State of the art and future perspectives of thermophilic anaerobic digestion

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Abstract The state of the art of thermophilic digestion is discussed. Thermophilic digestion is a well established technology in Europe for treatment of mixtures of waste in common large scale biogas plants or for treatment of the organic fraction of municipal solid waste. Due to a large number of failures over time with thermophilic digestion of sewage sludge this process has lost its appeal in the USA. New demands on sanitation of biosolids before land use will, however, bring the attention back to the use of elevated temperatures during sludge stabilization. In the paper we show how the use of a start-up strategy based on the actual activity of key microbes can be used to ensure proper and fast transfer of mesophilic digesters into thermophilic operation. Extreme thermophilic temperatures of 65°C or more may be necessary in the future to meet the demands for full sanitation of the waste material before final disposal. We show data of anaerobic digestion at extreme thermophilic temperatures.

Keywords Biosolid class A; extremely thermophilic; microbial management; thermophilic digestion

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Introduction

Thermophilic temperatures of 50 to 55°C are commonly applied throughout Europe for treatment of manure from several farms in large scale biogas plants or for treatment of the organic fraction of municipal solid waste (Ahring, 1995). The main reason for applying thermophilic temperatures is the better sanitizing effect of the higher process temperature compared to mesophilic temperatures (35 to 37°C) and the need for a lower retention times (Buhr and Andrews, 1977). Thermophilic anaerobic digestion also offers an improved performance when transforming lipid-containing waste (Ahring *et al.*, 1992).

In a worldwide perspective anaerobic digestion of sewage sludge is, however, far the most widespread use of anaerobic digestion and the digester volume found at some of the large wastewater treatment facilities in USA is far greater than all the combined thermophilic digester volume in the world. US EPA has further launched the need for special disinfection of biosolids such as digested sewage sludge before it can be deposited on agricultural land. The demands are among others: the concentration of coliforms is never to exceed 1,000 per gram of total dry solids or the concentration of *Salmonella* is never to exceed 3 MPN per 4 grams of total dry solids. Enteric virus concentration should be less than 1 plaque-forming unit (pfu) per 4 grams of total dry solids, and helminth ova concentration should be less than 1 ovum per 4 gram of dry solids (USEPA, 1993). Mesophilic digested biosolid will per definitions be Biosolid B and have very restricted use and digestion at thermophilic temperatures or other sanitizing after-treatment will be necessary to meet these new standards for Class A Biosolids. Ocean disposal is no longer allowed and the markets in USA for dried digested biosolid are saturated. Based on these new demands which are further under way in Europe, it should be obvious that thermophilic digestion is facing a bright future within the world of sludge treatment. One major hurdle for this development seems to be the little success and the many failures that have been experienced in the USA (Iranpour *et al*., 2001a).

Thermophilic temperatures kill most pathogenic bacteria and most viruses. The effect on the pathogens was found to be a combined effect of temperature and the anaerobic environment (Lund *et al*., 1996). However, some viruses such as the parvovirus will not be killed at a digestion temperature of 55°C (Lund *et al*., 1996) and the demand for proper disinfection of biosolids can be expected to increase in the future. Thermophilic digestion at extreme temperatures of 65°C or more must therefore be necessary for meeting future demands. Without concepts where at least part of the process proceeds at an extreme temperature with a full pasteurization, anaerobic digestion could be a past technology for treatment of biosolids.

Use of two-stages or several stages has become the way of overcoming the problems with the reliability of thermophilic digestion in USA. A short acid phase at thermophilic temperatures followed by a longer gas phase at mesophilic temperatures has been shown by several authors to give a good outcome (Wilson and Dichtl, 1998). Others have claimed that the mesophilic phase has to be the first phase followed by a thermophilic stage to obtain optimal VSS reduction and gas production (Gosh, 1998). One plant in Vancouver, Canada has gone to the extreme of using several stages in series all operated at thermophilic temperatures giving a total retention time of more than 30 days.

The reason for the many failures experienced in the lab as well as in full-scale application can be explained by a lack of understanding of the differences between the microorganisms active at thermophilic temperatures compared to mesophilic temperatures. Sewage sludge or other types of waste will mainly house mesophilic microbes including anaerobes and, therefore, all the necessary microbes for starting a fully operational anaerobic digestion process will normally be present in the waste material. The numbers of thermophiles and especially some specific groups such as acetate-utilizing methanogens, propionate-degraders or cellulose-degraders will often be very low or these groups can even be missing in the waste (Ahring, 1994). The occurrence of thermophiles will depend upon the history of the waste material and, therefore, some material will sometimes have unpredictably high numbers of for instance thermophilic methanogens. When starting a thermophilic digester it is very important to use a strategy allowing for optimal growth of the necessary thermophilic minority populations without over-growth of the populations which already meet the demand during start-up (normally the fermentative microbes).

Results

Successful transformation of a full-scale one-stage anaerobic sewage sludge digester (5,000 m^3) from mesophilic to thermophilic operation (55°C or 131°F) at the Terminal Island Treatment Plant (TITP) in Los Angeles, USA was achieved using a microbial management strategy. As no seed was available we used mesophilic digested sewage sludge as our inoculum and we heated the reactor to the final temperature of 55°C in one step (took 2 days). Due to the fact that this material is already digested the amount of easy degradable organic material will be very limited. Therefore, we avoid a situation where the process will be overloaded and where volatile fatty acids (VFA) will built up due to the much faster growth rate of the thermophilic VFA producers compared to the thermophilic VFA consumers. The feeding strategy of the reactor was based on measurements of the individual VFAs found in the reactor along with testing of the specific methanogenic activity (SMA) of samples taken from the reactor. Regarding the measurements of VFA we looked for trends in the development of both normal VFAs such as acetate, propionate and butyrate as well as iso-acids such as iso-butyrate and iso-valerate. For the SMA testing we compared the methane development over time of vials with reactor samples to other tests where we have added 50 mM of acetate, a methanogenic substrate. Our strategy is to pulse feed as early and much as possible, but at the same time keeping a close eye on the developments in VFA to ensure that the process is capable of handling the extra substrate added. Feeding will be initiated every time we see a decreasing trend in the VFA concentration in the reactor until we reach daily operation. The portion fed to the reactor is determined in accordance with the filling of the reactor as well as the desired end retention time. Figure 1 show the strategy along with the prospective development in total VFA and Figure 2 shows the actual data from TITP; as shown the actual case followed to a large part the model prediction except from a lower over-all level of VFA.

The development of the individual VFAs can be followed in Figure 3. Most of the times when the total VFA shows an increasing trend this was found to be due to other VFAs than acetate and propionate showing the importance of evaluating the whole finger-print of individual VFAs. The slight increase in propionate concentration followed the slight decrease in process temperature from time to time.

SMA was further found to be an excellent parameter for evaluation of the capability of the process for handling an extra load of feed. In Figure 4 we show some selected results from our SMA testing: a) The initial situation during start-up (2/24/2000) where the reactor has no immediate capacity to use extra methanogenic substrate. b) A week later (3/1/2000), and two weeks after thermophilic conditions has been applied, where the reactor has a small but notable capacity of handling an extra load. c) Two week further down the line (3/17/2000) and approximately a month after start-up, where the process has a clear extra

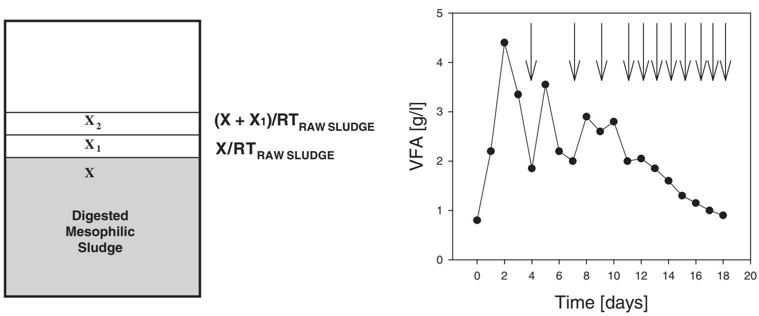

Figure 1 Start-up model

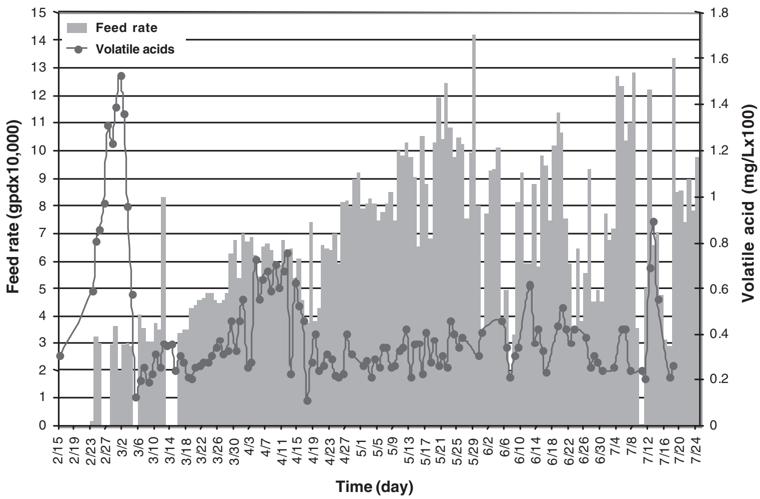

Figure 2 Feeding rate and total VFA in TITP during start-up

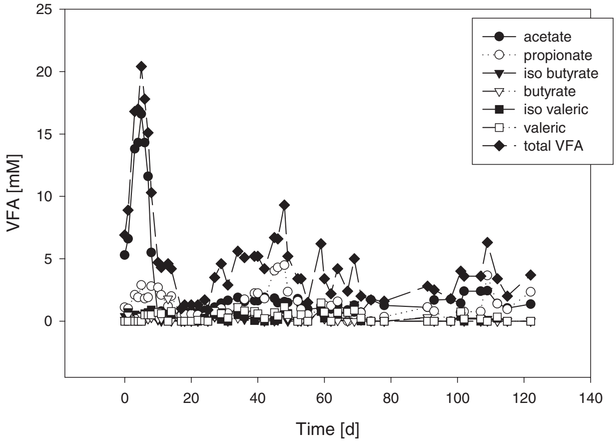

Figure 3 Individual VFAs in TITP during start-up

capacity for handling more input and where the digested sewage sludge in itself has very little extra capacity left. d) Nearly three months after start-up (5/8/2000) where the process shows a clear unused potential for handling more waste and where the sewage sludge is very well digested in the reactor and has very little gas potential left.

After approximately 3 month the thermophilic digestion system was fully operational and working with a retention time of approximately 12 days. Overall the process met the demands for a lower number of coliforms than 1,000 MPN/gTS except from a number of occasions which basically could be explained by a sudden decrease in process temperature (data not shown). Compared to the mesophilic digestion process with the same sludge, TS and VS reduction was increased 9.8% and 9.0%, respectively.

Holding time requirements (time/temperature requirement) without any draw and fill for producing Biosolid A with a process temperature of 55°C is one day. At 65°C, however, only 2 hours will be required which will comply much better with the basic routines found at most sewage sludge treatment plants. Laboratory experiments were performed using cattle manure to examine the possibility of using extreme thermophilic temperatures for digestion of waste. A stable digestion process was established at 65°C with 18% decrease

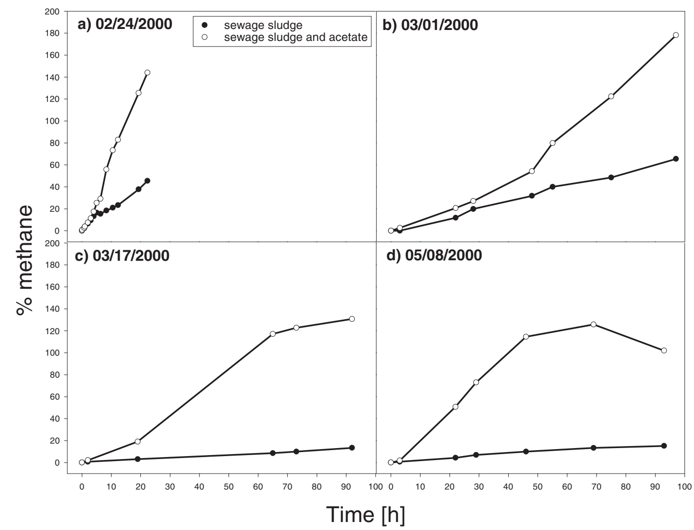

Figure 4 Selected SMAs during start-up of TITP

Table 1 Reactor performance data during stable operation

Parameter	55°C	65°C
Organic loading (g $l^{-1}d^{-1}$)	3.0	3.0
Methane yield(ml g $VS^{-1}d^{-1}$)	202 ± 29	165 ± 11
Total VFA (g acetate l^{-1})	< 0.3	1.8 – 2.4
Acetate (mM)	3 ± 1	20 ± 3
VS removal	28%	22%
pH	7.9	7.8

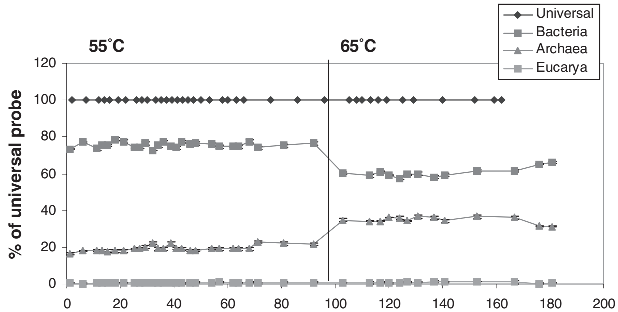

Figure 5 Data from 16S rRNA probing of the reactor

in the methane yield and with a slightly higher level of VFA in the effluent (2 g/l acetate compared to 0.3 g/l acetate) (Table 1). The lower gas yield was basically due to a higher concentration of VFA in the effluent. Even though the gas yield seemed more or less stable after the first weeks of operation at the elevated temperature major differences occurred in the actual microbial populations present in the reactors as demonstrated with 16S rRNA molecular probing (Ahring *et al.*, 2001a). Overall the fraction of bacteria decreased from approximately 78% to 64% while the fraction of Archaea increased from 18–23% to 34–36% of the RNA targeted by the universal probe (Figure 5). Also within the Archaea we found very significant changes favoring Crenarchaea over Euryarchaea (such as the methanogens) even that both groups were favorized by the increased temperature (Ahring *et al.*, 2001b). The dramatic increase in archaeal RNA at higher temperatures can only be explained by enhancement of the activity of Archaea due to the increased temperature.

Recently we have tested the outcome of a two-stage anaerobic system digesting cow manure where the first stage is done at 68°C for 3 days while the second stage is at 55°C for 12 days. The over-all performance is compared to the performance of a one-stage anaerobic reactor operated at 55°C for 15 days. After two months of operation the methane yield of the two-stage system was improved with approximately 10% compared to the one-stage system. This increase in methane yield is significant enough to make this process interesting just from an energy perspective. Experiments are now in progress to follow the performance of these systems along with their development in microbial populations.

Conclusions

Thermophilic anaerobic digestion has proven to be a mature technology in a European setting. Several failures have, however, resulted in reluctance in applying this technology in USA. New regulations in USA for unrestricted use of sewage sludge on farmland demands that further treatment than mesophilic digestion will be necessary in the future. Thermophilic digestion will be one of the ways to meet these new criteria. Therefore, thermophilic digestion has obtained renewed interest for sewage sludge digestion in USA and several trials are now in progress throughout the country.

Most of the previous failures with thermophilic digestion of sewage sludge can be assigned to the lack of knowledge about the digestion process. As demonstrated in this paper a controlled start-up strategy with focus on the performance of the microbial process will ensure that a reliable digestion process will be fully operational within less than two months. The effluent from this full-scale plant did further meet the requirements for Biosolid Class A.

Pathogen kill will be directly linked to the process temperature applied and future demand could be foreseen for elimination of other pathogens than the ones in focus today. Some virus has been found to be very resistant to high temperatures and ultra-thermophilic temperatures could be necessary for total elimination. Anaerobic digestion has proven to be possible even at these very high temperatures and anaerobic digestion at extreme temperatures could become very interesting in the future.

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