# Full-scale application of anaerobic digestion process with partial ozonation of digested sludge

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**Abstract** For improving sludge digestion and biogas recovery, a new anaerobic digestion process combined with ozonation was tested at a full-scale unit for 2 years and its performance was compared with a simultaneously operated conventional anaerobic digestion process. The new process requires two essential modifications, which includes ozonation for enhancing the biological degradability of sludge organics and concentrating of solids in the digester through a solid/liquid separation for extension of SRT. These modifications resulted in high VSS degradation efficiency of ca. 88%, as much as 1.3 times of methane production and more than 70% reduction in dewatered sludge cake production. Owing to accumulation of inorganic solids in the digested sludge, water content of the dewatered sludge cake also reduced from 80% to 68%. An energy analysis suggested that no supplemental fuel was necessary for the subsequent incineration of the cake from the new process scheme. The process is suitable to apply to a low-loaded anaerobic digestion tank, where power production is used.
**Keywords** Anaerobic digestion; centrifuge; dewatering; ozonation; methane; municipal sludge

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## Introduction

Large quantities of municipal sludge are produced at wastewater treatment plants. Facing the fact that sludge treatments and disposal of such large quantities result, in considerable greenhouse-gas discharge, it is a challenging area to find new solutions for reducing and recycling the sludge biomass to alleviate the $CO_2$ contribution. Indeed, minimization of greenhouse-gas emission as proposed in COP3 (Third Conference of Parties to the U.N. Framework Convention on Climate Change) led to the implementation of comprehensive regulations to reduce the production of wastes in Japan. According to the new regulations, in effect since 2001, high priority is placed on developing new ways to reduce the amount of waste on-site and to recycle biomass as much as possible. Anaerobic sludge digestion for on-site reduction of sludge quantities and biogas recovery is one of the attractive sludge treatment options that can fit into the waste-biomass utilization and recycling framework of new regulations, if further improvement in digestion efficiencies is achieved. As enhancement of digestion efficiency can reduce the sludge quantities on-site, it is encouraging to study and develop high performance anaerobic digestion process through modified process schemes. Recent study on a new high performance anaerobic digestion process with ozonation is one of such efforts to achieve higher solid degradation efficiencies (Goel *et al.* 2003a, b, 2004, Yasui *et al.* 2005). The process concept is similar to the one that is employed for the minimization of excess sludge production in the activated sludge system (Yasui *et al.* 2003). Based on the results of pilot-scale experiments in which 80% of solid degradation efficiency was achieved using anaerobic digestion with ozonation (Goel *et al.* 2004), an R&D project for full-scale testing was conducted from 2002 to 2003. The objective of the project was to verify the process performance with respect to solid degradation and biogas recoveries. This paper will focus on the results of the full-scale test and outline the important process parameters for successful implementation of this process.

## Material and methods

*Process schemes of the plants.* The full-scale test was carried out at a municipal wastewater treatment centre having secondary treatment capacity of 7,800 $m^3$/day (BOD removal only). The daily production of primary sludge and secondary excess sludge at the treatment centre was 1,035 kg-DS (874 kg-VS) and 759 kg-DS (649 kg-VS) respectively. The treatment centre has two mesophilic anaerobic digestion tanks each of 1,125 $m^3$ capacity with a mechanical mixer. The HRT of each anaerobic digester on the basis of the flow rate of municipal sludge fed was set at 45 days. Based on the historical operational data, the efficiency of TS and TVS reduction in the conventional digestion process was estimated to be 54% and 62% respectively. Approximately 10,000 ton/year of dewatered sludge cake with water content of about 80% was produced from the plant. During the test period, one of the digestion tanks was modified to a new process scheme (test reactor, Figure 1), while the other digester was operated according to the conventional digestion scheme (control reactor). The municipal sludge was divided and introduced in equal amount to the reactors during the full-scale testing. To complete the test process scheme, an ozonizer (average ozone input: 24 kg-$O_3$/day) to decompose sludge with ozone and a centrifugal device to withdraw inorganic-rich digested sludge with maintaining high SS concentration in the tank by solid/liquid separation were installed in the flow lines of the test reactor.

*Operational details.* For sludge ozonation, a fraction of the digested sludge was fed to the ozonizer and returned to the anaerobic digestion tank after removing residual ozone and oxygen in the liquid. At large fraction of the ozonated-digested sludge is then biologically converted to biogas in the anaerobic digestion tank. The flow rate of sludge fed to the ozonation reactor varied in the range of 22–44 $m^3$/day. Implementing a centrifuge for sludge retuning in the test reactor, retention time for the degradation of VSS compounds was extended. The centrifugal device was operated with and without addition of polymer coagulants depending on whether the thickened sludge is recycled to the anaerobic digester or discharged for disposal. When thickened sludge was discharged for disposal, the centrifugal device was operated without addition of polymer coagulants. Inorganic solids having higher density were concentrated by the centrifugal force into the thickened sludge, leading to withdrawal of sludge with low TVS/TS ratio (inorganic-rich solids). The decantant having lower density (VSS-rich solids) was returned back to the anaerobic digestion tank. When the thickened sludge was used for recycling as return sludge, the centrifugal device was operated with addition of polymer coagulants. The supernatant was discharged at the head of the primary settling tank in the wastewater treatment plant.

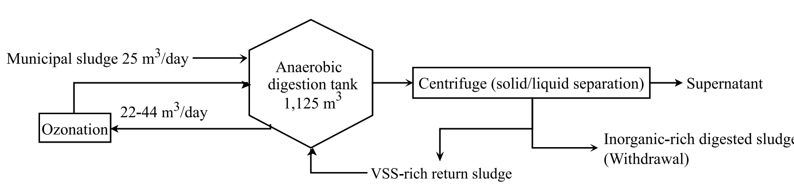


**Figure 1** Process scheme of the test reactor - the high-concentrated anaerobic digestion with partial ozonation of digested sludge

## Results

The trend of SS concentration and TVS/TS ratio in the reactors are as shown in Figure 2. In the control reactor SS concentration and TVS/TS ratio remained almost constant at 15–16 g/L and 0.70–0.72 respectively. During the start-up phase of the test reactor, no sludge was withdrawn. This led to increase in TS concentration in the anaerobic digestion tank to 55 g/L. TVS/TS ratio of the digested sludge kept on decreasing consistently due to improvement of organic solids degradation in the phase. To prevent further increase and to maintain TS concentration at about 60 g/L, intermittent sludge withdrawing was conducted in the test reactor from June 2003 while keeping TVS/TS ratio at about 0.6. Corresponding to the start of withdrawal, the TVS/TS ratio ceased decreasing and remained constant after August 2003. During this steady state, the degree of sludge digestion was summarized based on the mass balance using: (1) amount of municipal sludge fed to the reactor, (2) change in SS concentration in the reactor, and (3) amount of solid withdrawn during the operation. The results of this analysis are as shown in Figure 3. As the sum of (2) and (3) is equal to the undigested sludge mass, the slope of the graph indicates the fraction of undigested solid in the municipal sludge. A clear linear relationship can be seen in the control reactor between the amount of fed municipal sludge and of undigested solid. The line slope of 0.46 (*i.e.* digestion efficiency = 54%) was consistent with the historical data of digestion at the sludge treatment plant. The test reactor showed significant lower undigested solid mass. During the steady-state period, only 22% of TS was withdrawn from the test reactor which was less than 1/2 of that withdrawn from the control reactor.

Next, the degradation of VSS compounds was evaluated in the same manner as mentioned above. The undecomposed fraction of VSS compounds in the municipal sludge was only 12% at the test reactor and 37% at the control reactor as shown in Figure 4. The biogas production in both reactors was consistent with the quantity of TVS



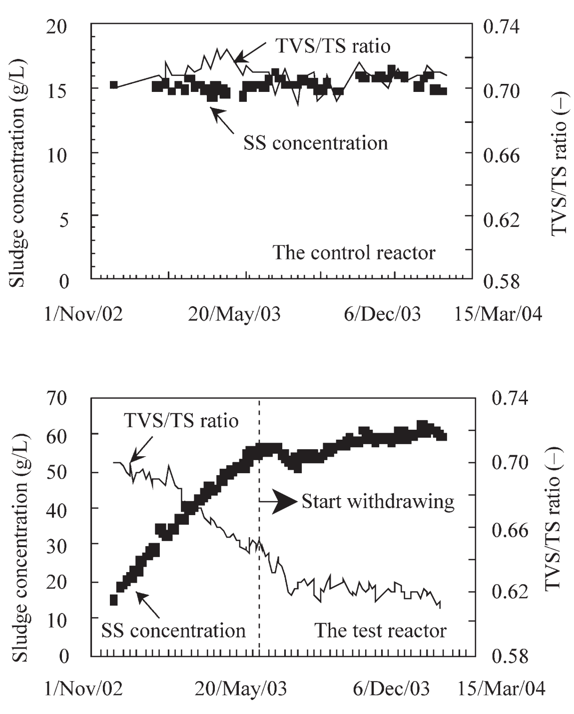


**Figure 2** The trend of SS concentration and TVS/TS ratio (top: the control reactor, bottom: the test reactor)

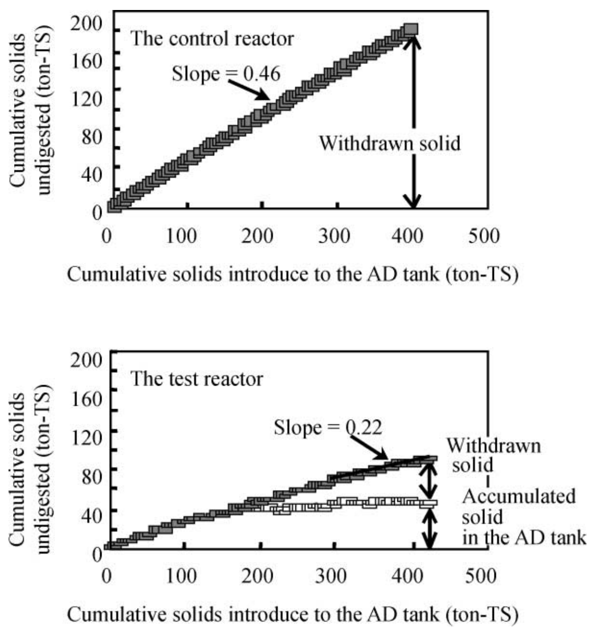


**Figure 3** The fraction of undigested sludge (top: the control reactor, bottom: the test reactor)

degradation. The biogas production at the test reactor was 1.3 times higher than that at the control reactor. According to the measurement of gas production rate and gas analysis, 0.54–0.57 $Nm^3$ of methane gas was produced through the degradation of 1 kg of degraded TVS compounds. The biogas was composed of 59–61% methane, 38–40% $CO_2$ and 1–2% miscellaneous gas, which did not show significant variation between the test and control reactors. Since only a small amount of ozone was dosed to the sludge at the ozonation stage, it is considered that the ozone treatment is not influential on the loss of fraction of COD for methane source (Goel *et al.* 2003a). The average municipal sludge loading to the anaerobic digestion tank was 1,270 kg-COD/day. The sum of output COD, *i.e.* sum of biogas COD, supernatant COD and withdrawn sludge COD, was 1250–1255 kg-COD/day, which was very close to the amount of input COD. Although the COD in the supernatant for the test reactor was slightly higher than that of the control reactor, it did not result in any deterioration of quality of treated effluent (COD, $BOD_5$

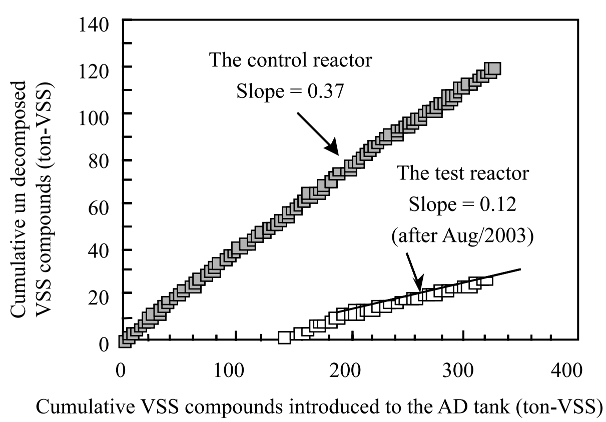


**Figure 4** The fraction of undecomposed VSS fraction

and SS) at the main wastewater treatment plant when compared to past operational records of 2000–2001(data not shown).

The trend of the production of dewatered sludge cake for the test and the control reactor is compared in Figure 5. The amount of dewatered sludge cake was significantly less than that of the control reactor. In the steady-state operation, the cake produced from the test reactor was 0.46 ton/day, which was less than 30% of that produced from the control reactor. Owing to lower TVS/TS ratio of sludge in test reactor, the water content of dewatered sludge cake was correspondingly reduced from 80% to 68% as shown in Figure 6. This decrease in water content contributed a significant reduction in volume of the dewatered sludge cake required for hauling and further disposal. Furthermore, the evaluation study for incineration of the dewatered sludge cake suggested that the energy value of the VSS compounds was enough to vaporize the water in the cake. This means that the application of anaerobic digestion process with ozonation makes it possible to minimize the consumption of supplement fuel for the subsequent incineration process. In addition, since the digestion minimizes the amount of nitrogenous compounds in the sludge, the potential of $N_2O$ production at the incineration stage can also be reduced. As $N_2O$ on greenhouse effect is 310 times higher than $CO_2$, the reduction of fuel and sludge amount to be incinerated may contribute to suppressing greenhouse-gas emission.



## Discussion

From the results of the full-scale testing, it was clarified that the anaerobic digestion process with ozonation could reduce sludge production significantly with more biogas recovery. The test also demonstrated that the new process is easily implemented for the

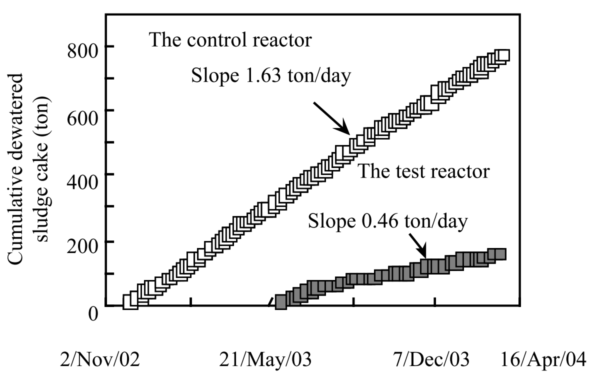


**Figure 5** Trend of the production of dewatered sludge cake

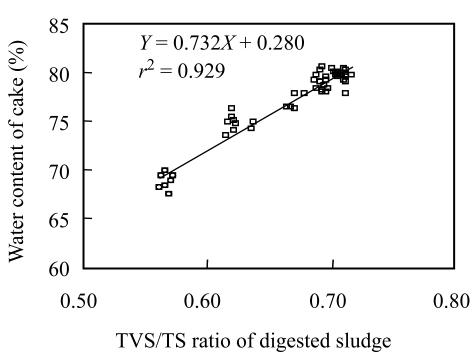


**Figure 6** Reduction of cake volume by lowering TVS/TS ratio of sludge

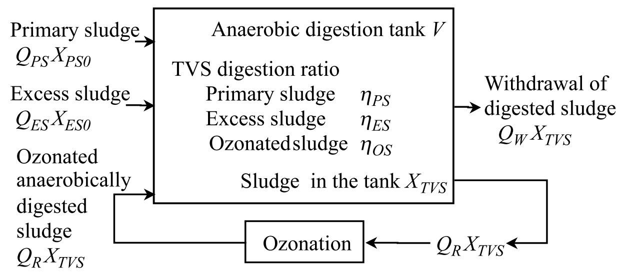


**Figure 7** Illustration of TVS digestion by the high-concentrated AD process with partial ozonation

existing anaerobic digestion plants by retrofitting only ozonizer and centrifuge facilities. For this evaluation, a simple steady-state model based on the mass balance of organics solids is used (Goel *et al.* 2003b). Figure 7 and Equation 1 show the essential details of this model. In the model analysis, concepts of first-order kinetics and the presence of biologically inert organics in the sludge were assumed and incorporated in the model to express the degradation of organic solids (*i.e.* primary sludge, excess sludge and ozonated digested sludge). Based on additional lab and pilot-scale experiments identification of model parameters was performed. From the results of the full-scale testing, the degree of solubilization of inorganics and water content of dewatered sludge cake were also incorporated into the calculation. To obtain the optimized operating conditions, the quasi-Newton method available in Microsoft Excel® solver was used to solve Equation 1. By applying the model, we estimated the impact of the new process scheme on its virtual application for existing plants. Seven anaerobic digester plants, which are under the jurisdiction of the municipality participating in the full-scale testing, were selected for the evaluation (Table 1). The estimated production of dewatered sludge cake compared with the current production is as shown in Figure 8. Further, considering the utilization of biogas with power generation for the sludge treatment facilities, the degree of recovery of electricity is estimated in Figure 9.

$$\begin{cases} X_{TVS} = \frac{(1-\eta_{PS})}{\eta_{OS}\cdot\frac{Q_R}{V}+\frac{Q_W}{V}}\cdot\frac{Q_{PS}}{V}\cdot X_{PS0} + \frac{(1-\eta_{ES})}{\eta_{OS}\cdot\frac{Q_R}{V}+\frac{Q_W}{V}}\cdot\frac{Q_{ES}}{V}\cdot X_{ES0} \\ \eta_{PS} = \eta_{\max-PS}\cdot\left\{1-\frac{1}{1+k_{PS}\left(\frac{Q_R}{V}+\frac{Q_W}{V}\right)^{-1}}\right\} \\ \eta_{ES} = \eta_{\max-ES}\cdot\left\{1-\frac{1}{1+k_{ES}\left(\frac{Q_R}{V}+\frac{Q_W}{V}\right)^{-1}}\right\} \\ \eta_{OS} = \eta_{\max-OS}\cdot\left\{1-\frac{1}{1+k_{OS}\left(\frac{Q_R}{V}+\frac{Q_W}{V}\right)^{-1}}\right\} \\ \eta_{TVS} = \left(\frac{Q_{PS}X_{PS0}+Q_{ES}X_{ES0}}{V}\right)^{-1}\cdot\frac{Q_W}{V}\cdot X_{TVS} \end{cases} \quad (1)$$

**Table 1** Plant capacities for the process evaluation

| Wastewater treatment plant | AD tank volume ($m^3$) | Primary sludge (kg-TS/day) | Excess sludge (kg-TS/day) | Wastewater treatment plant | AD tank volume ($m^3$) | Primary sludge (kg-TS/day) | Excess sludge (kg-TS/day) |
|---|---|---|---|---|---|---|---|
| Plant A | 9,850 | 5,966 | 5,501 | Plant E | 3,400 | 680 | 317 |
| Plant B | 4,615 | 2,200 | 2,533 | Plant F* | 2,250 | 1,035 | 759 |
| Plant C | 2,000 | 633 | 767 | Plant G | 1,292 | 483 | 220 |
| Plant D | 9,460 | 4,633 | 3,333 | | | | |

*Plant F: the site of the full-scale testing

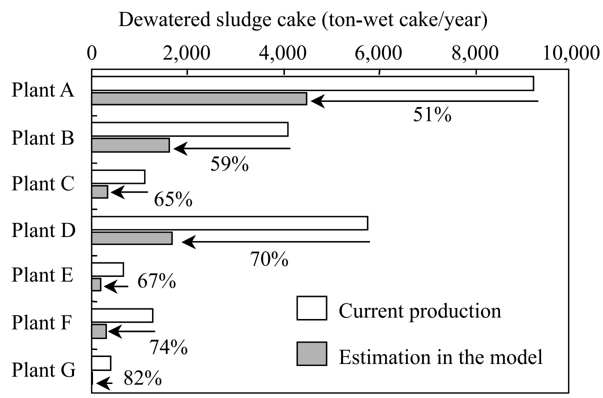


**Figure 8** Estimated production of dewatered sludge cake in the high-concentrated anaerobic digestion process with partial ozonation

Where, $Q$: flow rate ($m^3$/day), $V$: anaerobic digestion tank volume ($m^3$), $X$: TVS conc. (kgTVS/$m^3$), $k$: first-order coefficient ($day^{-1}$), $\eta$: TVS digestion efficiency $(-)$; subscript: $ES$: excess sludge, $OS$: ozonated anaerobically digested sludge, $PS$: primary sludge, $R$: return, $TVS$: total volatile solids, $W$: withdraw, $0$: initial; stochiometrics of TVS digestion efficiency (maximum TVS digestion efficiency) $(-)$: $\eta_{max\text{-}PS} = 0.702$, $\eta_{max\text{-}ES} = 0.615$, $\eta_{max\text{-}OS} = 0.357$; First-order kinetic coefficient ($day^{-1}$): $k_{PS} = 0.243$, $k_{ES} = 0.101$, $k_{OS} = 0.036$

The model suggests that the reduction of dewatered sludge cake is highly site specific. Volumetric TS loading on the anaerobic digestion tank was found to be the most influential process parameter. Higher volumetric TS loading rate gives less TVS degradation efficiency ($\eta_{TVS}$). As can be seen in Equation 1, the loading of input municipal sludge ($Q_{PS}X_{PS0}/V$ and $Q_{ES}X_{ES0}/V$) directly affects the sludge concentration in the anaerobic digestion tank ($X_{TVS}$). Thus, at higher loading, $X_{TVS}$ have to be regulated to meet the maximum allowable limit by increasing the specific sludge withdrawal rate ($Q_W/V$) and/or specific flow rate for ozonation ($Q_R/V$). The elevation of $Q_R/V$ and/or $Q_W/V$, however, reduces the digestion efficiency of individual sludge ($\eta_{PS}$, $\eta_{ES}$, $\eta_{OS}$), leading less $\eta_{TVS}$. The model analysis also suggests that a plant where it is possible to obtain excess electricity from the new anaerobic digestion process combined with power generation, is the wastewater treatment plant receiving more than 20,000 $m^3$/day of average dry weather flow. The process efficiency regarding power generation and consumption strongly

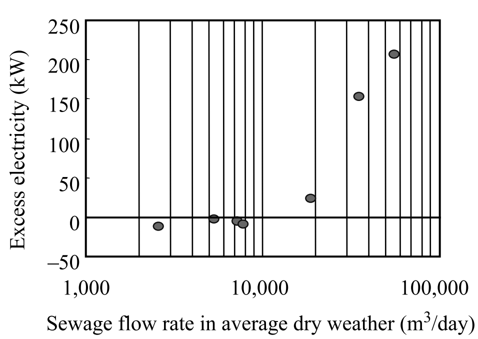


**Figure 9** Energy recovery with power generation * Electricity generation efficiency (kJ-electricity produced/kJ-methane) = 26%: below 10,000 $m^3$-sewage/day, 30%: 10,000–20,000 $m^3$/day, 37%: beyond 20,000 $m^3$/day

depends on the size of the facilities. In general, more energy recovery with power generation is expected if the process is applied to a larger plant since a bigger power production unit and ozone generators have better specific energy consumption efficiency. In such estimation, careful consideration is necessary because more energy conversion from sludge organics may be obtained even at less power input during ozonation if the plant equips anaerobic digestion tanks with lower volumetric loading rate as described in Equation 1.

## Conclusions

An anaerobic digestion process with ozonation on digested sludge was tested at a full-scale anaerobic digester. The process was successfully verified with improved biogas conversion efficiency of about 80% from the organics in municipal sludge. Owing to enhanced methane recovery, the process is expected to be a suitable option to utilize sludge containing slowly degradable organics as an energy resource. More energy recovery is expected in a larger wastewater treatment plant having low-loaded anaerobic digestion tanks. Owing to high VSS digestion, significantly less production of dewatered sludge cake with lower water content was consistently obtained that contributes to minimizing the fuel consumption in the subsequent incineration stage.

## References

Goel, R., Tokutomi, T. and Yasui, H. (2003a). Anaerobic digestion of excess activated sludge with ozone pre-treatment. *Wat. Sci. Tech.*, **47**(12), 207–214.

Goel, R., Tokutomi, T., Yasui, H. and Noike, T. (2003b). Optimal process configuration for anaerobic digestion with ozonation. *Wat. Sci. Tech.*, **48**(4), 85–96.

Goel, R., Komatsu, K., Yasui, H. and Harada, T. (2004). Process performance and change in sludge characteristics during anaerobic digestion of sewage sludge with ozonation. *Wat. Sci. Tech.*, **49**(10), 105–114.

Yasui H., Goel R., Fukase T., Matsuhashi R., Wakayama M., Sakai Y. and Noike, T. (2003). Bioleader®, a novel activated sludge process minimizing excess sludge production. In *IWA Leading Edge Conference*, 26–28/May 2003, Noordwijk/Amsterdam, The Netherlands.

Yasui H., Komatsu K., Goel R., Sato A., Matsuhashi R., Ohashi A. and Harada, H. (2005). Minimization of greenhouse gas emission by application of anaerobic digestion process with biogas utilization. *Wat. Sci. Tech.*, **52**(1–2), 545–552.