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Sludge minimisation technologies

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Abbreviation: ABR – anaerobic baffled reactors; AGF – anoxic gas flotation; ANANOX – anaerobic anoxic oxic; COD – chemical oxygen demand; DO – dissolved oxygen; DS – dry solids; EGSB – expanded granular sludge bed; EU – European Union; HRT – hydraulic residence time; MLSS (MLVSS) – mixed-liquor (volatile) suspended solids; OSA – oxic settling anaerobic; SCWO – supercritical water oxidation; SRT – solids retention time; SS – suspended solids; SVI – sludge volumetric index; THM – trihalomethanes; TOC – total organic carbon; TS – total solids; UASB – upflow anaerobic sludge blanket; VS (VSS) – volatile (suspended) solids; WAO – wet air oxidation; WWTP – wastewater treatment plant

Abstract

The treatment and disposal of excess sludge represents a bottleneck of wastewater treatment plants all over the world, due to environmental, economic, social and legal factors. There is therefore a growing interest in developing technologies to reduce the wastewater sludge generation. The goal of this paper is to present the state-of-the-art of current minimisation techniques for reducing sludge production in biological wastewater treatment processes. An overview of the main technologies is given considering three different strategies: The first option is to reduce the production of sludge by introducing in the wastewater treatment stage additional stages with a lower cellular yield coefficient compared to the one corresponding to the activated sludge process (lysis-cryptic growth, uncoupling and maintenance metabolism, predation on bacteria, anaerobic treatment). The second choice is to act on the sludge stage. As anaerobic digestion is the main process in sewage sludge treatment for reducing and stabilising the organic solids, two possibilities can be considered: introducing a pre-treatment process before the anaerobic reaction (physical, chemical or biological pre-treatments), or modifying the digestion configuration (two-stage and temperature-phased anaerobic digestion, anoxic gas flotation). And, finally, the last minimisation strategy is the removal of the sludge generated in the activated sludge plant (incineration, gasification, pyrolysis, wet air oxidation, supercritical water oxidation).

1. Introduction

Conventional municipal sewage treatment plants utilise mechanical and biological processes to treat wastewater. The activated sludge process is the most widely used for biological wastewater treatment in the world, but it results in the generation of a considerable amount of excess sludge that has to be disposed of. This sludge contains high fractions of volatile solids (VS) and retain large amounts of water (>95% by weight), resulting in extremely large volumes of residual solids produced, and significant disposal costs. In fact, treatment and disposal of excess sludge from wastewater treatment plants account for 25–65% of the total plant operation cost. Thereby, the conventional method converts a water pollution problem into a solid waste disposal problem.

This problem is becoming more and more pressing both in developing and industrial countries. In the latter, the disposal of excess sludge is one of the most serious challenges in biological wastewater treatment, for two main reasons:

1. New wastewater treatment regulations are causing a rise in the number of plants. In the EU countries, after the implementation of the *Urban Waste Water Treatment Directive 91/271/EEC*, the vast majority of the EU population will be served by sewage treatment facilities by the year 2005. This increase in the number of wastewater treatment plants is translated into a higher production of sewage sludge. An increase of nearly 40% is expected between 1998 and 2005, resulting in a generation of about 9.4 million tons (dry weight) every year, while for the year 2010 it is expected to exceed 10 million tons.
2. Sludge disposal routes are subject to more stringent environmental quality requirements imposed by legislation (the *Sewage Sludge Directive 86/278/EEC*, the Organic Farming Regulation (EEC) 2092/91, the Landfill Directive 1999/31/EC and the Commission Decision 2001/688/EC).

In order to take into account the positive aspects of sludge on soil, as well as to reduce the impact of waste on the environment (soil, vegetation, animals and man), the revision of the Directive 86/278/EEC and the development of a Biowaste Directive have been planned as necessary actions.

However, at the moment it has been preferred to develop a basis legislation on soil-protection that will become the reference for the proposed new legislation on biodegradable waste.

Main alternative methods for sludge disposal in EU are: landfill, land application and incineration, accounting for nearly 90% of total sludge production.

Ocean disposal of sludge is nowadays forbidden in practice, and sludge deposits in landfills are to be phased out, even though 35–45% of the sludge in Europe is disposed of in this manner. Legislation concerning land application of sludge is being tightened in order to prevent health risks to man and livestock due to the potentially toxic elements in the sewage sludge, i.e. heavy metals, pathogen and persist organic pollutants. Incineration ash will have to be treated as hazardous waste (due to the heavy metals content and general toxicity), resulting in high treatment cost for this alternative. Moreover, government and environmental groups seem reluctant to consider alternatives such as energy recovery from incineration or use of incineration ash as construction material and other beneficial uses.

Hence, deposition of sludge and its components will not be accepted in the future. This points to direct use of sludge on land as the most sustainable alternative. This is also reflected in the working document for a proposed new sewage sludge directive of EU (Anon 2000).

Therefore, the current legal constraints, the rising costs and public sensitivity of sewage sludge disposal necessitate the development strategies for reduction and minimisation of excess sludge production.

Reducing sludge production in the wastewater treatment instead of post-treating the sludge produced appears to be an ideal solution to this issue, because the problem would be treated at its roots.

Several strategies are currently being developed for minimisation of sludge production on biological wastewater treatment plants. In this paper we will give an overview of processes which result in sludge minimisation, and not the solids reduction that is a result of dewatering processes.

2. Processes for sludge minimisation

The biological sludge production in conventional wastewater treatment plants can be minimised in a number of ways. In fact, there is a high number of different processes by which sludge reduction can be achieved.

In this paper, it has been preferred to categorise the different processes according to the place of the plant where the minimisation takes place. Three main strategies are identified: in the wastewater line, in the sludge line, or in the final waste line (Table 1). Any existing processes for sludge minimisation can be placed in one of these strategies.

1. *Processes in the water line*: Reduction of sludge production in the biological wastewater

Table 1. Sludge minimisation processes

Processes in the water line	Processes that reduce the yield coefficient	Lysis cryptic growth	Chemical oxidation	Ozonation	FS
				Chlorination	FS
			Integration of chemical and heat treatment		FS
			High purity oxygen process		FS
			Enzymatic reactions		FS
		Maintenance metabolism	Membrane bioreactor		EM, IN
		Uncoupling metabolism	Chemical uncoupler		EM
			Oxic-settling-anaerobic process (OSA)		IN, FS
		Predation on bacteria	Two-stage system		EM
			Oligochaetes (worms)		EM
	Processes with low yield coefficient		Anaerobic/aerobic systems		EM, IN
Processes in the sludge line	Pre-treatment processes prior to anaerobic digestion	Physical pre-treatments	Cavitation	High Pressure homogenizers	EM, IN
				Ultrasonic homogenizers	EM, IN
			Thermal	Thermal hydrolysis	IN, FS
				Freezing and thawing	EM
			Mechanical	Impact grinding	EM, IN
				Stirred ball mills	EM, IN
				High performance pulse technique	EM, IN
				The Lysat-centrifugal technique	EM, IN
			Radiation	Gamma-irradiation	EM
		Chemical pre-treatments	Acid or alkaline hydrolysis		EM, IN
			Pre-treatment using ozone		EM
		Biological pre-treatments			EM
		Combined pre-treatments	Combination of thermal, decompression and shear forces		IN, FS
			Chemically enhanced thermal hydrolysis		EM, IN
	Modified anaerobic digestion processes		Two-stage anaerobic digestion		IN
			Temperature phased anaerobic digestion		IN
			Anoxic Gas Flotation (AGF)		IN,FS
Sludge removal processes			Incineration		FS
			Gasification and Pyrolysis		FS
			Wet Air oxidation (WAO)		FS
			Supercritical water oxidation (SCWO)		FS

[a] EM: embryonic (laboratory scale).
[b] IN: innovative (demonstration and limited use).
[c] FS: full-scaled (tested in several full-scale operations).

treatment. The idea is to reduce sludge production in the wastewater treatment rather than the post-treatment of sludge after generation. This can be achieved with two kind of processes: those that reduce the yield coefficient (i.e. ozonation, chemical uncoupler, etc), or those with an intrinsic lower one (i.e. anaerobic–aerobic processes).

2. *Processes in the sludge line*: Reduction of excess sludge production by enhanced treatment of the sludge. The aim in these processes is to reduce the final stream of sludge to be disposed of. Due to the high organic fraction of sewage sludge, anaerobic fermentation is the standard process in sludge treatment for reducing and stabilising the wastewater

solids.The anaerobic digestion process is composed of three steps: hydrolysis, acidogenesis and methanogenesis. The rate-limiting step in the overall process is the hydrolysis reaction, which makes the degradation of waste activated sludge especially low. Some technologies are being investigated in order to enhance the anaerobic digestion of sludge, some of them are pre-treatment processes prior to the anaerobic reactor (mechanical disintegration, thermal pre-treatments, biological hydrolysis with enzymes, etc), and others are changes in the reactor itself (temperature phased anaerobic digestion, AGF, etc).

3. *Processes in the final waste line*: These last technologies aim to treat the sludge produced to get a final stable, dewatered and pathogen free residue. They do not represent a minimisation strategy, but a post-treatment to dispose of the sewage solids. All are based on energy recovery (incineration, SCWO...).

In the discussion that follows, processes are briefly reviewed in order to show a comparison among them. The purpose of this evaluation is to outline the available technologies and to provide a general dialog for categorising processes.

Information was obtained from personal and reported experience. Some valuable reports about sludge minimisation technologies have been published by Liu and Tay (2001), Odegaard et al. (2002), Wei et al. (2003); Odegaard (2004).

Processes are presented as embryonic-EM (laboratory scale), innovative-IN (demonstration and limited use), and full-scaled-FS (tested in several full-scale operations).

3. Processes in the water line

As presented in Table 1, there are several processes to minimise the excess sludge production in the wastewater treatment rather than the post-treatment of sludge generated. Among the techniques, ozonation has been the most successfully applied in practice.

3.1. *Lysis-cryptic growth*

When certain external forces are applied, microbial cells undergo lysis or death during which cell contents (substrates and nutrients) are released into the medium, providing an autochthonous substrate that is used in microbial metabolism (Mason et al. 1986). The biomass growth due to this substrate is termed as cryptic growth (Mason & Hamer 1987). This results in a reduction of the overall biomass production.

There are two stages in lysis-cryptic growth: lysis (which is the rate-limiting step) and biodegradation. In order to improve the overall process performance, one approach is to use a lyse pre-treatment. Some methods for sludge disintegration can be considered: mechanical, thermal, chemical or biological treatments (Müller 2000a, b), in order to facilitate degradation in an *aeration tank*$^{(i)}$ or in a *sludge digester*$^{(ii)}$. The comparison and evaluation of the existing technologies to pre-treat the sludge before *anaerobic digestion*$^{(ii)}$ will be given later in this article. In this section, we present the techniques that can be applied in the water line, to disintegrate particles in an *activated-sludge process scheme*$^{(i)}$: ozonation, chlorination, integration of alkaline and heat treatment, increase of oxygen concentration and enzymatic reactions. When the treated sludge is returned to the biological reactor, degradation of the secondary substrate generated form the sludge pre-treatment takes place, hence resulting in a reduction in the sludge production.

3.1.1. *Ozonation*

A combined system of activated sludge process and intermittent ozonation has been successfully developed (Yasui & Shibata 1994; Sakay et al. 1997; Kamiya & Hirotsuki 1998; Egemen et al. 1999; Egemen et al. 2001; Ahn et al. 2002; Böhler & Siegrist 2003). A fraction of recycled sludge passes through the ozonation unit, and then the treated sludge is decomposed in the biological treatment. The recycling of solubilised sludge into the aeration tank will induce cryptic growth.

Research by Kamiya and Hirotsuki (1998) showed that the excess sludge production was reduced by 50% at an ozone dose of 10 mg/g MLSS in the aeration tank per day. When the ozone dose was kept as high as 20 mg/g, no excess sludge was produced. Sakai et al. (1997) found the same value, while for Yasui and Shibata (1994) the 100% sludge reduction was for a dose of 50 mg/g MLSS in the aeration tank per day.

A working principle for the ozonation-combined activated sludge process has been proposed by Kamiya and Hirotsuji (1998) as follows, (i) a part of activated sludge in the aeration tank is ozonated in the ozone reactor. Most activated sludge microorganisms in the ozonation reactor would be killed and oxidized to organic substances; (ii) these organic substances produced from the sludge ozonation can then be degraded in the subsequent biological treatment. It should be stressed that after introduction of ozonation into activated sludge process, the effluent quality in terms of dissolved organic carbon concentration is not influenced significantly, however, the sludge settleability in terms of SVI was highly improved as compared with control test without ozonation.

This technology is already established in full-scale plants (i.e. Yasui et al. 1996). *Biolysis O* is the process developed by Ondeo-Degrémont to reduce sludge generation using ozone. In this process, liquor extracted from the activated sludge basin is contacted with ozone in a reactor and returned to the activated sludge tank. A demonstration of Biolysis O in France produced sludge reductions of between 30 and 80%.

Future research should be focused on optimisation of ozone dosage, dosing mode (continuous or intermittent), and reactor configuration (bubble or airlift reactor).

Positive (✓) and negative (×) aspects of the ozonation technology are:

✓ No significant accumulation of inorganic solids occurred in the aeration tank at optimal ozone dose rates.
✓ The sludge settleability in terms of SVI was highly improved as compared with control test without ozonation.
✓ Successful full-scale experience.
× Sludge ozonation causes TOC slight increase in the effluent (although mainly composed of proteins and sugars, which should be harmless for the environment).
× High costs involved in ozonation.
× Consumption of ozone in the degradation of other possible organic materials that may be present.

3.1.2. *Chlorination*

Chlorine is a lower cost alternative to ozone. Chlorination treatment of excess sludge resulted in a 60% reduction of excess sludge (Chen et al. 2001a, b; Saby et al. 2002), at the chlorine dose of 0.066 g Cl_2/g MLSS and then returning this treated sludge with a duration of 20 h to an activated sludge system

Positive (✓) and negative (×) aspects of the chlorination technology are:

✓ The cost of chlorine is lower than that of ozone.
× Formation of trihalomethanes (THMs).
× Significant increase of soluble chemical oxygen demand in the effluent.
× Decreased sludge settleability.

3.1.3. *Integration of chemical and heat treatment*

Biological wastewater treatment processes are temperature sensitive. About 60% of sludge reduction was achieved when the returned sludge passed through a thermal treatment loop, 90 °C for 3 h (Canales et al. 1994). High temperatures can also be combined with acid or alkaline treatment to reduce or condition excess sludge. Rocher et al. (1999; 2001) showed that alkaline treatment by NaOH addition combined with thermal treatment (pH 10, 60 °C for 20 min) was the most efficient process to induce cell lysis. The coupling to this lysis system to a bioreactor allowed a 37% reduction in the excess sludge production.

Positive (✓) and negative (×) aspects of the integration of chemical and heat treatment are:

× Corrosion (high-grade materials are required).
× Production of odour.

3.1.4. *High purity oxygen process*

It is generally recognised that in activated sludge process, supply of dissolved oxygen plays a limiting role for further increasing loading rates of treatment facility. Although opinions vary in the literature with regard to the effect of dissolved oxygen concentration on sludge production (Boon and Burges 1974; McWhirter 1978; Abbassi et al. 1999), the mechanism of reduced sludge production with high DO operation is not clearly known. It is likely that the reduced sludge production at high DO concentration somehow is a consequence of DO-induced metabolic changes of activated sludge. A detailed study, however, is required.

It has been observed that the growth yield in purified oxygenation activated sludge process can by reduced to 54% compared to conventional system, even at high sludge loading rates (McWhirter 1978). Boon and Burges (1974) reported that, for a similar sludge retention time, the sludge yield in the pure oxygen system was only 60% of the yield obtained in the process utilising non-purified air. Wunderlich et al. (1985) showed that in high-purity oxygen activated sludge system, the sludge production was reduced from 0.38 to 0.28 mg VSS mg^{-1} COD removed as the SRT increased from 3.7 to 8.7 days. Abbassi et al. (1999) found that a rise of the dissolved oxygen concentration from 2 to 6 mg/l leads to a reduction on the amount of biomass in the reactor of about 25%. These results indicate that the pure oxygen aeration process operated at a relatively long SRT is more efficient in reducing of excessive sludge production.

Positive (✓) and negative (×) aspects of the high purity oxygen process are:

✓ High DO-activated sludge process can repress development of filamentous organisms.
✓ Ability to maintain a higher MLVSS concentration in the aeration tank.
✓ Better sludge settling and thickening.
✓ Higher oxygen transfer efficiency.
✓ More stable operation.
× The efficacy of the process is not clear.
× The mechanism is not fully known.
× High aeration cost.

3.1.5. *Enzymatic reactions*

Enzymatic reactions are biological processes based on enzyme activity. These reactions are the basis of a novel wastewater treatment process, formed by combining the conventional activated sludge system with thermophilic aerobic sludge digester in which the excess sludge is solubilised by thermophilic enzyme. It is called the S-TE process (Sakai et al. 2000; Shiota et al. 2002). The process consists of two different stages, one for a biological wastewater treatment and the other for a thermophilic aerobic digestion of the resulting sludge. A portion of return sludge from the wastewater treatment is injected into a thermophilic aerobic sludge digester, in which the injected sludge is solubilised by the thermophilic aerobic bacteria (e.g. *Bacillus* sp.) and mineralised by mesophilic bacteria. The solubilised sludge is returned to the aeration tank for its further degradation. Pilot scale facilities showed a 93% reduction in the overall excess sludge production, and a high efficiency BOD removal. A full-scale plant treating domestic sewage was operated for three years, showing a 75% reduction of overall excess sludge production.

Biolysis E, developed by Ondeo-Degrémont (although originally created by the Shinko Pantec Japanese company) uses a completely biological action to break down bacteria in the biomass, rendering them unable to reproduce. It consists of drawing mixed liquor from an activated sludge basin, thickening it and then passing it thorough a thermophilic, enzymatic reactor operating at about 50° to 60°. These conditions stimulate the development of a particular type of microbe. When activated, the microbes produce enzymes that attack the outer membrane of the bacteria present in the sludge, reducing their ability to reproduce. The enzymes are released by the bacteria in such a way that they are unable to reproduce and grow. The heated, degraded sludge then passes through a heat exchanger to recover some of its energy before flowing back to the activated sludge basin. No external enzymatic source is needed. Operating results show sludge reductions ranging from 30 to 80% (depending on the quantity of the sludge sent daily to the reactor).

Positive (✓) and negative (×) aspects of the enzymatic reaction process are:

✓ Full-scale experience.
✓ Decrease in the growth of filamentous organisms.
✓ Average cost (investment and operation) similar to or lower than that of classic treatment systems.
× Small increases of the effluent SS and COD concentrations.

3.2. *Maintenance and endogenous metabolism*

According to Pirt (1965), part of energy source is used for maintaining living functions of microorganisms, which is so-called maintenance metabolism. The maintenance energy includes energy for turnover of cell materials, active transport, motility, etc. Note that the substrate consumption associated with maintenance of the living functions of microorganisms is not synthesised of new cellular mass. Thus, the sludge production should be inversely related to the activity of maintenance metabolism (Chang 1993). On the other hand, to account for the decrease in biomass production that is usually observed when the specific growth rate decreases, Herbert et al. (1956) postulated that the maintenance energy requirement could be satisfied through endogenous metabolism. In this case, part of cellular components is oxidised to produce the energy for maintenance functions. The purpose is to reach conditions that naturally balance cell growth and decay.

Endogenous respiration is the autodigestion of biomass. The major advantage of the endogenous metabolism is that the incoming substrate could be finally respired to carbon dioxide and water, while results in a lower biomass production (Gaudy 1980; Martinage & Paul 2000). It should be realised that the control of endogenous respiration would have as much practical significance as the control of microbial growth and substrate removal in wastewater treatment processes.

Increasing the biomass concentration (controlling sludge retention time or sludge loading rate) it would be theoretically possible to reach a situation in which the amount of energy provided equals the maintenance demand. Canales et al. (1994), employing a membrane bioreactor, demonstrated that higher sludge ages increased the biomass viability.

3.2.1. *Membrane bioreactor*

Extended aeration processes (full oxidation) are known to produce little sludge, as they extend the oxidation to the stabilisation of the sludge. However, these processes have a very high footprint and energy demand. The only possibility to achieve full oxidation in a more compact plant is to be able to retain higher quantity of sludge per unit volume, or to increase the oxidation. While the latter can be obtained adopting pure oxygen processes (as discussed above), the high sludge age strategy can be implemented by adopting membrane bioreactors.

In a membrane reactor, solids retention time (SRT) can be controlled independently from hydraulic retention time (HRT), which will result in a higher sludge concentration (typically 15–20 g/l), and subsequently in a lower sludge loading rate. When this sludge loading rate becomes low enough, little or no excess sludge is produced (Yamamoto et al. 1989; Ghyooy and Verstraete 2000; Wagner & Rosenwinkel 2000; Rosenberger et al. 2002), but this option is quite expensive in terms of energy requirements.

In this type of reactor, around 90% of the influent COD is oxidised to CO_2, and suspended concentration in the reactor is almost constant, without sludge wastage (Yamamoto et al. 1989). Wagner and Rosenwinkel (2000) and Rosenberger et al. (2002) showed that in the membrane bioreactor systems bacteria maintenance metabolism caused little/zero sludge production.

It is a reasonable consideration that activated sludge process combining membrane separation has great potential in reduction of sludge production. In fact, it has been successfully applied in full-scale plants (Churchouse and Wildgoose 1999).

Positive (✓) and negative (×) aspects of membrane bioreactors are:

✓ Small footprint.
✓ Flexibility of operation.
× Sludge settling and dewatering is more difficult because of the characteristics of the sludge: open flocs, high viscosity and high SVI.
× Poor oxygenation: increased aeration cost.
× Membrane fouling, which requires frequent cleaning and replacement (high cost).
× Not feasible to operate membrane bioreactors with complete sludge retention in practice.
× Energy requirements.

3.3. *Uncoupling metabolism*

Metabolism is the sum of biochemical transformations, including interrelated catabolic and anabolic reactions. The yield of cells is directly proportional to the amount of energy (ATP) produced via catabolism (oxidative phosphorylation). The uncoupling approach is to increase the discrepancy of energy level between catabolism and anabolism, so that the energy supply to anabolism is limited. As a result, the growth yield of biomass decreases, and the production of sludge can be reduced. Uncoupled metabolism is observed under some conditions, such as: existence of inhibitory compounds or heavy metals, abnormal temperature, excess energy source, limitation of nutrients, and alternative aerobic-anaerobic cycle (Tsai 1990; Mayhew 1998; Liu 2000).

In an environmental engineering sense, the concept of energy uncoupling can be extended to the phenomenon in which the rate of substrate consumption is higher than that required for growth and maintenance. As a result, under energy uncoupling conditions the observed growth yield of activated sludge would be reduced markedly. In theory, reduction in the growth yield means that sludge production can be cut down by an equivalent percentage. This is a promising way to reduce excessive sludge production by controlling metabolic state of microorganisms in order to maximise dissociation of catabolism from anabolism.

3.3.1. *Chemical uncoupler*

For most aerobic bacteria, ATP is generated by oxidative phosphorylation. Such chemiosmotic mechanisms of oxidative phosphorylation can be effectively uncoupled by the addition of organic protonophores, which carry protons through cells' intracellular cytoplasm membrane, such as 2,4-dinitrophenol (dNP), para-nitrophenol (pNP), pentachlorophenol (PCP) and 3,3′,4′,5-tetrachlorosalicylanilide (TCS). In the presence of these compounds, the majority of organic substrate is oxidized to carbon dioxide rather than used for biosynthesis. As a result, the growth efficiency is lowered in uncoupler-containing activated sludge process.

Many researchers have investigated the development of uncoupler-containing activated sludge process for minimisation of excess sludge production (Okey and Stensel 1993; Low and Chase 1998; Mayhew and Stephenson 1998; Low et al. 2000; Chen et al. 2000). About 50% biomass reduction was achieved at a PCP concentration of 30 mg/l compared with no uncoupler (Okey and Stensel 1993). In a laboratory scale system, Low et al. (2000) reported that sludge production was reduced by 49% with the addition of pNP. In a batch culture of activated sludge, Chen et al. (2002) reported a growth yield reduction of 78% at a TCS concentration of 0.8 mg/l. Industrial application of energy uncoupling induced by organic protonophores in two full-scale activated sludge plants in Phoenix and Arizona have been reported by Okey and Stensel (1993).

Chemical uncouplers may provide a promising way for sludge reduction. Research with organic protonophores has shown that the dissipation of energy, through uncoupling biochemical processes such as oxidative phosphorylation, can directly reduce biomass production. However, the actual use of organic protonophores to achieve this is impractical for several reasons, which include the inherent toxicity of protonophores, Because of this, the removal of the additives is required prior to discharge. Further experimentation to establish alternative methods of uncoupling metabolism is desirable.

It is expected that the combination of pure oxygen aeration process with the metabolic uncoupling technique would generate a novel and efficient biotechnology for minimization of the excess sludge production.

Positive (✓) and negative (×) aspects of chemical uncouplers are:

✓ It only needs to add a defined uncoupler dosing.

× Little is known about the uncoupling mechanisms and the connections between chemical uncouplers impact on sludge yield and process conditions.

× Most of the organic protonophores are xenobiotic and potentially harmful to the environment.

× Unexpected increase in the O_2 requirement (obtained in full-scale application)

× Acclimation problems for the microorganism.

3.3.2. *Oxic-settling-anaerobic process (OSA)*

An OSA system is a simple modification of a conventional activated sludge process, in which thickened sludge from a final settling tank is returned to an aeration tank via a sludge holding tank, as shown in Figure 1. The working principle is to alternate anaerobic–aerobic cycling of activated sludge in order to stimulate catabolic activity, and make catabolism dissociate from anabolism, resulting in a minimised sludge yield. In the holding tank, no additional influent substrate is added and anaerobic conditions are maintained in it by a closed operation. A higher biomass concentration coupled with a longer retention period of the recirculated sludge in the sludge holding tank is necessary to maintain proper anaerobic conditions.

Westgarth et al. (1964) for the first time reported that a period of anaerobiosis in the high-rate activated sludge process could reduce

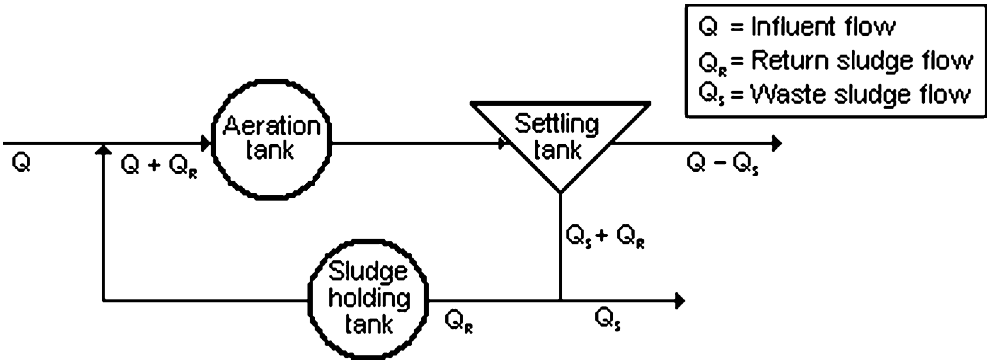

Figure 1. Schematic figure of the *OSA* process.

the rate of excess sludge production by half as compared with that conventional process without anaerobic reactor. Since then, several authors have studied the oxic and aerobic cycling for minimising sludge production (Chudoba 1991; Chudoba et al. 1992 a and Chudoba et al. b; Ghiglizza et al. 1996; Copp and Dold 1998; Chen et al. 2003). Chudoba et al. (1991) included an anaerobic sludge zone in the sludge recycle stream of a laboratory-scale system and achieved a significant sludge reduction. In this process, the repeated passages of activated sludge microorganisms through the anaerobic sludge zone may create conditions of physical stress. Up to 50% reduction in excess sludge production without affecting influent quality and sludge settleability was reported in a study by Chen et al. (2001a, b).

In view of industrial scale application, the OSA process provides a promising technology for reducing sludge production. However, further investigation on the carbon balance and microbial examination population is needed to understand the process.

Positive (✓) and negative (×) aspects of the OSA process are:

✓ It is relatively easy to introduce the anaerobic zone to the conventional activated sludge process.

✓ Control of the growth of filamentous organisms.

✓ No physical or chemical forces are needed.

✓ The OSA process improves the COD removal and the settleability of activated sludge.

✓ Capable of handling high-strength organic pollutants without serious sludge associated problems.

× Further research is needed to understand the process and establish the optimum operational conditions and improve the process operation.

3.4. *Predation on bacteria*

Considering a biological wastewater treatment process as an artificial ecosystem (habitat for bacteria and other organisms), sludge production could be reduced by bacteriovory. Both living and death bacteria can be utilised in trophic reactions (as a food source) by higher bacteriovoric microorganisms, such as protozoa (ciliates, flagellates, amoeba and heliozoa) and metazoa (rotifera and nematoda), that predate on the bacteria. Protozoa are considered to be the most common predators of bacteria, making up around 5% of the total dry weight of a wastewater biomass (70% of these are ciliates).

Main research on the predation on bacteria can be found in Welander and Lee 1994; Lee and Welander 1996a and b; Rensik and Rulkens 1997; Luxmy et al. 2001.

Two stage system and *Oligochaetes* have been investigated. Ratsak et al. (1993) demonstrated predatory grazing on biomass by employing the ciliated *Tetrahymena pyriformis* to graze on *Pseudomonas fluorescens* and reported a 12–43% reduction in the overall biomass production. Similarly, Lee and Welander (1996) employed protozoa and metazoa to achieve a 60–80% decrease in the overall biomass production in a mixed microbial culture. In both of these experiments, bacterial cells were cultured in a primary reactor vessel and the effluent was fed to a second reactor vessel in which the bacteriovores metabolised the bacterial cells.

The use of predatory activity to reduce the overall biomass production requires some caution. Cech et al. (1994) reported that for a mixed population in a one-stage laboratory scale reactor a concomitant decrease in phosphorous removal occurred while there was a marked increase in predator numbers.

Positive (✓) and negative (×) aspects of predation on bacteria are:

✓ Used in large operations today
× The worms growth is still uncontrollable, specially in the full-scale application
× High capital and operation costs

3.5. *Anaerobic treatment of sewage*

In the wastewater treatment field, systems based on anaerobic biological processes have traditionally been adopted to stabilise both primary and secondary waste sludge (Parkin & Owen 1986). However, over the last few years, the search for "sustainable" treatment systems capable of minimising energy consumption has encouraged the use of anaerobic biological systems even for intensive wastewater treatment. Initially these applications were used for high-strength organic wastewaters (such as those produced by some industries). Then, following the proposal of new and more efficient plant configurations, anaerobic systems were used also for the treatment of municipal wastewater, even though this contains a low organic substrate concentration (Lettinga et al. 1981). Some research has been done about the anaerobic/aerobic systems (Sanz & Fdz-Polanco 1989; Sanz & Fdz-Polanco 1990; Fdz-Polanco et al. 1994), and recent sustainability studies point out that anaerobic treatment is more sustainable than the aerobic one (Fdz-Polanco et al. 2005).

These innovative plant configurations (Mels et al. 2003) are all characterised by a high substrate removal rate per unit reactor volume, obtained by retaining the biomass in the reactor independently of the incoming wastewater (solids retention time, SRT, is higher than hydraulic residence time, HRT). The full-scale systems that have found a wider application are those based on the upflow anaerobic sludge blanket (UASB), which is a suspended growth system developed in the Netherlands in the early 1980s (Lettinga et al. 1980). Anaerobic biological systems arranged in series are called ABRs (anaerobic baffled reactors). The ABR uses a series of baffles to force wastewater to flow under and over (or through) the baffles as it passes from the inlet to the outlet (McCarty and Bachmann 1992). The main advantage of this set up is the ability to separate the two biological processes of acid formation and methane formation in which the anaerobic removal of carbonaceous substrate takes place (Eastman and Ferguson 1981; Weiland and Rozzi 1991).

Innovative anaerobic biological systems guarantee a fairly good removal of carbonaceous matter, but are markedly inadequate to remove nitrogen and phosphorous compounds. Consequently, use of the anaerobic system alone cannot guarantee compliance with legal standards, a goal that could be reached by using the so-called integrated systems in which anaerobic biological systems constitute only one of the stages in the treatment flow-sheet (Lettinga and Hulshoff Pol 1991).

The integrated systems developed over the last few years differ according to the various treatment systems that they consist of and the substrates that they eliminate. With specific reference to wastewater treatment in small communities, from as far back as 1988 the research staff at Italy's ENEA Institute (Ente per le Nuove tecnologie, l'Energia e l'Ambiente) proposed the two-stage biological integrated system known as *ANANOX®* (ANaerobic ANoxic-OXic, Garuti et al., 1992a and 1992b). Figure 2 presents a schematic diagram of the ANANOX® system. From a full-scale point of view, the ANANOX process is an example of process integration conceived for obtaining good effluent characteristics while minimising sludge production and energy demand. The first stage of this process uses an ABR comprising two floc sludge blanket sections, one anoxic sludge blanket (for denitrification) and a sludge trap (designed to avoid massive sludge escape from the reactor). The second stage is fed with the effluent of the first stage and is made up of an activated sludge aeration tank and a settling tank. The final effluent is partially recycled to the anoxic stage for denitrification. The configuration of the ANANOX system with its anaerobic, anoxic and aerobic sections prevents

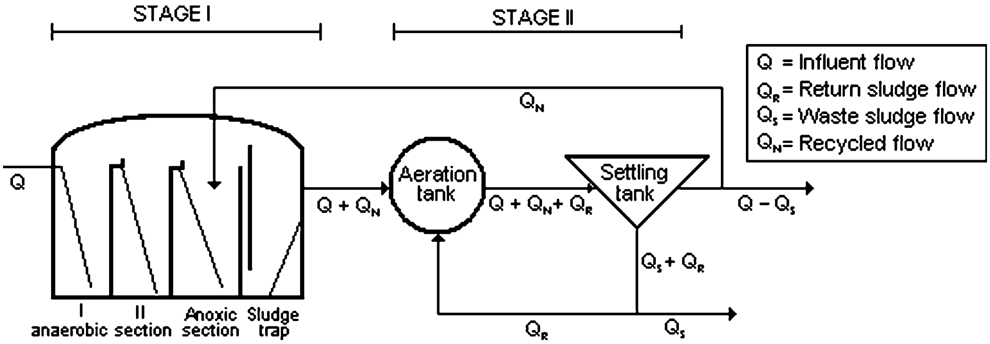

Figure 2. Schematic figure of the *ANANOX®* process.

biomass transfer, and the system can thus be classified as a "separated biomass" system.

The ANANOX system has so far been thoroughly tested on laboratory*scale pilot prototypes. In particular, during an extended investigation in 1990 and 1991 on a pilot-scale system installed at the waste treatment plant in the municipality of San Giovanni in Persiceto (Bologna Province - Italy), high values were obtained for the elimination of COD (89%), total suspended solids (89%) and total nitrogen (81%). In addition, there was an extremely small production of sludge (only 0.2 kg of TSS per kg of COD removed) and methane production equal to 0.103 m^3 per kg of COD removed. Moreover, the sludge from the anoxic section was found to contain *Thiobacillus denitrificants*, which under anoxic conditions can achieve denitrification by oxidising sulphides into sulphates.

Positive (✓) and negative (×) aspects of the anaerobic treatment process are:

✓ Able to achieve 30–50% reduction of sludge production

✓ Capable of reaching effluent standards in line with those laid down in the most stringent regulations that are generally applied.

✓ Robustness and versatility, and compact configuration (case of the ANANOX).

✓ Suitable for the treatment of sewage form communities with variable capacity and when high quality standards are required for the effluent.

× Must be subjected to numerous experiments that help to optimise the efficiency in the anaerobic phase and define the admissible values for organic load and upflow velocity in the ABR.

× The ANANOX process is not recommended for very low sewage temperatures. Research on the anaerobic treatment of very cold effluents has pointed out the potential of new reactor concepts, like the EGSB (Expanded Granular Sludge Bed), for which research on its application to sewage is in course.

4. Processes in the sludge line

In most large wastewater treatment plants, the raw sludge is stabilised using a biological process, which in the vast majority is anaerobic digestion.

The methanogenic process is generally limited by the rate of hydrolysis of suspended matter and organic solids, which is of particular importance during the anaerobic treatment of organic solid wastes such as slurries. There are two ways to enhance this process: pre-treatment of the sludge prior to anaerobic digestion, or modified anaerobic reactors.

Table 1 displays the existing sludge-line proceedings according to these two principles of treatment.

The pre-treatment processes prior to anaerobic digestion are subjects of a growing interest. By means of an efficient pre-treatment, the substrate can be made better accessible to the anaerobic bacteria, accelerating the digestion process (enhance the solubility of sludge solids), increasing the degree of degradation (increment of methane production), and consequently decreasing the amount of sludge to be disposed of. Other benefits can be, depending on the pre-treatment, the improvement of sludge dewatering, the reduction of pathogens, or the suppression of foaming.

These disintegration processes are based on physical, chemical, biological techniques, or a combination of them.

The MODIFIED ANAEROBIC REACTORS consist of a change in the digesters operation to achieve better sludge removal results.

All these techniques are reviewed in this paper.

4.1. *Physical pre-treatments*

The disintegration of solid particles present in the sludge releases cell compounds and creates new surface where biodegradation takes place.

Various disintegration machines are investigated in research projects. All of them are presented here.

4.1.1. *High pressure homogenizers*

These units consist of a multistep high-pressure-pump and a homogenising valve. The pump compresses the suspension to pressures up to several hundred bar. When passing through the homogenising valve, the pressure drops below the vapour pressure of the fluid, and the velocity increases up to 300 m/h. The cavitation bubbles formed implode, inducing into the fluid temperatures of several hundred degrees Celsius, which disrupts the cell membranes.

The patented *MicroSludge process* (Stephenson and Dhaliwal 2000) utilises alkaline pre-treatment to weaken cell membranes and reduce viscosity.

Main research has been done by Kunz and Wagner (1994), Müller (1996), Baier and Schmidheiny (1997), Müller (2000a, b), Lehne et al. (2001), Theodore et al. (2003) and Stephenson et al. (2004).

Positive (✓) and negative (×) aspects of high pressure homogenizers are:

✓ No odour generation.
✓ Easy to implement in a WWTP.
✓ Better dewaterability of the final sludge.
× Low reduction of pathogens.
× Clogging problems caused by coarse and fibrous particles.
× High tensions and erosion in the pump and homogenising valve.

4.1.2. *Ultrasonic homogenizers*

These devices consist of three components: A generator supplies a high frequent voltage of 20 to 40 kHz. A piezo-electrical material transforms electrical into mechanical impulses, which are transmitted by a sonotrode into the fluid. Cavitation bubbles are created by alternating overpressure and underpressure. When imploding, they generate a great amount of energy that causes cell disruption.

Main research has been done by Kunz and Wagner (1994), Müller (1996), Baier and Schmidheiny (1997), Chiu et al. (1997), Tiehm et al. (1997), Tiehm et al. (2001), Clark (1998), Clark and Nujjoo (2000), Neis et al. (2000), Onyeche et al. (2001), Mesas (2003), Hogan et al. (2004), De Silva and Nickel (2004).

There are some commercial devices, such as *Sonix*™ (Sonico®) or *Sonolizer*™ (EIMCO®).

Positive (✓) and negative (×) aspects of ultrasonic homogenizers are:

✓ Reliability of operation (high degree of research and development).
✓ No odour generation.
✓ No clogging problems.
✓ Easy to implement in a WWTP.
✓ Better dewaterability of the final sludge.
× Erosion in the sonotrode.
× Negative energy balance due to the high energy consumption of the equipment.

4.1.3. *Thermal hydrolysis*

Thermal pre-treatment destroys the cell walls and makes the inside of the cell accessible for biological degradation. The optimum temperature for this process is between 160 and 180 °C. Above 180 °C the formation of recalcitrant non-biodegradable compounds takes place. Main research has been done by Haug et al. (1983), Pinnekamp (1989), Li and Noike (1992), Tanaka et al. (1997), Kepp et al. (1999), Prechtl et al. (2001), Kepp and Solheim (2001), Guibelin (2002), Carballa et al. (2004).

There are some full-scale operating plants, through the C*ambi* patented thermal hydrolysis (Kepp et al. 1999; Weisz et al. 2000; Kepp and Solheim 2001).

Positive (✓) and negative (×) aspects of thermal hydrolysis are:

✓ Most effective treatment, according to energetic considerations.
✓ Very good dewaterability of the final sludge.
✓ Best sludge disinfection.
× Fouling of the heat exchangers.

× Possible bad odour if gas streams are not treated.

4.1.4. *Freezing and thawing*

By freezing and thawing activated sludge, the floc structure will be irreversibly changed into a more compact form, the bound water content will be reduced, and therefore the sludge dewatering characteristics can be improved (Chu et al. 1999).

Positive (✓) and negative (×) aspects of freezing and thawing are:

✓ Better dewaterability of the final sludge.
× Huge energy consumption (unless the freezing is natural).

4.1.5. *Impact grinding*

Two rotors revolve in opposite direction in a grinding chamber, generating pressure differences which diminishes the particle size. The flocs are disrupted, but the cells are not disintegrated (Cartmell et al. 2004; Peltola et al. 2004).

Positive (✓) and negative (×) aspects of impact grinding are:

✓ No odour generation.
✓ Enhances sludge settleability (no bulking problems).
× The cellular disintegration is not effective.

4.1.6. *Stirred ball mills*

This device consist of a cylindrical grinding chamber (up to 1 m^3 volume) almost completely filled with grinding beads. An agitator forces the beads into a rotational movement. The microorganisms are disintegrated in between the beads by shear- and pressure- forces.

Main research has been done by Kunz and Wagner (1994), Müller (1996), Baier and Schmidheiny (1997), Lehne et al. 2001; Müller 2001;), Winter (2002) and Müller et al. (2004).

Positive (✓) and negative (×) aspects of stirred ball mills are:

✓ Reliability of operation (high degree of research and development).
✓ No odour generation.
× Huge erosion in the grinding chamber.
× High energy friction losses.
× Clogging problems.
× The degree of disintegration of the sludge is lower compared to other techniques.

4.1.7. *High performance pulse technique*

This device is an electro-hydraulic method. The sludge is treated by a high voltage of up to 10 kV, in pulse periods of only 10 ms. The shockwaves created in the sludge induce sudden disruption and the release of organic substances takes place (Weise & Jung 1998; Weise and Jung 2001; Müller, 2001).

Positive (✓) and negative (×) aspects of the high performance pulse technique are:

✓ No odour generation.
✓ Erosion in the electrodes.
× Low research and development.

4.1.8. *The Lysat-centrifugal technique*

The centrifugal forces created in this thickening centrifuge are deliberately applied to cell destruction. This disruption takes place using a special beater (ring) which is integrated into the centrifugal thickener and which dissipates the kinetic energy provided by the centrifuge. Cell destruction takes place in the centrifuge effluent following thickening, thus the effluent is not loaded any higher as compared to normal centrifugation.

Main research has been done by Dohányos et al. (1997), Otte-Witte et al. (2000), Müller (2001) and Müller et al. (2004).

Positive (✓) and negative (×) aspects of the Lysat centrifuge are:

✓ Moderate energetic consumption.
✓ No odour generation.
× Low degree of sludge disintegration.
× Wear on the equipment plates.

4.1.9. *Gamma-irradiation*

Gamma irradiation has been studied mainly for its pasteurisation effect (Etzel et al. 1969; Yeager and O'Brien 1983). Also, gamma irradiation is known to release soluble carbohydrate from activated sludge (Mustapha and Forster 1985). The technology of irradiation – pasteurisation liberates the soluble carbohydrates existing in the sludge. It has been shown to quickly, efficiently and reliably deal with potential health hazard materials in sewage sludge.

Irradiation of sludge can be carried out with cobalt-60 source, which emits gamma rays. These rays penetrate and pass through the sludge, inactivating microorganisms and decomposing various organic compounds without leaving in any residual radioactivity or making the sludge radioactive. The finished product "clean sludge" can be utilised as an organic, sanitary fertilizer/soil conditioner or use as animal feed.

Main research has been done by Etzel et al. (1969), Mustapha and Forster (1985) and Müller (2001).

Positive (✓) and negative (×) aspects of the gamma irradiation are:

✓ The clean sludge obtained would minimise the risks of pathogenic microorganisms.
✓ Environmental sound solution for the problems of sludge handling and treatment.
× No significant improvements in terms of biogas volumes.

4.2. *Chemical pre-treatments*

The destruction of complex organic compounds can also be achieved by means of strong minerals acids or alkali.

Among chemical processes, the treatment using ozone is of special interest, because no chemicals are added. The use of acids or alkali dissolves the sludge cells at low or ambient temperatures.

Both techniques are presented here.

4.2.1. *Acid or alkaline hydrolysis*

We refer here to the use of alkaline as it is more widely used. During the alkaline pre-treatment, the pH of the sludge is increased up to 12, maintaining this value for a period of time (normally 24 h). This process may be used to hydrolyse and decompose lipids, hydrocarbons and proteins into smaller soluble substances such as aliphatic acids, polysaccharides and amino acids (Chiu et al. 1997; Mukherjee and Levine 1992).

Chemical addition can be used together with thermal pre-treatment, for the disintegration of sludge under normal pressures (Alsop et al. 1982; Hiraoka et al. 1984).

Compared to thermal hydrolysis, alkaline pre-treatment is more efficient in terms of COD solubilisation. However, the global removal efficiency (together with the anaerobic digestion) is lower, because not all the soluble compounds formed are biodegradable.

Positive (✓) and negative (×) aspects of acid or alkaline hydrolysis are:

✓ Low energetic requirements.
✓ Very good dewaterability of the final sludge.
× Modification of the sludge composition.
× Possible damage to the bacteria responsible for the microbiologic activities.
× Bad odour generation.
× Corrosion and fouling of the equipment.
× Higher COD in the final effluent due to the presence of non-biodegradable substances.

4.2.2. *Pre-treatment using ozone*

Among chemical processes, ozone is of special interest because no chemical are needed and no increase in salt concentration occurs. The aim of ozone pre-treatment is partial oxidation and hydrolysis of the organic matter. A complete oxidation is avoided and larger molecules are cracked into smaller ones instead. Barely degradable compounds are transferred into more easily degradable ones (Déléris et al. 2000; Déléris et al. 2002).

Several authors (Mustranta and Viikai 1993; Scheminski et al. 1999; Liu et al. 2001) have considered that the recommended ozone dose is between 0.05 and 0.5 g O_3/g TS. The optimum dosage for each operation depends on the type of sludge.

Positive (✓) and negative (×) aspects of ozone pre-treatment are:

✓ Better dewaterability of the final sludge.
× High energy consumption.
× Metals present in the initial sludge (Fe, Zn, Ag, Cu), are transferred to the liquid phase, that should be purified.

4.3. *Biological pre-treatments*

The biochemical sludge disintegration is based on enzyme activity that are either produced within the system (autolysis) or externally. The enzymatic lysis cracks the compounds of the cell wall by an enzyme catalysed reaction. This process is of interest in combination with mechanical disintegration as well, because enzymes are also located in the intracellular liquid (Thomas et al. 1993).

Solubilization of organic sludge by thermophilic aerobic bacteria as a pre-treatment for anaerobic digestion was investigated by Hasegawa et al. (2000). The mechanism seems to be that the bacteria secrets extracellular enzymes including proteases and amylases.

Positive (✓) and negative (×) aspects of biological pre-treatment are:

✓ Low energy consumption.
✓ No stress on the equipment.
× High cost.
× The usage of enzymes to better the sludge stability is not clear.
× High generation of odours.

4.4. *Combined pre-treatments*

4.4.1. *Combination of thermal, explosive decompression and shear forces*

This process was patented in 1998 by Rivard and Nagle (1998). The sludge is pressurised and pumped to a pre-treatment reactor, where it is mixed with steam to heat and soften the sludge. The pressure is suddenly reduced and explosive decompression forces are imparted which partially disrupt the cellular integrity of the sludge. Shear forces are then applied to the sludge to further discharge the cellular integrity of it.

4.4.2. *Chemically enhanced thermal hydrolysis*

Several authors have studied the effect of chemical additives together with thermal hydrolysis (Thor 1995; Recktenwald & Karlson 2003).

In the *Kepro-process* (developed by the Kemira Kemwater AB, and still in the development stage), the sludge after thickening (5–7% DS) is acidified by addition of sulphuric acid to a pH between 1 and 2. By this, most of the inorganic salts dissolve. The acidified sludge is next hydrolysed thermally in a pressure vessel (140 °C, 3.5 bars, 30–40 min), causing the particulate organic matter in the sludge solubilises to a great extent (about 40%). The sludge now contains dissolved phosphorous, ferrous, iron and COD as well as organic, cellulose-like particles, separated from the solution in centrifuges.

To the liquid phase, ferric salts and alkali is added to correct to pH upwards (pH = 3). At this pH, a pure ferric-phosphate is precipitated and separated by a centrifuge. 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.

More details can be found in Cassidy (1998), Eliasson et al. (2000) and Karlsson (2001).

Positive (✓) and negative (×) aspects of chemically enhanced thermal hydrolysis are:

✓ The solid residue can be used as a biofuel.
✓ Phosphate generation (for land application).
✓ The effluent can act as a carbon source in nutrient removal processes.
✓ Removal of nitrogen and heavy metals.
× Corrosion problems due to the use of acid at hot conditions.
× High operation and maintenance costs.

A comparison among the different pre-treatment processes has been reported by Kunz and Wagner (1994), Baier and Schmidheiny (1997), Müller (2000a, b), Lehne et al. (2001), Müller (2001), Müller et al. (2004), Mels (2001), Camacho et al. (2002), Menert et al. (2001) and Bougrier et al. (2004).

Some performance values are summarised and assessed in Table 2.

4.5. *Modified anaerobic digestion processes*

4.5.1. *Two-stage anaerobic digestion*

This process requires two reactors that separate the primary anaerobic respiration processes into a first acid stage and a second gas stage. The acid stage contains the hydrolysis reactions, acidification and acetification in the first small reactor. Some methanogenic activity may produce gas, but the production is primarily carried out in the second larger reactor. Ghosh and Kensuke Fenkushi (1999) has undertaken considerable research into this treatment, but the process is not yet used significantly despite the operating success.

Positive (✓) and negative (×) aspects of the two-stage anaerobic digestion are:

✓ Shortens reaction time to < 5 days.
✓ Improved methane content.
✓ Stable alkalinity.
× It is not considered to meet Class A sludge.
× Requires pre-thickening to > 5%
× General reluctance for adoption of process.

4.5.2. *Temperature phased anaerobic digestion*

This technique applies thermophilic digestion to the first stage and mesophilic to the second one. This process is the natural extension of thermophilic digestion, as is described by Pedie et al. (2000). Schaeffer et al. (2000) describe the development of process in a real situation.

Table 2. Comparison of pre-treatment technologies

Pre-treatment method	COD solubilisation (times higher than without the pre-treatment)	Sludge removal after anaerobic digestion (%)	Biogas production (% higher compared to the conventional operation)	Pathogen reduction	Influence on the dewatering results
High Pressure homogenizers	18–20	23–64	up to 300	Low	High
Ultrasonic homogenizers	6	40–70	10–60	Low	High
Thermal hydrolysis	10–20	60–80	up to 400	Total	Very high
Freezing and thawing	–	–	–	–	High
Impact grinding	10	5–9	10–36	No	High
Stirred ball mills	15	40–60	10	No	High
High performance pulse technique	–	–	–	No	Moderate
The Lysat-centrifugal technique	–	–	up to 25	No	High
Gamma-irradiation	–	–	–	High	–
Acid or alkaline hydrolysis	–	–	–	–	High
Pre-treatment using ozone	5	36	8	–	High
Thermal + explossive decompression + shear forces	8–12	40–85	–	–	–

Positive (✓) and negative (×) aspects of the temperature phased anaerobic digestion are:

✓ Achieves Class A sludge

✓ Inexpensive retrofit if used as a pre-stage.

✓ Higher efficiency in digester heating.

× Requires special training for operators staff.

× Corrosion and safety concerns.

× Not yet operational.

4.5.3. *Anoxic Gas Flotation (AGF)*

The AGF process is an improved anaerobic digestion process that uses anoxic gas (without oxygen) to float, concentrate and return bacteria, organic acids, protein, enzymes, and undigested substrate to the anaerobic digester for the rapid and complete conversion of waste slurries to gas and soluble constituents (Burke 1997).

This process can achieve a reduction in the solids content of about 37%.

There is a patent on a modification of the AGF process (*ClearCycle*$^{\text{TM}}$).

Positive (✓) and negative (×) aspects of the anoxic gas flotation are:

✓ Smaller anaerobic digesters can be used.

✓ Greater solids conversion to gas (higher methane gas production).

✓ Less energy for mixing and heating.

✓ Very high solids retention times.

✓ Reduced chemical utilisation for maintaining alkalinity.

5. Processes in the final waste line

Table 1 collected the most important processes to get rid of the sludge produced in biological wastewater treatment plants.

5.1. *Incineration*

Incineration of sludge involves burning it in the presence of oxygen at high temperature in a combustion device (Brunner 1991). Incineration reduces biosolids to a residue primarily consisting of ash, which is approximately 20% of the original volume. The incineration process destroys virtually all the volatile solids and pathogens, and degrades most toxic organic chemical, although compounds such as dioxin may be formed, and products of incomplete combustion must be controlled. Metals are not degraded and are concentrated in the ash and in the particulate matter that is contained in the exhaust gases generated by the process. Air production control devices (such as high-pressure scrubbers) are required to protect air quality. Moreover, incineration is an expensive disposal option for sludge, and leaves the problem of what to do with the residues, which are about 30% of the input mass. They are regarded as a hazardous waste a cause of the contamination of heavy metals (Eddings et al. 1994; Wang & Lin 1998; Dangfran et al. 2000).

Although incineration is nowadays considered (in Europe) the last method used in the treatment of sewage sludge, it is expected to increase because the agricultural use and landfilling of sludge are subject to heightened regulatory control.

However, incineration is a capital intensive investment, and it is also subject to strict regulation pertaining to combustion criteria, management of the off-gas treatment residues and treatment of fly and bottom ashes.

From an economic point of view, it can be justified for sludges not allowed to be used in agriculture.

Positive (✓) and negative (×) aspects of incineration are:

✓ A significant reduction of the sludge volume.

✓ Energetic valorisation of sludges.

✓ Recycling of sludge treatment subproducts, such as ashes and inert material, which can be used in filler material for asphalt and concrete production and in the fabrication of bricks.

✓ Low sensitivity to sludge composition.

✓ Reliable systems.

✓ Minimisation of odours, due to the closed systems and high temperature.

× Incinerators are capital intensive and usually justified only in larger volume situations (2000–5000 tons DS).

× Need to flue gas cleaning.

× Public concern.

5.2. *Gasification and pyrolysis*

Gasification and pyrolysis of wastewater sludge are rather new methods of sludge processing, and detailed information on them is limited.

Gasification is a thermal conversion of hydrocarbons to gas by partial combustion of the sludge in the presence of oxygen or air (Whipps and Whiting 1999). In the absence of air, the process is known as pyrolysis

Positive (✓) and negative (×) aspects of gasification and pyrolysis are:

✓ Destroys organic compounds.

✓ Synthesis gas can be used as chemical feedstock or, after additional processing, as a power source.

✓ Provides heat that can be converted to steam and power.

✓ Lower volumes of flue gas and NO_x emissions than incineration.

✓ Low dioxins/furans.

✓ Produces stable solid residues, that allows further recycling.

✓ COS, H_2S oxidised to elemental sulphur.

✓ Reduced CO_2 emission per kWh.

× Some processes produce char, that requires further disposal.

× Risks for scale up.

× Safety issues, especially with pure oxygen.

× Requires pre-treatment to meet < 500 μm as dried feed from dryer.

× Complex.

× No current cost data.

× Limited operating data.

5.3. *Wet Air Oxidation (WAO)*

The organic content of the sludge (approximately 5% DS) is oxidised in specific reactors at temperatures of between 200 and 300 °C, and at pressure levels between 30 and 150 bar (low/high pressure systems). The necessary pressure may be reached through high-pressure pumps or through specially designed reactors.

Weemaes and Verstraete (1998) and Djafer et al. (2000) have given an overview.

The oldest of this processes was the *ZIMPRO-process*, that was developed in the Netherlands in the 1960's. High energy-costs as well as corrosion-and odour-problems made the process unattractive. Recently, however, there has been renewec interest as addition of catalysts has made it possible to reduce temperature and pressure (*Bayer Leprox-process*) (Holzer and Horak 1999).

The main output of the process is sludge containing more than 95% of mineral components and less than 3% of low-molecular organic substances. The sludge is dewatered and then recycled or landfilled.

An upscale oxidation plant is being run in the Netherlands. However, it seems to have some operational difficulties.

Positive (✓) and negative (×) aspects of WAO are:

✓ Improves dewaterability.

✓ Low energy and no fuel requirements.

✓ Low air pollution concerns (no NO_x, SO_2, HCl, dioxins, furans, flyash).

✓ Small footprint.

✓ Suited to sludges with metal content.

✓ Reduction of greenhouse gas (CO_2) production.

✓ Residual solids are intrinsically resistant to leaching.

✓ COD and VSS reduction of 70 and 90%.

✓ High organic nitrogen removal (70%).

× Operates at 10 to 100 atmospheres and high temperatures (150–350 °C).

× Capital and maintenance cost is high.

× Does not reduce total solids significantly (7%).

× High ammonia production may be a problem with downstream treatment.

× High corrosion problems have caused some operations to be suspended.

× Cleaned and thickened feed to 5%.

5.4. *Supercritical Water Oxidation (SCWO)*

This process, also called hydrothermal oxidation, is explained by Gloyna (1998) and summarised for use with sludge by Shanableh and Shimizu (2000), Patterson et al. (2001) and Svanström et al. (2001, 2003).

It takes place at very elevated temperatures and pressures (typically 25 MPa and 600 °C), and is the total solution for the destruction of sewage sludge: carbon and hydrogen from organic and biologic substances are oxidised to CO_2 and H_2O; nitrogen, sulphur and phosphorous form N_2, SO_4^{2-} and PO_4^{3-}, respectively; organic chlorides are converted to Cl^-; and heavy metals are oxidised to the corresponding oxides. Almost all of these reactions have shown conversions of 99.99% at 600 °C with a residence time of 30 s or less (Svanström et al. 2001).

Although the cost is high, 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.

Positive (✓) and negative (×) aspects of SCWO are:

✓ High reduction in VS and TS (60–80%).

✓ Complete oxidation of organics (COD > 99.9% reduction).

✓ Low air emissions (NO_x, SO_2 scrubber needs; no HCl, halogens, furans, dioxins, PCB's).

✓ Residuals intrinsically resistant to leaching.

✓ Suited to sludges with metal content.

✓ Provides complete reduction in greenhouse gas over WAO.

✓ Suited to treatment of hazardous waste.

✓ Provides heat recovery and is self sustaining.

✓ Low fuel requirements.

× Corrosion problems.

× Requires safety systems for handling pure O_2 or H_2O_2 as oxidants.

× Requires sophisticated reaction chambers.

× May need to further treat the gas for nitrogen and sulphur compounds.

× Produces ammonia that may impact the liquid treatment process.

× High capital and maintenance cost.

× Requires feed waste to be cleaned and prethickened to 5–10%

× Feed sludge is required to be homogeneous and free from grits.

× Requires ash disposal and side-stream effluent handling.

× Energy considerations are necessary to determine process viability.

× Selection of oxidant, reaction time, temperatures and pressures requires study or pilot work.

6. Discussion

The treatment and disposal of excess sludge is one of the most serious problems in biological wastewater treatment globally, due to environmental, economic, social and legal factors.

It is also a growing issue world-wide since sludge production will continue to increase, as new wastewater treatment plants are built and environmental quality standards become more and more stringent.

With some traditional disposal routes coming under pressure (such as land application and incineration), and others (i.e. sea disposal) having been phased out, the challenge is to find cost-effective and innovative solutions and responding at the same time to environmental, regulatory and public pressures.

Recycling and use of sludge are preferred options for sustainable development, rather than incineration or landfilling. With this basis, the ideal solution to the sludge disposal problem is to combine sludge reduction with the removal of pollution at the source.

The range of possible choices can be divided into two major categories: (i) processes to be applied to new wastewater treatment plants; (ii) processes to be applied to existing treatment plants.

The first category$^{(i)}$ is larger, but the large availability of choices does not correspond to a similarly large application in the reality. This fact is mainly due to the difficulty to introduce innovations in the market (the period of time since the research phase and the application is frequently very long), but also to the high investment cost of the new processes.

The second category$^{(ii)}$ means introducing in the existing plant simple devices that do not alter the initial configuration. These technologies have a greater chance of finding broad application.

Of course, each sludge reduction option will end up with the generation of different sludge qualities, with consequent implications on the final disposal options.

The future direction of sludge management in Europe at this moment is uncertain. The decisions to be taken by the by the water utilities, national governments and the European Commission on policy, standards and affordability will dictate how sludge will be managed in the years to come.

This paper outlines the main available technologies and provides a general dialog for categorising processes.

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