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Novel anaerobic digestion process with sludge ozonation for economically feasible power production from biogas

K. Komatsu, H. Yasui, R. Goel, Y. Y. Li and T. Noike

ABSTRACT

A novel process scheme was developed to achieve economically feasible energy recovery from anaerobic digestion. The new process scheme employs a hybrid configuration of mesophilic and thermophilic anaerobic digestion with sludge ozonation: the ozonated sludge is first degraded in a thermophilic digester and then further degraded in a mesophilic digester. In small-scale pilot experiments of the new process scheme, degradation of VSS improved by 3.5% over the control (mesophilic-only configuration) with 20% less ozone consumption. Moreover, biogas conversion also improved by 7.1% over the control. Selective enrichment of inorganic compounds during centrifugation produced a dewatered sludge cake with very low water content (59.4%). This low water content in the sludge cake improved its auto-thermal combustion potential during incineration and added to the overall energy savings. We conducted a case study to evaluate power generation from biogas for a municipal wastewater treatment plant with an average dry weather flow of 43,000 m^3/d. Electricity production cost was 5.2 ¢/kWh for the advanced process with power generation, which is lower than the current market price of 7.2 ¢/kWh. The new anaerobic digestion scheme with power generation may reduce greenhouse gas emissions by about 1,000 t-CO_2/year compared with the conventional process without power generation.

Key words | anaerobic digestion, centrifugation, inorganic components, mesophilic–thermophilic hybrid flow scheme, ozonation, power generation

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INTRODUCTION

To curb global warming, reducing greenhouse gas (GHG) emissions is urgently needed. To that end, sources of renewable biomass energy should be expanded to include organic wastes. Municipal biological sludge is an ideal biomass resource because it is generated at all municipal wastewater treatment plants (WWTPs) at a consistent quality and quantity. Power can be produced from the biogas generated by anaerobic digestion (AD) of municipal sludge; however, power generation from biogas is generally not economically feasible in Japan and is typically limited to very large WWTPs with capacity greater than 120,000 m^3/d average dry weather flow. At present, only 24 of the 300 WWTPs using the AD process are equipped with a power generation system. The high capital and operation cost for power generation equipment are the main factors preventing power generation from biogas. These high costs can be attributed to the elaborate control systems required to meet the stringent electricity quality controls in Japan (e.g., minimal frequency of shutdown events, minimum fluctuation of voltage (V) and frequency (Hz) when uploading for either internal or external use). In addition, financial support is not available for generating electricity from biogas. Another factor contributing to the limited interest in power generation from biogas is the low methane recovery due to poor degradation efficiencies of solids. The purpose of this study was to develop a modified process that can (i) improve methane recovery with

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reasonable net energy/material consumption, and (ii) enhance the degradation efficiency of solids and reduce the quantity of sludge for final disposal.

The degradation efficiency of solids is influenced primarily by the rate-limiting step of hydrolysis (Eastman & Ferguson 1981; Tiehm *et al.* 2001) and the relatively high fraction of nonbiodegradable material in the sludge. Therefore, many studies have attempted to improve digestion efficiencies with thermal, mechanical, and chemical pre-treatment/post-treatment of solids (Appels *et al.* 2008). One of the most effective treatments is ozonation (Weemaes *et al.* 2000; Battimelli *et al.* 2003; Goel *et al.* 2003*a*; Bougrier *et al.* 2007). In a modified flow scheme with ozonation of digested sludge, the degradation efficiency of solid wastes was approximately 80% (Goel *et al.* 2003*b, c*; Yasui *et al.* 2005). The key points of this scheme are (i) increased degradation of previously nonbiodegradable components by ozonation of digested sludge, and (ii) prolonged solid retention time by centrifugation of the sludge. Further implementation and optimisation of this flow scheme at a full-scale plant revealed that very slow degradation of the ozonated sludge was still a rate-limiting factor (Yasui *et al.* 2005). Thus, additional ozone was required to maximise biogas production, which reduced the economic advantage of this alternative. We hypothesised that the low degradation rate of ozonated sludge was due to the low activity of mesophilic microbes, which suggests that the system could be improved by thermophilic digestion (Komatsu *et al.* 2010). Another factor limiting application of this process is the accumulation of inorganic solids in the digester, which results in an unusually high SS concentration in the digester. Therefore, several changes were made to the centrifugation process to achieve density-based preferential withdrawal of inorganic solids from the digester.

In the present study, we utilised the higher activity of thermophilic microorganisms to accelerate the degradation of solids in the ozonated sludge and preferentially remove inorganic solids to reduce the accumulation of solids in the digester. Using waste activated sludge (WAS), degradation of primary sludge solids was reasonably good (>70%), whereas WAS solid degradation efficiencies were 40% to 50%. The improvements were verified by long-term small-scale pilot experiments. A case study for a typical WWTP was formulated to determine the implication of the new process on power generation cost economics and potential reductions in GHG emissions.

MATERIALS AND METHODS

Performance of mesophilic–thermophilic hybrid flow scheme with preferential inorganic withdrawal

Small-scale pilot experiments were carried out in the actual municipal WWTP using two different process flow schemes. The experimental process configuration for each system is shown in Figure 1. The first flow scheme with a mesophilic digester was used as a control. The advanced flow scheme combined mesophilic and thermophilic digesters. Both systems consisted of anaerobic digesters, a centrifuge to separate the solids and liquids of the digested sludge, and an ozonation reactor. In the control flow scheme, the WAS and ozonated sludge were both digested in a single mesophilic digester. In the thermophilic–mesophilic hybrid configuration, the feed sludge was digested in the mesophilic digester, and only ozonated sludge was digested in the thermophilic digester. The working volume of each digester was 850 to 910 L, and the temperatures in the digesters were

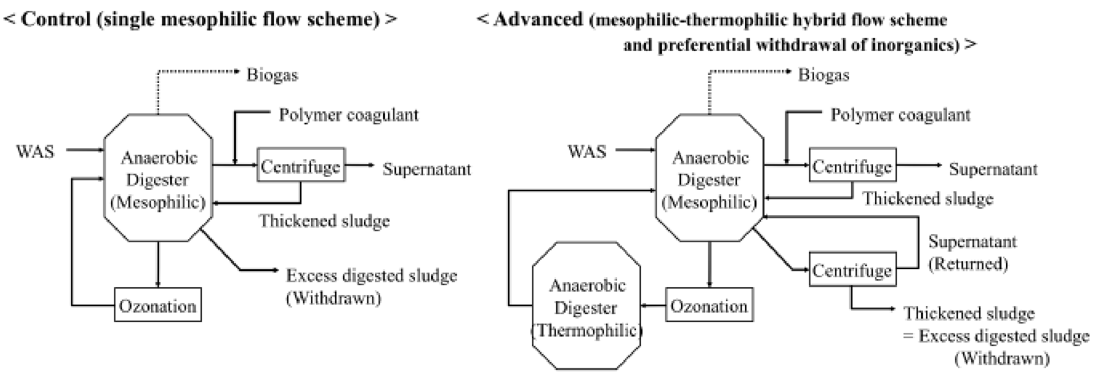


Figure 1 | Experimental process configuration.

maintained at 33 to 35°C (mesophilic) and 53 to 55°C (thermophilic).

As is the case for most municipal WWTPs in Japan, the sewage used in this study came from a separate sewer network system. The WWTP used a conventional BOD removal process with a SRT of about 20 days. The process flow scheme did not employ a primary settler and therefore produced only WAS. The WAS ratio of volatile solids to total solids (VS/TS ratio) was 0.82 to 0.84. This relatively high ratio may have been due to the raw wastewater, which contained little inorganic particulate sand/silt. In both systems, WAS was thickened by flotation before feeding to the digesters. The hydraulic retention time for the total digester volume was set to 24 to 30 days, and the VS loading rate to the digester was 0.88 to 0.95 kg/m^3/day. A portion of the digested sludge was centrifuged with a cationic polymer coagulant; the thickened sludge was then returned to the digester, and the supernatant was discharged. The polymer dosage was optimised to obtain clear supernatant (SS < 1,000 mg/L). Another portion of the digested sludge was ozonated and then returned to the digester. The daily amount of the ozonated sludge was set to one-fiftieth (1/50) of the digested sludge mass in the digester. The ozone dose during sludge ozonation was set to 0.03 g-O_3/g-VS, based on the study of Goel *et al.* (2003*b*). In the control system, the excess digested sludge was withdrawn directly from the digester. In the advanced system, sludge withdrawal was performed by centrifugation without the polymer coagulant. Withdrawal was performed such that the TS concentration was maintained at about 70 g/L in the digester.

Dewatering test of excess digested sludge

The dewaterability of the excess digested sludge was evaluated by a lab-scale belt press. The excess digested sludge from the small-scale pilot experiments was coagulated with cationic polymer and then dewatered with the belt press. The coagulated sludge was pressed between two filter cloths (0.05 MPa) for 10 min. Under these conditions, the water content of the dewatered sludge cake could be determined for the actual plant.

RESULTS AND DISCUSSION

Digestion efficiencies and ozone consumption

The mass balances of volatile solids after 3 months for each system are shown in Table 1. The degradation ratio of VSS was 80.8% in the advanced system, which was 3.5% higher than that of the control (77.3%) (Table 1, row 6). Ozone consumption was calculated as 0.045 g-O_3/g-VS degraded in the advanced system and 0.055 g-O_3/g-VS degraded in the control system. This result suggested that overall ozone

Table 1 | Mass balance of volatile solid components

		Advanced (hybrid)	Control (single mesophilic)
Measurement period	(days)	60	63
(1) Feed	(kg)	81.3 (100%)	55.2 (100%)
(2) Net change of mass in the digester	(kg)	−5.2 (−6.4%)	5.3 (9.7%)
(3) Withdrawn as excess sludge	(kg)	16.5 (20.3%)	3.4 (6.2%)
(4) Discharged in the supernatant (suspended)	(kg)	4.2 (5.2%)	3.7 (6.7%)
(5) Discharged in the supernatant (soluble)	(kg)	5.4 (6.6%)	5.6 (10.1%)
(6) Degraded VSS (1)−{(2) + (3) + (4)}	(kg)	65.7 (80.8%)	42.7 (77.3%)
(7) Converted to biogas (1)−{(2) + (3) + (4) + (5)}	(kg)	60.4 (74.3%)	37.1 (67.2%)
(8) Ozonated VS component	(kg)	89.6	87.8
	(gO_3/g-degraded VSS)	(0.045)	(0.055)
(9) Biogas production	(Nm^3)	47.4	30.2
	(Nm^3/kg-feed VS)	(0.58)	(0.55)

consumption could be reduced by 20% by incorporating thermophilic digestion.

The flow scheme in this study is an improvement over an earlier process flow scheme, which consisted of a single-stage thermophilic digester with ozonation (Komatsu *et al.* 2010). The new scheme solved two important problems detected in the previous scheme: high levels of soluble organic compounds in the effluent resulting in poor methane recovery and high polymer demand during solid–liquid separation. In the advanced system with two-stage thermophilic and mesophilic digestion, the percentage of soluble organic compounds did not increase and was almost the same as that of the control (Table 1, row 4). Thus, the biogas conversion ratio of the advanced system was 74.3%, which was 7.1% higher than that of the control (Table 1, row 7). Correspondingly, the specific biogas production increased to 0.58 Nm^3/kg-VS, which was 6.6% higher than that of the control.

The deterioration of effluent quality or solid/liquid separation of sludge in thermophilic digestion, as well as its remediation with mesophilic digestion, have previously been reported for aerobic and anaerobic digestion (Reusser & Zelinka 2004; Suvilampi *et al.* 2005). These phenomena appear to be due to differences in microbial flora under mesophilic and thermophilic conditions. Under thermophilic conditions, microbial activity is higher, but the range of microbial flora and their substrate utilisation is limited. In contrast, mesophilic microbial flora and their substrate utilisation are diverse (Kobayashi *et al.* 2007).

Dewaterability of excess digested sludge

The average water content of dewatered sludge cake from the advanced system was 59.4%, which was 16.7% lower than that obtained by the control (76.1%). Because of this reduced water content and the overall improvement in VS reduction, the volume of the dewatered sludge cake generated in the advanced system was about half that produced by the control. Furthermore, the mean polymer dose was estimated to be 4.6 g-polymer/kg-TS in the advanced system, which was one-third of that used in the control system (14.4 g-polymer/kg-TS).

The improved sludge dewaterability was attributed primarily to the enrichment of inorganic solids in the excess digested sludge. A higher content of inorganic compounds in digested sludge is thought to ease the removal of the interstitial water from sludge floc, thereby decreasing the water content of dewatered sludge. Figure 2 shows the relationship between the VS/TS ratio and water content after dewatering, along with data from the actual WWTP (mesophilic chemostat flow scheme) and data acquired at other municipal WWTPs (Yasui *et al.* 2005).

The water content in the dewatered sludge cake appears to have a linear relationship with the VS/TS ratio when dewatering is performed at optimised coagulation conditions. Further, data from different plants produce a line with similar slope, although the intercept varies depending on the origin of sludge, type of dewatering machine, and other operational conditions. The VS/TS ratio in the digester was almost identical in the control and advanced systems (control, 0.62–0.64; advanced, 0.62–0.65), and the VS/TS ratio of centrifuged excess digested sludge in the advanced system was 0.41 to 0.47. The low VS/TS ratio was also expected to reduce polymer consumption, because polymer required to neutralise the negative charge of organic compounds was reduced.

Incineration of the dewatered sludge cake uses two heat sources to vaporise water: the organic matter contained in the digested sludge and supplemental fuel (e.g., heavy oil). As the water content of the dewatered cake increases, more supplemental fuel is required. Figure 3 shows the critical line where calorific content of the sludge is equal to the heat required to vaporise the water contained in the cake. The shaded area under the bold line shows the region in which auto-thermal (no supplemental fuel) combustion of the dewatered cake is possible.

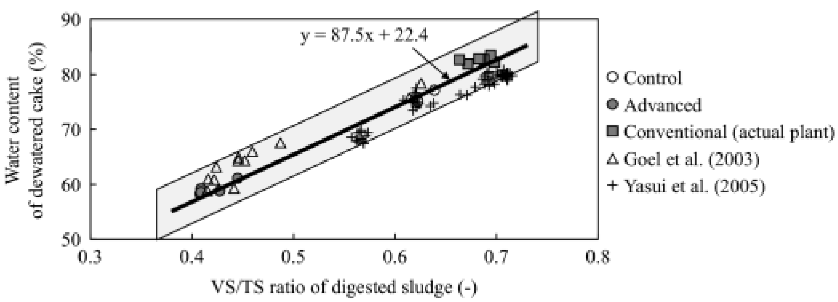


Figure 2 | Relationship between the VS/TS ratio and water content of the dewatered cake.

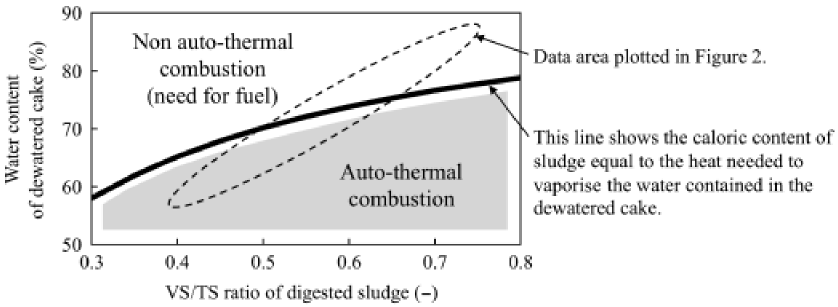


Figure 3 | Auto-thermal combustion of dewatered sludge cake.

Table 2 shows the supplemental fuel (heavy oil) requirements for a typical fluidised bed incinerator at 850°C. These calculations assume low calorific value of the digested sludge (*ca.* 23.3 kJ/g-VS) and an elemental composition of 49.8% C, 7.5% H, 7.4% N, 1.9% S, and 33.5% O. According to this estimate, when the water content of the dewatered sludge is less than 70%, auto-thermal combustion of the dewatered sludge is possible, which reduces GHG emission from burning fossil fuel.

Water qualities of the supernatant

The mean concentrations of COD, NH_4-N and PO_4-P of the supernatant are summarised in Table 3. The COD concentration of the advanced system was almost identical to that of the control. Most of the soluble organic components generated from ozonated sludge in the thermophilic digester were converted to biogas in the mesophilic digester. The NH_4-N concentration was higher in the advanced system, due to improved VSS degradation. In contrast, the concentration of soluble PO_4-P was lower in the advanced system, although it was expected to increase at the higher VSS degradation ratio. Because the PO_4-P concentration in the supernatant is affected by the dissolution–precipitation equilibrium of calcium and ferrous phosphates and struvite according to their solubility products (Wild *et al.* 1997), some of the generated PO_4-P is thought to have precipitated in the digester with Ca and Mg. In some cases, the PO_4-P concentration may increase if the corresponding elements (Ca, Mg, and Fe) of the feed sludge are low.

Power generation cost evaluation

A case study was performed to estimate the cost of power generation (PG) with biogas from the advanced AD process. Capital and operation costs were based on sludge production

Table 2 | Calculated heat balance in dewatered cake incineration

		Advanced (hybrid)	Control (single mesophilic)	Conventional (mesophilic chemostat)
Water content		59.4%	76.1%	82.6%
VS/TS ratio	(–)	0.44	0.63	0.68
Low calorific value	(kJ/kg-TS)	10,247	14,672	15,837
Air needed for incineration[1]	(kg-air/ton-cake)	269	960	1,226
Heat value[2]				
(1) Emission in incineration	(kJ/ton-cake)	1,650,250	2,555,245	2,919,899
(2) Recovery for preheating	(kJ/ton-cake)	179,431	640,409	817,356
(3) Input {(1)–(2)}	(kJ/ton-cake)	1,470,819	1,914,836	2,102,543
Supplemental fuel for incineration	(L-heavy oil/ton-cake)	−29[3]	6	32

[1]Calculated as 1.3 times theoretical air mass value calculated from the element composition of dewatered cake.
[2]Based on: temperature of feed cake = 20°C, incineration temperature = 850°C, preheating temperature with recovery air = 650°C, and heat loss of incinerator = 7.0%.
[3]No need for supplemental fuel.

Table 3 | Water quality of the supernatant

		Advanced (hybrid)	Control (single mesophilic)
COD	(mg/L)	1,230	1,490
NH_4-N	(mgN/L)	1,830	1,210
PO_4-P	(mgP/L)	219	287
Ca	(mg/L)	42	30
Mg	(mg/L)	3.8	1.3
Fe	(mg/L)	1.1	0.8

at a municipal WWTP (dry weather flow at 43,000 m^3/d). The WWTP was assumed to produce 7,740 kg-TS/day with 58% from primary sludge and 42% from WAS; the combined VS/TS ratio of 0.83 and digester loading rate of 0.97 kg-VS/m^3/day were used in calculations. In the AD process with ozonation, degradation of VS components was expressed as a first-order rate with respect to solid concentration. The first-order degradation rates for WAS and ozonated sludge in advanced and mesophilic systems were calculated from the mass balance data shown in Table 1. Maximum degradation ratios and the primary sludge first-order degradation rate proposed by Yasui *et al.* (2005) were used in calculations. The water content of dewatered sludge cake was determined with the relationship shown in Figure 2. The estimation procedure for PG costs is shown in Figure 4.

Results of the case study are shown in Table 4. The PG cost for the advanced process was 5.2 ¢/kWh (assuming 130 Japanese yen = 1 euro). This is much lower than the PG cost of 21.3 ¢/kWh for the conventional process. The addition of thermophilic digestion and selective withdrawal of inorganic components from the digester improved process performance and produced electricity at a cost lower than the market price of electricity (7.2 ¢/kWh).

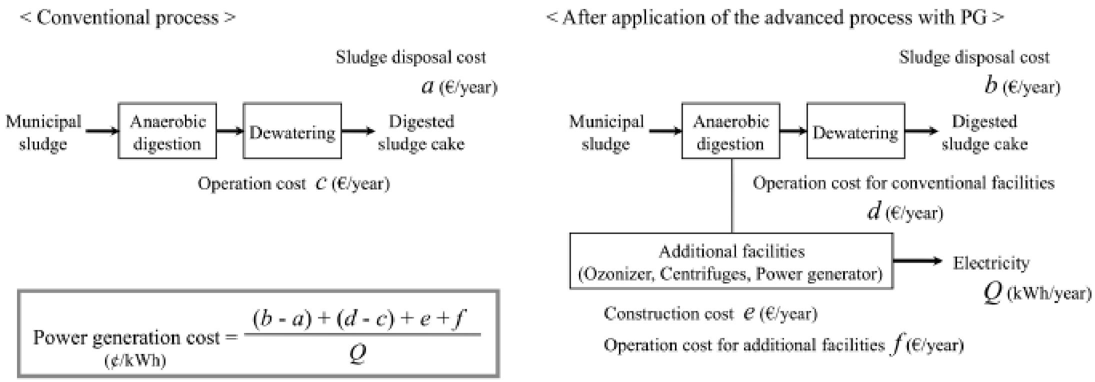
GHG reduction evaluation

Improving solid degradation efficiency effectively reduces GHG emissions of various municipal sludge treatments (Barber 2009). In the advanced AD process with PG, estimated GHG emissions were based on electricity consumption, coagulant use, and fuel consumption for incineration. GHG emission factors of 0.384 kg-CO_2/kWh, 6,534 kg-CO_2/t-coagulant, and 2.77 kg-CO_2/L-heavy oil were used for calculation (Japan Sewage Works Association 1999). Results are shown in Table 5. GHG emission from the advanced process with PG was 113 t-CO_2/year, which was about one-tenth of the expected emissions from the conventional AD process (1,101 t-CO_2/year) and one-fourth of the emissions from the conventional AD process with PG (424 t-CO_2/year). Further, if sludge cake transport and final disposal are taken into account, the GHG reduction effects are expected to be more favourable for the advanced process scheme.

CONCLUSION

An advanced thermophilic–mesophilic hybrid anaerobic digestion process with sludge ozonation was developed to increase the solid degradation ratio and recovery of energy-rich methane gas. Conclusions from the study are:

1. In the advanced process, the degradation ratio of VSS components was 3.5% higher than the 77.3% observed in the control process, and ozone consumption was reduced to 80% of the control. Moreover, the soluble organic fraction that remained after thermophilic digestion was



$$\text{Power generation cost (¢/kWh)} = \frac{(b-a)+(d-c)+e+f}{Q}$$

Figure 4 | Power generation (PG) cost for the advanced anaerobic digestion process.

Table 4 | Cost evaluation results of power generation

		Conventional AD Process	Conventional AD Process + PG	Advanced AD + Ozonation Process + PG	Notes
<Additional facilities>					
Ozoniser	(kgO_3/h)	-	-	8	
Centrifuge for sludge recycle	(kW)			52.5	
Centrifuge for inorganic discharge	(kW)	-	-	35.5	
Power generator	(kW/unit × unit)	-	170 × 2	170 × 2	Generation efficiency: 29%
<Additional energy consumption>					
Consumed electricity	(10^3 kWh/year)	-	111 (*q*)	2,015 (*q*)	
<Output>					
Biogas conversion ratio		50%	50%	83%	
Biogas production	(Nm^3/day)	2,736	2,736	4,201	CH_4 conc. 60%
Digested sludge production	(kg-TS/day)	4,528	4,528	2,243	
Water content of dewatered sludge cake		83%	83%	65%	Calculated from VS/TS ratio of digested sludge (Yasui *et al.* (2005))
Dewatered sludge cake production	(m^3/day)	26.6	26.6	6.5	
<Cost>					
Sludge disposal cost	(10^3 €/year)	1,197 (*a*)	1,197 (*b*)	290 (*b*)	123 €/m^3-sludge cake*
Construction cost for additional facilities	(10^3 €/year)	-	168 (*e*)	397 (*e*)	Subsidy: 55% Service life: 15 years
Operation cost for additional facilities	(10^3 €/year)	-	232 (*f*)	832 (*f*)	**Electricity market price: 7.2 ¢/kWh** Operator: 64,500 €/person/year Polymer coagulant: 6.5 €/kg-polymer
Difference in operation cost from conventional process	(10^3 €/year)	-	0 (*d*−*c*)	−174 (*d*−*c*)	Lower operation time and less polymer coagulant for dewatering

Table 4 | (continued)

		Conventional AD Process	Conventional AD Process + PG	Advanced AD + Ozonation Process + PG	Notes
<Benefit>					
Generated electricity (gross)	(10^3 kWh/ year)	-	1,875 (*Q*)	2,851 (*Q*)	
Generated electricity (net)	(10^3 kWh/ year)	-	1,764	578	*Q*–*q*
Power generation cost	**(¢/kWh)**	**-**	**21.3**	**5.2**	{(*b*-*a*) + (*d*–*c*) + *e* + *f*}/*Q*

AD, anaerobic digestion; PG, power generation. Costs assume 1 € = 130 JPY.
*Charge of sludge disposal is based on wet-volume because the cake is incinerated after hauled by truck to the incineration site.

effectively degraded in the mesophilic digester. Thus, the biogas conversion ratio of the advanced process was 7.1% higher than that of the control digester.

2. In the advanced process, inorganic solids were selectively enriched in the excess digested sludge by centrifugation without adding the polymer coagulant, considerably improving dewaterability. The mean water content of the dewatered sludge cake decreased to 59.4%. The low water content of the dewatered sludge cake allowed auto-thermal combustion in the incineration process.
3. In a case study for a municipal WWTP (average dry weather flow, 43,000 m^3/d), the advanced process scheme was determined to generate electricity at only 5.2 ¢/kWh, which is lower than the current market price of 7.2 ¢/kWh. Further, conversion of the typical AD process without PG to the advanced scheme with PG could reduce GHG emissions by approximately 1,000 t-CO_2/year.

Table 5 | Evaluation results of greenhouse gas emissions (t-CO_2/year)

	Conventional AD Process	Conventional AD Process + PG	Advanced AD + Ozonation Process + PG
i) Electricity consumption	67	110	890
ii) Coagulant use	173	173	318
iii) Fuel consumption for incineration	861	861	0
iv) Biogas utilization	0	−720	−1,095
Total GHG (i + ii + iii + iv)	1,101	424	113
Difference from conventional process	**-**	**−677**	**−988**

AD, anaerobic digestion; GHG, greenhouse gas; PG, power generation.

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