Field test of methane fermentation system for treating swine wastes


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Abstract A methane fermentation system for treating swine wastes was developed and successfully demonstrated in a field test plant (0.5 m³/d). The system was composed of a screw-press dehydrator, a methanogenic digester, a sludge separator, an oxidation ditch (OD) and composting equipment. A performance evaluation was carried out regarding physical pre-treatment using the screw-press dehydrator, methane fermentation for pre-treated slurry, and post-treatment for digested effluent by OD. Total solids (TS) and chemical oxygen demand (CODCr) removal by the screw-press pre-treatment were 38% and 22%, respectively. Properties of the screenings were as follows: water content 57%, ignition loss 93%, specific gravity 0.33. The pretreated strong slurry was digested under mesophilic conditions. Digestion gas (biogas) production rate was 25 m³/m³-slurry (NTP) and methane content of the biogas was 67%. CODCr removal of 65% with methane fermentation treatment of the slurry operating at 35°C was observed. No inhibition of methane fermentation reaction occurred at the NH₄⁺-N concentration of 3,000 mg/l or less during methane fermentation by the system. Mass balance from the present pilot-scale study showed that 1 m³ of mixture of excrement and urine of swine waste (TS 90 kg/m³) was biologically converted to 25 m³/m³-slurry (NTP) of biogas (methane content 67%), 100 kg of compost (water content 40%, ignition loss 75%), and 0.80 m³ of treated water (SS 30–70 mg/l).

Keywords Ammonia; anaerobic digestion; biogas; oxidation ditch; screw-press dehydrator; swine waste

Introduction

The amount of animal wastes excreted per year in Japan was estimated at 94.3 million tons in 1997. Intensive animal raising in limited areas such as in Japan results in a large accumulation of animal wastes, and this has been causing serious water pollution problems (Haga et al., 1998).

Anaerobic digestion has been industrially used as a treatment system for municipal, industrial, and agricultural wastes. A major advantage of anaerobic treatment processes is that compared with aerobic processes energy consumption is low and there is little excess sludge production. Anaerobic digestion with biogas production from organic wastes has recently become a topic of increasing interest throughout the world (Sharma et al., 1997; Shikura and Harada, 1999). For example, in anaerobic digestion process using pig manure (5.6–10% of dry matter), the biogas yield amounts to 231 L of biogas per kg of volatile solids feed (Francese et al., 2000). In addition to biogas, the anaerobic digestion process also generates digested sludge, which is mainly utilized as fertilizer for plant production because the nutrients in the raw material remain in the mineralized sludge as accessible compounds (Francese et al., 2000). It is a rapidly developing technology with a large number of recently started plants, especially in Europe (Sharma et al., 1997). In Denmark a...
A demonstration program for large scale-biogas plants has resulted in the establishment of more than 20 large collective biogas plants treating a mixture of manure and organic industrial waste (Shikura and Harada, 1999).

On the other hand, ammonia is considered to be the main cause of inhibition when digesting swine or cattle manure, which often has total ammonia concentrations higher than 4 g-N/l. It has been shown that the biogas process can be adapted to an ammonia concentration of about 4 g-N/l without any reduction of the methane yield (Hashimoto, 1986; van Velsen, 1979). Therefore, it is important to study both process performance and inhibitory limits of ammonia concentration in anaerobic digestion of animal wastes.

This study was undertaken to promote widespread adoption of methane fermentation systems for animal wastes in Japan. In this study, a methane fermentation system for treating swine wastes was developed and successfully demonstrated in a field test plant (0.5 m^3/d). An important characteristic of the system examined is its simple constitution including pre-treatment process for swine wastes and post-treatment process for effluent digestates and sludges from anaerobic digestion. The present investigation shows the characteristics of physical pre-treatment using a screw-press dehydrator, mesophilic anaerobic digestion, and biological post-treatment for effluent digestates using an oxidation ditch. Also, mass balance of this methane fermentation system is reported. As a result of the accumulation of these practical data on field tests, realization of a practical methane fermentation process for animal wastes can be expected.

**Materials and methods**

**System description**

A pilot-scale experiment using a setup capable of treating up to 0.5 m^3/day of swine wastes was conducted in Japan at the Kanagawa Prefectural Government’s Livestock Industry Research Institute (Kataoka et al., 1999, 2001). A system flow diagram is presented in Figure 1. The system is composed of a screw-press dehydrator, a raw slurry-storage tank (3.5 m^3), two acidification digesters (1 m^3 each), two methanogenic digesters (4 m^3 each), two sludge separators (2.5 m^3 each), an oxidation ditch (OD) (10.5 m^3) and composting equipment.

![Figure 1 Flow sheet of methane fermentation system for treating swine waste](https://iwaponline.com/wst/article-pdf/45/12/103/424843/103.pdf)
Preparation of swine wastes
Since excrement and urine discharged from the pigsty at the Livestock Industry Research Institute have been treated by composting and OD process, respectively, they were separately gathered and transported two or three days a week. The urine contained wash wastewater used in the pigsty. The excrement and urine were mixed at the ratio of 1:1.5–2.5 (specific gravity of excrement; approximately 1) and subsequently pre-treated by screw-press dehydrator.

Properties of the excrement were as follows: water content 53.0–72.4% (average 65.6%), ignition loss 75.4–89.3% (average 85.8%). Characteristics of the urine polluted water were as follows: (average value) total solids (TS) 4,740 mg/l, volatile solids (VS) 2,640 mg/l, total-COD$_{Cr}$ (T-COD$_{Cr}$) 5,480 mg/l, total-COD$_{Mn}$ (T-COD$_{Mn}$) 1,290 mg/l, total-BOD (T-BOD) 2,310 mg/l, $\text{NH}_4^+$-nitrogen (NH$_4^+$-N) 740 mg/l, Kjeldahl-nitrogen (Kjeldahl-N) 890 mg/l, and pH 7.7.

Operational conditions for pre-treatment
Physical pre-treatment of swine wastes to remove the solid impurities was carried out using the screw-press dehydrator without chemical grouting at the rate of approximately 300 L/h.

Operational conditions for anaerobic digestion
Two cylindrical tanks (working volume, 4 m$^3$ each) were used for anaerobic digestion treatment. The pre-treated strong slurry (T-COD$_{Cr}$ 9.0%, T-BOD 3.0%, TS 5.5%, Kjeldahl-N 0.48%) was fed 4 times a day and anaerobically digested under mesophilic (35°C) conditions; HRT of 15.4 d; volumetric organic loading rate of 4.4–4.8 kg COD$_{Cr}$/m$^3$•d. From October to March, the digestion tanks were maintained at 35°C by blowing steam directly three times a day using a steam boiler. The anaerobic digestion tank was agitated intermittently (3 min agitation/5 min static) with a mechanical agitator. Iron hydroxide pellet was used for the desulfurization of biogas in two dry desulfurization towers (25 kg charged in each).

Post-treatment process for treating digestates from anaerobic digestion
The effluent digestate from the methanogenic digester was separated into supernatant and thickened sludge in the sludge separator, and these were subsequently treated using the OD and the screw-press dehydrator. One particular feature was that the digestates were diluted with an equal amount of effluent from the OD in order to promote solid-liquid separation of digestates by gravity sedimentation. The thickened digested sludge in the sludge separation tank was dehydrated. The filtrate was returned to the sludge separation tank and subsequently treated by the OD process. The sludge cake was composted. The properties of the supernatant are shown in Table 2. As shown by the T-BOD/T-N (total nitrogen) ratio of 0.64 and T-BOD/NH$_4^+$-N ratio of 1.1, the supernatant had a high nitrogen content relative to BOD.

Operational conditions of oxidation ditch treatment
The OD tank, which was 12.6 m$^3$ in total volume and 10.5 m$^3$ in effective volume, was equipped with screw-type surface aerator. The operational conditions of OD treatment were as follows: intermittent aeration (2h aeration and 1h static), HRT 10 days, BOD volumetric loading 0.12kg/m$^3$•d, T-N loading 0.10–0.18 kg/m$^3$•d. From November to March, the OD was maintained at 20°C by heating using a steam boiler.

Analytical methods
The concentrations of BOD, COD$_{Cr}$, TS, VS, suspended solids (SS), volatile suspended solids (VSS) and Kjeldahl-N were determined according to Standard Methods (APHA,
1992). The COD$_{Cr}$ analysis was carried out by closed reflux titrimetric method. The dissolved oxygen analysis of the 5-day incubated samples for BOD determination was carried out by azide modification method. The ammonia (NH$_4^+$-N) concentration of anaerobic digestion samples was determined by titrimetric method. The concentrations of NH$_4^+$-N, nitrite (NO$_2^-$-N), nitrate (NO$_3^-$-N) and PO$_4$-P of OD and treated water samples were analyzed using a continuous-flow analyzer (Bran+Luebbe TRAACS 800, Germany).

The composition of the biogas produced was analyzed using a gas chromatograph (GL Sciences GC-320, Japan) with an active carbon 30/60 column and a thermal conductivity detector. Volatile fatty acids (VFA) in the supernatant were analyzed using an HPLC (ERC-8717, ERMA Optical Works) with a Shodex RS pak KC-811 column and a Refractive Index ERC-7510 detector.

The water content was determined after 24 h in a drying oven at 105°C, and ignition loss and ash were analyzed by incineration at 600°C for 2 h.

Results and discussion

Performance of pre-treatment by screw-press dehydrator

Performance of screw-press treatment. Under farm situations, solids separation by use of mechanical separators or screens is often employed. Such separation is done because it effectively reduces the size of the digester, eases handling and pumping, and also reduces the incidence of clogging.

TS, VS and COD$_{Cr}$ removal by the screw-press treatment was 38%, 40% and 22%, respectively. The volume of screw pressed slurry was approximately 77% of that of the mixture of excrement and urine. The volume of the screw-pressed screenings was about 0.94 that of the swine waste (specific gravity: approximately 1). The screw-pressed thick slurry, which contained screw-pressed slurry at about 1.25 times the volume of urine and wastewater, was a concentrated slurry composed of undigested organics mixed with urine and wastewater.

Properties of screw-pressed slurry. The screw-pressed slurry was strong, with TS of 5.5%, T-COD$_{Cr}$ of 9.0%, and T-BOD of 3.0% (Table 1). The pre-treatment for swine wastes using the screw-press removed solid fractions but did not affect the concentration of BOD components and soluble fractions. The BOD/COD$_{Cr}$ ratio of the pre-treated slurry was approximately 0.33.

Properties of screenings. Properties of the screenings were as follows: water content 57%, ignition loss 93%, specific gravity 0.33. Main ingredients of the screenings were

<table>
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<th>Pre-treated slurry (mg/l)</th>
<th>Anaerobic digested slurry (35°C)</th>
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<tbody>
<tr>
<td>TS</td>
<td>55,400</td>
<td>37,900</td>
</tr>
<tr>
<td>VS</td>
<td>40,500</td>
<td>19,800</td>
</tr>
<tr>
<td>T-COD$_{Cr}$</td>
<td>90,100</td>
<td>28,400</td>
</tr>
<tr>
<td>S-COD$_{Cr}$</td>
<td>31,600</td>
<td>4,710</td>
</tr>
<tr>
<td>T-BOD</td>
<td>30,100</td>
<td>6,910</td>
</tr>
<tr>
<td>S-BOD</td>
<td>16,700</td>
<td>710</td>
</tr>
<tr>
<td>S-TOC</td>
<td>10,700</td>
<td>1,440</td>
</tr>
<tr>
<td>VFA</td>
<td>14,900</td>
<td>230</td>
</tr>
<tr>
<td>Kjeldahl-N</td>
<td>4,840</td>
<td>4,400</td>
</tr>
<tr>
<td>pH</td>
<td>6.1</td>
<td>8.0</td>
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</table>
undigested organics arising from compound feed and swine bristles. The screw-pressed screenings consisted of swine waste impurities of a diameter of 1 mm or greater. As these components that are difficult to decompose by methane fermentation were removed at the first stage of the system, no clogging or scum arose in the pumps, pipes, tanks and other equipment following the methane fermentation.

**Performance of anaerobic digestion of pre-treated swine slurry**
The pre-treated slurry was digested under mesophilic conditions; HRT of 15.4 d; COD$_{Cr}$ volumetric loading of 4.4–4.8 kg COD$_{Cr}$/m$^3$•d; COD$_{Cr}$-sludge loading of 0.18–0.23 kg COD$_{Cr}$/kg SS•d. The properties of the digested sludge under 35°C heating were pH 7.7–8.0, oxidation-reduction potential −530 mV, SS 2.1–2.4%, NH$_4^+$-N 2,500–3,000 mg/l. It was found that COD$_{Cr}$ and BOD removal was 64% and 78%, respectively; VS and SS removal was 52% and 45%, respectively; biogas production rate was 25 m$^3$/m$^3$-slurry (NTP); and methane content of the biogas was 67% (Table 1, Figure 2).

**Biogas production.** Figure 2 shows the temperature, HRT, biogas production rate and biogas composition during operation of the anaerobic digestion. The biogas production rate was 5–15 m$^3$/m$^3$-slurry under unheated operation from summer to autumn and

![Figure 2 Methane fermentation treatment of screw-pressed swine slurry](https://iwaponline.com/wst/article-pdf/45/12/103/424843/103.pdf)
20–28 m³/m³-slurry under 35°C steam-heated operation during winter. Biogas production was substantially stable when the sludge temperature was maintained at 35°C. The methane content of the biogas held steady in the range of 66–69%. Other gas components were CO₂ 31–34%, H₂S 0.1–0.4%, and NH₃ 1 ppm or less. During heated operation at 35°C, H₂S was produced at a high rate of 0.35–0.4%. No organic overloading or problems with the pumps, pipes, fermentation tank etc. were observed during the continuous operation. In this field test, the biogas was subjected to dry desulfurization and used to fuel a gas light within the field-test facility.

**Effects of ammonia on anaerobic digestion for treating animal wastes**

Methane fermentation reaction is inhibited in the presence of high ammonia concentration. It has been reported that methane fermentation is generally inhibited under mesophilic conditions when the NH₄⁺-N concentration in the tank rises above 3,000–4,000 mg/l (Hansen et al., 1998; Krylova et al., 1997; Lay et al. 1998; Poggi-Varaldo et al., 1997) (Table 2). Ammonia may be present in either of two forms, ionic (NH₄⁺) or free (NH₃) (NH₄⁺ ⇔ NH₃). Free ammonia has a strong inhibitory effect on methane fermentation. Free ammonia concentration is determined by three factors: NH₄⁺-N concentration, temperature and pH. It is ordinarily represented as the theoretical value calculated using an equation (Lay et al., 1998). NH₄⁺-N concentration in the methane fermentation tank at HRT 15.4 d under 35°C heating was 2,500–2,800 mg/l and the free ammonia concentration was in the range of 250–500 mg/l (calculated value) (Figure 4). No particular rise in S-CODCr, S-TOC, or VFA concentration was observed in the tank at this time (Figures 3 and 4). It was therefore considered that no inhibition of methane fermentation reaction occurred at the NH₄⁺-N concentration (3,000 mg/l) during methane fermentation by the system (Table 2).

**Biological post-treatment of digestates by an OD process**

The effluent digestate from the anaerobic digester was separated into supernatant and thickened sludge in the sludge separator and subsequently treated using the OD and the screw-press dehydrator. One particular feature was that the digestates were diluted 1:1 with effluent from the OD in order to promote solid-liquid separation of digestates by gravity sedimentation. The quality of effluent from the OD (>20°C) was BOD 72 mg/l, SS 40 mg/l and T-N 224 mg/l (Table 3). The quality of effluent from the OD (20°C) was BOD 47 mg/l, SS 337 mg/l and T-N 649 mg/l. Throughout the present field tests, organic colored substances (dark-brown) and phosphate remained in the effluent at approximately 2,500 degrees and 200 mg/l, respectively.

![Figure 3 COD Cr removal of screw-pressed slurry by methane fermentation](https://iwaponline.com/wst/article-pdf/45/12/103/424843/103.pdf)
Figure 4  Effect of ammonia on methane fermentation of screw-pressed swine slurry

Table 2 Compilation of inhibition by ammonia nitrogen in mesophilic anaerobic digestion for treating solid waste

<table>
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<tr>
<th>Solid waste</th>
<th>Total ammonia NH₄⁺-N (mg/l)</th>
<th>Free NH₄⁺-N (mg/l)</th>
<th>pH</th>
<th>Operational conditions</th>
<th>Ammonia inhibition</th>
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<tr>
<td>Municipal solid waste</td>
<td>2,800</td>
<td>–</td>
<td>30% TS</td>
<td>Fill and Draw</td>
<td>No inhibition</td>
<td>Poggi-Varaldo et al. (1997)</td>
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<td>Salmon waste</td>
<td>3,500</td>
<td>–</td>
<td>35% TS</td>
<td>Batch experiment</td>
<td>No inhibition</td>
<td>Chamy et al. (1998)</td>
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<tr>
<td>Cattle manure</td>
<td>4,000</td>
<td>84</td>
<td>7.5</td>
<td>Continuous experiment</td>
<td>No inhibition</td>
<td>Hashimoto (1986)</td>
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<tr>
<td>Swine manure</td>
<td>2,500–2,800</td>
<td>250–500</td>
<td>7.0–8.2</td>
<td>HRT 15 day</td>
<td>No inhibition</td>
<td>Present study</td>
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<tr>
<td></td>
<td>6,000</td>
<td>750</td>
<td>8.1</td>
<td>Continuous experiment</td>
<td>63% of max</td>
<td>Hansen et al. (1998)</td>
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<td>Continuous experiment</td>
<td>methane recovery</td>
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<td>Garbage</td>
<td>6,202</td>
<td>185</td>
<td>7.5</td>
<td>Batch experiment</td>
<td>50% of max</td>
<td>Chu et al. (2001)</td>
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<td>Kinetic analysis</td>
<td>methane recovery</td>
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Table 3 Water quality on OD treatment

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<tr>
<td>T-BOD</td>
<td>(mg/l) 1,240</td>
<td>72</td>
<td>47</td>
</tr>
<tr>
<td>T-COD₅₆</td>
<td>(mg/l) 4,220</td>
<td>191</td>
<td>618</td>
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<tr>
<td>NH₄⁺-N</td>
<td>(mg/l) 1,170</td>
<td>54</td>
<td>201</td>
</tr>
<tr>
<td>NO₂⁻-N + NO₃⁻-N</td>
<td>(mg/l) 57</td>
<td>149</td>
<td>410</td>
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<tr>
<td>T-N</td>
<td>(mg/l) 1,950</td>
<td>224</td>
<td>649</td>
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<tr>
<td>SS</td>
<td>(mg/l) 8,440</td>
<td>40</td>
<td>337</td>
</tr>
<tr>
<td>pH</td>
<td>(-) 7.9</td>
<td>7.5</td>
<td>7.2</td>
</tr>
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</table>
Mass balance

Mass balance from the present pilot-scale study showed that 1 m$^3$ of mixture of excrement and urine of swine waste (TS 90 kg/m$^3$) was biologically converted to 25 m$^3$/m$^3$-slurry (NTP) of biogas (methane content 67%, 600 kJ/m$^3$-slurry), 100 kg of compost (water content 40%, ignition loss 75%), and 0.80 m$^3$ of treated water (SS 30–70 mg/l) (Figure 5). In the anaerobic digestion process at HRT 15.4 d under 35$^\circ$C, 61% of COD$_{Cr}$ of pretreated slurry was converted to methane gas and 29% of COD$_{Cr}$ remained as digested sludge.

Nitrogen balance (T-N 6 kg/m$^3$) indicated that 3.2 kg (53%) of the nitrogen migrated to the compost and 0.18 kg (3%) to 0.18 m$^3$ of treated water. By calculating the nitrogen balance of the post-treatment of digestates based on nitrogen removal by the OD treatment, sludge dehydration, and the result of the composting operation, it was estimated that the digestates (0.9 m$^3$) produced from 1 m$^3$ of swine waste mixture of excrement and urine contained 4.32 kg of T-N, of which 56.5% (2.44 kg) migrated to the dehydrated sludge, 4.2–12.0% (0.18–0.52 kg) migrated to the treated water, and 21.5–49.3% (0.93–2.1 kg) was converted to nitrogen gas (Figure 6).

It was confirmed that the present biological system is applicable to treatment of animal wastes.

Conclusions

A methane fermentation system for treating swine wastes was developed and successfully demonstrated in a field test plant (0.5 m$^3$/d). The main features of this system were (1) physical pre-treatment using the screw-press dehydrator without chemical grouting, (2) mesophilic anaerobic digestion of pre-treated slurry, and (3) post-treatment of digestates by the OD process. The performance of the methane fermentation system is summarized in Table 4.

1. TS, VS and COD$_{Cr}$ removal by the screw-press treatment was 38%, 40% and 22%, respectively. Properties of the screenings were as follows: water content 57%, ignition loss 93%, specific gravity 0.33. The screw-pressed slurry was considerably strong, with TS of 5.5%, T-COD$_{Cr}$ of 9.0%, T-BOD of 3.0%, and T-N of 0.48%.

2. The pretreated strong slurry was digested under mesophilic conditions. Biogas production rate was 25 m$^3$/m$^3$-slurry (NTP) and methane content of the biogas was 67%.
3. No inhibition of methane fermentation reaction occurred at the NH$_4^+$-N concentration of 3,000 mg/l or less during methane fermentation by the system.

4. Post-treatment for the digestates was achieved by separation into supernatant and thickened sludge in the sludge separator and subsequent treatment using the OD and the screw-press dehydrator. The quality of OD effluent (>20°C) was BOD 72 mg/l, SS 40 mg/l, and T-N 224 mg/l. However, organic colored substances (dark-brown) and phosphate remained in the effluent.

5. Mass balance from the present pilot-scale study showed that 1 m$^3$ of mixture of excrement and urine of swine waste (TS 90 kg/m$^3$) was biologically converted to 25 m$^3$/m$^3$-slurry (NTP) of biogas (methane content 67%), 100 kg of compost (water content 40%, ignition loss 75%), and 0.80 m$^3$ of treated water (SS 30–70 mg/l).

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References


