Anaerobic codigestion of sewage sludge and rice straw

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Abstract: We investigated the feasibility of anaerobic codigestion of sewage sludge and rice straw. Laboratory-scale mesophilic and thermophilic digesters were operated with hydraulic retention times of 20 and 15 days, respectively. The feeding ratio of sewage sludge and rice straw was 1:0.5 based on the total solids (TS). Before digestion, the rice straw was ground to ca. 5 mm in length (grinding pretreatment), ground and soaked in distilled water (water pretreatment), or ground and soaked in a hydrolytic enzyme solution (enzyme pretreatment). The effect of these pretreatments on the digestion performance was investigated. A digester fed sewage sludge alone was operated as a control. Both water pretreatment and enzyme pretreatment effectively reduced the TS and volatile solids (VS) of rice straw. The addition of rice straw increased methane production by 66–82% in mesophilic digesters and by 37–63% in thermophilic digesters. Higher methane production was also observed in digesters with water pretreatment and with enzyme pretreatment than in digesters with grinding pretreatment. Specific methane production increased in most cases, and the maximum of 0.311 L/g-added-VS was observed in the enzyme pretreated rice straw mesophilic digester. In addition, a decrease in the ammonia-nitrogen concentration and an improvement in the sludge dewaterability were achieved by the addition of rice straw.

Keywords: Anaerobic codigestion; enzyme pretreatment; methane; rice straw; sewage sludge

INTRODUCTION

The Japanese government agreed on the "Biomass Nippon Strategy" in December 2002 (Kurashige, 2003). This strategy sets specific goals for the use of currently unused biomass such as rice straw and forestry residues. Anaerobic digestion is an effective means to recover energy from biomass by producing biogas, which consists primarily of methane and carbon dioxide. We focused on the use of rice straw, which is produced in large quantities, i.e., about 13 million tons each year, as a by-product of rice production in Japan. Currently in Japan, the most commonly used method to dispose of rice straw is to incorporate it into the soil; however, anaerobic digestion of rice straw has several advantages over this use. The incorporation of rice straw into the soil may lead to the deterioration of soil conditions and the emission of methane to the atmosphere (Watanabe et al., 1995). In contrast, anaerobic digestion stabilizes rice straw, produces a residue that can be used for soil conditioning, and recovers energy in the form of methane (Tchobanoglous et al., 1993).

The anaerobic digestion of rice straw is feasible (Zhang and Zhang, 1999); however, anaerobic digestion of rice straw alone is inefficient because the nutrients and minerals required for bacterial growth are not present at sufficient levels in rice straw. Rice straw has a carbon-to-nitrogen (C/N) ratio of around 75, whereas the suggested optimum C/N ratio for anaerobic digestion is in the range of 20 to 30 (Parkin and Owen, 1986). However, sewage sludge has a C/N ratio that varies from 6 to 16 (Tchobanoglous et al., 1993). Therefore, the addition of sewage sludge to rice straw improves the C/N ratio for anaerobic digestion. Anaerobic digestion of sewage sludge is widely used in Japan (Mikami et al., 1997). Many existing anaerobic digesters in sewage treatment plants have surplus capacity because they are operated at quite long retention times. Consequently, the anaerobic codigestion of sewage sludge and rice straw using existing digesters may be an attractive method for efficient energy recovery from rice straw. Some of the possible benefits of codigestion are: the use of the existing infrastructure, an improved balance of nutrients, an increased organic load of biodegradable matter, and better yields per unit digester volume (Cecchi et al., 1996).

Rice straw is a lignocellulose containing primary cellulose and hemi-cellulose. Lignocellulose such as rice straw is difficult to degrade using conventional anaerobic digestion processes. Pretreatment of rice straw by mechanical size reduction and/or heating improves its digestion (Zhang and Zhang, 1999). We examined the effect of pretreating the rice straw with a hydrolytic enzyme before codigestion. Enzyme pretreatment has several advantages; the method is simple, and the enzyme itself can be converted to methane in the anaerobic digestion process. We operated laboratory-scale digesters to codigest rice straw with sewage sludge in mesophilic and thermophilic conditions. A digester fed sewage sludge alone was operated as a control reactor. Our objectives were: to investigate the feasibility of anaerobic codigestion of sewage sludge and rice straw, to investigate the effects of rice straw on the digestion performance and dewaterability of digested sludge, and to determine the effect of different pretreatment methods on the digestibility of rice straw.

METHODS

Substrates

The feed sewage sludge was a mixture of thickened primary sludge and waste activated sludge from a municipal wastewater treatment plant, which was operated using conventional activated sludge processes. The feed total solids (TS) of the sewage sludge were about 3.5%. The sludge was stored at 4ºC until feeding. Rice straw was collected from a paddy field in Nagaoka City, Niigata Prefecture, Japan. The rice straw was completely dried in an oven at 105ºC for more than 20 h. The dried rice straw was ground to a length of about 5 mm using a hammer mill and then used as the substrate.

Pretreatments methods

Three different rice straw pretreatment methods were compared: grinding pretreatment alone, grinding plus soaking in distilled water (water pretreatment), and grinding plus soaking in an enzyme solution (enzyme pretreatment). Previous studies have shown that enzyme pretreatment is an ineffective method for enhancing the anaerobic digestion of biofibers (Angelidaki and Ahring, 2000) and energy crops (Lehtomäki et al., 2004). However, enzyme pretreatment was not intensively investigated in these studies. We used a recently developed hydrolytic enzyme manufactured by Menicon Co., Japan. It is able to hydrolyze not only cellulose, but also hemi-cellulose, which is a major component of rice straw. The most effective conditions for enzyme pretreatment were determined previously in batch anaerobic digestion experiments. For the enzyme pretreatment procedure, the ground rice straw was soaked in the enzyme solution (5 g/L) at 36ºC for 20 days, with a liquid-to-solid ratio of the solution-to-rice straw of 10 mL/g-TS. Distilled water was used in the water pretreatment instead of the enzyme solution. After pretreatment, direct liquid–solid mixtures were used as the substrates for semi-continuous anaerobic digestion.

Digester operation

We operated mesophilic digesters (MControl, MRun 1, MRun 2, and MRun 3) at 36ºC with a hydraulic retention time (HRT) of 20 days and thermophilic digesters (TControl, TRun 1, TRun 2, and TRun 3) at 55ºC with a HRT of 15 days. Mesophilic digesters and thermophilic digesters were operated at different times. The digesters were operated in semi-continuous mode with daily wasting and feeding. The periods of operation for mesophilic and thermophilic digesters were 55 days and 57 days, respectively. The seed sludges used for mesophilic and thermophilic digestion were taken from a full-scale sewage sludge digester operated using mesophilic and thermophilic conditions.

Table 1 shows the rice straw pretreatment conditions and digester operating conditions. The feeding ratio of sewage sludge and rice straw was kept constant at 1:0.5 based on TS. A digester fed sewage sludge alone was operated as a control. The laboratory-scale digesters were 2.4-L bottles with a working volume of 1.8 L. Approximately 90 mL (mesophilic digesters) or 120 mL (thermophilic digesters) of well-mixed liquid was withdrawn daily and replaced with the same volume of substrate. In the water pretreatment or enzyme pretreatment runs, the wasting/feeding volume was increased by about 10% to take into account the additional volume of liquid used in the pretreatment. Therefore, the actual HRT of these runs was shorter than 20 days or 15 days. Based on a method developed by Stroot et al. (2001), the digesters were only mixed at the time of wasting and feeding time. The average characteristics of the feed substrates are shown in Table 2. The slightly higher concentration of chemical oxygen demand (COD) in MRun 3 and TRun 3, compared with other rice-straw-fed runs, was attributed to the COD of the enzyme.

Table 1 Rice straw pretreatment conditions and digester operating conditions.

Run	Pretreatment conditions	Sewage sludge : Rice straw (TS basis)	Temperature (ºC)	HRT (days)	OLR
MControl	-	1 : 0	36	20	1.44
MRun 1	Grinding alone	1 : 0.5	36	20	2.14
MRun 2	Water pretreatment	1 : 0.5	36	20	2.14
MRun 3	Enzyme pretreatment	1 : 0.5	36	20	2.14
TControl	-	1 : 0	55	15	1.80
TRun 1	Grinding alone	1 : 0.5	55	15	2.73
TRun 2	Water pretreatment	1 : 0.5	55	15	2.73
TRun 3	Enzyme pretreatment	1 : 0.5	55	15	2.73

OLR = organic loading rate, units : g-VS/L/day

Table 2 Feed substrate characteristics.

Run	TS (%)	VS (%)	COD (g/L)
MControl	3.56	2.88	37.2
MRun 1	5.31	4.28	48.6
MRun 2	5.31	4.28	48.6
MRun 3	5.31	4.28	49.2
TControl	3.56	2.70	32.3
TRun 1	5.31	4.10	43.7
TRun 2	5.31	4.10	43.7
TRun 3	5.31	4.10	44.3

Analyses

Biogas was collected in Tedlar bags and the volume produced was measured daily using liquid displacement at 25ºC. The biogas composition was analyzed using a gas chromatograph (Shimadzu, GC-8A model) equipped with a thermal conductivity detector. Standard methods (APHA, 1998) were used for the measurement of pH, ammonia-nitrogen, TS, volatile solids (VS), and COD (using dichromate). Soluble COD (SCOD) was measured in the same manner as total COD (TCOD), except samples were centrifuged at 15000 rpm for 10 min then filtered through a 0.45-μm filter before analysis. For the measurement of ammonia-nitrogen, sample preparation was carried out using the same method as for measuring SCOD. A dewatering experiment was performed to evaluate the dewaterability of the digested sludge after the continuous experiments had finished. The dewatering procedure was conducted according to the method described by Ochi et al. (2005), using an organic polymer coagulant. The water content of the dewatered sludge was determined by measuring the TS content of the sludge.

RESULTS AND DISCUSSION

Digester stability

The primary indexes used to evaluate digester performance were pH, TS, VS, TCOD, SCOD, ammonia-nitrogen, methane production, and methane content of the produced biogas. All indexes, except for ammonia-nitrogen, stabilized after day 12 in mesophilic digestion and after day 17 in thermophilic digestion. In the case of ammonia-nitrogen, a decrease in concentration was observed in the initial operating period in all runs, but this stabilized in the latter period. Figures 1 and 2 show the time course of TS, VS, SCOD, and ammonia-nitrogen levels in mesophilic digestion and thermophilic digestion, respectively. A steady-state condition was achieved in all runs.

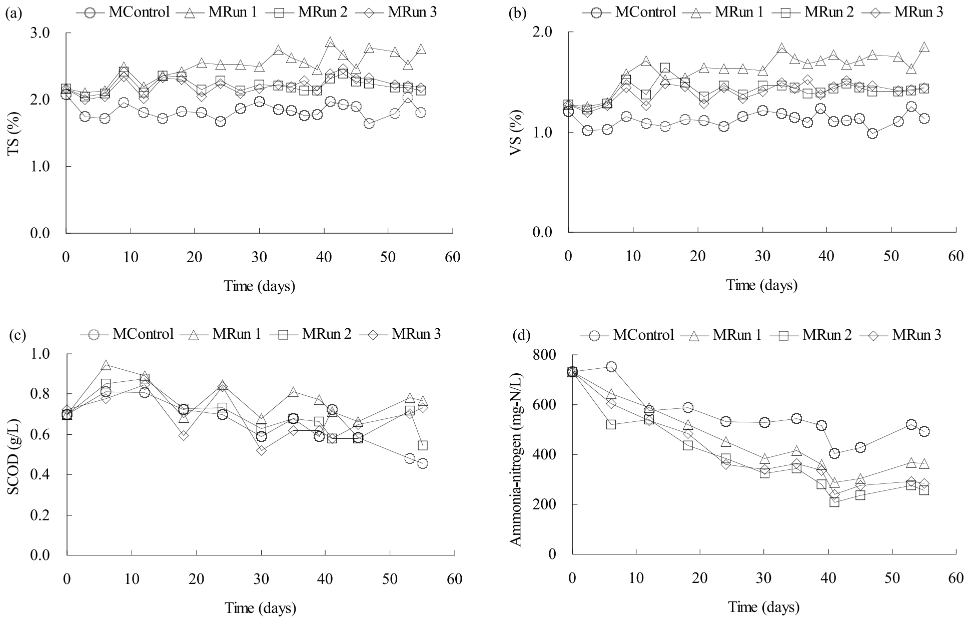

Figure 1 Time course of (a) total solids (TS), (b) volatile solids (VS), (c) soluble chemical oxygen demand (SCOD), and (d) ammonia-nitrogen levels in mesophilic digestion.

Steady-state performance of the digesters

Table 3 shows the steady-state performance of the digesters. The values shown are the averages from day 12 in mesophilic digestion and from day 17 in thermophilic digestion, except for the value of ammonia-nitrogen, which was averaged from day 30 for mesophilic digestion or from day 26 for thermophilic digestion.

Effect of rice straw addition in mesophilic digestion

The pH was similar in all digesters (Table 3). TS and VS were increased by the addition of rice straw. However, compared with MControl, the removal efficiency increased in all runs, except for VS in MRun 1. By assuming that the reduction in sewage sludge in rice-straw-fed runs was the same as in the control digester, rice straw removal in MRun 1, MRun 2, and MRun 3 was estimated as 58, 78, and 77% for TS, and 60, 78, and 79% for VS, respectively. Both water pretreatment and enzyme pretreatment enhanced the reduction in rice straw. However, the concentration of TCOD in rice-straw-fed runs was almost the same as in the control. This does not agree with the results for VS, but may be attributed to the difficulty of measuring TCOD (Moen et al., 2003). Therefore, the measurement of VS might be a more reliable index of organic residues than TCOD. SCOD concentrations were slightly increased (6–21%) by adding rice straw. Lower SCOD concentrations were observed in the water pretreatment and enzyme pretreatment runs. The concentration of ammonia-nitrogen in the rice-straw-fed runs was much lower than that of the control. This was probably caused by the higher C/N ratio of the substrate in the rice-straw-fed runs. Compared with the control, a maximum reduction of 44% was observed in MRun 2.

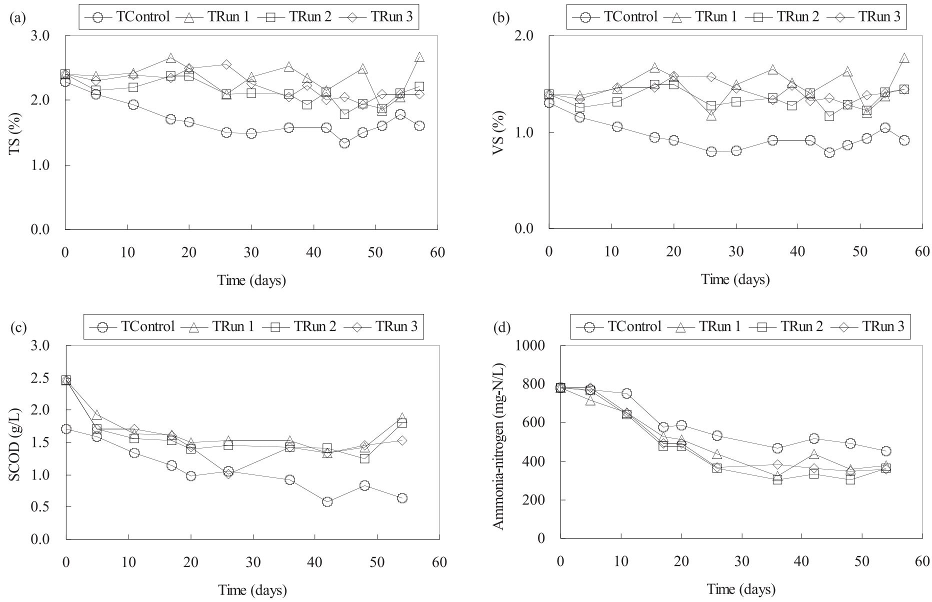

Figure 2. Time course of (a) TS, (b) VS, (c) SCOD, and (d) ammonia-nitrogen levels in thermophilic digestion.

Table 3. Steady-state performance of the digesters (mean ± standard deviation).

Run	MControl	MRun 1	MRun 2	MRun 3	TControl	TRun 1	TRun 2	TRun 3
pH	6.9 ± 0.1	6.9 ± 0.1	6.9 ± 0.1	6.9 ± 0.1	7.2 ± 0.1	7.1 ± 0.1	7.1 ± 0.1	7.1 ± 0.1
TS (%)	1.83 ± 0.10	2.57 ± 0.17	2.22 ± 0.09	2.23 ± 0.12	1.58 ± 0.12	2.34 ± 0.27	2.08 ± 0.18	2.19 ± 0.20
TS removal (%)	48.6	51.6	58.2	58.0	55.8	56.0	60.8	58.8
VS (%)	1.13 ± 0.07	1.69 ± 0.09	1.44 ± 0.07	1.42 ± 0.07	0.89 ± 0.08	1.49 ± 0.19	1.34 ± 0.11	1.42 ± 0.09
VS removal (%)	60.8	60.5	66.4	66.8	66.9	63.5	67.2	65.3
TCOD (g/L)	13.1 ± 2.2	13.7 ± 2.1	14.2 ± 1.6	12.9 ± 1.8	11.6 ± 1.8	15.1 ± 3.6	13.5 ± 2.2	14.9 ± 3.4
TCOD removal (%)	64.8	71.8	70.8	73.8	64.1	65.4	69.1	66.4
SCOD (g/L)	0.63 ± 0.11	0.76 ± 0.08	0.67 ± 0.10	0.67 ± 0.10	0.88 ± 0.21	1.55 ± 0.17	1.46 ± 0.17	1.40 ± 0.19
Ammonia-nitrogen (mg-N/L)	490 ± 54	355 ± 44	276 ± 48	304 ± 43	493 ± 34	387 ± 51	333 ± 29	364 ± 12
Methane content (%)	62.9 ± 2.2	59.5 ± 2.4	61.3 ± 1.5	61.4 ± 1.6	57.7 ± 1.5	52.7 ± 1.3	54.9 ± 1.4	55.8 ± 1.6
Methane production (L/L-added-substrate)	7.3 ± 0.4	12.1 ± 1.0	12.6 ± 0.9	13.3 ± 0.9	6.7 ± 0.6	9.2 ± 0.7	10.4 ± 1.4	10.9 ± 1.2
Specific methane production (L/g-added-VS)	0.253 ± 0.014	0.283 ± 0.023	0.294 ± 0.021	0.311 ± 0.021	0.226 ± 0.019	0.211 ± 0.016	0.239 ± 0.031	0.250 ± 0.027

The addition of rice straw lowered the methane content of the biogas produced by approximately 2 to 3%. However, the volume of methane produced increased significantly. Compared with MControl, methane production in MRun 1, MRun 2, and MRun 3 increased by 66, 73, and 82%, respectively. Both the water pretreatment and enzyme pretreatment increased the efficiency of methane production from rice straw, and methane production from MRun 3 was higher than that from MRun 2 by 0.7 L/L-added-substrate. Based on stoichiometry, approximately 0.3 L/L-added-substrate was produced if the enzyme dosed in MRun 3 was completely converted to methane. Consequently, the net methane production efficiency was highest in the enzyme pretreatment run. Adding rice straw also increased the specific methane production. Compared with the control, the specific methane production in MRun 1, MRun 2, and MRun 3 increased by 12, 16, and 23%, respectively, and the maximum value was 0.311 L/g-added-VS in MRun 3.

Effect of rice straw addition in thermophilic digestion

A slight decrease in pH was observed in rice-straw-fed runs (Table 3). Adding rice straw increased TS and VS. Using the same assumption as for mesophilic digestion, rice straw removal in TRun 1, TRun 2, and TRun 3 was estimated as 57, 71, and 65% for TS, and 57, 68, and 62% for VS, respectively. As in mesophilic digestion, water pretreatment or enzyme pretreatment effectively increased the reduction in rice straw. However, water pretreatment was more effective than enzyme pretreatment. Comparing the rice-straw-fed runs, TCOD was lowest in TRun 2. The addition of rice straw increased SCOD concentrations by 59–76%. Compared with mesophilic digestion, higher SCOD concentrations were observed in all runs. Moen et al. (2003) reported a similar observation in thermophilic digesters treating sewage sludge alone. As with the mesophilic digestion, a decrease in the ammonia-nitrogen concentration was observed in rice-straw-fed runs. Compared with the control, a maximum reduction of 32% was observed in TRun 2.

The methane content of the produced biogas was 2–5% lower in rice-straw-fed runs, but the volume of methane produced increased. Compared with TControl, methane production in TRun 1, TRun 2, and TRun 3 increased by 37, 55, and 63%, respectively. Water pretreatment or enzyme pretreatment enhanced the methane production from rice straw. As in mesophilic digestion, the net methane conversion efficiency from rice straw was considered to be highest in the enzyme pretreatment run. Compared with the control, the specific methane production decreased by 7% in TRun 1, but increased in TRun 2 and TRun 3 by 6 and 11%, respectively. On the whole, however, under the same pretreatment, the addition of rice straw was not so effective at increasing methane recovery in thermophilic digestion compared with mesophilic digestion.

Dewaterability

A dewatering experiment was conducted using digested sludge under steady-state conditions (Figure 3). The mixing of rice straw with sewage sludge reduced the water content of dewatered sludge from about 86 to 82% in mesophilic digestion and from about 79 to 75% in thermophilic digestion. The improvement of sludge dewaterability may be due to the high level of cellulose fibers in rice straw (Örmeci and Vesilind, 2000). Comparing mesophilic and thermophilic digestion, a lower water content of dewatered sludge was observed in thermophilic digestion. In a review, Buhr and Andrews (1977) reported that the improvement of sludge dewaterability is one of the chief advantages of thermophilic digestion.

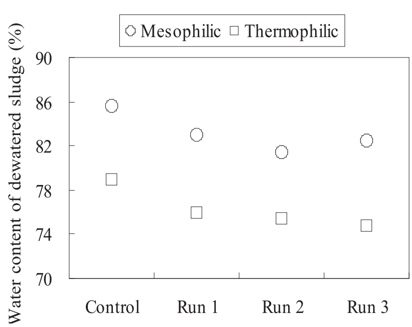

Figure 3 Effect of rice straw addition on the dewaterability of digested sludge.

CONCLUSIONS

All digesters achieved steady-state conditions. Water pretreatment or enzyme pretreatment caused a reduction in TS and VS from rice straw in both mesophilic and thermophilic digestion. The addition of rice straw increased methane production by 66–82% in mesophilic digesters and by 37–63% in thermophilic digesters. Except for TRun 1, specific methane production also increased by 6–23%. The maximum specific methane production of 0.311 L/g-added-VS was observed in the enzyme-pretreated mesophilic digester. SCOD concentrations were slightly increased (6–21%) by adding rice straw in mesophilic digestion, whereas an increase of 59–76% was observed in thermophilic digestion. The concentration of ammonia-nitrogen in rice-straw-fed runs was much lower than that of the control, and the maximum reduction was 44%. A dewatering experiment showed that the sludge dewaterability was improved by adding rice straw. Our results indicate that it is useful to codigest rice straw with sewage sludge using existing digesters in sewage treatment plants.

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