Thermophilic and Enzymatic Treatments for Improved Digestion

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Abstract Concerns over food safety have led to stringent pathogen control for sludge products in the UK. Sludge pre-treatment is the preferred approach for digester upgrades to meet new pathogen standards and improved biogas generation. The more advanced anaerobic processes offer greater advantages in terms of energy balance than the Thermal pasteurization and thermophilic aerobic processes. There is increased evidence to suggest that pasteurization may be achievable by Volatile Fatty Acid (VFA) fermentation at a mesophilic temperature. Such a step would provide a significant cost reduction breakthrough in sludge treatment. The new evidence also indicates that any fermentative activities under thermophilic condition were quite small compared to fermentation under mesophilic condition. The rapid initial increase in soluble COD under thermophilic anaerobic condition may simply be due to a physical dissolution process not enzymatic activity. Biological anaerobic pre-treatments will typically produce 50-60% volatile solids (VS) destruction.
Keywords Agriculture; Biosolids; Enzymic Hydrolysis; Pathogen; VFA

INTRODUCTION

Mesophilic Anaerobic Digestion (MAD) is commonly used worldwide for treating sewage sludge. The process is attractive because it is generally robust, requires little operator input, reduces the odorous nature of sludge, and produces biogas for energy. MAD has the highest net energy output of any sludge treatment processes and is often used in the treatment of sludge for agricultural recycling. In the UK, it is common practice to combine primary and secondary sludge streams before digestion and this typically produces a volatile solids (VS) destruction rate of about 45%. Good mass reduction is important because it minimises the disposal costs. In the early 80's concerns over the safety of sludge use in agriculture began to emerge in Switzerland and Germany and these led to the development of pasteurization as a digestion pre-treatment. Pasteurization was achieved either by thermal treatment or a thermophilic biological process. All modern day advanced digestion processes trace their origins back to this pioneering work in Europe which led eventually to the construction of over 70 advanced digestion plants (Zwiefelhofer, 1991).

In the UK, concerns over food safety from the British Retail Consortium led to the introduction of the Safe Sludge Matrix at the end of 1998 (ADAS, 2001) which set out two new standards for sludge treatment. It requires at least 99% removal of *E. coli* for arable applications (known as conventional standard); or at least 99.9999% removal for surface applications (enhanced treated). In the latter case the final product must also be free of *Salmonella* (not detectable in 2 g dry solid). Currently there are more than 500 digesters in the UK processing over 700,000 tonnes of dry sludge per year. The average loading rate for these digesters used to be 1.5 kg VS/m^3/d in 1969, but with the increased use of mechanical thickening, loading is now between 2.0 and 3.2 kg/m^3/d. The continual increase in digester loading has also led to the quality of product (in many cases) becoming poorer. Additionally, lower digester retention times reduce the amount of volatile solids converted to biogas and the potential energy recoverable. As feed solids are increased so the digestate becomes more viscous, making the digesters harder to mix, this in turn may lead to operational difficulties such as short circuiting and foaming. Clearly, the challenge to the UK

Water Industry is how to achieve the new sludge standards and greater energy output while overcoming some of the operational difficulties at the same time.

In the main, the preferred approach in the UK is to upgrade to meet new quality regulations by bolting on a pre-treatment stage to the existing digesters. This offers the advantage that the existing systems can continue to operate while the new process is being built. Currently, certain pre-treatment methods are receiving much interest. Apart from increasing the degree of disinfection to achieve compliance with regulations, these particular pre-treatment methods also make the sludge more amenable to digestion, which increases solids destruction and biogas production. However, the costs / benefits can vary significantly with different pre-treatment methods and therefore the choice of methods can be difficult to make. Whilst the 70˚C regime was traditionally popular for pasteurization (Cumiskey 2005), it presents a number of difficulties. High sludge temperatures require high water temperatures (typically +85˚C) and this in turn leads to scaling and potential sludge baking problems. There are now three types of digestion pre-treatments in the UK: conventional pasteurization, thermophilic biological treatments, and thermal hydrolysis. Thermophilic pre-treatments are often the preferred upgrades for MAD facilities that need to guarantee enhanced treated sludge for agricultural recycling. This paper presents a brief review of the thermophilic and enzymatic pre-treatment techniques and some of the latest research data this subject area.

PRE-TREATMENT TECHNIQUES

The aim of these digestion pre-treatments is two-fold; namely: to deliver an enhanced treated standard product (equivalent to USEPA class "A" biosolids) and to improve the overall VS destruction rate. The first requirement is achieved by providing the necessary pasteurizing condition.

Pasteurization

Thermal inactivation of pathogens is a first order process. This can be described by the following equation:

$$dN/dt = -kN$$

Solving for t

$$t = D \log (N_0/N)$$

t is the time taken to reduce an initial pathogen population N_0 to N. The constant D is the time taken to reduce the pathogen population by a factor of 10. It is often known as the decimating factor and it differs for different type of micro-organisms at different temperature. Figure 1 shows a plot of temperature and time requirement to achieve "Class A" biosolids as defined in USEPA 503 regulation.

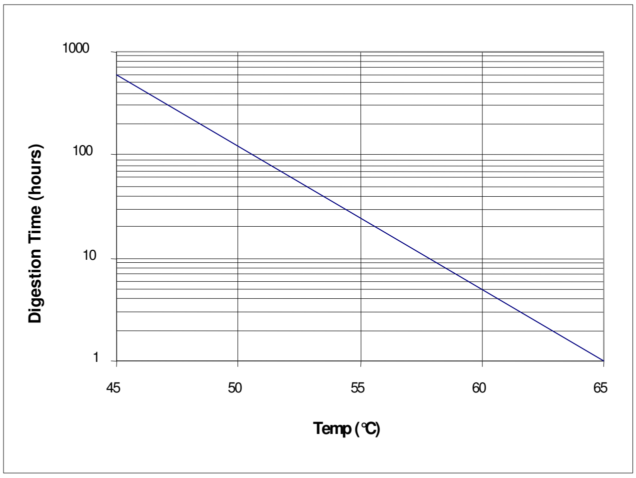

Figure 1 Time / temperature requirement for class "A" biosolids

Thermophilic aerobic digestion (TAD & ATAD)

The exploitation of biogenic heat was first seen with the composting of organic wastes. In the early

1970's autothermic thermophilic aerobic digestion (ATAD) emerged as a potential process for the stabilization and pasteurization of sewage sludge (Andrews and Kambhu, 1971). Schwinning and Cantwell (1999) reported a significant increase in the number of ATAD plants in North America with the advent of the 503 regulation. Dual-stage process development followed the development of thermophilic aerobic digestion (TAD) as a means of reducing the cost of heating for sludge pasteurization. It would be ideal if a self-heating aerobic stage could be used to achieve pasteurization. However, because of the high capital cost associated with the high HRT (at least 4 days), most dual stage processes tend to employ systems with low HRT (typically 12 hours) which have supplementary heating. TAD followed by MAD has proved to be an energy efficient process combination for the production of pasteurized and stabilized sludge suitable for agricultural uses. Many of these full-scale processes have been installed in Germany, Switzerland and France over the last 20 years and have been operating successfully. Although pasteurization has been the main driver in most of these cases, operators also recognized other substantial process benefits such as reduced secondary storage cost, increase throughput, improved sludge rheology and destruction of halogenated hydrocarbons.

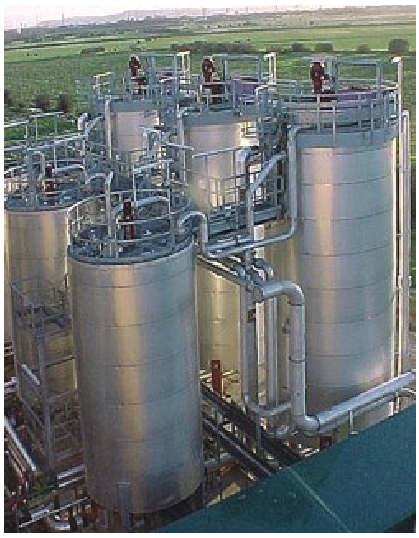

Figure 2 Alpha Biotherm Plant at Ellesmere Port Wastewater treatment works

Heat is the by-product of two separate processes that take place simultaneously in an aerobic reactor. In the synthesis of biomass (growth) heat is released as a result of the free energy change. In the respiration process more heat is produced as a result of the oxidation of organic matter to CO_2 and H_2O. The net combined Heat Production = 21 MJ/kg VS. Both TAD and ATAD have been used as pre-treatment methods for MAD. However, ATAD is not popular in the UK because of the high cost of aeration and the requirement to treat the large volumes of exhaust air to minimize the odour risk.

Ellesmere Port digester performance (2001 average)
Digester temperature 35°C
Average Feed 6.2 % DS at 65%VS
Average feed rate m^3/d; HRT 23.7 days
Loading 1.70 kgVS/m^3/d
Overall VS reduction 48.3%

Aerobic systems were installed primarily to provide guaranteed pathogen reduction to secure the land disposal route for biosolids rather than to improve volatile solids destruction. Furthermore, it should be noted that aerobic decomposition of organic matter generates carbon dioxide and water, reducing the volatile matter available for methane production. At best they only have a marginal impact on the biogas production.

Thermophilic anaerobic digestion
In the mid 90’s a number of researchers began to investigate the use of thermophilic anaerobic processes (TAnD) as a mean for sludge disinfection and VS destruction improvement. The main advantages of TAnD over TAD and ATAD include saving in aeration cost and greater biogas yield. A notable study was carried out by Roberts (1998) to determine the most appropriate bioreactor retention time for use as the first stage in a thermophilic/mesophilic dual digestion process. The study found that with retention times in the range 8 to 48 hours, the bioreactors showed little accumulation of volatile fatty acids (VFA). Roberts claimed that apart from achieving the required

disinfection, varying the retention time in the first stage digester had little effect on the properties of the sludge produced and that the overall VS reduction was not as great as reported by other workers.

Dague *et al* (1998) patented a thermophilic/mesophilic dual digestion process in which they specified a retention time in the thermophilic reactor up to about 5 days, and the retention time in the mesophilic reactor up to about 15 days. The Dague process is known as Temperature Phased Anaerobic Digestion (TPAD) and Anaerobic Stabilisation Thermophilic/Mesophilic (ASTM) in North America and Europe respectively. Over twenty full-scale TPAD plants have been constructed in the USA, and ten ASTM plants constructed in Germany. Hoyland (2006) reported that VS destruction of such plants were generally in range 50% to 60%.

The lack of biological diversity in the thermophilic range is probably responsible for the reduced hydrolytic and acidogenic activities. It would seem, therefore, that although TAnD systems were energetically more favourable than TAD and ATAD, their poor VFA generation capability and the long retention time requirement by TAnD have negated their advantages somewhat.

Enzymic Hydrolysis

Recent work by Le (2005) showed that sludge disinfection could be achieved at a mesophilic temperature. The inventor suggested that disinfection was resulted from the actions of the hydrolytic enzymes released by the food spoilage bacteria and the accumulation of their metabolites. His invention is known as the Enzymic Hydrolysis process in the UK. Fig. 3 shows variations in the decimating factor against temperature for *E. coli* in digested sludge and Enzymic Hydrolysis system (unpublished work). It also shows a comparison with the estimated decimating factors from Equation 3 of Section 503.32 (USEPA 503 regulation). The EPA regulation restricts treatment to temperatures of at least 50°C because information on the time-temperature relationship at lower temperatures is uncertain. The current data suggests that under Enzymic Hydrolysis condition the disinfecting temperature of the EPA regime could be reduced by at least 10°C without reducing its effectiveness. The differences in the decimating factors between digested sludge and enzymatically hydrolysing sludge are most likely due to the low pH and high VFA levels in Enzymic Hydrolysis systems. To date nine full-scale Enzymic Hydrolysis plants have been built (or nearing completion). Four of the plants are operational; the first one has been in service since 2003. Overall VS destruction rates of 54 % to 62% have been reported for such plants (Le *et al*, 2006).

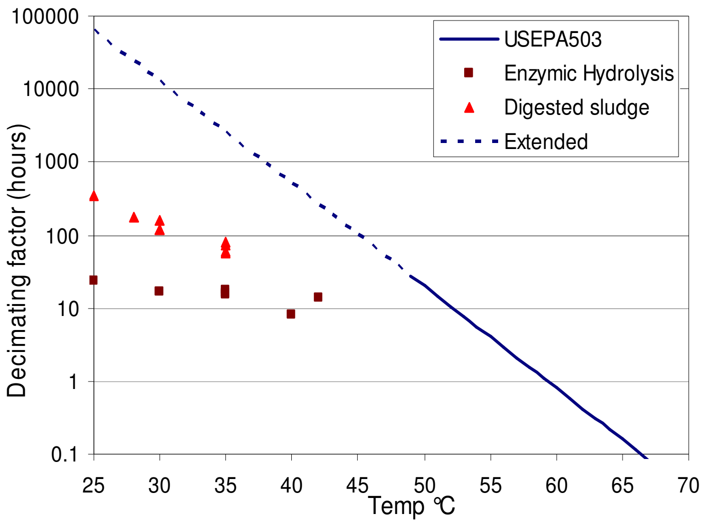

Figure 3 Decimating factors in various environments

ENZYMIC HYDROLYSIS APPLICATIONS

The first application of Enzymic Hydrolysis was reported by Mayhew *et al* (2004). They described a plug flow system based on six completely mixed reactors in series to achieve sludge disinfection by reducing the *E. coli* content in sludge by at least 99.9%. Indeed, the first three full scale installations in the UK (by United Utilities) were of this design.

The ability to achieve pasteurization (i.e. at least 99.9999% *E. coli* kill) at a mesophilic temperature would provide significant benefits to operators and the environment. Firstly, the heating requirement would be reduced by at least a third; secondly the equipment would be simpler and less costly; and thirdly greater biological activities in the mesophilic temperature range mean greater biogas productivity. The decimating factor for *E. coli* under Enzymic Hydrolysis condition at 42°C is about 10 hours (Fig. 3). This suggests that the treatment would only require 60 hours plus some extra time as a safety margin. Such a design is highly feasible, however, to date it has not been realised in practice since regulatory approval and market acceptance take time to establish. Work is still ongoing to prove the mesophilic pasteurization process. In the mean time by combining the advantage of excellent VS destruction capability of the original process (42°C) with a proven pasteurization regime (55°C) United Utilities created Enhanced Enzymic Hydrolysis (EEH), a hybrid process that aimed to improve biogas yield whilst achieving reliable pathogen control capability at the same time. The technology is particularly appealing because of its low operating temperature enabling it to work successfully with low-grade heat such as waste heat from CHP plants which enables it to maximise renewable energy production.

The Blackburn sewage works is now home to the first EEH Demonstration Plant completed at the end of 2005 with the contribution of the LIFE Financial Instrument of the European Community. Blackburn is a major sludge centre in England NW region. Every year the centre processes 14,000 tonnes sludge (tDS) by MAD for 0.5M people from the Blackburn and South Lancashire area and safely recycles it to agriculture. This European project includes a Demonstration and Monitoring programme set out to show the technical capability of EEH technology as well as the economic and environmental impact of its operation. The following sections report on some of the latest developments in Enzymic Hydrolysis, in particular an understanding of the variations in biological activities between mesophilic and thermophilic operations.

Analytical methods and procedures

Sludge samples

All sludge samples were spot samples. Hydrolyser samples were taken from dedicated sampling ports from individual reactor tanks. Digested samples were fresh samples taken directly from the discharge points of the digesters. Analysis followed within 6 hours of sampling or 24 hours if kept at 4°C.

Process Trend Monitoring for Hydrolysis and VFA production

Sludge samples were filtered through Munktell MGC 150 mm filters. Filtrate was analyzed directly for COD, total VFA (VFA), and ammonium using Dr. Lange cuvette test kits, LCK 114, 365, and 303 respectively, with a Dr. Lange LT200 incubation block and Lasa50 spectrophotometer.

Other analyses

All other analyses were done by United Utilities Lingley Mere Laboratories, using accredited methods. *E. coli* enumerations were carried out with the Most Probable Number Method.

Bench scale thermophilic anaerobic pre-treatment trials

These trials were carried out in four 2-litre bottles using thickened sludge collected from the Blackburn works. The bottles were used as bioreactors in series (B1, B2, B3 and B4). At 24-hour intervals a sample was taken from each reactor for analysis. B3 was then used to feed B4; B2 was used to feed B3 and so on. The reactors were flushed with butane to displace any air before the lids were replaced after each sampling/feeding event. They were maintained at 55ºC in a water bath for 12 days and were shaken three times each day to ensure good mixing.

The Blackburn EEH plant

The EEH plant at Blackburn was designed to pre-treat 540m^3/d (average flow) of sludge to achieve at least 99.9999% reduction of *E. coli* before digestion. The feed sludge was designed to be pre-thickened by gravity belt thickeners to 6.8%DS and fed to the plant from an air-mixed buffer tank. Following two days retention (at the design peak flow of 741m^3/d) in the EEH plant the sludge is fed to the 4 existing anaerobic digesters, each with a nominal working volume of 2,200m^3 (assuming an active volume of 95%). The EEH plant design was a simple modification of the plug flow design described by Mayhew *et al* (2004). Pasteurization was guaranteed by introducing a batch hold time into the thermophilic stage to ensure that all the sludge was held at 55˚C for at least 4 hours, a common practice in Europe (Carrington *et al*, 1998). The solution was to use the first three reactors (R1-R3) for hydrolysis/fermentation and R4 as a balancing tank. R5 and R6 alternate between being the digester feed tank and the batch hold tank for the thermophilic sludge (Figure 4). This system allows the plant to operate the mesophilic stage in plug flow and the thermophilic stage as a batch hold, whilst maintaining a continuous feed to the digesters.

Figure 4 Schematic diagram of the EEH process

Results and Discussion

Hydrolytic and fermentative activities

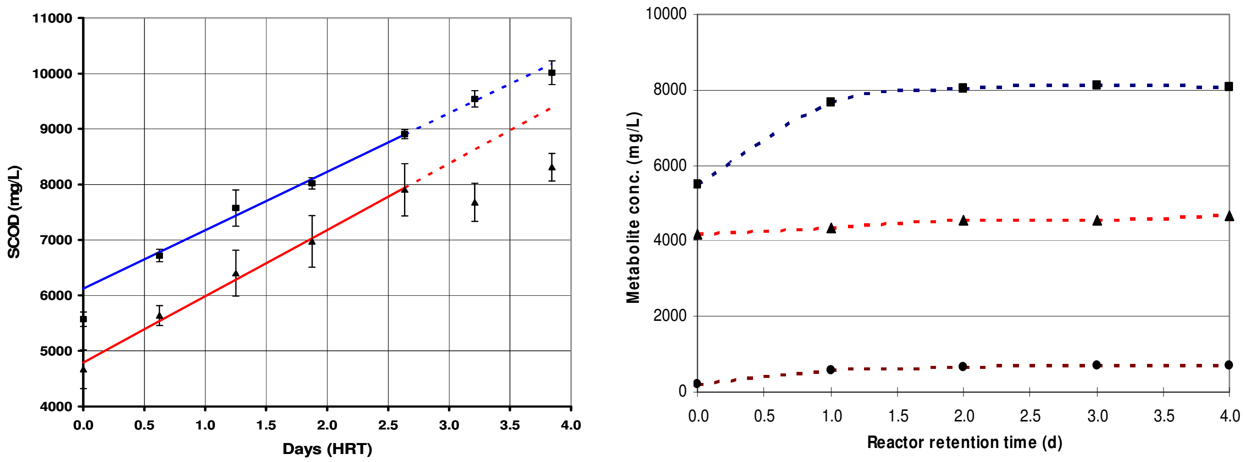

Figure 5 Trends in metabolite production: (•) ammonia (■) sCOD (▲) VFA (as COD). Left chart: full scale plant data (feed; R1-R6). Right chart: bench scale data (feed; B1-B4). Broken lines denote 55˚C and solid line 42˚C.

Hydrolytic activities are best observed by monitoring the soluble COD profile (sCOD) of the process. On the other hand fermentative activities are more readily demonstrated by the changes in other metabolite levels (ammonia and VFA). Such activities were clearly exhibited by the process both on bench scale and full scale plant (Fig. 5). Both the sCOD and the VFA levels increased at a constant rate during the mesophilic phase. However, while the rate of VFA production seemed to plateau out after R3 where the process temperature was raised to 55°C, the sCOD level continued to rise. Shifting the process temperature from 42°C to 55°C is likely to inactivate the mesophilic bacteria responsible for acid fermentation but it is possible that the hydrolytic bacteria are less affected by the temperature increase. However, the bench scale data appears to suggest otherwise. The rapid increase in sCOD is not accompanied by any significant fermentation of VFA or ammonia. By contrast, in the mesophilic temperature range the production of both VFA and ammonia correlate directly to the rise in sCOD level (mesophilic ammonia data not shown). A more likely explanation is that at 55°C the organic substrates undergo rapid dissolution, a physical process that is virtually completed with 24 hours. These observations are consistent with the results of Roberts (1998) which indicated that short reactor retention times at 55°C were insufficient for the development of acidogenic activities. They also offer an explanation for the longer treatment times required to achieve significant improvement in VS destruction by TAnD processes.

Pathogen reduction performance

The main purpose of the Blackburn project was to improve the pathogen destruction capability of the digestion process to enable the sludge to be safely recycled to agriculture. Good and reliable pathogen destruction performance was therefore vital for the success of the project.

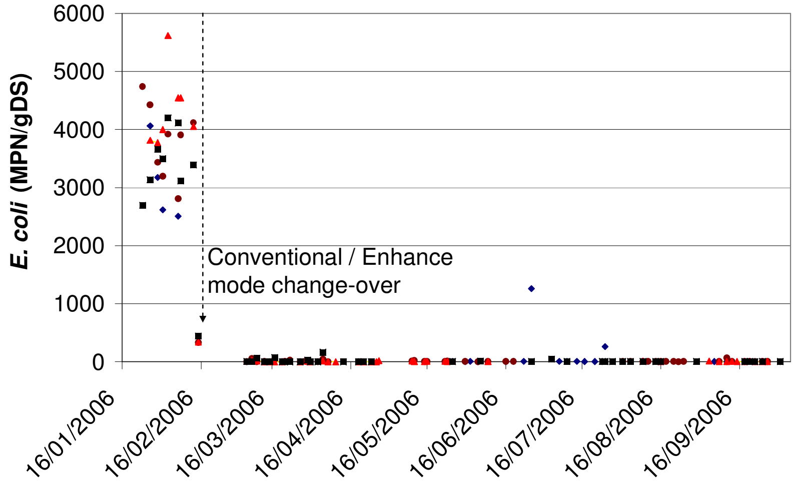

Figure 6 E. coli content in digested sludge

During the first six weeks of operation the EEH plant ran in the conventional mode. It was found that the plant was able to destroy 99.95% of *E. coli* (Fig. 6) and 99% *Salmonella* (data not shown. In the enhanced mode of operation the plant was able to destroy 100% *Salmonella.* The destruction of *E. coli* was beyond the level of detection for this indicator micro-organism. A failure (June 2006) was attributed to a contamination of the sample. Overall, the EEH plant at Blackburn has been able to provide reliable pathogen control for enhanced treated standard biosolids. The product has been used as a seedbed fertiliser for maize and cereal crops. It has proved to be of low odour and has provided the opportunity for surface spreading on grassland, even in close proximity to residential areas.

CONCLUSION

Sludge pre-treatment is the preferred approach for digester upgrade to meet the stringent standard for pathogen control and to improve biogas generation. The more advanced anaerobic processes offer greater advantages in terms of energy balance than the Thermal pasteurization and thermophilic aerobic processes. There is increased evidence to suggest that pasteurization may be achievable by VFA fermentation at a mesophilic temperature. Such a step would provide a significant cost reduction breakthrough in sludge treatment. The new evidence also indicates that any fermentative activities under thermophilic condition were quite small compared to fermentation under mesophilic condition. The rapid initial increase in soluble COD under thermophilic anaerobic condition may simply be due to a physical dissolution process not enzymatic activity.

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