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The impact of intermediate thermal hydrolysis on the degradation kinetics of carbohydrates in sewage sludge

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HIGHLIGHTS

- Carbohydrates degradation is a complex multi-step mechanistic process.
- Thermal hydrolysis enhanced carbohydrates degradation for both process configurations.
- Degradation rate was fast then slowed down due to nature of remaining compounds.
- Carbohydrate degradation rate impacts on sludge digester HRT and the loading rate.

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ABSTRACT

The purpose of this paper is to report the results, from laboratory-scale investigations, on the impact of intermediate thermal hydrolysis process (ITHP) on already digested sludge in general, and sludge carbohydrate content degradation process efficiency in particular. The ITHP performance data were compared with the performance of established conventional thermal hydrolysis process (THP). The degradation of sludge carbohydrates as a result of thermal pre-treatment and anaerobic digestion followed the first order kinetics. The overall sludge organic matter degradation kinetics rate constants indicated that the use of THP as an intermediate digestion step can enhance the already digested sludge organic matter degradation; further reducing the sludge mass and increasing its conversion to biogas.

1. Introduction

Anaerobic digestion of complex, particulate organic material has been described as a multi-step process of series and parallel reactions catalysed by a consortium of bacterial communities (Gujer and Zehnder, 1983; Pavlostathis and Giraldo-Gomez, 1991). These steps are: (i) hydrolysis of complex organic materials such as carbohydrates, proteins, and lipids, (ii) acidogenesis or fermentation of the hydrolysed products to volatile fatty acids (VFA), (iii) acetogenesis, the conversion of long chain VFA to short chain VFAs, and (iv) methanogenesis processes, the conversion of acetic acid, carbon dioxide and hydrogen into methane (Gujer and Zehnder, 1983; Sanders, 2001). These steps are interdependent and the performance of one step affects the next.

The step from a synchronised process for the conversion of substrate to biogas depends on the performance of a consortium of bacteria present in the total digester volume. For example, the performance of acetogenic bacteria relies on the performance of the hydrogen scavenging bacteria, (CIWEM, 1996). If acidogenic bacteria convert the organic matter to fatty acids at a higher rate than the methanogenic bacteria can utilize them, then the acidogenesis step itself is inhibited due to toxic waste accumulation in their environment. For maximum anaerobic digestion process efficiency, i.e., hydrolysis, acidogenesis, acetogenesis and methanogenesis, there must be a balance in the rate of conversion from one step to the next (Vivalin et al., 2004).

Sewage sludge as a digester feed is often composed of complex biodegradable matter which must be solubilised and broken down into smaller monomers before being assimilated by bacterial cells (Gunnerson and Stuckey, 1986). Dead microbial biomass is considered as part of the substrate and as particulate material (Batstone et al., 2002). Furthermore, during the anaerobic digestion process, the sludge constituents are solubilised by the bacterial action into chemical oxygen demand (COD). The soluble COD is in turn fermented into volatile fatty acids (Gallert and Winter, 2005; Shana

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et al., 2012). The VFAs are ultimately converted into biogas by methanogenic bacteria.

Several authors noted that during the process of anaerobic digestion of sewage sludge, the methanogenic process is limited by the hydrolysis rate of organic matter; although methanogenesis could, in some cases, be the rate limiting process particularly when the digester hydraulic retention time (HRT) is low (Pavlostathis and Giraldo-Gomez, 1991; Vivalin et al., 2008; Batstone et al., 2009; Donoso-Bravo et al., 2010). At low HRT, there is an increased risk of washing out the methanogenic bacteria population from the digesters.

The recognition of the sludge hydrolysis stage as being the main rate limiting factor in anaerobic digestion of sewage sludge has led to the development and application of sludge pre-treatment technologies and thus the intensification of the process. The most widespread pre-treatment process used in Europe is the thermal hydrolysis process (THP) where sludge is heated to about 170 °C and 7 bar pressure for about 30 min and then anaerobically digested. According to Panter (2008), the conventional THP process makes the sludge digestion process more tolerant to organic matter shock load and improves sludge volatile solid reduction (VSR) from 30–45%, to 50–60%.

However, a preliminary study reported by the authors (Shana et al., 2011) indicated that when two separate mesophilic anaerobic digesters were fed, one with a thermally hydrolysed sludge and the other with un-treated raw sludge feed (both containing equal amount of volatile solids (VS) content 76–78% VS), both produced similar volatile solids content in their respective digestates (60–65% VS). This finding indicates that only 35–40% of the potential energy is converted to biogas during the digestion process and 60–65% of VS remained in the digestate. This particularly takes place when the digestion process is highly loaded in terms of or ganic matter. Therefore, the drive to maximise the use of existing assets, above the optimum organic load capacity, and further reducing the digester hydraulic retention time (HRT) can significantly reduce the overall sludge digestion process efficiency. Even with the more advanced anaerobic digestion technologies, such as the thermal hydrolysis process (THP), around 60% of the initial biodegradable organic matter is recycled to land.

Shana et al. (2011) also showed that the novel ITHP configuration produced 20% more biogas compared to THP configuration with around 62% biogas methane composition and 66% volatile solid reduction. This finding compares well with the results obtained by Kumar and Lo (2012) using an aerobic digester feed with microwave and alkali pre-treated sludge. Shana et al. (2011) further reported that the use of ITHP made sludge that was resistant to biochemical action during anaerobic digestion process, soluble, and biodegradable. This results in an improvement in the anaerobic sludge digestion process efficiency.

Therefore, recognising the above reported limitations of conventional mesophilic anaerobic digestion (MAD) and THP pretreatment, and based on the preliminary result obtained by the authors (Shana et al., 2011), it was clear that the use of THP as an intermediate thermal hydrolysis process can potentially improve the digestion process efficiency compared to the current configuration (THP + MAD). In the present study, a novel technology process configuration (ITHP) based on three stages (MAD + ITHP + MAD) is investigated and the extent of sewage sludge constituents' degradation, particularly the carbohydrate degradation kinetic characteristics, were evaluated and compared with conventional (THP + MAD). The aim is to develop an understanding of the complex carbohydrate degradation kinetics mechanisms involved and hence optimise the system for a much improved anaerobic digestion and biogas production.

2. Methods

2.1. Thermal hydrolysis rig

A THP rig consisting of a 20 l reactor vessel and a 50 l flash tank was used to thermally hydrolyse sludge (details can be found in Shana et al., 2011). Two types of sludges were hydrolysed: (1) a mixture of 60:40 ratio by weight of primary to surplus activated sludge (SAS) dewatered cake, and (2) digested sludge cake from a digestion plant with a similar Primary to SAS ratio. Steam was used to thermally hydrolyse each sludge mixture at 7 bar pressure, 170 °C for 30 min. The hydrolysed sludge samples were used in a batch digestion rig described below.

2.2. Batch digestion set up

Two batch anaerobic digestibility rigs based on the Water Research Centre (WRc) design (Fernandes and Kimber, 1990) were used in this experiment. They consisted of sixteen 1000 ml graduated bottles, with a heated water bath and gas collection flexible hose system. Sludge digestion process took place in 1-l glass incubation bottles, sealed with rubber bungs with flexible pipes, which were connected to gas collection columns. The bottles were placed in a heated water bath at 38 °C, where the temperature was kept constant. During the course of the experiments, the gas from the incubation bottles was collected in the gas columns allowing the volume to be measured.

2.3. Experiment set-up, analysis and sampling

2.3.1. Thermal hydrolysis process (THP) configuration

In each glass incubation bottle, 75 ml of the raw hydrolysed sludge with 8% sludge dry solid and 76% volatile solid content, was mixed with a digesting sludge seed volume of 725 ml. The total volatile solids load used was 5.65 kg per m^3 digester capacity. Gas production (volume) was recorded at 24 h interval. It should be noted that the gas composition was not measured as it would have meant interfering with the overall digester gas production rendering the results inaccurate.

2.3.2. Intermediate thermal hydrolysis process (ITHP) configuration

Digested hydrolysed sludge cake with 12.5% dry solid and 64% volatile solid content (volatile solid measured before thermal hydrolysis stage) was hydrolysed. Using the batch digestibility rig, in each bottle, 60 ml of the hydrolysed digested sludge was mixed with a digesting sludge seed volume of 740 ml. The seed used was collected from a lab-scale semi-continuous ITHP digester, which had been running for over a year. The total volatile solid load used was 5.63 kg per m^3 digester capacity. Gas production was recorded at 24 h interval.

Sewage sludge was initially sampled at shorter intervals within 24 h of the start of the batch tests. Samples were taken at 0 (initial), 1, 3, 6, 8, 15, 19, and 24 h. This shorter sampling time interval was used in order to investigate carbohydrate degradation as a part of sludge organic matter and its conversion to biogas which is known to take place within a few hours of the setting up of the digesters. After this short period of intensive sampling time, further samples were taken at 24 h intervals extending to 360 h of sludge digestion period. The aim of the extended time sludge sampling plan was to evaluate the rate of the total carbohydrate degradation kinetics and establish the mechanisms involved during anaerobic digestion of high organic matter loaded sludge. For reproducibility purposes, three replicate samples from the batch digestibility experiments were collected and analysed and average values reported in the paper.