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Influence of an Intermediate Thermal Hydrolysis Process (ITHP) on the Kinetics of Anaerobic Digestion of Sewage Sludge

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Over the last 16 years, different sludge pre-treatment processes have been retrofitted to existing sewage sludge treatment plants in order to improve anaerobic digestion treatment process efficiency. Some of these pre-treatment technologies, notably the thermal hydrolysis process (THP), have greatly increased the sludge throughput and allowed more efficient utilisation of treatment assets without adversely impacting on the biology of sewage sludge anaerobic digestion process. Whilst the digester throughput is increased by utilising the THP process, the biogas yield has not increased significantly or the expected increase in volatile solid reduction (VSR) has not been realised. In an attempt to improve the impact of THP on the process performance, a new sludge treatment process configuration was developed which consists of an intermediate step of thermal hydrolysis (ITHP). The results obtained from laboratory scale digestion investigations showed marked improvements in the sludge digestion process efficiency during ITHP process in comparison with conventional mesophilic anaerobic digestion (CMAD) and THP digestion process configurations. To establish the reasons for these differences, the sludge organic matter kinetics was investigated by quantifying the degradation rates of the main sludge constituents; protein, carbohydrates and lipids as well as volatile fatty acids (VFA) for the ITHP process configuration.

1. Introduction

Different sludge pre-treatment processes have been retrofitted to existing sewage sludge treatment plants in the UK Water industry. The aim is to improve the overall sludge anaerobic digestion treatment process efficiency, notably the thermal hydrolysis process (THP), which has greatly increased the sludge throughput and allowed more efficient utilisation of treatment assets. However, the performance data indicates that conventional MAD or THP combined with MAD do not necessarily result in an improved sludge digestion process efficiency (Shana et al., 2011). It was noted that in the CMAD as well as the THP process configurations, the higher the volatile solid's load, the lower the percentage volatile solid reduction. This statement was in line with studies conducted by other scholars such as Norli, 2006.

The amount of biogas generated from a tonne dry solid of sludge fed achieved was 350 m^3/d from CMAD and 387 $m^{3/}$d from the THP digestion process configuration. To bridge this low sludge digestion process inefficiency gap, a new process configuration, the intermediate thermal hydrolysis process (ITHP) i.e. MAD +THP+MAD, was proposed and tested over the last 3 years. The ITHP is an optimum

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configuration that involves two stages of digestion with thermal hydrolysis in between.Extensive laboratory scale sludge treatment and digestion trials demonstrated that the ITHP process configuration improved the overall sludge digestion process efficiency.

1.1 Sludge as multi-substrate and its degradation kinetics during mesophilic anaerobic digestion process

During anaerobic digestion process the sludge constituents are hydrolyzed into soluble COD and by means of bacterial action, the COD is fermented into VFA. The VFA is then taken up by the acetogenic and methanogenic bacteria and ultimately converted to biogas and trace materials (Gallert and Winter, 2005). Most of sludge components are part of sludge organic matter content (carbohydrates, fibre, protein and fat) and are derived directly from plant and animal biomasses. The organic components in sewage sludge are degraded at different rates and extent during MAD (Gonzalez 2006). The rate of change in substrate concentration in a completely mixed system follows first-order degradation kinetic. The substrate concentration (S) can be expressed as (Padilla-Gasca and López-López, 2010)*:*

$$\frac{dS}{dt} = \frac{Q}{V} S_0 - \frac{Q}{V} S - K_1 S \qquad (1)$$

According to these authors, under steady state conditions, the rate of change in substrate concentration (*-dS/dt*) is negligible, therefore, Equation (1) is reduced to:

$$\frac{S_0 - S}{\theta_H} = K_1 S \qquad (2)$$

Where, θ_H is hydraulic retention time (HRT)

The kinetics study of anaerobic digestion is also described by typical microbial growth curve (Bailey and Ollis, 1986 in Karivelil, 1992). According to these authors, the equations relating to specific microbial growth rate to the biomass concentration could be expressed by:

$$\frac{dX}{dt} = \mu X \qquad \text{or} \; \frac{1}{X} . \frac{dX}{dt} = \mu \qquad (3)$$

Where, μ is a microbial growth rate

Integrating the above equation with a substrate concentration (X) at time (t) equal to initial substrate concentration (X_o) i.e. $X = X_o$ at $t = t_{lag}$ yields

$$\text{Ln} \; \frac{X}{\text{Xo}} = \mu (t - t_{lag}) \; \text{or} \; X = X_o e^{\mu (t - tlag)} \qquad (4)$$

Where $t > t_{lag}$

According to Karivelil (1992), from Equation 4, the time interval t_d required to double the microbial population is given by:

$$t_d = \frac{\ln 2}{\mu} \; . \qquad (5)$$

2. Materials and methods

A series of batch digestion experiment was conducted using the Water Research Council (WRc) standard biodegradability apparatus (Fernandes and Kimber; 1990). The methods of sludge feed preparation and details of experimental work were previously reported in Shana et al, (2011).

3. Results

3.1 Kinetic study of volatile fatty acid (VFA) degradation

Figure 1 shows the VFA degradation rate in the ITHP digestion process follows pseudo-1st order degradation kinetics. The rate constant (K) for the ITHP and CMAD, as shown in Figure 1, are **-**0.15 and **-**0.49 d^{-1} for the first six days of sludge digestion period.

In the ITHP process, the VFA degradation was step-wise, and this type of digestion trend was also reported by Miron et al., (2000) in Seghezzo, 2004 and concluded this being as an inherent characteristic of complex substrate digestion process.

The VFA concentration in the CMAD configuration was reduced from 515 mg/L initial concentration to 53 mg/lover a period of three days. Figure 4 shows this VFA degradation kinetics trend based on the proportion of final VFA concentration in the digested sludge and initial VFA concentration from MAD and ITHP sludge digestion process. The data shown this figure calculated based on equation 2 above.

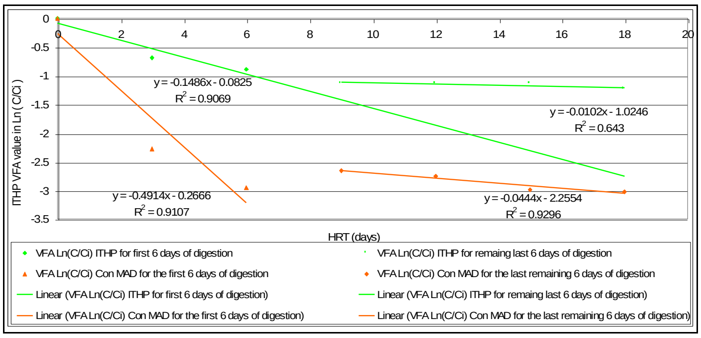

Figure 1: VFA degradation characteristics – Psuedo1st order reaction kinetics

The rate constants were determined as per Vavilin et al., 1996 method described in Gonzalez (2006) given in Equation (8):

$$K = \ ((Cinitial\ - C)(1/HRT))/C \qquad (8)$$

Where C initial = an initial VFA concentration and C = concentration of sludge composition (mg/L), HRT = digester hydraulic retention time, and K = kinetic constant per days.

Table 1 shows the average calculated values of rate constants for using the VFA data for the ITHP and CMAD digestion configurations based on Equation (8). There is disparity between the rates from Vavilin's method, and results from this investigation.

Table 1. Rate constant for each of the digestion configurations tested (shows the K value for VFA degradation taken from the slope of the graphs in Figure 4 compared with calculated value as above)*

Method	K value (d^{-1}) from ITHP	K value (d^{-1}) from CMAD
Vavilin et al	0.23	1.83
This experiment	-0.15	-0.49

3.2 Kinetic Study of Sewage Sludge Constituents during Anaerobic Digestion Process

The primary constituents of sewage sludge are proteins, lipids, fibre and carbohydrates. The parameter discussed above, i.e., VFA is the results of protein, lipids, fibre and carbohydrates degradation. The extent and speed of the degradation process depend on the nature of the sludge treated and the pre-treatment process applied. The degradation characteristics of proteins, lipids fibre and carbohydrates found in both CMAD and ITHP digested sludge over 12 d of sludge digestion period are shown in Figures 2 to 5.

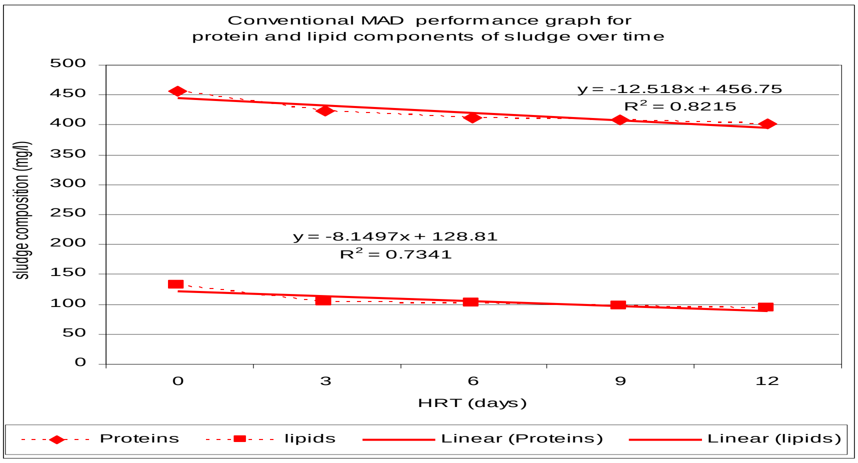

Figure 2: Protein and lipid composition degradation in ITHP digestion configuration

Figure 2 shows that the Protein and lipid concentration in CMAD was reduced slowly with time as the digestion process progressed. The CMAD digester content had an initial protein concentration of 456 mg/L of protein and 130.45 mg/L of lipid. These were reduced to 400 mg/L protein and 92.88 mg/L lipids after twelve days of digestion period, corresponding to about 12.3% protein and 29 % lipid concentrations reduction. However, both protein and lipids degradation kinetics in the CMAD process followed zero order kinetics throughout the digestion period assessed. Figure 3 shows that the degradation characteristics of carbohydrate and fibre composition of sludge during twelve days retention time in the CMAD process. The carbohydrate digestion process clearly followed the first order kinetics (K= -1.17 d^{-1}) during the first six days of digestion period. Fibre degradation was rapid and also followed first rate order reaction kinetics (K= -1.59 d^{-1}), in the CMAD process. The lipid degradation in the CMAD was K= -8.15 d^{-1} .Overall, carbohydrate and fibre degradation was faster than lipid and the slowest degrading sludge constituent was protein during MAD process. Therefore, Protein degradation may be considered as a rate limiting process in the MAD process.

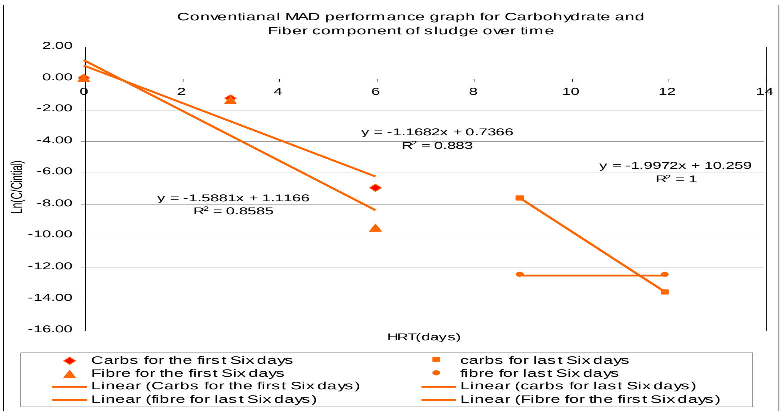

Figure 3: Carbohydrate and Fibre composition degradation over time in Conventional MAD digested sludge

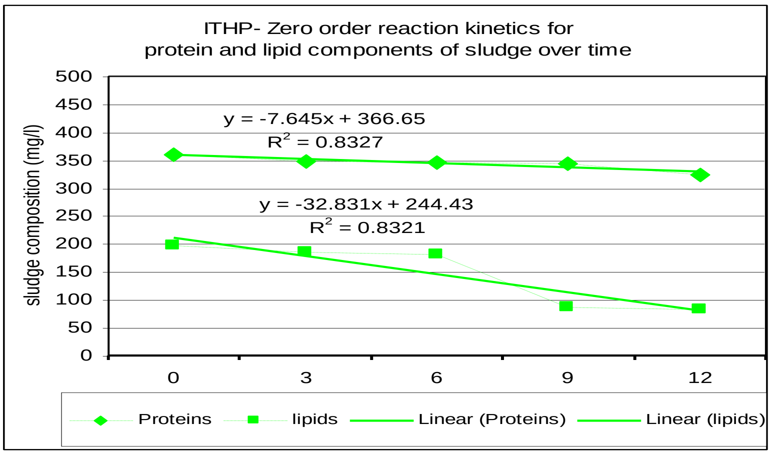

Figure 4:. Protein and lipid composition degradation over time in ITHP digested sludge

Figure 4 shows that the protein degradation kinetics in the ITHP process followed zero order kinetics throughout the digestion period. Only 10 % of the remaining protein from the first stage of MAD in the ITHP configuration was destroyed upon re-digestion process. In contrast, the lipid digestion process in the ITHP followed a pseudo first order degradation reaction kinetics, showing the slow and stepwise degradation process of the lipids in the digested sludge. Figure 5 shows the degradation characteristics of carbohydrate and fibre in the ITHP process. The data shows that the carbohydrate concentration reduced rapidly with time and most of the degradation process took place within the first six days of digestion and clearly followed the first order kinetics (K= -0.98 d^{-1}). The fibre degradation process in the ITHP was rapid with linear trend and followed first rate order reaction kinetics (K= -0.88 d^{-1}) and that of lipid degradation was K= -32.83 d^{-1}. Overall, the sludge composition degradation rates in the ITHP process configuration was enhanced as evidenced by continued protein, lipid, carbohydrate and fibre degradation rates achieved during the second MAD stage of the ITHP digestion process configuration. In conclusion, in the ITHP process, the carbohydrate and fibre degradation was faster than lipid and protein in the ITHP process, but the additional protein degradation achieved was significant and may be one of the reasons for the enhanced sludge digestion process efficiency achieved in the ITHP digestion process configuration.

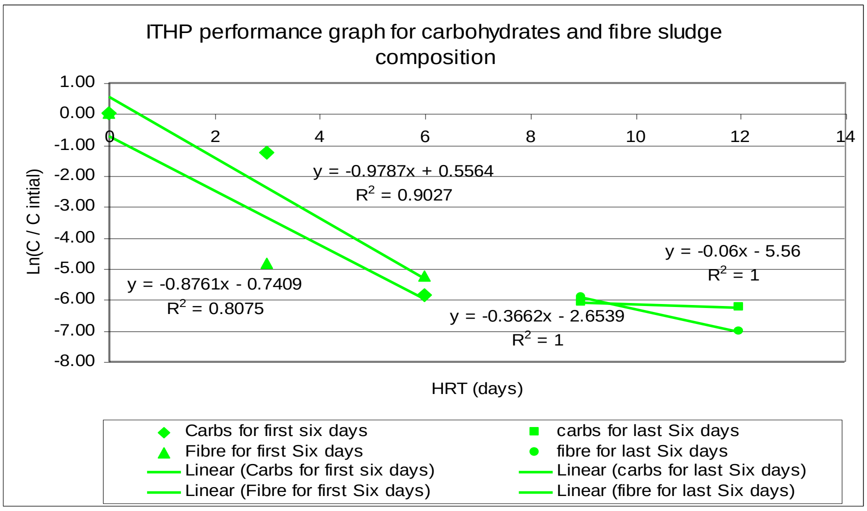

Figure 5: Carbohydrate and Fiber composition degradation over time in ITHP digested sludge.

4. Conclusions

In the ITHP digestion configuration, the main degradation rate limiting substrate was protein as evidenced by 12 % removal rate during the first step of digestion and a further 10% protein reduction after THP and second stage of digestion .The degradation of carbohydrate in both CMAD and ITHP followed a first order reaction kinetics with rate constants of -1.17 d^{-1} and -0.98 d^{-1}. The degradation of fibre in both CMAD and ITHP also followed a first order reaction kinetics with rate constants of -1.59 d^{-1} and -0.88 d^{-1} respectively. However, the degradation of lipids in both CMAD and ITHP followed zero order kinetics with rate constant of -8.15 d^{-1} and -32.83 d^{-1} respectively. The benefit of ITHP configuration was supported by the rate of carbohydrate, protein, lipids and fibre degradation results reported above.

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