis of kitchen waste (KW), corn stover (CS), and chicken manure (CM) at different substrate-to-inoculum (S/I) ratios in co-digesters. SMY = specitific methane yield, SD = standard deviation, differential = SMY − Weighted SMY. The mixture ratios of KW + CS, KW + CM, CS + CM, and KW + CS + CM were 1:1, 1:1, 1:1, and 1:1:1, based on VS.

Total volatile fatty acids (TVFA) of effluent analyses (Table 3) shows that a higher VFA existed in the KW reactor (TVFA = 2969 mg L^{-1}, propionic acid = 1117 mg L^{-1}) than in other reactors (TVFA < 300 mg L^{-1}, propionic acid < 70 mg L^{-1}) at the higher S/I ratio of 3.0. Higher TVFA and propionic acid content could result in the inhibition of methane production in

Table 3. Characteristics of Substrates and Effluent in Reactors at S/I Ratios of 1.5 and 3.0[a]

substrate	C/N ratio	TVFA (mg L^{-1})	acetic acid (mg L^{-1})	propionic acid (mg L^{-1})	final pH	TVFA/TA ratio
			S/I = 1.5			
KW	20.3	261	26	58	7.4	0.04
CS	54.0	247	25	57	7.1	0.04
CM	10.9	259	38	55	7.4	0.04
KW + CS	28.5	244	27	52	7.2	0.04
KW + CM	14.3	246	26	54	7.4	0.04
CS + CM	16.8	253	37	53	7.2	0.04
KW + CS + CM	38.0	246	29	51	7.2	0.04
			S/I = 3.0			
KW	20.3	2969	1418	1117	6.9	0.49
CS	54.0	242	27	65	7.1	0.04
CM	10.9	130	25	59	7.6	0.03
KW + CS	28.5	198	26	54	7.4	0.03
KW + CM	14.3	199	24	52	7.6	0.03
CS + CM	16.8	190	28	56	7.3	0.03
KW + CS + CM	38.0	190	27	55	7.4	0.03

[a]S/I ratio, substrate-to-inoculum ratio; C/N ratio, carbon-to-nitrogen ratio; TVFA, total volatile fatty acids; TA, total alkalinity; KW, kitchen waste; CS, corn stover; CM, chicken manure. The mixture ratios of KW + CS, KW + CM, CS + CM, and KW + CS + CM were 1:1, 1:1, 1:1, and 1:1:1, based on VS.

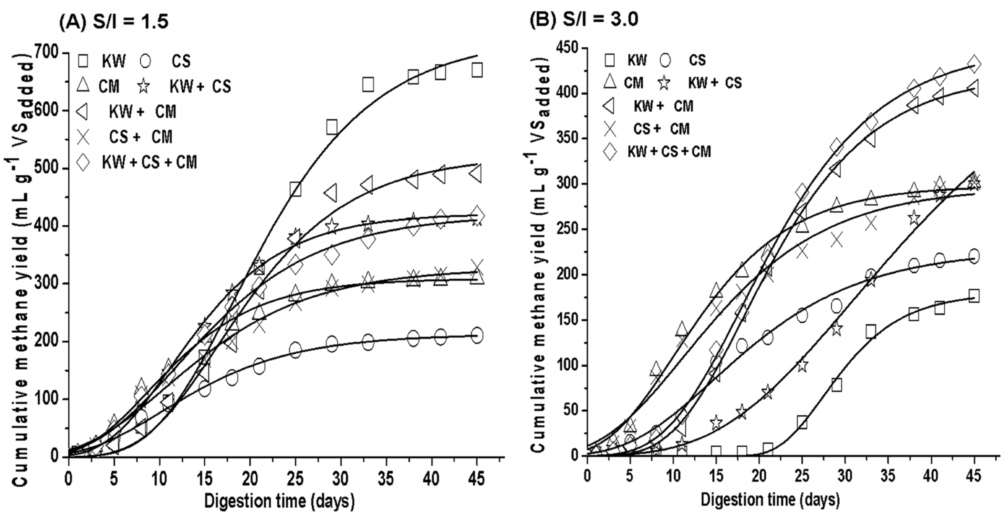


Figure 4. Modified Gompertz plots of cumulative methane yields in reactors at S/I ratios of 1.0 (A) and 3.0 (B). KW, kitchen waste; CS, corn stover; CM, chicken manure. The mixture ratios of KW + CS, KW + CM, CS + CM, and KW + CS + CM were 1:1, 1:1, 1:1, and 1:1:1, based on VS.

the KW reactor. According to Callaghan et al.,[30] the ratio of TVFA to total alkalinity (TA) can be used to judge digester stability. If the ratio of TVFA to TA is less than 0.4, the digester should be stable; if the ratio of TVFA to TA is in the range of 0.4−0.8, some instability will occur in digester; if the ratio of TVFA to TA is greater than 0.8, significant instability occurs in the digester. For the KW digester (at an S/I of 3.0), the ratio of TVFA to TA was 0.49 (the total alkalinity of all reactors was found between 6000 and 6500 mg $CaCO_3$ L^{-1}), implying that some instability occurred in the reactor. Co-digestion of KW with CM or CS or their mixture could significantly reduce the value of the TVFA/TA ratio and support microbial growth for efficient digestion, while increased buffering capacity would help maintain the stability of the anaerobic digestion system. In brief, adjusting to a proper C/N ratio and reducing the ratio of TVFA/TA may produce synergistic effects of co-digestion of KW, CS, and CM.

The modified Gompertz model, which has been widely used due to good simulation results and wide applications, was used in this synergistic effect analysis. Figure 4 presents the experimental and model results for mono- and cosubstrates at S/I ratios of 1.5 and 3.0, and the calculated parameters are shown in Table 4. As can be noted, the model can well predict the cumulative methane yield. At an S/I ratio of 1.5, CS or CM co-digestion with KW improved its methane production potential (B_0) and maximal methane production rate (μ_m). The corresponding lag phase time (λ) showed a relatively increase. On the other hand, CS co-digesting with CM could improve the B_0 and shorten the λ, which was beneficial to the anaerobic digestion process. At an S/I ratio of 3.0, KW co-digestion with CS or CM could improve its methane production potential and shorten the lag time. For mono- and co-digestion of CS and CM, co-digestion could shorten the lag phase time from 4.82 days (for CS) and 2.36 days (for CM) to 1.73 days.

Table 4. Parameters of Methane Production from Modified Gompertz Equation for Synergistic Effect Study[a]

substrate	B_0 (mL g^{-1} VS_{added})	μ_m (mL g^{-1} VS_{added} d^{-1})	λ (d)	R^2
		S/I = 1.5		
KW	728	30.7	9.35	0.99
CS	213	9.6	1.99	0.99
CM	309	16.6	1.91	0.99
KW + CS	422	22.1	4.19	1.00
KW + CM	522	23.6	8.26	0.99
CS + CM	328	13.3	1.64	0.99
KW + CS + CM	420	17.4	2.85	1.00
		S/I = 3.0		
KW	179	13.0	22.39	1.00
CS	228	8.5	4.82	0.99
CM	298	14.4	2.36	0.99
KW + CS	472	11.2	15.52	1.00
KW + CM	422	18.6	9.95	1.00
CS + CM	297	11.6	1.73	0.98
KW + CS + CM	452	18.7	9.17	1.00

[a] B_0, methane production potential; μ_m, maximal methane production rate; λ, lag phase time (day); KW, kitchen waste; CS, corn stover; CM, chicken manure. The mixture ratios of KW + CS, KW + CM, CS + CM, and KW + CS + CM were 1:1, 1:1, 1:1, and 1:1:1, based on VS.

CONCLUSION

KW, CS, and CM can be used as feedstocks to produce biogas in mono- and co-digesters through the AD process. KW contains more readily biodegradable compositions and is easily converted to biogas, but it has a low buffering capacity. Therefore, at a higher S/I ratio (such as 3.0 S/I ratio), poor methane production performance was found. Corn stover contains a high percentage of lignocelluloses, which cannot be effectively digested by anaerobic bacteria and leads to low biogas yield and long digestion time. Chicken manure (CM) has good buffer capacity, but it has a low C/N ratio, which also leads to low AD performance. Co-digestion of KW, CS, and CM could increase the specific methane yield attributed to a proper C/N ratio and the reduced TVFA/TA ratio. Besides, for commercial methane production, the substrate-to-inoculum (S/I) ratio in the digester should be of more concern since a higher S/I ratio could significantly influence the efficient biogas production.

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE

AD: anaerobic digestion
BMP: biomethane potential
CM: chicken manure
CS: corn stover
C/N ratio: carbon-to-nitrogen ratio
FS: fixed solids
KW: kitchen waste
TMP: theoretical methane potential
SBY: specific biogas yield
SD: standard deviation
S/I ratio: substrate-to-inoculum ratio
SMY: specific methane yield
TS: total solids
VS: volatile solids
WAMC: weighted average methane content
Weighted SMY: weighted specific methane yield
TVFA/TA ratio: total volatile fatty acids to total alkalinity ratio

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