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Activated Sludge Treatment Process to Increase Bio Gas Production-A Need of Present Energy Crisis Scenario

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ABSTRACT- In today's energy demanding life style, biogas as the typical renewable as well as eco-friendly new energy source will replace fossil fuel inevitably. So, to increase biogas production is a problem of major concern in terms of environment, finance and technology. The objective of this paper is to present efficient and effective methods of increasing biogas production in anaerobic digestion of waste activated sludge treatment process.

This paper presents a review of the main pre-treatment methods which keeps the potential to increase biogas production in anaerobic digestion process. The methods include thermal, oxidative, thermochemical, mechanical (ultrasonic, grinding, high pressure homogenization) as well as other methods such as enzymatic hydrolysis and so forth. Emphasis is mainly put on their impact on biogas production. All these methods can enhance biogas production to some extent, but the energy requires and the operation cost varies. The paper displays the interesting literatures which compares the effect on biogas production between pre-treated and raw sludge, and also put forward the advantages and disadvantages of each pre-treatment method. There is no conclusion about which method is the best. Further research has to be done for a better outcome.

KEYWORDS: waste activated sludge; anaerobic digestion; biogas production; pre-treatment; energy; wastewater treatment plants (WWTP).

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INTRODUCTION

Biogas, as a renewable energy, can be produced from a variety of organic raw materials and utilized for various energy services, such as heat, combined heat and power or as a vehicle fuel. Biogas can be produced by anaerobic digestion or fermentation of biodegradable materials such as biomass, manure, sewage, municipal waste, green waste, plants material and energy crops. Emphasis is laid on sludge from municipal wastewater treatment plants in this paper. As we know, large amounts of waste activated sludge, containing organic and mineral components, are produced by municipal and industrial wastewater treatment plants. Sludge handling represents a bottleneck in wastewater treatment plants, due to environmental, economic, social and legal factors. If handled properly, sludge can be a valuable resource for renewable energy production and a source of nutrients for agriculture.

The treatment required is dependent on the characteristics of the sludge. However, the general process comprises thickening, digesting, further stabilizing and sludge disposal. The process flowchart of sludge processing steps has been shown in Fig. 1. A first step is its thickening by gravity, flotation or belt filtration. In doing so, the amount of sludge can be reduced to as little as a third of its initial volume.

The separated water is recycled to the influent of the wastewater treatment plants (WWTP). Subsequently, the pre-treatment with varied methods including mechanical, biological and chemical pre-treatment is accomplished to enhance the dewaterability and digestibility of sludge. Followed is the crucial step: digestion. The most common treatment options include aerobic digestion, anaerobic digestion and composting. Among these biological treatments, anaerobic digestion is frequently the most cost-effective, due to the high energy recovery linked to the process and its limited environmental impact. In fact, more than 36,000 anaerobic digesters are in operation up to 1998. With AD playing an important role for its ability to further transform organic matter into biogas (60-70% vol of methane, CH₄), thereby the amount of final sludge solids for disposal is reduced, most of the pathogens are destroyed and possible odour problems associated with residual putrescible matter are limited.¹

Biogas is currently produced mostly by digestion of sewage treatment sludge, with minor contributions from fermentation of gasification of solid waste or of lignocellulosic material (process currently being further developed). The typical details of biogas are given in Table-1.

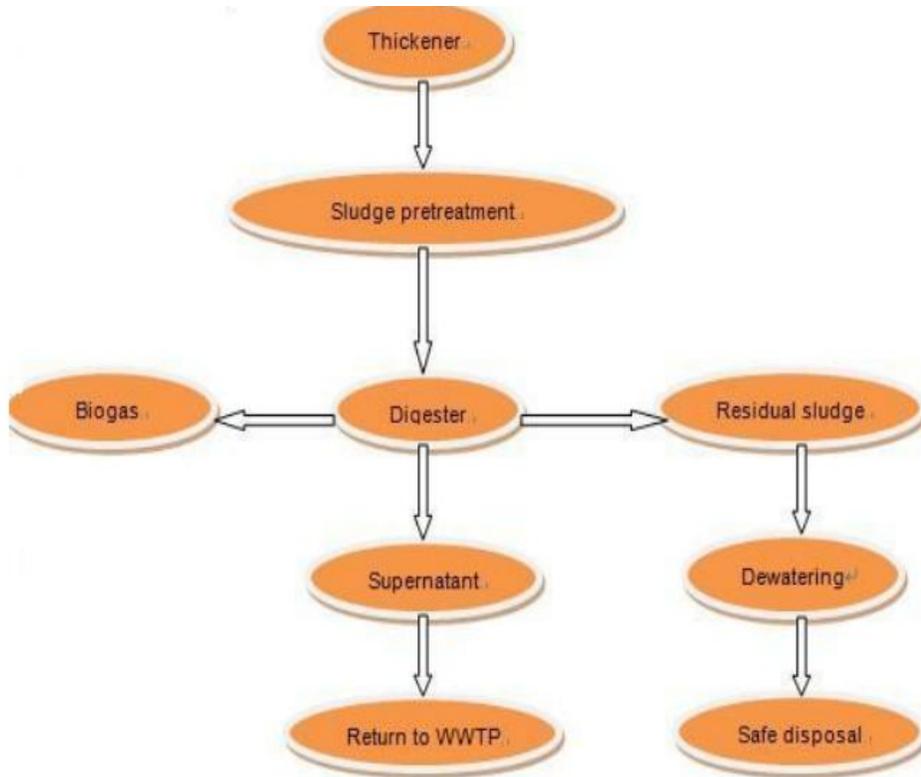


Fig. 1 Process flowchart of the sludge processing steps

Table 1. Typical details of biogas

Composition	55-70% methane, 30-45% carbon dioxide, traces of other gases
Energy content	6.0-6.5kWm ⁻³
Fuel equivalent	0.6-0.65L oil/m ³ biogas
Explosion limits	6-12% biogas in air
Ignition temperature	650-750 °C
Critical pressure	75-89 bar
Critical temperature	-82.5 °C
Normal density	1.2 kg/m ⁻³
Odour	Bad eggs (the smell of hydrogen sulphide)

BASIC CONCEPT

Anaerobic digestion

Anaerobic digestion (AD) is a series of process in which microorganisms break down biodegradable material in the absence of oxygen, used for industrial or domestic purposes to manage waste and/or to release energy. The main features of AD process are mass reduction, biogas production and improved dewatering properties of the treated sludge. There are four key biological and chemical steps of AD process: hydrolysis, acidogenesis, acetogenesis and methanogenesis as shown in Figure 2.

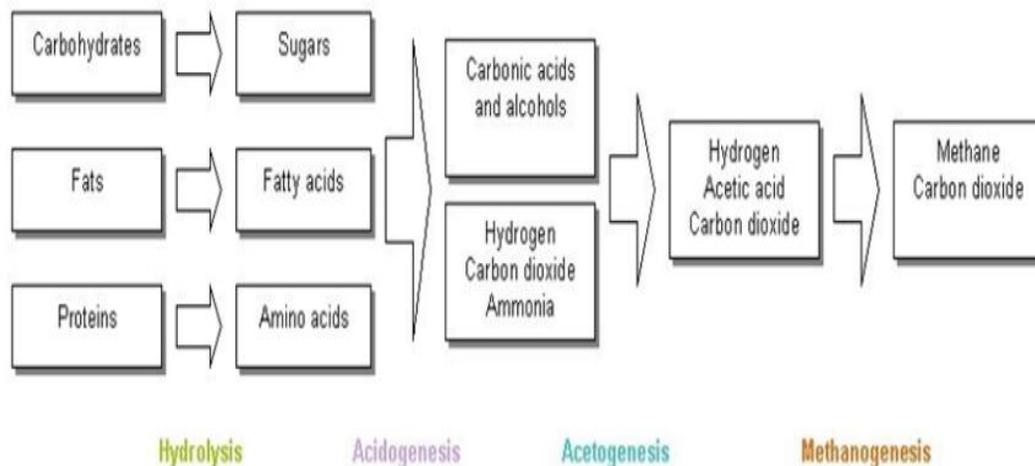


Fig. 2 The key stages process stages in anaerobic digestion.

1. *Hydrolysis-*

In most cases sludge contains lots of large organic polymers. In order to access the energy potential of the materials, the long chains must firstly be broken down to their smaller components such as sugar being readily available for other bacteria. This process is so called hydrolysis. The hydrolysis step degrades both insoluble organic material and high molecular weight compounds such as lipids, polysaccharides, proteins and nucleic acids, into soluble organic substances (e.g. amino acids and fatty acids).

2. *Acidogenesis-*

The components formed during hydrolysis are further split during acidogenesis, the second step. Volatile fatty acids are produced by acidogenic (or fermentative) bacteria along with ammonia, carbon dioxide, hydrogen sulphide and other by-products.²

3. *Acetogenesis-*

The third step is acetogenesis, where the carbonic acids and alcohols are further digested by acetogens to produce mainly acetic acids as well as hydrogen and carbon dioxide.

4. *Methanogenesis-*

Finally, methanogenesis produces methane by two groups of methanogenic bacteria: the first group splits acetate into methane and carbon dioxide and the second group uses hydrogen as electron donor and carbon dioxide as acceptor to produce methane.

SLUDGE FROM MUNICIPAL WASTEWATER TREATMENT PLANT

Sludge generated from municipal wastewater treatment plants are mainly primary sludge and activated sludge. The end-product after handling the two types of sludge through anaerobic or aerobic digestion is digested sludge.

Primary sludge

Primary sludge is also called raw sludge which comes from the bottom of the primary clarifier. Primary sludge is easily biodegradable since it consists of more easily digestible carbohydrates and fats, compared to activated sludge which consists of complex carbohydrates, proteins and long chain hydrocarbon. So biogas is more easily produced from primary sludge.

Activated sludge

Activated sludge is also called excess sludge or waste activated sludge which comes from the secondary treatment. It's a result of overproduction of microorganisms in the activated sludge process. The content of activated sludge was just mentioned above. Activated sludge is more difficult to digest than primary sludge.

Digested sludge

After anaerobic digestion of primary and activated sludge the residual product is digested sludge. The digested sludge is reduced in mass, less odorous, safer in the aspect of pathogens and more easily dewatered than the primary and activated sludge.

SLUDGE PRE-TREATMENT FOR INCREASED BIO-GAS PRODUCTION

Evidently, anaerobic digestion has a great future amongst the biological technologies of sludge treatment in view of biogas generation as well as reducing solids mass. However, the low overall biodegradation efficiency of the sludge solids and long retention times (20-30 days) result in only moderate efficiencies.

In anaerobic digestion, the biological hydrolysis is identified as the rate-limiting step. Most soluble organic materials which can be converted into biogas are produced during hydrolysis process. Consequently, the biogas production depends for the most part on the biodegradability and hydrolysis rate. Biogas production can thus be improved by several pre-treatment in order to lyse sludge cells further to facilitate hydrolysis. In this step, both solubilisation of particulate matter and biological decomposition of organic polymers to monomers or dimmers take place. That is, cell walls are ruptured and extracellular polymeric substances are degraded resulting in the release of readily available organic material for the acidogenic micro-organisms.

Thermal, chemical, biological and mechanical processes, as well as combinations of these, have been studied as possible pre-treatments cause the lysis of or disintegration of sludge cells permitting the release of intracellular matter that becomes more accessible to anaerobic microorganisms. This fact improves the overall digestion process velocity and the degree of sludge degradation, thus reducing anaerobic digester retention time and increasing methane production rates.³ The paper will provide a series of literature reviews concerning optimum conditions to obtain enhanced biogas production in varied pre-treatments of sludge hereafter.

Thermal pre-treatment

It is very well known for many years that a thermal pre-treatment can improve the degradability of sludge. While the carbohydrates and the lipids of the sludge are easily degradable, the proteins are protected from the enzymatic hydrolysis by the cell wall. Heat applied during thermal treatment destroyed the chemical bonds of the cell wall and membrane, thus makes the proteins accessible for biological degradation. Maximum biodegradability, in percentage, meaning the maximum percentage of substrate COD that is converted to methane, was calculated according to El-Mashad *et al.* So that biodegradability can serve as an indicator for measuring the biogas production.⁴

Thermal pre-treatment is studied using a wide range of temperatures ranging from 60 to 270° C. In practice, the optimum temperature is in range of 160-180°C and treatment times from 30 to 60min. Pressure associated to these temperatures may vary from 600 to 2500 kPa.⁵ Various experiments and research of thermal pre-treatment have been done to proclaim this conclusion.

Li and Noike showed that optimum temperature in terms of 33% volatile suspended solids degradation increased and 100% methane production was 170°C and contact time was 60min.⁶ No further improvement for longer contact times. This is in line with the findings which concluded that temperature and duration of the optimum pretreatment depends on the nature of the sludge: the greater the proportion of difficult hydrolyzing biological sludge substrates, higher the intensity of pretreatments needed.

Bougrier et al compared the thermal pretreatments (130° C, pH=10, 150 ° C and 170 ° C during 30min) performance of waste activated sludge collected from urban wastewater plants with untreated sludge samples. The results indicated that there was positive effect on solubilization rates and methanization when thermal pretreatment was added. Particularly, the 170°C treatment led to comparable results in anaerobic digestion performance increase: about 80% improvement in removal of matter and in biogas yield.⁷

Haug and co-workers worked on thermal treatment at lower temperatures in order to improve dewaterability as well as digestibility and at the same time avoid the problems that occurred with higher temperature thermal pretreatment. They showed that the largest effect on digestibility was for activated sludge was at 175°C. This temperature was about the limit for digestibility before digestion was inhibited (presumably because of the formation of inhibitory and/or refractory compounds).⁸

At 175 ° C, digestion of the thermally pre-treated sludge resulted in an increase of 60-70% in methane production over not pre-treated sludge. Higher temperatures led to decreased gas production.

In general, thermal pre-treatment of waste activated sludge can considerably increase methane production for mesophilic anaerobic digestion and to a lesser extent for thermophilic anaerobic digestion, for that thermophilic digestion is already more efficient at volatile suspended solids reduction and methane production as compared with mesophilic digestion, hence reduces benefits of pre-treatment.

However, some researches on combination of low temperature (<100 ° C) pre-treatment prior thermophilic digestion also have been done and the effects are notable. Climent *et al.* investigated the thermal pre-treatment at low temperatures between 70 ° C to 134 ° C prior to thermophilic digestion and revealed an increase of 50% in biogas production at 70 °C with 9h. No effect for high-temperature treatment.⁹

There was a effect of a low temperature pretreatment (70 ° C) on the efficiency of the thermophilic anaerobic digestion of primary and secondary waste sludge. The 70 ° C pre-treatment showed an initial solubilisation effect (increasing volatile dissolved solids by almost 10 times after 9h), followed by a progressive generation of volatile fatty acids. Biogas production increased up to 30% than that of raw sludge.

Evidently, the thermal pre-treatment requires the input of a considerably amount of heat, since the sludge feedstock needs to be preheated to the operating temperature (~700kJ/m³) at the expense of using some of the biogas produced. Moreover, the biogas production is not in proportion to the temperature.

Most researches have shown that excessively high temperatures (higher than 170-190° C) lead to decreased sludge biodegradability in spite of achieving high solubilisation efficiencies. Indeed, in some cases, there is formation of toxic, refractory compounds during pre-treatment which is a major drawback.¹⁰

Chemical pre-treatment

Chemical pre-treatment is also an efficient and cost-effective method to hydrolyze the cell wall and membrane and thus increase solubility of the organic matter contained within the cells. According to different principles, chemical methods can be divided to acid and alkaline (thermal) hydrolysis, oxidation. The most frequent studies oxidative methods are ozonation and peroxidation. Acid and alkaline hydrolysis will be introduced in the thermo-chemical pre-treatment part.

1. Ozonation

Ozone is a strong cell-lytic agent, which can kill the microorganisms in activated sludge and further oxidize the organic substances released from the cells.^{11,12} Among the techniques to disintegrate sludge, ozonation of sludge is one of the effective ways and yields the highest degree of disintegration.³ Following ozonation, the characteristics of the sludge are greatly changes. The flocs are broken down into fine, dispersed particles. Floc integration

and solubilization generates a large number of micro-particles dispersed in the supernatant in addition to soluble organic substances¹³.

The sludge biodegradation is affected by ozone dose. Several researchers have investigated the impact of ozone dose on sludge biodegradation. Ozonation treatment has two counteracting effects: degradation of molecules and cell structures that are undegradable for methanogenic bacteria will increase biogas production; oxidation of organic molecules that are degradable for methanogenic bacteria will decrease biogas production.¹⁴ Saktaywin *et al.* found that around 60% of soluble COD generated due to ozonation was biodegradable at the early stage of ozonation, while the remaining soluble organic matter was refractory.¹² Yeom *et al.* showed that when the ozone dose was 0.1 g O₃/g TSS, the biodegradation was about 2-3 times greater compared with raw sludge in both aerobic and anaerobic conditions for 5 days.¹⁵

According to Weemaes *et al.* the biogas production increased with 80% at ozone treatment with 0.1 g O₃/g COD, the effect was not pronounced at higher ozone concentration.¹⁶

Due to its well-known potential and performance, sludge ozonation is used in combination with activated sludge process in wastewater treatment plant. A review of studies concerning the combination of ozonation with activated sludge process has been recently proposed by Chu *et al.*¹⁷ The schematic process is as shown in Fig. 3. Ozonation can be introduced to the returned activated sludge line (Route I) or to the sludge digestion line (Route II). For Route I, the ozonation aims to reduce excess sludge production by promoting cryptic growth.

As a result, the amount of sludge that can serve as substrate for biogas production is decreased dramatically. However, this combination is beyond the scope of the present paper, the reader who is interested in the principle is referred to the literature of Chu *et al.*¹⁷ For Route II, ozonation adopted as pre-treatment before anaerobic/aerobic digestion is used to enhance the solubility of sludge solids and increase the degree of degradation. Both the final amount of sludge for disposal and the digestion time can thus be reduced. Particularly, for anaerobic digestion, the biogas production can be increased.

This process has been commercialized by the Japanese Kurita company and about 30 installations have been implemented¹⁸.

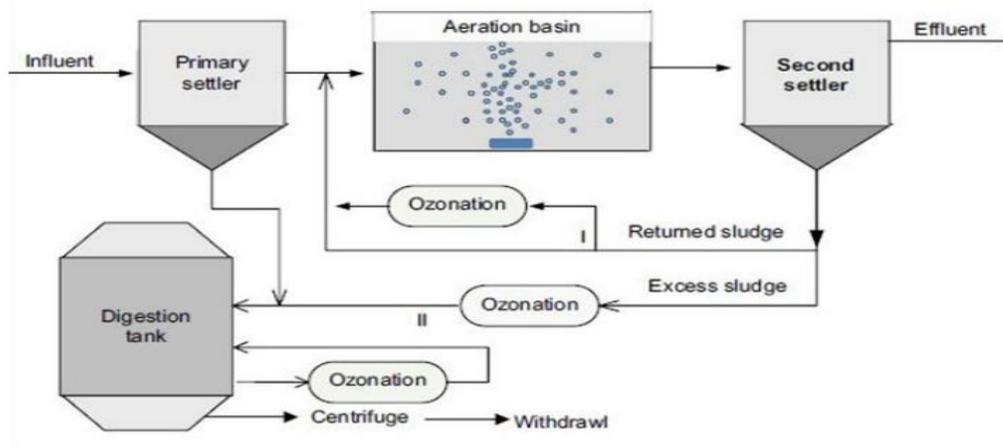


Fig. 3 Application of ozonation for sludge reduction.

2. Peroxidation

Several peroxidation techniques, including the well-known Fenton peroxidation and nobel reactions involving peroxymonosulphate (POMS) and dimethyldioxirane (DMDO), can also achieve a transformation of refractory COD into readily available and soluble BOD, further enhance the biogas production. Fenton pre-treatment disintegrates extracellular polymeric substances and breaks cell walls, thus intracellular water is released. Hence the amount of soluble COD and BOD in the sludge water increases considerably. The oxidation process utilizes activation of H_2O_2 by iron salts (Fe^{2+}). A major drawback of this method is the necessity of bringing the sludge to a very low pH.

More recent research uses alternative peroxidants such as POMS and DMDO which do not require stringent reaction conditions and significantly increases the biogas production during the anaerobic treatment of raw secondary sludge. Dewil *et al.* studied biogas production when treating sludge with Fenton peroxidation, POMS and DMDO techniques prior to anaerobic digestion on lab-scale. The results showed a maximum increase of 75% was measured with Fenton, while the POMS treatment increased the biogas production by a factor of nearly 2, against an even higher 2.5 for the DMDO treatment.¹⁹

3. Other oxidant

Recently, a new oxidant peracetic acid (PAA) has been proposed to enhance anaerobic digestion biogas production. PAA has a strong effect of oxidation on microorganism. It's reported that PAA is able to destroy the barrier of spores, to dissolve the core, and to make the material such as DNA protein leaking. It can be inferred that PAA can

dissolve and oxidize cells to promote the release of organic matter, thereby reduce the sludge volume and improve the efficiency of subsequent anaerobic digestion.²⁰

According to their experiments, the excess sludge was pre-treated by PAA, and then anaerobic digestion was conducted for 20 days in 35 ° C to detect the biogas production compared with the sludge without pre-treatment. The results showed that the total biogas production was enhanced 72% than that of the raw sludge. They also observed that at the PAA concentration of 0.011%, there was almost no PAA or H₂O₂ left in excess sludge solution after 12 hour's reaction. Hence it avoids the harmfulness causes by the sterilization of PAA to the anaerobic microorganism.

Wet oxidation method has also been applied in sludge treatment. This process uses oxygen or air at high temperature (260° C) and pressure (10MPa) (Zimpro Environmental, 1993). The method can solubilize a large part of the sludge but the problems with odour, corrosion and high energy cost restrict its practical applications.

Thermochemical pre-treatment

Alkali treatment is normally combined with thermal treatment; it's so called thermo chemical treatment. There is no consensus on the efficiency of alkali agents. J. Kim *et al.* showed that the order of efficacy in sludge solubilization was NaOH>KOH>Mg(OH)₂ and Ca(OH)₂, whereas Penaud *et al.* demonstrated that pre-treatment with KOH was more efficient than using NaOH.^{21,22}

With regard to the effect of thermo chemical pre-treatment (addition of alkali) on solubilisation and biodegradability, different studies give contradictory results. Indeed, Haug *et al.* determined a decrease in biodegradability of 60%, while Penaud *et al.* observed no effect on the biodegradability.^{8,22} Tanaka *et al.* showed that thermo chemical pre-treatment led to significant increase in biodegradability, which could reach 230%. It's noted that thermo chemical pre-treatment gives the best results in the biogas production compared with thermal, chemical, ultrasonic methods under the same conditions.²³ Kim *et al.* compared the four pre-treatment methods, they selected optimum conditions for thermal (121 ° C for 30 min), chemical (7 g/l NaOH addition), ultrasonic (42 kHz for 120 min) and thermo chemical (121° C for 30 min, 7 g/l NaOH addition) pre-treatment's, in the end, they got the biogas production following the anaerobic digestion of the thermally (4842 l/m³WAS), chemically (4147 l/m³WAS), ultrasonically (4413 l/m³WAS) and thermo chemically (5037 l/m³WAS) respectively²¹.

Valo *et al.* tested the COD removal rates and biogas production under two conditions (thermal treatment at 170° C and thermo-chemical at 130 ° C with PH = 10 for 30 min, continuous anaerobic digestion). They found that the COD removal rates were significantly increased compared with the untreated raw WAS, being 71% and 60% of raw WAS COD, for thermal and thermo chemical treatment respectively, while the biogas productions were increased by 54% and 74%.²⁴

Mechanical pre-treatment

Mechanical pre-treatment plays an important role because it favors solubilisation of particulate matters in liquid phase. In general, the most often used techniques in mechanical pre-treatment are ultrasonication, grinding and high pressure homogenization. By these methods, the aim is to increase the degradability of organic matters by disrupting the flocs and/or lysing the bacterial cells. The principles and applications of the methods above will be introduced hereafter.

1. Ultrasonic pre – treatment

Ultrasonication is a promising and effective mechanical pre-treatment method to enhance the biodegradability of the sludge. This technology has several inherent merits like efficient sludge disintegration (>95%), improvement in biodegradability, improved bio solids quality, increase in methane percentage in biogas, no chemical addition, less retention time, sludge reduction and energy recovery (1kW) of ultrasound energy generates 7 kW of electrical energy including losses²⁵.

Ultrasonication enhances the sludge digestibility by disrupting the physical, chemical and biological properties of the sludge. As mentioned above, hydrolysis is the rate-limiting step in anaerobic digestion process. Ultrasonic lysis accelerates the hydrolysis reactions by disrupting cells. The bacterial cells are disunited by pressure waves and cavitation generated from an ultrasonic generator leading to elution of intracellular organic substances. In addition, some soluble particulate organic matter may even be transformed into a soluble state under the cavitation explosion of transient bubbles. The disruption of sludge particles derived from sonication treatment would enhance subsequent acidogenesis, acetogenesis and methanogenesis reactions, which would in lead to an improvement in methane generation and reduction of sludge volume²⁶.

There are two key mechanisms associated with ultrasonic treatment: cavitation, which is favored at low frequencies, and chemical reactions due to the formation of OH^\cdot , HO_2^\cdot , H^\cdot radicals at high frequencies²⁷. High-power ultrasound (200W) is generally performed at low frequencies (20 kHz) in order to get an effective sludge disruption. The mechanical phenomena of sludge sonication leads to sludge floc disintegration and microorganisms' lyses, according to the treatment time and power, equating to specific energy applied¹⁷. The effect of sonication time on the sludge disintegration and the subsequent anaerobic digestion (batch test) was evaluated by Wang *et al.* They tested the methane amount under different sonication time groups when other parameters were the same (9 kHz, 200 W, and 20-25 ° C)²⁸.

The results showed that, compared with the control, the methane amount increased by 12%, 31%, 64% and 69% on the 11th day, with corresponding ultrasonic pre-treatment of 10 min, 20 min, 30 min and 40 min, respectively. The optimum pre-treatment for enhancing the methane generation should be approximately 30 min. Although cell disintegrations of 100% can be obtained at high power levels, power consumption then becomes a serious drawback.⁵

Rana Kidak *et al.* showed that the efficiency of the sludge disintegration was higher with higher power, but if considered the particle size, there was no further decrease of the particles when the ultrasonic power was beyond 100 W. They also summarized the conclusion that high power-short retention time was more effective than low power-long retention time for municipal sludge.²⁹

2. Grinding

One predominant technique is the wet milling, which is more of a grinding method. Wet milling uses small beads to rupture cell walls, the size of the beads used are thus critical for maximal sludge disintegration³⁰. Of several milling devices, the ball mill using small diameter (0.2-0.25 mm) balls has the best performance.³¹ The use on an agitator ball mill was studied by Kunz *et al.*³² Sludge was pressed through a cylindrical or conical space by an agitator including shear-stresses high enough to break the bacterial cell walls.

3. High pressure homogenizer

One of the most frequently used methods for large-scale operation is high pressure homogenization, compressing the sludge to 60 MPa³³. The compressed suspension is then depressurized through a valve and projected at high speed against an impaction ring. The

cells are hereby subjected to turbulence, cavitation and shear stresses, resulting in cell disintegration². Lacking of available literatures on mechanical pre-treatment, the methods mentioned above are not comprehensive. However, it's seen that their efficiency of improving anaerobic digestion of waste activated sludge is rather lower than other methods.

Other pre-treatment methods

The use of microbial enzymes for the enhancement of degradation of waste activated sludge called the Enzymatic Hydrolysis (EH) process was proposed by Mayhew *et al*³⁴. EH process was first used to kill pathogens, however, an enhancement of biogas production was observed during anaerobic digestion. Microwave pre-treatment is another method which has already been proven to enhance anaerobic digestion.

The anoxic gas flotation (AGF) process as an innovative anaerobic digestion process also has the potential to enhance biogas production. This process uses anoxic gas 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 sludge to gas and soluble constituents. By virtue of greater solids destruction and gas scrubbing of AGF process, methane production can be enhanced and also the biogas quality can be improved.

COMPARISON OF PRE-TREATMENT METHODS

Although these pre-treatment methods contribute to accelerating anaerobic digestion and enhancement of biogas production, they have their own drawbacks. Thermal pre-treatment requires of a considerable amount of heat to preheat the sludge feedstock, so it's unavoidable to consume some of biogas produced. Ultrasonication is no doubt the most powerful method to disrupt cell walls, but power consumption becomes a serious drawback⁵. Other mechanical methods such as grinding and high pressure homogenization are less effective than other methods. Even ball milling are not always impactful. Baier *et al.* found several industrial sludges failed to be affected by this technique³⁰.

Although they do not require chemicals or heat, most of mechanical techniques consume a lot of power. Regarding oxidative methods, both the cost and energy consumption of ozone production are high. While peroxidation method is likely to bringing the sludge to a very low pH (optimum at 3), which inhibits methanogenic bacteria's activity. Thus the cost of chemical reagent to adjust the pH has to be taken into account.

In addition, according to the study of Weemaes *et al.*, the most important sludge pre-treatment methods are summarized together with their costs, advantages and drawbacks (Table-2).⁵

Due to the characteristics of sludge (primary, waste activated, digested, sludge age...) and the anaerobic conditions (batch, continuous, HRT, temperature...), it's difficult to compare the effect of pre-treatment methods described above. However, the present paper focuses on waste activated sludge from municipal wastewater treatment plants and biogas production.

Kim *et al* selected optimum conditions for thermal, chemical, ultrasonic and thermo chemical pretreatments, in the end, they got the order according to biogas production: ²¹

Thermo chemically > Thermally > Ultrasonically > Chemically

Barjenbruch *et al.* compared thermal treatment (80–121° C), high pressure homogenization (600 bar) and enzymatic treatment (carbohydrase addition) for pre-treatment prior to continuous anaerobic digestion with 10 days HRT. An increase of biogas production was observed in the following order: low intensity thermal treatment at 90 and 121 ° C (>20% increase) > high pressure and thermal treatment at 80°C(>16–17% increase) > enzymatic treatment (>13% increase)³⁵.

Actually, it is not comprehensive to compare these methods only in term of biogas production. Also in practice, the solubilization of sludge, dewaterability, total suspended solids and energy cost as well as chemical consumption have to be into account. In view of limited literature, the emphasis has just been laid on the biogas production of the pre-treatment methods.

Table 2- Comparison of Estimated costs, merits and demerits of different methods

Method	% cell disintegration	Estimated cost (EURO per tonne TDS)	Major merit	Major demerit
Thermal (Cambi)	30	190	--	Relatively low yield, dependence on sludge type
Oxidation (German-Bayer RLoprox)	90	800	High disintegration efficiency	Low pH, corrosive, high cost

Thermochemical	15-60	Not available	Relatively simple	Corrosion, odour, subsequent neutralization
Ball mill	90	414-2500	High efficiency, Relatively simple	Energy intensive
High pressure homogenization	85	42-146	High efficiency, Low energy levels	Complicated
Ultrasound	100	8330	Complete disintegration	Energy intensive

CONCLUSION

There are currently considerable concerns in developing efficient and environmental friendly ways to convert waste activated sludge to biogas, as clean, renewable fuel for multiple utilizations. It is well known that the hydrolysis is the bottleneck in anaerobic digestion. The predominant techniques used to overcome the problem are reviewed in this paper.

As shown in Table -2, it is hard to say which method is the best because each has its own strong point and weak point. Yet, until now, none of the pre-treatment technologies has found a real breakthrough. Mechanical pre-treatment methods often appear to require high capital equipment and are energy intensive. Thermal and thermo chemical methods usually require high temperatures to achieve acceptable results. Oxidative methods cost high and have the problem of low pH. However, until recently, it appears that taking into account the increased costs of sludge disposal, the operational cost and the investment needed for sludge ozonation may be offset by the decreased operational costs for sludge treatment and disposal.

Hence, sludge ozonation may become a cost-effective opportunity. In order to obtain the biogas production as high as possible, as well as to reduce the excess sludge disposal, considerable efforts are needed in further research in the future.

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