

# Sludge minimization technologies – an overview

**H. Ødegaard**

Norwegian University of Science and Technology, N-7491 Trondheim, NTNU, Norway  
(E-mail: [hallvard.odegaard@bygg.ntnu.no](mailto:hallvard.odegaard@bygg.ntnu.no))

**Abstract** The management of wastewater sludge from wastewater treatment plants represents one of the major challenges in wastewater treatment today. The cost of the sludge treatment amounts to more than the cost of the liquid in many cases. Therefore the focus on and interest in sludge minimization is steadily increasing. In this paper an overview is given for sludge minimization (sludge mass reduction) options. It is demonstrated that sludge minimization may be a result of reduced production of sludge and/or disintegration processes that may take place both in the wastewater treatment stage and in the sludge stage. Various sludge disintegration technologies for sludge minimization are discussed, including mechanical methods (focusing on stirred ball-mill, high-pressure homogenizer, ultrasonic disintegrator), chemical methods (focusing on the use of ozone), physical methods (focusing on thermal and thermal/chemical hydrolysis) and biological methods (focusing on enzymatic processes).

**Keywords** Sludge disintegration; sludge minimization; sludge production

## Introduction

To manage the excess sludge from wastewater treatment plants will be one of the most challenging tasks for the wastewater sector in the years to come. Due to the fact that wastewater treatment is expanding quickly both in developed countries (because of more stringent effluent criteria) and in developing countries (due to building of new treatment plants), we have to prepare for a dramatic increase in the global sludge production. This situation, coupled to the fact that there are increasing social and environmental concerns regarding use of sludge on land, has resulted in great interest in processes aimed at reduction and minimization of excess sludge production.

In this paper we shall define sludge minimization processes as those resulting in solids reduction (i.e. sludge stabilization processes) and not the sludge reduction that is a result of dewatering processes (thickening, dewatering, drying) or incineration.

Sludge is being produced by physical/mechanical, biological and chemical wastewater treatment methods. The potential for sludge production reduction in primary (mechanical) treatment itself is not present because the sludge production actually equals the amount of solids that is removed. In order to reduce the amount of primary sludge one has to disintegrate it. When chemical means are used to improve solids removal or to achieve phosphate removal, one has different operational strategies to follow in order to reduce the amount of sludge being produced such as a) reduce the amount of coagulant being used or b) change the coagulant being used.

In biological wastewater treatment processes there are principally two main strategies by which sludge reduction can be achieved, a) by enhanced pre-treatment (reduced load), b) by yield reduction and c) by sludge disintegration processes by which a greater part of the sludge becomes more biodegradable so that more can be mineralised and assimilated by the biomass.

## Reduction of the sludge production

### Sludge production reduction in primary treatment

Traditionally pre-treatment takes place by primary settling, reducing the SS-load by around

50% and the BOD-load by around 30%. This may dramatically be improved by introduction of enhanced pre-treatment by chemical coagulant addition. In some cases where phosphate removal is more important than organic matter removal (which is often the case in Norway) chemical treatment is used alone.

When a coagulant is added to wastewater, either to enhance removal of suspended and organic matter or to achieve phosphate precipitation, the sludge being produced consists of different portions: a) the suspended and colloidal matter being removed, b) the metal-hydroxide being precipitated and c) the metal-phosphate being precipitated. The first one of these components is dependent on the amount of suspended solids being removed and the two others on the amount of metal coagulant being added. This can be expressed in a simplified equation:

$$SP = SS_{in} - SS_{out} + K \cdot D$$

where SP is sludge production ( $\text{g/m}^3$ ),  $SS_{in}$ ,  $SS_{out}$  are suspended solids in and out of the plant ( $\text{g/m}^3$ ), K is a precipitation constant (typically around 3 for iron and 5 for aluminium) and D is the metal dose ( $\text{g Me/m}^3$ ). In a typical chemical plant where the dosage of iron may be in the order of 20 mg Fe/l, the precipitation term ( $K \cdot D$ ) may represent around 30% of the total sludge production.

If only suspended and organic matter removal is aimed for, a significant sludge reduction may be achieved by reducing the amount of metal for instance by replacing metal coagulant by a cationic polymer that does not produce any additional sludge (Ødegaard, 1998). It has been shown that complete replacement of the metal cation may be uneconomical as it results in a very high polymer requirement in order to achieve similar suspended solids removal. A combination of a very low metal dose (i.e. 5–10 mg Fe/l) in combination with a quite low polymer dose may give a very good separation of suspended (>90%) and organic (>70%) matter at a substantially reduced sludge production when compared to the use of metal salt alone (Ødegaard *et al.*, 2004a; Mels, 2001).

When a metal coagulant is introduced in order to achieve phosphate precipitation, there is a stoichiometric need for metal in order to precipitate the necessary phosphate. In practice, however, pH and therefore alkalinity of the water plays a very important role. Most operators add much more than what is stoichiometrically required (in order to bring the pH down to a value where phosphate precipitates well) – with unnecessary excess sludge production as a result.

#### **Reduction of sludge production in biological wastewater treatment**

One may minimize the biological sludge production in principally three ways: a) by enhanced pre-treatment, b) by yield reduction and c) by in-line sludge disintegration (physical, chemical and thermal). Sludge disintegration (both in the wastewater and the sludge line) will be treated below.

*Enhanced pre-treatment.* Improved particle and colloid removal by pre-coagulation as mentioned above (with cationic polymer alone or in combination with a very low metal dose – i.e. 5–10 mg Fe/l combined with 2–3 mg/l cationic polymer) will result in considerably reduced SS– (80–90%) and BOD load (60–80%) with a corresponding reduced biological sludge production. The increased primary sludge production will then have to be taken care of in the sludge treatment line by sludge disintegration methods (see below). Mels (2001) demonstrated that enhanced pre-treatment by polymer coagulation did not increase the final sludge production significantly.

Anaerobic pre-treatment is another option. An analysis of the potential of (anaerobic)

pre-treatment to reduce the excess sludge production of wastewater treatment plants can be found in Mels *et al.* (2003).

*Reduction of biomass production in biological processes.* From practical experience it is well known that the net sludge production in an activated sludge plant decreases with increasing sludge age. The disappearance of suspended organic matter can be a result of numerous mechanisms like maintenance energy requirements, endogenous respiration, decay of cells, grazing by higher animals, or lysis due to adverse environmental conditions (pH, toxic substances or temperature). Van Loosdrecht and Henze (1999) summarized the mechanisms and processes involved, as shown in Tables 1 and 2.

Liu and Tay (2001) reviewed several practical strategies (like oxic-settling-anaerobic process, high dissolved oxygen process, sludge retention time control, uncoupler-containing activated sludge process, etc.) that could be used for minimizing sludge reduction in aerobic processes through utilization of the mechanisms and processes mentioned above.

Chemicals of various types and mode of action have been reported to cause metabolic uncoupling of bacterial and eukaryotic cells. Preventing energy transfer allows the continuation of catabolic paths but halts biomass accumulation. After initial screening of chemical candidates, Mayhew and Stephenson (1998) investigated the potential of chemical uncoupling by using 2,4 dinitrophenol (2,4 DNP) as an additive to the activated sludge process. After 7 weeks of chemical treatment the mean yield coefficient of the treated simulation ( $Y = 0.30$ ) was significantly lower than that of the control ( $Y = 0.42$ ) while the BOD-removal was not significantly different.

Lee and Welander (1996a, 1996b) have proposed the LSP (Low Sludge Production) process based on a two-stage process. The first bacterial stage is designed and operated to favor the growth of dispersed bacteria, which consume much of the soluble organic matter in the effluent. The second predator stage is designed and optimized for the growth of filter-feeding micro-animals, which consume the bacteria from the previous stage. The principle is applied especially in activated sludge plants for the pulp and paper industry.

**Table 1** Primary mechanisms involved in reduction of biomass mass (van Loosdrecht and Henze, 1999)

Mechanism	Description	Caused by
Maintenance	Energy consumption for cell maintenance under the use of external primary substrate or internal stored substrate such as glycogen or PHA	Basic metabolic energy reagents such as membrane potential, renewal of proteins etc
Decay	Processes which reduce the weight and specific activity of biomass	Internal and external factors
Internal decay	Decay caused by cell external factors	Death and self-oxidation of cell constituents
External decay	Decay caused by external factors	Predation
Lysis	Solubilisation of biomass, releasing secondary substrates into the liquid	Enzymes, pH, toxicants, viruses
Predation/grazing	Higher animals consuming micro-organisms	Protozoa, metazoa, etc.

**Table 2** Processes involved in reduction of biomass mass (van Loosdrecht and Henze, 1999)

Process	Description
Maintenance	Direct consumption of cell external or internal substrates for maintenance of the cell integrity
Endogenous respiration	Respiration with oxygen or nitrate using cell internal components
Death-regeneration including growth and lysis (cryptic growth)	Decay followed by growth on the secondary substrate arising from the decay

The modification from a conventional process to a LSP-process in a Norwegian CTMP-plant resulted in a dramatic sludge yield from 0.20 to 0.02 kg TSS/kg COD<sub>removed</sub> (Welander *et al.*, 2000, 2002).

Rensink and Rulkens (1997) reviewed the use of metazoans in order to reduce sludge production. They also reported on pilot plant experiments where mineralization of sludge was studied by the use of metazoans in the form of worms such as Tubificidae. The sludge production in a pilot plant activated sludge system for treating settled, domestic wastewater was reduced from 0.40 to 0.15 g MLSS/g COD<sub>removed</sub> when Tubificidae were added to the system.

### Reduction of excess sludge production by sludge disintegration

Recently, a lot of interest has been devoted to sludge disintegration and solubilization techniques in order to cope with the biological limitations in terms of degradation of particulate matter. In most cases one is considering combined processes where the disintegrated sludge is fed back to a biological step for further biodegradation. The disintegration processes are based on mechanical, electrical, thermal, thermo/chemical, biological and oxidative techniques (see Table 1).

The various methods may be applied to the liquid treatment chain and/or in the sludge treatment chain as demonstrated in Figure 1 (Paul and Salhi, 2003).

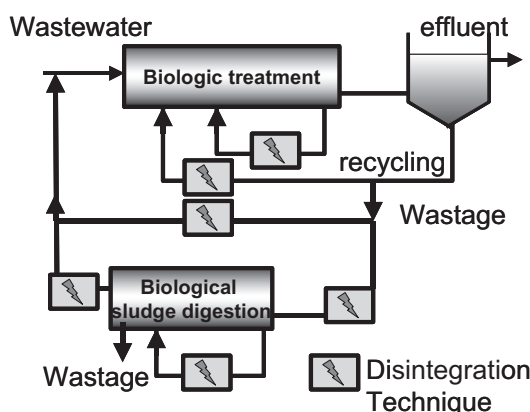
The processes most focused on are a) chemical oxidation disintegration by ozone, b) mechanical disintegration by various methods and c) thermal or thermal/chemical disintegration.

### ESP-reduction by mechanical disintegration

The mechanical disruption process involves the action of externally applied stress or pressure on the cells. Cells are disrupted when the external pressure exceeds the cell internal

**Table 3** Sludge disintegration processes

Biological	Mechanical	Physical	Chemical
Enzymatic lysis Autolysis	Stirred ball-mill High-pressure homogenizer Ultrasound Lysatcentrifuge	Freezing Osmotic shock Thermal treatment High-yield pulse technology	Acid or base hydrolysis Oxidation with H <sub>2</sub> O <sub>2</sub> /O <sub>2</sub> /Fentons reagent Oxidation with ozone



**Figure 1** Various places in a biological process where disintegration techniques may lead to reduction in ESP (Paul and Salhi, 2003)

pressure. Mechanical disruption of sludge has gained acceptance due to its various successful industrial scale applications. As shown in Table 3 there are several mechanical disintegration technologies that may be used. Good reviews of the various disruption methods have been given by ATV (2000, 2001).

*The stirred ball-mill.* The stirred ball-mill consists of a cylindrical or conical tank, vertically or horizontally arranged. It has a disc mixer and 0.2–0.3 mm ball-shaped millstones inside. The sludge is mechanically crushed when passing through the mill. The balls are following the sludge out of the mill, separated from the sludge downstream and recycled to the mill.

*The ultrasonic disintegrator.* The application of ultrasound for treating sludge prior to anaerobic digestion has been recognized by Chiu *et al.* (1997) and Thiem *et al.* (1997, 2001). Ultrasound is the term used to describe energy waves at frequencies above 230 kHz propagated via a compression/rarefaction mechanism. Low power ultrasound technologies have been known and used for a long time in non-destructive applications. High power ultrasound is applied for sludge disintegration. At sufficiently high power densities, the rarefaction cycle will exceed the attractive forces of the molecules of the liquid and bubbles will form. These will grow until they implode, creating localized extreme pressure and temperature conditions (cavitation) with cell lysis as a result.

*The high-pressure homogenizer.* This is a simple device consisting of two main components; a multistage high-pressure pump and a homogenizer valve. The high-pressure pump forces the sludge through the valve at a velocity of 300 m/sec and the static pressure in the valve reaches that of the vapour pressure of the liquid. The cavitation bubbles that result induce the forces that disintegrate the sludge. Tests have shown that the high-pressure homogenizer could be most efficient considering the energy aspect.

Table 4 summarizes the state of art of the most well known mechanical methods ATV (2001).

#### Sludge disintegration by use of chemical oxidation

The by far most investigated oxidant is ozone (Yasui *et al.*, 1994 and 1996; Sakai *et al.*, 1997; Ried *et al.*, 2002; Ahn *et al.*, 2002; Böhlér and Siegrist, 2004). The ozone disrupts the cell, the cell content is released to the bulk solution and the ozone partly oxidizes the solubilized organics. The oxidation by ozone of the recycled sludge may have other benefits in addition to sludge reduction – like reduced bulking and internal carbon source production and many of the studies are more oriented towards these goals than towards sludge minimization. An overview of ozonation studies is given in Liu (2003).

Sludge solubilization and reduction depend strongly on the ozone dosage (Yasui and

**Table 4** Experiences with the most established mechanical disintegration technologies

	The stirred ball-mill	The ultrasonic disintegrator	The high-pressure homogenizer
Extent of operational experience			
Lab	++	++	++
Pilot-plant	++	++	++
Full-scale	+	+	—
Long term operation	—	—	—
Operational stability	+/-	++	—
Technical state of the art	+	+	—

++ Very much/very good, + much/good, — little/poor, — very little/very poor

Shibata, 1994; Déléris *et al.*, 2000; Camacho *et al.*, 2002; Ried *et al.*, 2002, Böhler and Siegrist, 2004). Böhler and Siegrist (2004) found a nearly linear increase of the sludge reduction with increasing ozone dosage up to an optimal dosage of  $0.05 \text{ gO}_3 \text{ gSS}^{-1}$ , where 25–35% sludge reduction is reached. If the ozonated sludge is recycled to the activated sludge system new biomass will grow on the solubilized degradable organic fraction. But also an inert soluble organic fraction is produced.

Ried *et al.* (2002) measured a nearly 30% reduction of the excess sludge production in the ozonated lane of a two-lane full-scale activated sludge plant (SRT 15 days) by treating daily 10% of the activated sludge with an ozone dosage of  $0.052 \text{ gO}_3 \text{ gSS}^{-1}$  ( $0.08 \text{ gO}_3 \text{ gSS}^{-1}$  initial excess sludge).

Böhler and Siegrist (2004) have estimated the cost and energy consumption for ozone treatment. They found that the cost for operation and investment of sludge ozonation was compensated for by the decreasing operation cost for sludge treatment and disposal. They estimated the energy consumption for partial ozonation of the return sludge with an excess sludge reduction of 30% to about 15% of the total electrical energy consumption of a municipal WWTP.

#### **Sludge disintegration by thermal (or thermal/chemical) methods**

Thermal treatment of sludge may be used alone or together with chemical addition for many different purposes in addition to sludge minimization. The method involves heating the sludge to a temperature at which cells disintegrate and lysis takes place.

One may differentiate between processes that take place under  $100^\circ\text{C}$  in which disintegration may take place under normal pressure while a pressure reactor is needed at higher temperatures, up to  $250^\circ\text{C}$ . Lower temperature processes have mainly been investigated with the aim to improve anaerobic digestion (Hiraoka *et al.*, 1984). A 15% increase in methane production was demonstrated by Li and Noike (1992) at a pre-treatment temperature of  $80^\circ\text{C}$ . Much stronger effects are reported, however, at higher temperatures.

*Thermal pressure hydrolysis.* The thermal pressure hydrolysis was introduced already in the 1940s (the Porteous process). The main purpose at that time was sludge conditioning at  $180\text{--}220^\circ\text{C}$ . Several negative effects of the process (odour, high COD in sludge water, etc.) led, however, to closure of many of these plants. A renewed interest in thermal hydrolysis came in the 1990s with new ambitions for the process; sludge minimization, hygienization (Ødegaard *et al.*, 2002b), production of carbon source (Barlindhaug and Ødegaard, 1996a,b), improved biogas production (Kepp *et al.*, 1999) and phosphate recycling (Karlsson, 2001).

The thermal treatment may take place in the liquid stage (for instance on the return sludge line of an activated sludge process) as in the BioThelys-process (Chauzy *et al.*, 2003) or in the sludge stage as in the Cambi process (Kepp *et al.*, 2000; Weisz *et al.*, 2000) and Krepro process (Cassidy, 1998; Recktenwald and Karlsson, 2003). Typical operating conditions are  $150^\circ\text{C}$ , 12 bar and a retention time of 30 min at the required temperature. The degree of hydrolysis (here defined as the  $\text{COD}_{\text{dissolved}}/\text{COD}_{\text{total}}$ ) increases with increasing temperature and varies in the range of 30–45% at 30 min contact time when the temperature is in the  $150\text{--}180^\circ\text{C}$  range.

The CAMBI process is used in four different full-scale plants (in Denmark, Norway, UK and Ireland). In this process the sludge is heated for about 30 min at a temperature increasing from  $130^\circ\text{C}$  to  $180^\circ\text{C}$  through addition of steam. In the Norwegian 150,000 pe plant the excess sludge is dewatered to 15–20% DS before the thermal hydrolysis. After the hydrolysis the sludge viscosity is acceptable for pumping and digestion even at DS-content of 10–12%DS. 17 days of anaerobic digestion reduces the COD by 60% leading to a

considerably reduced final sludge production, total disinfection of the sludge as well as improved dewaterability after digestion (Weisz *et al.*, 2000).

*Chemically enhanced thermal hydrolysis.* In the Krepro-process, which has been tested out for a 3 year period in a full-scale demonstration plant in Helsingborg, Sweden, the sludge after thickening (5–7% DS) is acidified by addition of sulfuric acid to a pH between 1 and 2. By this, most of the inorganic salts dissolve. Then the acidified sludge is hydrolyzed thermally in a pressure vessel at a temperature of 140°C at about 3.5 bars for 30–40 minutes and by this the particulate organic matter in the sludge “solubilizes” to a great extent (about 40%). The sludge now contains dissolved phosphorus, ferrous iron and COD as well as organic, cellulose-like particles (the fiber fraction) separated from the solution in centrifuges (DS ~ 50%). To the liquid phase ferric salts and alkali are added to correct the pH upwards (pH = 3). At this low pH a very pure ferric-phosphate is precipitated and separated by a centrifuge (DS in cake: 35%). The soluble organic matter and ferrous iron, still in the water phase, is recycled to the influent where the iron acts as coagulant and the soluble organic matter acts as carbon source in the biological nitrogen removal processes.

*Wet oxidation.* Another example of a combined chemical/thermal process is wet oxidation in which chemical oxidation (by the addition of  $O_2$ ) takes place at high temperature (150–330°C) and high pressure (6–20 Mpa). Weemaes and Verstraete (1998) have given an overview. The oldest of these processes was the ZIMPRO-process that was developed in The Netherlands in the 1960s. High energy-costs as well as corrosion- and odor-problems made the process disappear. Lately there has been new interest as addition of catalysts has made it possible to reduce temperature and pressure (Bayer Leprox-process) (Holzer and Horak, 1999).

Supercritical water oxidation, that takes place at very elevated temperatures and pressures (typically 25 MPa and 600°C), is a total solution for destruction of sewage sludges: carbon and hydrogen from organic and biologic substances are oxidized to  $CO_2$  and  $H_2O$ ; nitrogen, sulfur and phosphorus (from e.g. biological materials) form  $N_2$ ,  $SO_4^{2-}$  and  $PO_4^{3-}$ , respectively; organic chlorides are converted to  $Cl^-$ , and heavy metals are oxidized to the corresponding oxides. Almost all of these reactions have been shown to reach conversions of 99.9999% at 600°C with a residence time of 30 sec or less (Svanström *et al.*, 2004). Water above 374°C and 22 MPa is a supercritical fluid and oxidation is effective at the milder end of the supercritical water oxidation temperature conditions with the presence of water as the reaction medium (Tester *et al.*, 1993).

Stendahl and Järfverström (2004) report from pilot-plant tests in Sweden with the Aqua Reci process and conclude that the supercritical water oxidation process was not only feasible to decompose organics to more than 99.9%, but also to oxidise ammonium into nitrogen. The cost calculation for a plant of a capacity of 10,000 tons DS was €248/ton DS (or €62/ton 25% sludge). It is claimed that the value from the process in the form of sludge volume reduction with more than 90% recovery of energy, phosphate and coagulants represents a value that will compensate the cost of running the process.

#### **Biochemical sludge disintegration**

The biochemical sludge disintegration processes are based on enzyme activity that is either produced within the system (autolysis) or externally.

An example of the first one is the S-TE process (Shinko Pantec, 1999), in which the excess sludge is brought to a continuous thermophilic aerobic sludge digester (TASD) that from the start is fed by thermophilic aerobic bacteria that are isolated from the composted sludge (identified as *Bacillus stearothermophilus*). They grow actively at 60–70°C and

produce sludge solubilization enzymes that are following the digested sludge back to the aeration tank of the activated sludge plant. As the bacteria cannot grow under 45°C, they do not inhibit the growth of the bacteria in the aeration tank but they will not die in the tank either since they are spore-forming and germinate again when returned to the TASP. Therefore it is claimed that reseedling of aerobic bacteria is not necessary. Pilot plant experiences showed that the excess sludge was brought down to nearly zero while the COD and SS in the effluent of the activated sludge plant increased 10–30%.

## Conclusions

Based on this overview of sludge minimization technologies, the following conclusions may be drawn.

1. Several technologies exist that are applicable for sludge minimization/disintegration.
2. All the disintegration methods require added energy consumption.
3. Most of the methods give some unwanted side-effect.
4. A thorough economical evaluation is needed in each case to find out whether or not the extra effort is worthwhile.
5. The best candidates for use of sludge disintegration techniques are those plants where disposal costs are high or where sludge handling is problematic.

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