Book Chapter

Aspects on Anaerobic Digestion of Municipal Sludge, Some Aspects on its Sustainability and Possible Enhancements

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Abstract

The anaerobic treatment of organic rich pollutants has a very long history within the water industry. Two major applications have been used: Treating sludge streams from midsized and large wastewater treatment plants and for industrial wastewater streams containing high concentrations of organic carbon. This paper presents the status of anaerobic digestion of sludge streams in municipal wastewater. The paper highlights both the potentials and limitations of the technology. In particular, three different critical aspects are discussed. The actual efficiency of the treatment from an energy viewpoint, the possibilities and constraints of reuse of the sludge, and the development of sustainable techniques to recover carbon and phosphorus from the digested sludge. Accordingly, recent studies on the hydro thermal carbonization (HTC) process with respect to its possibilities to enhance phosphorus recovery from the treated sludge are discussed. Finally, presentation is included of developments of how to handle the reject water from the HTC-process.

Keywords

Sludge Digestion, Solids Retention Time, Primary Sludge, Waste Activated Sludge, SRT, Biogas Gas Production, HTC, Carbon, Phosphorus Recovery

Introduction

The anaerobic digestion of municipal sludge is by convention based on natural processes found in nature. Wastewater management has been developed to a very high extent based on the conviction that a sustainable path for wastewater and sludge treatment is to mimic the processes found around us. What we try to do is to accelerate the processes by different ways to optimize the driving forces. The anaerobic digestion is in this respect a typical example. As a matter of fact, the concept of anaerobic decomposition was established in science dealing with water treatment more than 100 years ago. Early examples of anaerobic digestion are found especially within European countries, either as decentralized small "septic tanks", anaerobic ponds or as separate sludge reactors at larger plants. Early typical large anaerobic digesters were built during the 1930s for instance in Stockholm, the capital of Stockholm. The updated and modernized plants are to a large extent still based on the early technological concept.

The initial reasons for the use of sludge treatment with anaerobic digestion may be summarized as follows:

- To combat and control odors from raw sludge;
- To limit the sludge production;
- To establish an accepted sludge stabilization;
- To use the digested sludge as a fertilizer in farmland areas.

Today many anaerobic digesters are found all around the world serving many cities and towns. In **Figure 1** a photo of a large facility serving the city of Eskisehir in Turkey is shown. The facility was put into operation in year 2011.

Figure 1: Anaerobic digesters at the WWTP of Eskisehir, sized for more than 660 000-person equivalents.

Method

The anaerobic digestion may be performed principally at three temperature levels:

- Thermophilic digestion at a temperature of 50 – 57 °C;
- Mesophilic digestion at a temperature of 37 °C;
- Psycrophilic digestion at low temperatures < 15 °C.

The dominant model so far has been the mesophilic model worldwide. However, a development towards the thermophilic model has taken place during the last 30 to 40 years, especially at larger plants.
The fundamental biological process that occurs in the anaerobic process may – very simplified – be characterized by the following phases:

- A hydrolysis and acidification stage, when organic compounds are released by a transformation into organic acids, such as proprion and acetate. This reaction stage performs under acidic conditions, and may inhibit the following process stage, unless the process will adjust to a higher pH level. During start-up of an anaerobic digestor, it is normally imperative to add alkaline compounds to the sludge.

- A gasification phase when the acids are converted into gases such as CO_2 and CH_4. Once the gasification stage is established the pH-adjustment of the process will continue without any further external alkaline addition.

The anaerobic processes that occur are indeed complex and will also cause other reactions. The content of sulphates in the transportation water will be reduced to H_2S. This conversion may promote a precipitation metal of sulphides. The anaerobic process will also hydrolyze organic nitrogen bound in the sludge into ammonia nitrogen.

The interest for the anaerobic digestion has grown in the latest decades, thanks to its energy potential. The methane gas is seen as a valuable energy form to be recovered. The traditional way has been to use this energy for internal needs, within the wastewater treatment facility itself. By converting the gas into heat and electricity the operation of some of the wastewater treatment plants could be operated with a minor external supply of energy. Such an example was the modernization of a medium sized Swedish WWTP (capacity 40 000 person equivalent), serving the town of Sandviken, see [1]. By adopting an advanced chemical precipitation model and a final filtration step for the wastewater treatment, the amounts of sludge containing organics increased at the plant. The conversion of the sludge stabilization process was done by going from quick lime addition into mesophilic digestion. This resulted in a production of methane gas that was sufficient to provide a self-supply of energy for the plant, covering both the needed electrical supply for process units and the major part of the heating demands.

Anaerobic Digestion, A Model for Energy Recovery

The overall carbon balance over a mesophilic digestion is illustrated in ***Figure 2***

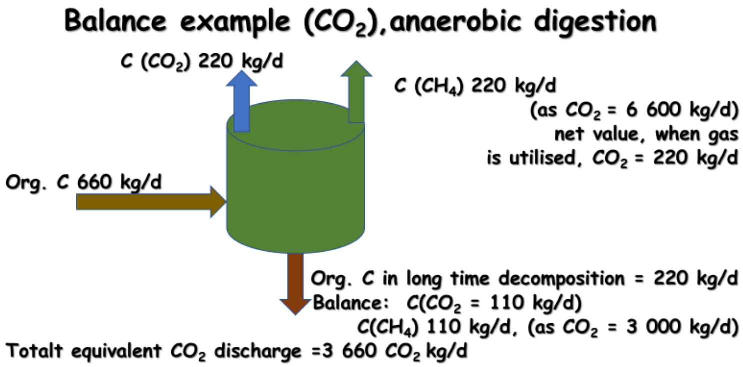

Figure 2: Typical carbon balance over a mesophilic digestion, with conversion figures on carbon dioxide and methane gas inserted.

As seen from the figure, around one third of the inlet organic carbon is converted into methane gas within the anaerobic process itself, and thereby possible to utilize for energy production. The remaining two thirds of the inlet carbon will end up in direct carbon dioxide or in the digested sludge. However, in a longer perspective this deposit of sludge will result in a conversion of organic carbon into carbon dioxide and methane gas, thus a further addition to the atmospheric CO_2 load.

The specific methane gas production from one kg of organic matter is around 1 normal cubic meter (Nm^3). In turn the gas energy content is around 5 – 6 kW/Nm^3. Finally, the conversion in turn into electricity will be between 35 and up to 40 % of the energy content in the gas. The heat from the gas engine is normally used for heating the raw sludge by means of heat exchangers. The surplus heat maybe used for heating the technical buildings and control facilities.

However, with the new focus on the “fossil combat”, the interest for biogas has got a new perspective. The further refining of the biogas to be used for buses and cars has become a very popular alternative for the use of gas. This model is promoted as an example of a “circular resource use”.

The main critical issue in relation to the residual product, the separated sludge, will be discussed in the following chapter, along with some other issues.

Results

As already presented the anaerobic digestion applied for municipal sludge processing has been established early in the modern wastewater business. In this perspective it is not at all surprising that the technology has undergone developments as well as being questioned. In this chapter, some crucial points are highlighted regarding the technology. First, a presentation of methane gas production versus extended aeration of biological excess sludge is discussed.

The development of advanced biological nitrogen removal has put focus on the available organic carbon in municipal wastewater. As the nitrogen removal process needs organic carbon for the denitrification stage, this in turn means a “competition” between two process stages in a modern wastewater treatment plant. On one side the carbon needs for denitrification, and on the other side the conversion of organic carbon found in the wasted activated sludge into methane gas in the anaerobic digestion process. This new situation was the starting point for a study conducted by the Lund Technical University in co-operation with Sweco Environment, see [2]. The critical question put was the following: To what extent does the nitrogen removal stage affect the methane gas potential found in the waste activated sludge? Sludge from one of the major Swedish treatment plants, the Sjölunda WWTP, serving the city of Malmö in the southern part of Sweden was used for testing. By simulating different aerobic solids retention times (SRT) for the excess sludge, a very clear relation was found. ***Figure 3*** presents the results. The figure clearly illustrates the difference between a waste activated sludge with a SRT of 2 days, and sludges representing typical extended aeration models, with a span of aerated SRTs from 10 days to 20 days. The used anaerobic digestion time was 10 days for all sludge samples. For the short time SRT (2 days) case, a potential methane gas formation is found at 300 Nml/g VSS. This result is compared with the results for different samples with extended aeration times that ended up in a potential of <100 Nml/g VSS. Further evidence of the change of the waste activated sludge organic content is presented in ***Table 1***. The ratio VS/TS decreased from a level of 0.72 to around 0.64:1, as the aerated time is increased from 2 days to 20 days. It would be observed that the major impact is reached even at an extended aeration time of 10 days.

Table 1: TS and VS content of activated sludge from Sjölunda WWTP after thickening.

Activated sludge	TS (%)	VS (%)	VS/TS
Activated sludge (3)	1.07	0.77	0.72
10d-SRT extra aerated sludge	0.71	0.45	0.64
12d-SRT extra aerated sludge	0.80	0.51	0.64
16d-SRT extra aerated sludge	1.1	0.71	0.64
20d-SRT extra aerated sludge	0.90	0.57	0.62

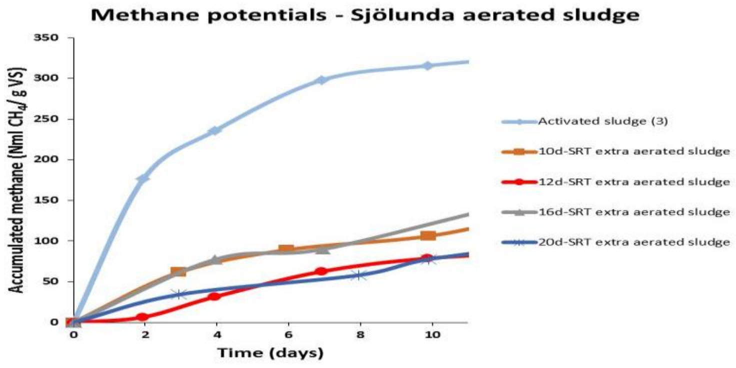

Figure 3: Relation between digestion time and accumulated methane gas production related to different extra aerated Solids Retention Times (SRT) in the activated sludge reactor.

Based on these results some critical questions were raised:

The negative internal process consequences are sometimes underestimated in municipal sludge management in relation to waste activated sludge and the anaerobic digestion process.

The amounts of easily available organic carbon for gas production are limited in biologically wasted sludge with extended aeration time. This in turn results in that the potential in waste activated sludge with an extended SRT as an energy source may be questioned.

Another side-effect often overlooked is the anaerobic hydrolysis of organically bound nitrogen and phosphorus in the sludge. As an internal (additional) pollution load on a wastewater treatment plant, this matter may be found important. Experiences from large plants indicates especially an internal nitrogen load – mainly as ammonia nitrogen (NH_4-N) – which may be as high as 20 to 25 % of the total nitrogen load on the biological stage.

Further observed process complications with respect to an anaerobic digestion of both primary sludge and waste activated sludge rich in nutrient include struvite formation (in this perspective an unwanted). This in turn has caused operation problems of downstream dewatering process, as the struvite crystallization may clog reject pipes within the plant.

Results and Evaluation on a Pre-Study on HTC-Process Performance

Controlled laboratory tests were performed on dewatered municipal sludge from three different plants within the Gästrike Water Company, Sweden, operation field. The tests aimed to investigate the performance on the HTC-process with respect to the material balance over the process. The three plants are named Hedesunda WWTP, with an operating load of around 1 500 pe, Hofors WWTP, with an operating load of around 9 000 pe, and Norrsundet WWTP, with an operating load of around 2 000 pe. A further study objective was to define the process water composition downstream the HTC-process. Based on the adopted wording this water stream is labelled “reject water” in this study.

Basically, earlier findings of HTC-process have by large been verified. Summarizing the results are as follows:

- The carbon balance shows that between 70 and 81 % of the feed amounts of C are found in the “Hydrochar” phase (the solid phase);
- Virtually all phosphorus in the sludge feed are found in the Hydrochar part; (Hedesunda: 87%; Hofors: 95% and Norrsundet: 97%);
- The capture of heavy metals in the Hydrochar has been high, with low discharge parts in the eject water;
- Nitrogen in the raw sludge is mainly found as organic nitrogen and has to a large extent been hydrolyzed into ammonia nitrogen, and found in the reject water;
- The reject water has high concentrations of BOD, COD and TOC. One possibility may be to recirculate the reject water to an anaerobic digestion, whereby increasing the gas yield by 15 to 30 %, related to the local conditions.

The further investigation of the reject water management has included the needed demands for an environmentally safe handling and treatment. A preliminary outline has been performed by addressing a forthcoming situation with different possible treatment capacities for the HTC-facility. ***Table 2*** includes the balance data for a reject water treatment facility. It is important to understand that the potential capacity of the HTC-facility is expressed as the equivalent process capacity for the reception of dewatered sludge converted into "PE" or person equivalents. On the other hand, the reject water "impact" is presented as daily discharge figures, also expressed as PE.

Load level, m^3/year		**5 000**	**10 000**	**20 000**
Equivalent capacity in PE	PE	**100 000**	**200 000**	**400 000**
Daily reject water flow		3,3	6,7	13,3
Pollutants		**kg/d**	**kg/d**	**kg/d**
P [mg/l]	10	0.03	0.07	0.13
N-tot [mg/l]	5 500	18.2	37	73.2
TOC [mg/l]	12 500	41.3	83.8	166.3
BOD_7 [mg/l]	20 000	66	134	266
COD_{Cr} [mg/l]	55 000	182	369	732
Equivalent load in PE (based on N-tot	PE	1 300	2 640	5 230

The study found that some further interesting options may be obtained, by combining the HTC-process with a reject water treatment:

- Acceptable discharge levels for the treated reject water may be arranged;
- Recycling of treated reject water as a dilution capacity for the HTC-process;
- Further capture of energy by heat exchange of the treated reject water;
- Further energy production from the biogas from the anaerobic digestion.

Discussion

The endlessly sharpening of sludge quality demands may be a result of both more complex polluting agents found in the sludge and the needs for reusing the wanted properties in the sludge. For a long time, use of different sludge streams aimed especially for the use of humus (organic carbon) and nutrients, mainly phosphorus and nitrogen. The first well known sludge quality problem in this respect was the heavy metal content found in sludge, especially Cd (Cadmium), Hg (Mercury), Pb (Lead) Cr (Chromium) and Cu (Copper). This matter has been mitigated to a significant extend in some countries mainly by a systematic “up-stream” work, combined with more stringent law restrictions and strict quality control of added precipitant agents.

In many countries strict regulatory conditions on sludge stabilization and hygienization have been implemented. This has often resulted in a separate hygienization reactor treating the sludge in a batch mode for 2 to 4 hours at an elevated temperature > 70 – 80 ^{o}C.

In 2017 the German Environmental Agency [3] presented a study providing far more critical conditions for digested sludge. The crucial concern, especially in the industrial countries, is now revolving around pharmaceutical remains in the sludge stream. The more specific point is the risk that these remains in turn will promote multi-resistant bacteria in fertile soil. The study points out the only possible final treatment for the sludge is a mono incineration.

As a summary would these new demands necessarily mean the end of anaerobic digestion?

Taking into consideration that the technical lifetime for an anaerobic digestion installation is 15 to 25 years, this question may be raised. Many examples may be presented from the market. However, at the end of the lifetime the normal solution is to renovate or upgrade the installations. Then the question arises: Will an anaerobic digestion after an upgrade be possible to combine with further, refined technologies? Some initial promising pathways are presented in the following.

Demands on reuse of carbon and phosphorus in municipal sludge has become a subject of increasing importance the last few years. The rapidly changing industrialized world will create additional demands and thereby also a possible prolongation of the anaerobic digestion process. As pointed out, the demands for carbon and phosphorus as renewable matters are important today.

The need to extract more carbon as methane gas may become an attractive model. The demands for phosphorus recovery is becoming even more urgent. The high-quality superphosphate sources are soon exhausted. The dominance of super phosphate with higher contents of polluting heavy metals, i.e. Cd and similar compounds may become the main available source, thus in turn calling for either more refined technology for these superphosphate resources or calling for other pathways to find "cleaner" phosphates.

This in turn has raised the interest to recover phosphorus from municipal sludge. One model may be to extract struvite from the wastewater process either by means of enhanced water processes or by a direct handling of the sludge. The present water industry market demonstrates some competing companies for struvite production.

Another way to enhance phosphorus at the wastewater treatment plant may be found in the so called "Phostrip Process" that is based on the anaerobic/aerobic model for activated sludge. This process may allow for a separate phosphorous-rich side stream. **Figure 4** illustrates the principal flow sheet model. For further information regarding this process scheme, see [4].

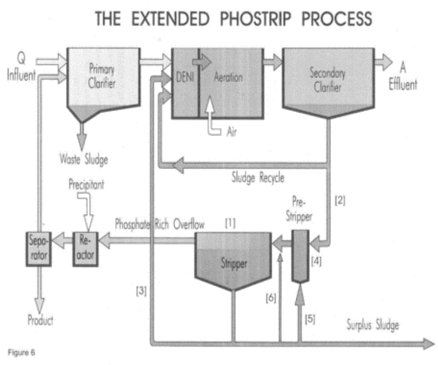

Figure 4: Principal flow sheet for the Phostrip Process.

However, an emerging alternative is the development of the Hydro Thermal Carbonization (HTC) process. In many respects the initial focus on the HTC process is found in the studies by professor Bergius in the 1910s. For various reasons the interest for the potentials of the HTC process declined with the low-cost fossil fuels during the 20th century. However, the insights of the risks for a climate change driven by the CO_2-emmissions have revitalized the interest for the HTC process. The process has been further studied and developed during the last three decades after the initial research work by professor Marcus Antonietti at the Max Planck University. A very comprehensive presentation has been given by Maria-Magdalena Tririci [5]. The process is characterized as follows:

Organic rich matters, such as municipal sludge, is treated in a batch mode or in a plug-flow reactor by the following process conditions:

- Operating process temperature 190 – 230 ^{o}C;
- Operation pressure up to 20 bars;
- Efficient reaction time 2 – 5 hours, related to the raw material quality.
- The inlet solids concentration would be > 10 to 20 % DS, to establish feasible conditions

Findings so far from many test studies are given in, for instance [6], that provide fundamental analysis of the process. Further tests are presented in [7] through to [10]. Of special interest in this perspective are the studies regarding the potential to combine the mesophilic digestion with the HTC-process and to recycle the process water to the digestion. As a conclusion of this process option the report concludes as follows, quote:
"Shortly, the principle of the process is that 0.2 m^3 of the HTC process water is added to 1 m^3 of digested sewage sludge giving a total influent flow to the digester of 1.2 m^3. The effluent from the digester is concentrated to 10 %DS and hydrothermally carbonized. The produced HTC slurry is separated into hydrochar and 0.2 m^3 process water and the loop starts again. Based on the obtained results in this study, the increased methane yield from the process can be estimated to 30 %."

In **Figure 5** is shown a proposed process scheme, based on the presentation in the report [9].

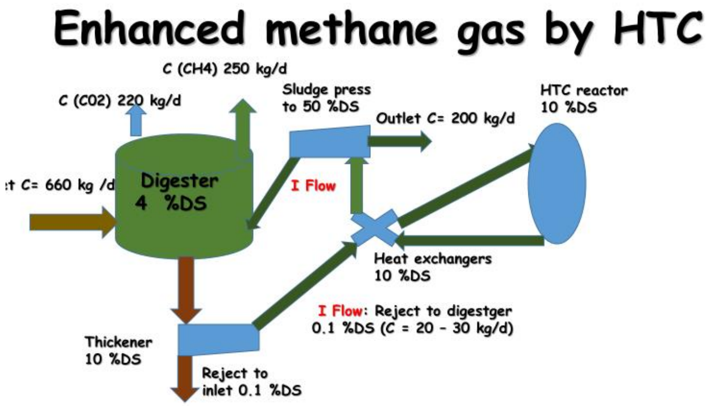

Figure 5: Simplified balance on the combination anaerobic digester and HTC-reactor with recycle of reject to digestion.

This in turn points out a further step for the enhancement of the mesophilic process, however the question of the impurities in the sludge may remain, such as heavy metals bound in the hydrochar and the question of complex organic compounds.

A recent study on the possibilities to concentrate and extract phosphorus from the hydrochar indicates that more than 90 % of the phosphorus is retained in the hydrochar, see [10].
To summarize, the following is highlighted on the actual status with respect to the HTC-process:

- The hydrochar would contain up to 90 % of the inlet carbon content, as well as a similar level of phosphorus.
- The dewaterability of the concentrate is far more efficient by mechanical technology compared with conventional sludge streams. The concentration maybe up to 50 to 60 % DS, as compared with conventional models reaching 25 – 35 % DS.
- The process itself is theoretically exothermic, thus a potential for an additional energy recovery.
- Tests have demonstrated that by recycling the reject water to the anaerobic digester stage the methane gas production may be increased by 20 - 30 %.

A full-scale facility operated in China is presented in [11].
Although the HTC technology seems to include promising and attractive options, there are still important questions to be raised and clarified in further studies. The important points that need further investigations are inter alia:

- To further clarify the quality of reject water from the hydrochar, with respect to residual pollutants;
- To evaluate to what extent the HTC process may become a feasible way to disintegrate pharmaceutical remains found in municipal sludge.

Nethertheless, the process will allow for some very promising pathways within future municipal sludge management. Some advantages maybe stated already at this stage:

- The process will incorporate both sludge stabilization and hygienization by convention;
- The option to recover both phosphorus and carbon as potential valuable raw materials;

- The process would be more than possible to combine with classic anaerobic digestion process;
- The far better dewatering results in comparison with conventional sludge treatment systems.

Conclusions, Perspectives

The current knowledge on municipal sludge as both a potential resource for carbon and phosphorus recovery is contributing to an increased interest to develop and refine technologies for the capture and reuse of these resources. As a matter of fact, the techniques presented are not at all new. However, new conditions with respect to environmental and sanitation concerns and far more stringent requirements will call for further both theoretical studies and engineering work, possibly to combine the techniques in different ways.

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