Reduction of excess sludge production using mechanical disintegration devices

G.W. Strünkmann*, J.A. Müller, F. Albert* and J. Schwedes***

*Institute of Mechanical Process Engineering, Post Box 3329, Technical University of Braunschweig, D-38023 Braunschweig, Germany

**PFI Consulting Engineers, Karl-Imhoff-Weg 4, 30165 Hannover, Germany

(E-mail: *g.struenkmann@tu-bs.de*; *Mueller@pfi.de*; *f.albert@tu-bs.de*; *j.schwedes@tu-bs.de*)

Water Science & Technology **Vol 54 No 5 pp 69–76** © IWA Publishing 2006

Abstract The usability of mechanical disintegration techniques for the reduction of excess sludge production in the activated sludge process was investigated. Using three different disintegration devices (ultrasonic homogeniser, stirred media mill, high pressure homogeniser) and different operational parameters of the disintegration, the effect of mechanical disintegration on the excess sludge production and on the effluent quality was studied within a continuously operated, laboratory scale wastewater treatment system with pre-denitrification. Depending on the operational conditions and the disintegration device used, a reduction of excess sludge production of up to 70% was achieved. A combination of mechanical disintegration with a membrane bioreactor process with high sludge age is more energy effective concerning reduction of sludge production than with a conventional activated sludge process at lower sludge ages. Depending on the disintegration parameters, the disintegration has no, or only minor, negative effect on the soluble effluent COD and on the COD-removal capacity of the activated sludge process. Nitrogen-removal was slightly deteriorated by the disintegration, whereas the system used was not optimised for nitrogen removal before disintegration was implemented.

Keywords Activated sludge process; effluent characteristics; excess sludge reduction; mechanical disintegration; membrane bioreactor

Introduction

Excess sludge production is a main drawback of the biological wastewater treatment due to its need of sludge disposal. The costs for sludge disposal are a main part of the total operational costs of a wastewater treatment plant. In many countries, the possibilities of sludge disposal do undergo stringent national legislation, e.g. in Germany and in Switzerland, the deposition of sludge in landfills is entirely forbidden (AbfAblV, 2001; Böhler and Siegrist, 2003). Furthermore, e.g. in Europe, extended demands on effluent quality do lead to an increase of excess sludge production during biological wastewater treatment (98/15/EC, 1998; Commission of the European Communities, 2004). Therefore, in the last decade, a lot of effort has been made to influence the system of biological wastewater treatment in a way to reduce excess sludge production. These investigations followed two different routes. Firstly, a sludge pre-treatment before anaerobic sludge treatment was investigated to increase digestibility of already produced excess sludge (Müller, 2000; Neis *et al.*, 2000; Goel *et al.*, 2003).

Secondly, efforts to suppress sludge production itself during wastewater treatment were also carried out. In 1994, Yasui and Shibata presented a way to reduce excess sludge production in the aeration basin using an ozone-treatment of the sludge in bypass of the aeration basin (Yasui and Shibata, 1994). Also in 1994, Canales *et al.* proposed that a thermal treatment of the activated sludge can be used for reduction of excess sludge production (Canales *et al.*, 1994). Since then, many different routes to reduce the

doi: 10.2166/wst.2006.548

excess sludge production in the wastewater treatment train have been investigated. A good overview is given by Ödegaard (2003). Especially, the treatment with ozone and the thermal treatment are widely investigated by now. With the ozone-treatment, different authors do report results between 60% reduction of sludge production (RSP) and even up to zero excess sludge production in laboratory as well as in industrial scale (Sakai *et al.*, 1997; Deleris *et al.*, 2002; Salhi *et al.*, 2003). For the thermal treatment, Camacho *et al.* reported a possible RSP of nearly 60% in a semi-technical scale (Camacho *et al.*, 2003). The main effect of both ozone- and thermal treatment leading to a reduced excess sludge production is an increase of cell-lysis and an increased release of intracellular organic matter into the sludge water (Salhi *et al.*, 2003; Camacho *et al.*, 2004). Although different mechanical disintegration techniques are also well known for being usable to increase cell-lysis and to break up cell walls, and therefore to increase the release of intracellular organic matter (Müller *et al.*, 1998; Neis and Thiem, 1999), only poor information on the usability of mechanical disintegration techniques for a reduced production of excess sludge in the aerobic wastewater treatment can be found in the literature. Camacho *et al.* approved the feasibility of mechanical disintegration of sludge using a high pressure homogeniser for reducing the excess sludge production (Camacho *et al.*, 2002), but no deeper investigations on this field have been reported until now. Therefore, in this work, a comparison of different mechanical disintegration techniques with varied disintegration parameters was carried out concerning the influence of the mechanical treatment on the excess sludge production of an activated sludge system.

Methods

Wastewater treatment system

Continuous studies were performed with a lab-scale activated sludge system fed with primary settled wastewater at a constant flow rate. The system was composed of two lines running in parallel with one aeration basin in each line with a volume of 25 L and a pre-denitrification tank (DeNi) with a volume of 11 L each. Into one line a stressing device could be implemented, the other line is used as a control (Figure 1).

The aeration basins were equipped with two submerged membrane plates each instead of a clarifier to separate solids from liquid. Each line was inoculated with activated sludge from Braunschweig wastewater treatment plant (350,000 population equivalents). Before every experiment, the lines were run in parallel without sludge disintegration to ensure comparability in sludge production. During this period, amount of daily extracted sludge was calculated based on a constant solids retention time (SRT), leading

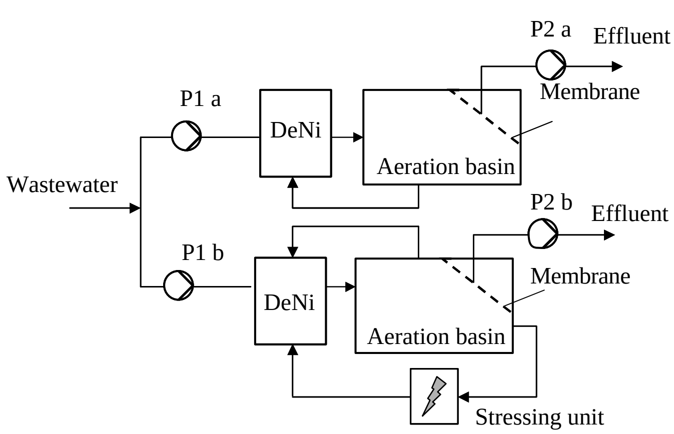

Figure 1 Schematic setup of wastewater treatment system with pre-denitrification

to a correlated sludge concentration in the reactors. After implementation of the stressing into the wastewater treatment process, sludge extraction was carried out only to maintain a constant sludge concentration in the systems, resulting in different SRT in the treated and in the untreated line. Initially, the membranes only were used to replace the settling tank, but in one test they were also used to enable the systems to be operated as conventional membrane bioreactors (MBR) with a very high solids retention time of approximately 54 d in the untreated reactor and therefore also an increased concentration of total suspended solids. With this wastewater treatment system, the effect of mechanical disintegration on the excess sludge production, but also on the capacity of COD- and nitrogen-removal, could be investigated.

Mechanical sludge disintegration

Sludge disintegration was carried out batchwise, meaning that a certain amount of sludge was extracted daily from the aeration basins of the stressed line, given into the stressing unit and treated with the parameters chosen for the respective test. After stressing, the treated sludge was sampled for analysis and then given back into the line.

Disintegration devices. As disintegration devices, an ultrasonic homogeniser (UH), a stirred media mill (SMM) and a high pressure homogeniser (HPH) were used.

Ultrasonic homogenisers are composed of two main parts, an ultrasonic transducer that transforms electrical impulses into mechanical oscillations with frequencies of 20 kHz and higher and a sonotrode that transmits these oscillations into the solution to be treated. At high acoustic energy the pressure inside the treated sample may locally drop below vapour pressure of the liquid during contraction of the sonotrode. Therefore, gas bubbles are formed which grow for a few pulsation cycles. These cavitation bubbles do collapse in only a few milliseconds after they were formed. The collapse of the bubbles causes very high, but locally focussed, pressure forces of 50 MPa and more and also a temperature of some thousand Kelvin. These extreme physiological conditions lead to high local energy inputs and therefore floc rupture and also break up of bacteria that are in the range of the bubbles. In this work, an UIP 1000 transducer (Dr. Hielscher, Germany) with a maximum power output of 1000 Watt was used. Mean power output during the experiments was around 420 Watt. Different volumes of sludge were treated batchwise, without cooling. Therefore sludge temperature increased from 20 °C up to 30–40 °C during stressing, depending on the energy input.

The stirred media mill used in this project had a volume of 3.8 dm^3 and was equipped with a cooling jacket. In stirred media mills, microorganisms are stressed between agitated grinding beads (Bunge *et al.*, 1992). Agitation of the grinding media is carried out by a stirrer. Between the beads, bacteria do suffer high pressure forces and, due to different velocities of the grinding beads, also high shear forces. The used stirred media mill had to be cooled during operation; therefore, despite the experiments with the ultrasonic homogeniser, the sludge was not heated up.

High pressure homogenisers do have two main operation units: a high pressure pump that compresses the sludge to pressures of up to some hundred bars and a decompression valve in which the compressed sludge is relaxed to environmental pressure again. During this relaxation, the sludge is highly accelerated and cavitation may occur with the same effects as in the ultrasonic homogeniser. When the accelerated sludge leaves the valve, it bearing a smashing plate, leading to additional impact forces. The cavitation, as well as the impact forces, can lead to a break up of flocs and of cell-walls. In this work a pressure drop of 650 bar was implemented. The HPH was not cooled during operation, leading to an increase of sludge temperature of 20 to over 40 °C.

Disintegration parameters. Within the different experiments two main stressing parameters were varied. The specific energy input E_{spec}, defined as the amount of energy acting on 1 kg of total suspended solids, gives information on how much energy is needed with the disintegration device used to achieve a certain effect. Using E_{spec}, the energy efficiency of different disintegration devices can be compared. Dependent on the device, the higher the specific energy input is, the higher is the amount of cell break-up. The second parameter that was varied was the frequency of treatment. The stressing frequency (SF) is defined as:

$$SF = \frac{\text{amount of sludge treated per day}}{\text{total sludge volume of the system}} [d^{-1}] \quad (1)$$

By varying the stressing frequency and the specific energy input, the total amount of energy brought into the system can be controlled. Table 1 gives a summary of the experiments carried out with the different disintegration devices, the different stressing parameters and the amount of total suspended solids in the control and the stressed line. In experiment 6 the systems were operated as membrane bioreactors with a SRT in the control of approximately 54 d; within the other experiments the SRT was below 20 d, equivalent to conventional activated sludge systems.

Analysis

COD, Ammonia-Nitrogen, Total Nitrogen. COD, ammonia-nitrogen ($N\text{-}NH_4^+$) and total nitrogen (TN) were analysed using photometric test kits.

COD_{total} in sludge supernatant. The membranes used do cut off all solids from the effluent; therefore only the soluble COD could be measured in the effluent. When using a settling tank for solid/liquid separation, in the effluent there is always a part of non-settling solids. To determine the influence of mechanical disintegration and, combined with this, also the drastic decrease of floc-size on the amount of COD as particular, non-settling matter, the COD_{total} in the supernatant was measured after settling. The total amount of COD in the sludge supernatant after 30 min of settling in a graduated cylinder (COD_{total}) was measured, using a sample of the supernatant. This sample was neither centrifuged nor filtered before analysis.

Degree of COD-release. The amount of COD released during the mechanical disintegration of the sludge depends on the stressing conditions chosen. Comparing the amount of COD released due to the stressing with a maximal possible COD-release, defined as the released COD after 10 min of alkaline fusion with 1 molar NaOH at 90 °C, a degree of COD-release (DD_{COD}) can be defined (Müller, 2000). The degree of COD-release is a quantity of how efficient the mechanical disintegration was and it

Table 1 Experimental parameters to determine the influence of mechanical sludge disintegration on the excess sludge production

Test	$TSS^{control}$ (g/L)	$TSS^{stressed}$ (g/L)	Disintegration device	SF (d^{-1})	E_{spec} (kJ/kg_{TSS})
1	3.52	3.42	UH	0.2	30.000
2	2.68	2.60	SMM	0.2	30.000
3	2.31	2.04	HDH	0.2	30.000
4	2.31	2.60	UH	0.4	2.000
5	2.31	2.48	UH	0.05	47.000
6 (*MBR*)	8.65	6.59	UH	0.2	16.000

is defined as:

$$DD_{COD} = \frac{COD_{stressed} - COD_0}{COD_{alkaline} - COD_0} \cdot 100\% \tag{2}$$

where COD_0 is the concentration of COD in the sludge-liquid before stressing, $COD_{stressed}$ is the concentration after stressing and $COD_{alkaline}$ is the concentration after alkaline fusion. All COD concentrations were measured in the 0.45 μm filtrate of the supernatant of a sludge sample centrifuged for 10 min at 10,000 *g*.

Results and discussion

COD-release due to disintegration

Within all experiments the specific energy input chosen was high enough to effect a release of intracellular organic matter, detected by the degree of disintegration (Table 2). While at the very low specific energy input of only 2,000 kJ/kg_{TSS} in experiment 4, the mean DD_{COD} was only around 4% DD_{COD} increases with increasing E_{spec}. At identical E_{spec} of 30,000 kJ/kg_{TSS} the HDH achieved a higher amount of COD-release than the SMM and the UH, while the DD_{COD} achieved with the SMM was still higher than with the UH. This is in accordance with prior investigations (Müller *et al.*, 1998).

Excess sludge production

To determine the influence of the mechanical disintegration on the excess sludge production within the different tests, the cumulative TSS production was correlated to the cumulative COD-removal. The slope of the linearisation of these data (not forced through zero) is defined as the observed sludge production yield (Y_{obs}). Based on this, the reduction of sludge production can be calculated according to the following equation:

$$RSP = \left(1 - \frac{Y_{obs}^{stressed}}{Y_{obs}^{control}}\right) \cdot 100\% \tag{3}$$

In Figure 2, the excess sludge productions found in the experiments 1–3 with different disintegration devices and with E_{spec} of 30,000 kJ/kg_{TSS} and SF of 0.2 are shown. In all three tests, the Y_{obs} of the stressed line is lower than for the untreated control, which is a lower sludge production. It is obvious that the HPH is the most efficient device for the conditions chosen in these tests. With the HPH the RSP was 72%, while with the SMM the RSP was 36% and with the UH it was only 24%. This correlates with the different degrees of COD-release found for the specific energy input of 30,000 kJ/kg_{TSS}.

The observed yields and the calculated values of RSP for all tests described above are given in Table 3. Despite the very good results of experiments 1-3, choosing the inadequate disintegration parameters, an increase of sludge production can also be achieved by mechanical disintegration, expressed as a negative value of RSP. During experiments 4 and 5, the total specific energy input brought into the system, expressed as $E_{spec} * SF$, was much lower than for experiments 1–3. Although in both tests a release of COD was achieved due to the disintegration of the partial volume, the overall disintegration conditions were obviously not stringent enough to cause a reduction in

Table 2 Mean values of degree of COD-release as a result of specific energy input achieved in the different experiments

Test/Device	1/UH	2/SMM	3/HPH	4/UH	5/UH	6/UH
E_{spec} (kJ/kg_{TSS})	30,000	30,000	30,000	2,000	47,000	12,000
Mean DD_{COD} (%)	11.4	14.2	20.6	4.2	20.0	6.9

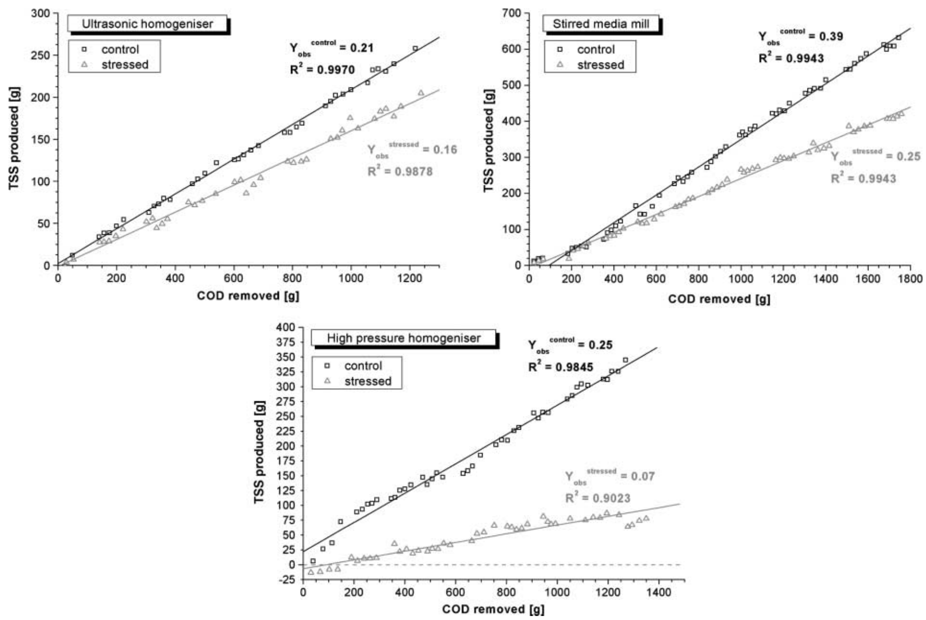

Figure 2 Comparison of TSS production as a function of COD removal for untreated and treated line with $E_{spec} = 30{,}000\,kJ/kg_{TSS}$ and $SF = 0.2\,d^{-1}$ for UH (test 1), SMM (test 2) and HPH (test 3)

excess sludge production. This could be due to two different effects. In experiment 4, with the very low energy input but high stressing frequency, the stressing of the sludge mainly resulted in a break up of sludge flocs and only in a minor break up of bacteria cell walls, as seen by the very low DD_{COD}. Due to the floc disruption, the oxygen- and substrate-supply of the microorganism within the flocs is increased, possibly leading to an increased growth of biomass. This consideration could be verified by respirometric tests, using a sequenced batch respirometer as described in Spérandio and Paul (2000) and Chockalingam *et al.* (2004). In experiment 5, E_{spec} was high enough to achieve a strong release of intracellular matter, but as only 5% of the total volume was treated each day, this obviously was not enough to influence the overall process. The small volume of treated sludge contains a high amount of released organic matter and therefore easily biodegradable compounds. This might accelerate the growth of the biomass in the untreated volume of the system.

A combination of MBR-operated activated sludge system with mechanical disintegration (experiment 6) turned out to be useful for the reduction of excess sludge production. With this system, a disintegration leads to a nearly three times higher RSP at only almost a third of specific energy input needed as compared with experiment 1.

Process efficiency

As the mechanical disintegration leads to an increased COD in the treated volume, the total COD-load of the stressed line is increased. Furthermore, as found in prior

Table 3 Observed sludge production yields Y_{obs} in the control and stressed lines and calculated reduction of excess sludge production RSP

Test	**1**	**2**	**3**	**4**	**5**	**6 (*MBR*)**
$Y_{obs}^{control}$ (g_{TSS}/g_{COD})	0.21	0.39	0.25	0.25	0.25	0.19
$Y_{obs}^{stressed}$ (g_{TSS}/g_{COD})	0.16	0.25	0.07	0.32	0.27	0.06
RSP (%)	24	36	72	− 28	− 8	68

Table 4 Effluent COD- and nitrogen-concentration and COD-removal efficiency and COD_{total}-concentration in supernatant of settled sludge samples

Test	$COD_{effluent}$ (mg/L)		$COD_{removed}$ (%)		COD_{total} (mg/L)		$N-NH_4^+$ (mg/L)		TN (mg/L)	
	Control	Stressed	Control	Stressed	Control	Stressed	Control	Stressed	Control	Stressed
1	19	18	97.8	97.9	–	–	–	–	–	–
2	29	27	97.0	97.3	77.3	144	5.4	8.0	18.0	22.4
3	21	25	97.9	98.3	284	448	0.36	0.47	21.4	30.7
4	21	18	97.9	98.3	284	313	0.36	0.30	21.4	21.4
5	21	18	97.0	96.9	284	392	0.36	0.38	21.4	28.2
6 (*MBR*)	14	25	98.4	97.1	–	–	–	–	–	–

respirometric tests, not all of the released COD is degradable within the hydraulic retention time of the systems of 24 h. Nevertheless, the COD-removal of the activated sludge system is not strongly affected. In the range of common standard deviation, except for the MBR-operated experiment 6, the COD concentration in the effluent of the membranes and the COD-removal capacity of the treated systems were not deteriorated (Table 4). In an activated sludge system without membrane separation of the solids, an increased COD in the supernatant has to be taken into account, as seen in the increased COD_{total} in the supernatant of the settled sludge. Nitrogen removal is partly deteriorated by the mechanical disintegration. This is in agreement with observations made by other authors (Camacho *et al.*, 2002; Deleris *et al.*, 2002).

Conclusions

Regarding the results of this study, it can be concluded that mechanical disintegration can have a strong effect on the excess sludge production during biological wastewater treatment. The results can be summarised as follows.

- A reduction of excess sludge production of up to 70% is possible using mechanical disintegration of sludge.
- The high pressure homogeniser is the most effective of the investigated devices.
- A combination of MBR-operated activated sludge system with mechanical disintegration is especially useful for reduction of excess sludge production.
- Excess sludge production is strongly dependent on the disintegration conditions chosen, using insufficient disintegration parameters, also an increase of sludge production can be realised.
- $COD_{soluble}$ in the effluent of the membranes used was not increased by mechanical disintegration.
- An increase of COD_{total} concentration in the outlet of a clarifier can be possible when using mechanical disintegration.
- Nitrogen removal is negatively affected by mechanical disintegration methods.

Thus, it can be said that mechanical disintegration is feasible for the reduction of excess sludge production. As the amount of energy needed in this laboratory scale trial was relatively high, further research and development needs to be carried out, e.g. by thickening of the sludge before mechanical disintegration, resulting in a more energy efficient stressing (Müller *et al.*, 1998). The results of COD-removal quality and nitrogen removal have to be verified with systems without a membrane separation but with a settler, to ensure that no increased COD- or nitrogen-concentration in the effluent of the WWTP will occur when mechanical disintegration devices are integrated into the activated sludge process.

Acknowledgements

The authors are indebted to the European Commission for funding main parts of this work within the research and development project EVK 1-CT2000-00050 "Ways of Innovation for the Reduction of Excess Sludge".

References

98/15/EC (1998). *Commission directive of 27 February 1998 amending Council Directive 91/271/EEC with respect to certain requirements established in Annex II thereof.*

AbfAblV (2001). *Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen* BGBl I 2001, 305.

Böhler, M. and Siegrist, H. (2003). Partial ozonation of activated sludge to reduce excess sludge, improve denitrification and control scumming and bulking. *IWA Specialists Conference* "*Biosolids 2003, Wastewater Sludge as a Resource*", Trondheim, Norway.

Bunge, F., Pietzsch, M., Müller, R. and Syldatik, C. (1992). Mechanical disruption of *Arthrobacter* sp. DSM3747 in stirred ball mills for the release of hydantoin-cleaving enzymes. *Chem. Eng. Sci.*, **47**(1), 225–232.

Camacho, P., Geaugey, V., Ginestet, P. and Paul, E. (2002). Feasability study of mechanically disintegrated sludge and recycle in the activated-sludge process. *Wat. Sci. Tech.*, **46**(10), 97–104.

Camacho, P., Ginestet, P. and Audic, J.M. (2003). Pilot plant demonstration of reduction technology during activated sludge treatment of wastewater, *WEFTEC* 2003, Los Angeles, California.

Camacho, P., Ginestet, P. and Audic, J.M. (2004). Understanding the mechanisms of thermal disintegrating treatment in the reduction of sludge production. *IWA Conference 2004*, Marrakech, Morocco.

Canales, A., Pareilleux, A., Rols, J.L., Goma, G. and Huyard, A. (1994). Decreased sludge production strategy for domestic wastewater treatment. *Wat. Sci. Tech.*, **30**(8), 97–106.

Chockalingam, L.R., Strünkmann, G.W., Müller, J.A. and Paruchuri, G.R. (2004). Influence of ultrasonic disintegration on sludge growth reduction and its estimation by respirometry. *Environ. Sci. Technol.*, **38**(21), 5779–5785.

Commission of the European Communities (2004). Report from the commission to the council, the European parliament, the European economic and social committee and the committee of the regions "Implementation of Council Directive 91/271/EEC of 21 May 1991 concerning urban wastewater treatment, as amended by Commission Directive 98/15/EC of 27 February 1998", Brussels.

Deleris, S., Geaugey, V., Camacho, P., Debellefontaine, H. and Paul, E. (2002). Minimization of sludge production in biological processes: an alternative solution for the problem of sludge disposal. *Wat. Sci. Tech.*, **46**(10), 63–70.

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

Müller, J. (2000). Sewage sludge disintegration as a key step in sewage sludge minimization. *Wat. Sci. Tech.*, **41**, 123–130.

Müller, J.A., Lehne, G., Schwedes, J., Battenberg, S., Näveke, R., Kopp, J., Dichtl, N., Scheminski, A., Krull, R. and Hempel, D.C. (1998). Disintegration of sewage sludge and influence on anaerobic digestion. *Wat. Sci. Tech.*, **38**(8–9), 425–433.

Neis, U. and Thiem, A. (1999). Ultrasound in waste water and sludge treatment. *Ultrasound in Environmental Engineering*, Hamburg, TUHH reports on sanitary engineering Vol. 25.

Neis, U., Nicke, K. and Thiem, A. (2000). Enhancement of anaerobic sludge digestion by ultrasonic disintegration. *Wat. Sci. Tech.*, **42**(9), 73–80.

Ödegaard, H. (2003). Sludge minimization strategies – an overview. *IWA Specialist Conference* "*Biosolids 2003, Wastewater Sludge as a Resource*", Trondheim, Norway.

Sakai, Y., Fukase, T., Yasui, H. and Shibata, M. (1997). An activated sludge process without excess sludge production. *Wat. Sci. Tech.*, **36**(11), 163–170.

Salhi, M., Deleris, S., Debellefontaine, H., Ginestet, P. and Paul, E. (2003). More insights into the understanding of reduction of excess sludge production by ozone. *IWA Specialist Conference* "*Biosolids 2003, Wastewater Sludge as a Resource*", Trondheim, Norway.

Spérandio, M. and Paul, E. (2000). Estimation of biodegradable COD-fractions by combining respirometric experiments in various S0/X0 ratios. *Wat. Res.*, **34**(4), 1233–1246.

Yasui, H. and Shibata, M. (1994). An innovative approach to reduce excess sludge production in the activated sludge process. *Wat. Sci. Tech.*, **30**(9), 11–20.