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A Novel Approach of Cleaner Production Concepts to Evaluate Promising Technologies for Sludge Reduction in Wastewater Treatment Plants

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Abstract

Excess sludge has been becoming one of the great environmental pressures on the future of sludge treatment and disposal. An ideal way to solve sludge-associated problems is to minimize sludge production rather than the post-treatment of the sludge produced. Cleaner Production (CP) has been successful in application for waste reduction of industries. Interestingly, CP concepts are first used for analysis and assessment of techniques which can reduce waste sludge from wastewater treatment plants. This article provides a review of the performance of various methods including both reduction of sludge production at source and sludge disintegration techniques such as mechanical, thermal, chemical and biological ways. The methods are compared regarding energy consumption, operational reliability for application on wastewater treatment plants. The influences of techniques on environment and on treatment processes are described. The evaluation of capital and operational costs is also evaluated. It is hoped that this paper would be helpful for researchers and engineers to develop novel and efficient methods to reduce excess sludge from biological systems.

Keywords: Activated Sludge; Cleaner Production; Disintegration; Evaluation; Sludge Reduction

Introduction

The activated sludge process is the most widely used biological wastewater treatment for both domestic and industrial plants in the world [1]. The excess sludge generated from the biological treatment process is a secondary solid waste that must be disposed of in a safe and cost-effective way [2]. With the expansion of population and industry, the increased excess sludge production is generating a real challenge in the field of environmental engineering technology. The cost of the excess sludge treatment and disposal can account for 30-40% of the capital cost and about 50-60% of the operating cost of many wastewater treatment facilities [3,4]. Moreover, the conventional disposal methods such as landfill or ocean dumping may cause secondary pollution problems and are strictly regulated in many countries [5]. Excess sludge disposal has shown a significant challenge and attracted great attention in both academic and engineering fields.

So far, there have been at least four techniques seriously considered with respect to excess sludge handling. First method is to recover useful resources from sludge, e.g. production of fuel byproducts through sludge melting or sludge pyrolysis and extraction of useful chemicals from sludge [6,7,8]. Second way is to convert the excess sludge to value-added construction materials or activated carbon [9,10]. Third way is to innovatively manage existing outlets of sludge disposal [11,12] and the last one is to reduce sludge production from the wastewater treatment process rather than the post-treatment or disposal of the sludge generated. Among these four approaches, the development of innovative technology for reducing excess sludge production is essential and also related to the Cleaner Production concepts on waste minimization and pollution prevention.

Cleaner Production (CP) was defined as a continuous application of an integrated, preventive environmental strategy applied to processes, products and services in order to increase efficiency and reduce risks to human and the environment [13]. With the original definition, CP is relevant to all industries, whether they are small or big, or they have a low or high consumption of raw materials, energy, and water [14,15]. CP concepts can be applied to a wastewater treatment system which is an industry where the final product is well-defined, and where the quality of the raw materials used to produce that product are uncontrollable [16].

Getting back the waste sludge issue, currently it is one of the most serious challenges in biological

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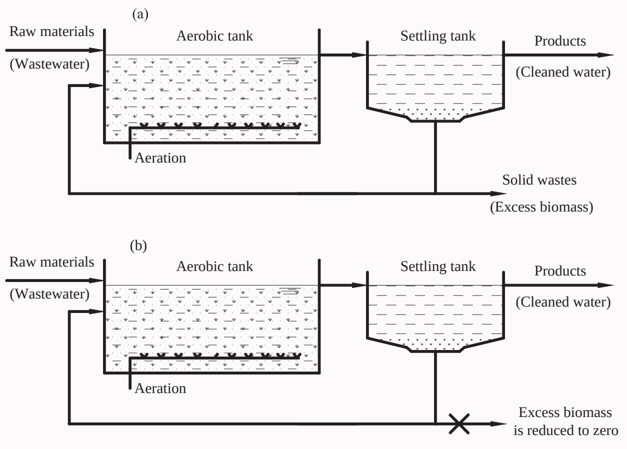

Figure 1: A classical biological wastewater treatment plant with waste activated sludge (A) and "zero" or minimization waste generation (B).

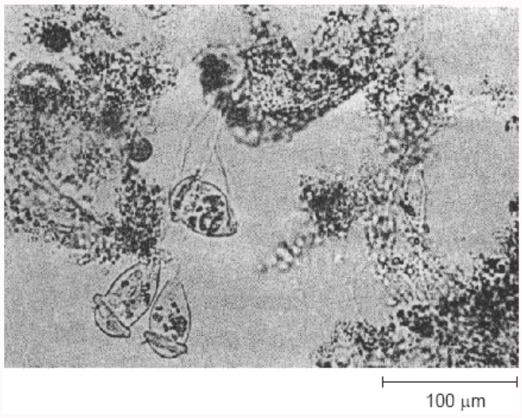

Figure 2: Microscope image of flocks in aeration tank [32].

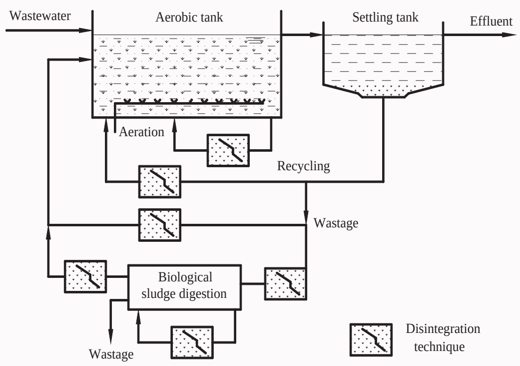

Figure 3: Various places in a biological process where disintegration techniques can be set up to minimize excess sludge production [50].

wastewater treatment [17,18]. There are various sludge disintegration techniques attracted attentions as promising alternatives to reduce sludge production. Sludge disintegration techniques have been reported to enhance the biodegradability of excess sewage sludge [19]. Sludge disintegration methods reported in the literature include both physical methods such as ultrasound, ball mill, and homogenizer treatments [20, 21] and chemical methods such as ozone, acid, and alkali treatments [22,23]. Besides, thermal treatment [24] and enzyme treatment [25] have also been tested.

Based on the cleaner production concepts, therefore, this article focuses on appraising and comparing these promising techniques for minimization of waste biomass from biological wastewater treatment systems on the basis of merits and demerits. The effective and an economic evaluation of the technologies are also included.

Cleaner Production Concepts for Wastewater Treatment Plants

Cleaner Production avoids or minimizes waste and pollution before it is generated [26]. Through the concepts of Cleaner Production (CP) on the biological wastewater treatment systems, the three questions below are answered: WHERE waste sludge is generated; WHY waste sludge is generated; and HOW waste sludge can be minimized. The application of CP tools will result in treatment process evolving from typical process (Figure 1a) to desired process (Figure 1b).

During operation of biological wastewater treatment processes, a part of activated sludge should be withdrawn and disposed in order to maintain appropriate level of biomass concentration in the reactor in the range of 1500-4000mg/L [27]. Daily production of excess sludge from conventional activated sludge process is around 15-100 L/kg BOD_5 removed, in which over 95% is water [28,29]. In the case of domestic wastewater treatment, waste activated sludge generates about 13.5kg TDS/IE year. (where TDS: Total Dry Solids; IE: Inhabitant Equivalent) [30]. General characteristics of activated sludge are listed in Table 1. Sludge is composed largely of organic matter (59-88%, w/v) that can decompose and produce offensive odours [31]. The microscope image of flocks and the cell structure of bacterium living in aeration tank is illustrated in Figure 2 [32].

In the following, the most promising process techniques that can be applied to industrial scale operation for control of excess sludge production in the activated sludge process were discussed. The techniques are separated into two main groups of sludge reduction within process (i.e. at source) and sludge disintegration methods.

Reduction of Sludge Production within System

In aerobic wastewater treatment processes, control of the wastage rate is employed providing either a constant Food to Microorganisms (F/M) ratio or to regulate the sludge retention time (SRT). The F/M ratio describes the amount of substrate that a given amount of biomass is utilizing. A low F/M ratio would result in lower biomass production [33].

The biomass concentration is a function of the sludge return rate and therefore is an accessible control parameter. By increasing biomass concentration it would theoretically be possible to reach a situation in which the amount of energy provided equals the maintenance demand. Low and Chase [34] presented a relationship to describe substrate utilization for maintenance and biomass production in substrate-limited continuous microbial cultures. Results showed that the biomass reduction occurred, i.e. biomass reduction by 12% and 44% when the biomass concentration was increased from 3 to 6g/L and from 1.7 to 10.3g/L, respectively.

Besides those, a relationship between sludge yield (Y_{obs}) and the sludge retention time (SRT) can be described by the following expression [35].

$$\frac{1}{Y_{obs}} = \frac{1}{Y_{\max}} + \frac{\theta_c K_d}{Y_{\max}}$$

Table 1: General characteristics of activated sludge [31].

Items	Value
Total dry solids (TDS) (%)	0.83-1.16
Volatile solids (% of TDS)	59-88
Grease and fats % of TDS)	5-12
Protein % of TDS)	32-41
Nitrogen (N) % of TDS)	2.4-5.0
Phosphorus (P) % of TDS)	0.6-2.3
Potash (K) % of TDS)	0.2-0.29
pH	6.5-8.0
Alkalinity (mg/L as $CaCO_3$)	580-1100
Organic acids (mg/l as Hac)	1100-1700
Energy content (MJ kg^{-1})	18.6-23.2

where Y_{max} is the true growth yield; θ_c: sludge retention time; and K_d is specific endogenous rate. The above equation shows that the observed growth yield is inversely dependent on the sludge retention time and endogenous rate in steady state activated sludge process. This equation also provides a theoretical basis for in-plant engineers to control the total sludge production by adjusting the θ_c during the wastewater biological treatment. In other words, increasing SRT can reduce sludge production in aerobic wastewater treatment processes. For example, Stall and Sherrard [36] reported that excess sludge production was reduced by 60% when the θ_c was increased from 2 to 18 days.

Membrane bioreactor (MBR) process has obvious advantages over conventional activated sludge one, e.g. excellent effluent quality, small footprint, less sludge production and flexibility of operation, and becomes a promising alternative for wastewater treatment [37]. MBR can be operated in long SRT even complete sludge retention because SRT can be controlled completely independently from hydraulic retention time (HRT) by membrane instead of clarifiers for the separation of sludge and effluent. The long or complete sludge retention allows MBR operation at much higher sludge concentration. The higher the sludge concentration, the lower the sludge loading rate. As a result, the microorganisms therefore utilize a growing portion of feed for maintenance purpose and consequently less for growth. When the sludge loading rate becomes low enough, little or no excess sludge is produced any more. Chaze and Huyard [38] reported that sludge production of a bench scale side-stream MBR treating domestic wastewater was greatly reduced at long SRT between 50 and 100 days. The low sludge production (0.002-0.032kg/d) was observed in a pilot submerged MBR operating for one year without sludge discharge [39]. Zero sludge production could be achieved at high sludge concentration (15-23g/L) and F/M ratios as low as about 0.07 kg COD/kg MLSS.d or 0.066kg COD/kg MLSS.day in a pilot submerged MBR with complete sludge retention [40,41]. In a membrane separation-combined activated sludge reactor, 100% of the sludge can be kept in the reactor and the sludge retention time should be long enough. Material balance on COD in this type of reactor shows that around 90% of the influent COD is oxidized to carbon dioxide and suspended solid concentration in the reactor is almost constant, without sludge wastage [42].

Enhanced hydrolysis of biomass in membrane bioreactor (MBR) or in extended aeration process, and use of protozoa and metazoa for decreasing sludge production in aerobic wastewater treatment [42,44,45]. Ghyooy and Verstraete [46] proposed a two-stage membrane-assisted bioreactor to reduce sludge production. The first stage was a completely mixed reactor without sludge retention for the stimulation of dispersed bacterial growth, and the second stage was an activated sludge system in which growth of protozoa and metazoa was stimulated. Solid-liquid separation was achieved by submerged membrane filtration in the second stage. Results showed that such a system yielded a 20-30% lower sludge production than the conventional activated sludge system, and this may be due to higher amount of predators in the second stage of membrane-assisted reactor configuration.

Lee and Welander [47] 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. 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 0.02kg TSS/kg COD removed [48].

In short, 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 or grazing by higher animals [49].

Reduction of Sludge by Sludge Disintegration Techniques

Recently, various sludge disintegration techniques have attracted attentions as promising alternatives to reduce sludge production. 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, thermal, chemical or thermochemical, and biological techniques shown in Table 2. The various ways may be applied to the treatment plant for sludge pretreatment as illustrated in Figure 3.

Mechanical Methods

Mechanical sludge disintegration methods are generally based on the disruption of microbial cell walls by shear stresses. Cells are disrupted when the external pressure exceeds the cell internal pressure. Mechanical disruption of sludge has gained acceptance due to its various successful industrial scale applications. The disruption of microbial cells by the colloid mill process was reported by Harrison

Table 2: Sludge disintegration processes.

Mechanical methods	Physical methods	Chemical methods	Biological methods
Stirred ball-mill	Thermal treatment	Acid or base hydrolysis	Enzymatic lysis
High-pressure homogenizer	Osmotic shock	Oxidation with ozone	Autolysis
Ultrasound	High-yield pulse	Oxidation with H_2O_2/O_2/Fentons reagent	

Table 3: Comparison of different sludge disintegration methods on operational behavior [71].

	Mechanical methods (Ultrasonic disintegrator)	Thermal methods	Chemical methods		Biological methods
			Ozone	Acids Alkali	
Low energy consumption	-	-	o	++	++
Resistance to wear	+	-	o	o	++
Reliability of operation	+	o	o	+	+
Extent of research experiences	+	+	+	o	o
Stage of development for application	+	+	+	+	+

++ excellent, + good, o middle, - poor.

Table 4: Comparison of different sludge disintegration methods on treatment processes [71].

	Mechanical methods	Thermal methods	Chemical methods		Biological methods
			Ozone	Acids Alkali	
Rate of sludge degradation	++	+	+	+	+
Degree of sludge degradation	+	o	++	o	o
Bacteria disinfection	+	++	+	+	o
Influence on the dewatering results	o	+	o	+	o
Generation of odor	o	--	-	-	-

++ excellent, + good, o middle, - poor, -- very poor.

[51]. Sludge is pumped through the central opening device of a stationary disk. A second disk rotating at a speed of $30ms^{-1}$ close to the first ruptures the cell walls. Each pass through the mill could rupture about 50% of the sludge but the heating of the cell suspension because of energy dissipation may cause complications. Harrison also described the high speed shaker ball mill as a mechanical sludge disintegration device. In the treatment reactor, moving impellers transfer kinetic energy to grinding glass beads thereby creating high shear stresses that break the cell walls.

One of the most widely known methods for large scale operation is high pressure homogenization. In a high pressure homogeniser, the sludge is compressed to 60 Mpa [52]. The suspension then leaves the compressor through a valve at a high speed, smashing on an impaction ring. The cells are hereby subjected to turbulence, cavitation and shear stresses, resulting in cell disintegration. Cell disintegrations up to 85% were achieved at relatively low energy levels (30-50MJ/m^3).

Springer et al. [53] presented a laboratory research investigating a process in which sludge was lysed mechanically in a Kaddy mill, a high shear device generating heat, before being recycled back to the treatment reactor. The process would produce zero sludge growth but removed somewhat less COD compared with the conventional system (80% to 87%).

Based on cavitation processes, ultrasound can be used to disrupt cell walls. Rivard and Nagle [54] found an enhancement in biodegradability of sewage sludge to 80-83% by a sonication treatment of 4-8min at 55°C. Shimizu et al. [55] used sonolysis to leak out biopolymers of activated sludge and found a 60% solubilization by treating the sludge suspension for 1h at 200W. King and Forster [56] investigated ultrasound as a pre-treatment step before anaerobic sludge digestion. For 64s, sludge was sonolysed at 31kHz and 3.6kW. The soluble COD concentration thereby increased from 270mg COD/L to 3500mg COD/L. The anaerobic biodegradability increased from 45% to 50%.

Although the various mechanical sludge disintegration methods seem to be very effective in breaking sludge cells, most of them implicate high power consumption. Harrison and Pandit [57] claimed that hydrodynamic cavitation was the most energy efficient process among different mechanical cell disruption techniques (0.74MJ/m^3 treated sludge over 30-50MJ/m^3 for high pressure homogenisation and 1792MJ/m^3 for sonication). King and Forster [56] gave comparable values for respectively high-pressure homogenizers (2-7MJ/kg TDS) and sonolysis (200 MJ/kg TDS).

The high energy levels were most probably the reason why the application of mechanical disruption methods is still limited.

Thermal Methods

Heat treatment results in the breakdown of the gel structure of the sludge and the release of intracellular bound water [57]. Thermal hydrolysis involves heating of the sludge, usually to a temperature in the range of 150-200°C. The pressures adjoining these temperatures are in the range of 600-2500kPa [58]. Increased temperature had a major positive effect on the yields of soluble COD. At 150°C the yield was around 15-20%, while at 200°C the yield was around 30% [59]. Increased retention time (RT) only increased the yields of soluble COD at the lowest temperatures (at 160°C, the yield was 23.8% for 15min RT and 26% for 50min RT). At 200°C, no influence of the RT was found [57]. The effect of lowering the pH by adding acid was found to be quite similar to that of increasing RT. The biodegradability of the hydrolysate however decreased with the temperature of the process while the combination of acid and oxygen increased the biodegradability.

Tanaka et al. [23] investigated several pretreatments prior to anaerobic digestion to enhance solubilization of combined waste activated sludge (WAS). For the thermal pretreatment, VSS solubilization was around 15% between 115 and 150°C and then increased further above 160°C, reaching 30% at 180°C (1h heating).

The effect of thermal pre-treatment on the characteristics of degradation of WAS in anaerobic digestion was studied by Li and Noike [60]. The investigated conditions ranged between 62 and 175°C, and 15 and 120min. For a treatment at 75°C for 30min, they noted a solubilization of 55%. The thermal hydrolysis of pre-precipitated sludge was reported by Smith and Göransson [58]. At 160°C and 6 MPa, a very low solubilization of only 15% was found.

Apparently, the origin of the sludge is of primary importance for the final solubilization to be reached with thermal hydrolysis.

Chemical and Thermochemical Methods

In chemical and/or thermochemical hydrolysis techniques, an acid or base is added to solubilize the sludge cells. Whereas for thermal destruction methods high temperatures are required to achieve acceptable results, the (thermo)chemical treatments are often carried out at lower or ambient temperatures. A thermal alkaline treatment process was studied by Inagaki et al. [61]. For the excess sludge, treatment temperatures in the range of 37-87°C had little effect on solubilization rates, but solubilization rose as the treatment pH increased by adding NaOH. At 37°C and pH 9, Inagaki et al. [61] noted a solubilization of 35%. A solubilization rate of 45% was estimated to be the maximum for temperatures under 100°C.

Tanaka et al. [23] investigated a chemical and a thermochemical pretreatment before anaerobic digestion. In the chemical pretreatment NaOH was added to combine WAS. It was found that VSS solubilization increased as the alkali dose increased up to 0.6g NaOH/g VSS, and became constant around 15% above the dose of 0.6g NaOH/g VSS (1h contact time). In the thermochemical pretreatment, maximum solubilization was reached at a dose of 0.3g NaOH/g VSS and 130°C (5min heating), yielding a solubilization of 45% for combined WAS and 70-80% for domestic WAS, which again confirms the importance of the nature of the sludge source. Analysis of the domestic hydrolysate showed a solubilization of 90%, 64% and 61% for carbohydrates, proteins and lipids, respectively.

Woodard and Wukasch [62] studied thermochemical pretreatment of WAS with sulphuric acid at high temperatures and investigated the influence of the acid dose, temperature, time and initial suspended solids concentration. The acid dose was the only parameter having a statistically significant effect on solubilization. Addition of 4g H_2SO_4/g TSS at room temperature and a contact time of 5min reduced the TSS concentration by an impressive and unexpected 61%. Very rapid hydrolysis and VSS reduction through acidification with H_2SO_4 was also confirmed by Meunier et al. [63]. Smith and Göransson [58] looked at thermochemical treatments at low as well as high pH values. Thermal acidic hydrolysis was performed with HCl or H_2SO_4, giving a hydrolysis yield of about 30-50%.

With respect to alkaline pretreatments, variable results have been found. An additional advantage of alkali instead of acid is that it is readily compatible with subsequent biological treatment.

Biological Methods

Biological hydrolysis can be considered as a partial anaerobic sludge digestion. In conventional anaerobic digestion processes, acidogens and acetogens first solubilize and hydrolyse sludge microbes prior to the actual conversion to methane by the methanogens. By controlling the hydraulic retention time and temperature, it is possible to confine the anaerobic digestion of sludge to the acidogenic and acetogenic phase and take advantage of the soluble organics produced [64].

Concerning the biological hydrolysis of activated sludge, Kitazume et al. [65] studied sludge solubilization by using acid-forming anaerobes. They isolated seven strains of high acid forming anaerobes which solubilized volatile solids in activated sludge more than 50%, besides converting most of the solubilized part to volatile fatty acids (VFA), principally to acetic acid. Inoculating these isolated anaerobes contributed to accelerating the initial digestion rate more than 20% and increasing methane production more than 10% in batch cultures running for 30 days.

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 solubilization by thermophilic enzyme (S-TE) process in which the excess sludge is brought to a continuous thermophilic aerobic sludge digester that from the start is fed by thermophilic aerobic bacteria that are isolated from the composted sludge (identified as *Bacillus stearothermophilus*) [66]. 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. 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%. The enzymatic lysis that cracks the compounds of the cell wall by an enzyme catalyzed reaction is of interest in combination with mechanical disintegration as well, because enzymes are also located in the intracellular liquid. They can cause a further disintegration of the cells after a mechanical disintegration by autolysis [67].

Biological hydrolysis is an easy and inexpensive method for the in-situ production of a readily degradable carbon source for nutrient removal. An additional advantage is that less sludge is produced, compared with a system with external carbon addition.

Assessment and Comparison of Sludge Reduction Techniques

The effects of sludge reduction techniques on treatment process

For minimizing sludge production by increasing sludge retention time, it may not necessarily be advantageous because of the potentially adverse effects of high MLSS [21,68].

For example, the sludge properties of MBR, i.e. small, weak and open sludge flocks, high viscosity and high sludge volume index (SVI), make sludge settling and dewatering more difficult. Problems commonly encountered under high SRT operation of MBR are poor oxygenation leading to increased aeration cost, and extensive membrane fouling which requires frequent membrane cleaning and replacement. It is therefore not feasible to operate MBR with complete sludge retention in practice, and there must exist a minimal rate at which excess sludge is wasted in order to keep an optimal range of sludge concentration in MBR. At present, the sludge concentrations in MBR typically vary from 15 to 23g/L [41].

Although MBR has successfully been applied in full-scale WWTPs, a cost analysis shows that the costs of sludge treatment and disposal will be the main factor of total plant operation costs instead of the costs of membrane module replacement [69]. In order to further decrease MBR capital and operating costs more research should focus on membrane materials, design of membrane module, the impact of membrane on microbial community, membrane fouling and its countermeasures.

The performance of some disintegration methods can be compared with each other using the specific energy, which is defined as the amount of mechanical energy that stresses a certain amount of sludge. Among the mechanical methods the stirred ball mills shows the lowest energy consumption, the ultrasonic homogenizer the highest [70]. High degrees of disintegration are obtained with all methods. Besides the energy consumption there are other factors like wear and tear or the suitability of the machine for the practical application on a wastewater treatment plant which are of great influence on the selection of the right method. Table 3 gives an assessment of the disintegration methods.

Depending on the method, different components are exposed to wear. For example, in stirred ball mills the grinding beads show wear and tear, at the high pressure homogenizers the homogenizing valve erodes and the seal of the high pressure pump shows an increased wear, the ultrasonic sonotrode shows erosion, the electrodes of the high performance pulse technique burn down and the metal shear plates of the centrifugal technique wear out. Using thermal or chemical treatment corrosion is the major problem, thus high grade materials are required. The costs for spare parts and maintenance seem to constitute a large part of the total running costs of the treatment. Research experience has been gained with stirred balls mills and ultrasonic disintegrators in a large number of investigations, some of them at full scale. Thermal and ozone treatment has been investigated in a number of research projects as well as in a few full scale applications.

When using thermal or chemical treatment, fouling problems occur especially in heat-exchangers. There are some other effects that have to be taken into account, like the possible generation of odor or the increased amount of flocculent needed for the dewatering. All effects of pre-treatment are summarized and assessed in Table 4.

By using mechanical disintegration cell-disruption occurs, which leads to a noticeable increase in gas-production and in the degree of degradation. When using a treatment with a low energy input only floc-destruction will happen with little influence on the digestion process. The increase in gas-production is significant, especially when short retention times in the digester are used. The gas production of pre-digested sludge can also be improved by disintegration. The thermal disintegration using a temperature range of 135 to 180°C seems to be optimal concerning the gas production. The processing time is of little influence [24].

Especially for thermal disintegration, generation of hardly degradable organic compounds and odor has to be considered. A temperature of more than 200°C causes a decrease in yield of gas [72]. Odor problems have often been reported at thermally treated sludge. This has been one of the major drawbacks for thermal pre-treatment so far. Chemical treatment of sludge also causes odor generation, while the mechanical treatment does not have any influence. It is possible to realize very good dewatering properties of the sludge by thermal treatment. But this is only achieved if the process temperature is above 160°C, which on the other hand will lead to an increased generation of hardly degradable compounds [8]. It has been reported that adding ozone prior to digestion leads to better dewatering results of the digested sludge [73].

With all processes an increase in energy input leads to a further reduction of pathogenic micro-organisms. The best results are obtained by thermal treatment while mechanical treatment reduces the concentration of pathogens only by 1 to 2 orders of magnitude [74].

Cost evaluation of sludge reduction techniques

The capital costs and the operational and maintenance (O&M) costs vary considerably among treatment processes. Mechanical disintegration is highly promising for enhancing digestion efficiency, owing to the method's relatively low capital costs and energy consumption and that it does not release harmful off-gases. Comparing the pretreatment methods concerning the efficiency of COD-release and energy consumption, ultrasound and thermal methods are using a higher amount of energy. Rough cost estimates are between 70 and 150 US$/ton TS for capital and O&M costs [31].

Mechanical disintegration has been investigated primarily on laboratory to pilot-scale. Problems encountered were the heating of the cell suspension because of the high shear-stresses the sludge cells are being subjected to [52]. Moreover, mechanical disintegration often appears to require high capital equipment and is energy intensive. In particular, sonication was found to be an energy intensive alternative (1792MJ/m^3 sludge treated).

On the other hand, thermal and thermochemical treatments require high temperatures and high pressures to achieve acceptable results. Not only is equipment needed to raise the temperature and the pressure, also expensive construction materials are required in order to prevent corrosion problems. Furthermore, odor problems can be encountered in thermal hydrolysis techniques [2].

Most authors mention that acidic or basic conditions should be applied in combination with elevated temperatures, thereby creating quite aggressive reaction conditions. Moreover, raising or lowering the pH requires the addition of chemicals which increase the ionic strength of the sludge. If the hydrolysate is used in biological applications, e.g. anaerobic digestion or nutrient removal, subsequent neutralisation is required, which again implies the addition of chemicals. In the Krepro-project, the cost of chemicals (alkali and sulphuric acid) represents 54% of the total running costs [75].

In addition, due to high costs caused from ozone production e.g. over 50% of the total operation costs it is important to decrease the amounts of ozone required for sludge reduction [76].

A combination of the activated sludge process with ozone treatment of excess sludge was suggested as a new approach for zero sludge production [76,77]. The combination of the treatments was selected based on the cost effectiveness and their synergistic effect. Alkaline treatment serves not only as a sludge solubilizing reagent reducing the ozonation cost, but also as a buffering reagent preventing pH drops by the ozone treatment and the nitrification in the MBR and could reduce the costly ozone dosage by 60% [5]. Alkali treatment is known to be relatively cheap and the savings in ozone dosage may result in the significant decrease of total treatment cost [19]. In overall, the combination of alkali and ozone treatments appears to be very effective in reducing the ozonation cost as well as controlling the pH in the bioreactor. A comparison between the conventional sludge treatment process and the recirculation of sludge via ozonation in the activated sludge one has shown that the operation costs (based on average costs in Japan) associated with the process were 13.7JPY/m^3 wastewater lower than those of conventional dewatering and disposal (28.9JPY/m^3 wastewater) [76]. An additional advantage might then be that a pathogen-free and odorless end-product is produced [78]. Until recently, the costs related to ozone-treatment of sludge might have been disproportional to those of low-cost sludge disposal routes but in view of the rapid abolishment of the latter, the ozonation of sludge may become a cost effective opportunity.

Conclusions

Cleaner Production (CP) can contribute to revising basic conceptions of the sludge reduction in biological wastewater treatment plants, highlighting the link between treatment process and pollution. With concepts of CP, the waste sludge must be significantly reduced in order to prevent pollution and to reduce end-of-pipe treatment costs (i.e. handling, disposal and/or landfill). By the approach of CP concepts, the most promising process techniques dealt with minimization of excess sludge production were discussed. This review shows that the chemical-combined activated sludge processes would be more efficient for excess sludge reduction. The chemical assisted sludge reduction processes have advantages of easy control, stable performance, and high operation flexibility. The relatively high operation cost of these systems currently limits their application in industrial practice. However, it is expected that the increased operation and capital costs due to chemical addition can be compensated from saving the cost of excess sludge post treatment. In this sense, the chemical-enhanced sludge reduction techniques would be attractive and have great industrial potentials. Important drawbacks that still have to be overcome include the reduction of addition of chemicals and the prevention of corrosion problems.

In addition, employing any technique for sludge reduction has an impact on microbial community that may influence the sludge settling and dewatering, and the effluent quality. Application of novel analytical and investigative methods such as modern molecular biological techniques can lead to new insights into the impact on microbial population. Further research is necessary to assess more detailed the economical feasibility and the environmental impacts of sludge reduction techniques.

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