Evaluation of anaerobic digestion processes for short sludge-age waste activated sludge

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Abstract
It is well established that waste activated sludge (WAS) with an extended sludge age (normally > 10 days) has inherently poor degradability. The majority of previous research has focused on enhancing the degradability of long sludge-age WAS by using different anaerobic processes or by incorporating different pre-treatment methods prior to anaerobic digestion. However, there is very little information on the properties of short sludge-age WAS. In this paper, the anaerobic digestibility of WAS with an age of 2-4 days was evaluated under three different anaerobic processes, including single-stage mesophilic (37°C) and thermophilic (55°C) anaerobic digestion (AD) and temperature phased anaerobic digestion (2 days at 55°C, followed by 37°C). Degradability extent was strongly linked to sludge age being 85% (2 days), 73% (3 days), and 63% (4 days). Extent was not influenced by digestion temperature. Hydrolysis rates for the 2 day material were the same for thermophilic and mesophilic conditions. However, rate of degradation for 3 and 4 day material was strongly enhanced (by 45%) at thermophilic conditions. This indicates that longer sludge age material is more amendable to pre-treatment than short age material, but that under normal (non accumulation) conditions of 3 days or greater, there is a substantial kinetic advantage in operating at thermophilic conditions.

Keywords
Anaerobic digestion; waste activated sludge; Short sludge-age; Thermophilic; Mesophilic; Temperature phased anaerobic digestion

INTRODUCTION

Many modern wastewater treatment plants (WWTPs) employ biological nutrient removal (BNR) process in their wastewater treatment design, aiming to meet the restricted discharge limits of nitrogen and phosphorus concentrations in the effluent. Waste activated sludge (WAS) is the residue generated in a substantial quantity from this process. It consists of different groups of microorganisms, organic and inorganic matters produced in the process and inert, non-degradable materials from the influent (Batstone and Jensen, 2011). The WAS composition is heavily related to the operation strategies of the BNR process, such as temperature, aerobic/anoxic fraction, and in particular, sludge retention time (SRT), also known as sludge age. The conventional BNR process is designed and operated typically with > 10 days SRT, which benefits nitrification and denitrification, but results in the extended sludge age for WAS (Batstone et al., 2008). The degradability of long sludge-age WAS is inherently poor, e.g. <35% for WAS with an age of >15 days (Gossett and Belser 1982). Therefore, substantial efforts are directed towards investigations of anaerobic digestion of long sludge-age WAS, and a number of pre-treatment methods have been developed and applied prior to anaerobic digestion to improve sludge digestion efficiency.

With the rising importance of sustainable and energy-effective goals of wastewater treatment process, high-rate aerobic treatment processes with (very) short SRTs are emerging as suitable alternatives, due to their low energy and space requirements. This low cost, high-rate process achieves still a degree of nutrient removal through biomass growth and storage, while minimising the organics oxidation in the process. The WAS generated from the high-rate process has a short sludge-age (normally <5 days), which has a huge potential for methane production in the

subsequent anaerobic sludge digestion. However, there is little analysis to evaluate anaerobic digestion performance of short sludge-age WAS. It also has not been established, which anaerobic process (thermophilic or mesophilic) can maximise sludge digestion efficiency, while minimising footprint and energy demands. In this study, the digestion efficiency of WAS with short sludge-ages is evaluated using different anaerobic processes under batch conditions, including thermophilic and mesophilic anaerobic digestion and temperature phased anaerobic digestion (TPAD), to fill the knowledge gaps in this area.

METHODS AND MATERIALS

Biochemical methane potential (BMP) tests

Single-stage thermophilic (55°C) and mesophilic (37°C) anaerobic digestion batch tests in this study were effectively BMP tests based on methods described by Angelidaki et al. (2009). Two-stage TPAD directed batch tests consisted of two independent thermophilic pre-treatment stage (55°C, 2 days retention time) and the second mesophilic stage (37°C, normally 30-40 days retention time). The set-up and operation procedures of two-stage TPAD batch tests were described previously in Ge et al. (2011). Inoculum used in the thermophilic batch tests and the first stage of TPAD batch tests was harvested from a continuous 1 L lab-scale reactor operated at 55°C and 4 days HRT. Inoculum used in the mesophilic batch tests and the second stage of TPAD batch tests was collected from a full-scale anaerobic digester (35°C, 20 days HRT) located in Brisbane, Australia. Substrate used in the batch tests was WAS generated from a lab scale high-rate sequencing batch reactor (SBR) treating abattoir wastewater, with 2 days, 3 days and 4 days sludge age respectively.

All the batch tests were performed in 160 mL non-stirred glass serum vials (100 mL working volume). A inoculum:substrate ratio of around 1.5 (volatile solids (VS) basis) was maintained in all the tests. Bottles were flushed with high purity nitrogen gas for 3 min sealed with a rubber stopper retained with an aluminium crimp-cap, and stored in temperature controlled incubators (±1°C). Blanks contained inoculum and MilliQ water to measure the background methane produced from the inoculum. All tests were carried out in triplicates, and all error bars indicate 95% confidence in the average of the triplicate.

RESULTS AND DISCUSSION

BMP tests

The methane production from each digestion test was monitored, and the methane production curves were fitted to a first order kinetic model. Estimation of sludge degradability (extent of degradation, f_d) and apparent hydrolysis coefficient (rate of degradation, k_{hyd}) was based on gas flow. Figure 1 shows the 95% confidence regions of k_{hyd} and f_d for each sludge digestion test. For the 2 days sludge age WAS, statistically, the three anaerobic processes offered a similar degradability extent (approx. 84%) and hydrolysis rate (approx. 0.29 d^{-1}). For the WAS with ages of 3 days and 4 days, the degradability extents were also similar in the three anaerobic processes, with 73% f_d for the 3 days sludge-age WAS and 63% f_d for the 4 days sludge-age WAS. However, the hydrolysis rate was significantly improved under thermophilic anaerobic digestion compared to others, indicating single-stage thermophilic anaerobic digestion with a short HRT (e.g. 5-8 days) could achieve a high sludge degradability in full scale plants (corresponding to small volume of vessels and capital investments). Additionally, high degradability of the WAS with shorter sludge ages in full scale plants translates to high methane production. This high methane production can be used to produce heat and power for the whole treatment process, which will significantly reduce the energy demands and may achieve a total net energy generation from the process.

It also should be noted that the sludge degradability in this case decreased nearly 10% with every additional day extension of sludge age. This decrease in degradability is very significant, compared to the degradability of longer sludge age (>8 days) WAS, which decreases approximately 3-8% when extending the sludge age by an additional 5 days (Batstone et al., 2011). Moreover, this difference in the sludge degradability can not be easily offset by adding sludge pre-treatment methods prior to anaerobic digestion, as low impact per-treatment methods (e.g. ultrasonic pre-treatment, biological pre-treatment, etc.) generally enhance sludge degradation rates, but not the extent of digestibility (Carrere et al., 2010). Alternative high impact pre-treatment methods (e.g. thermal hydrolysis) can improve degradation extent, but they are capital and energy intensive.

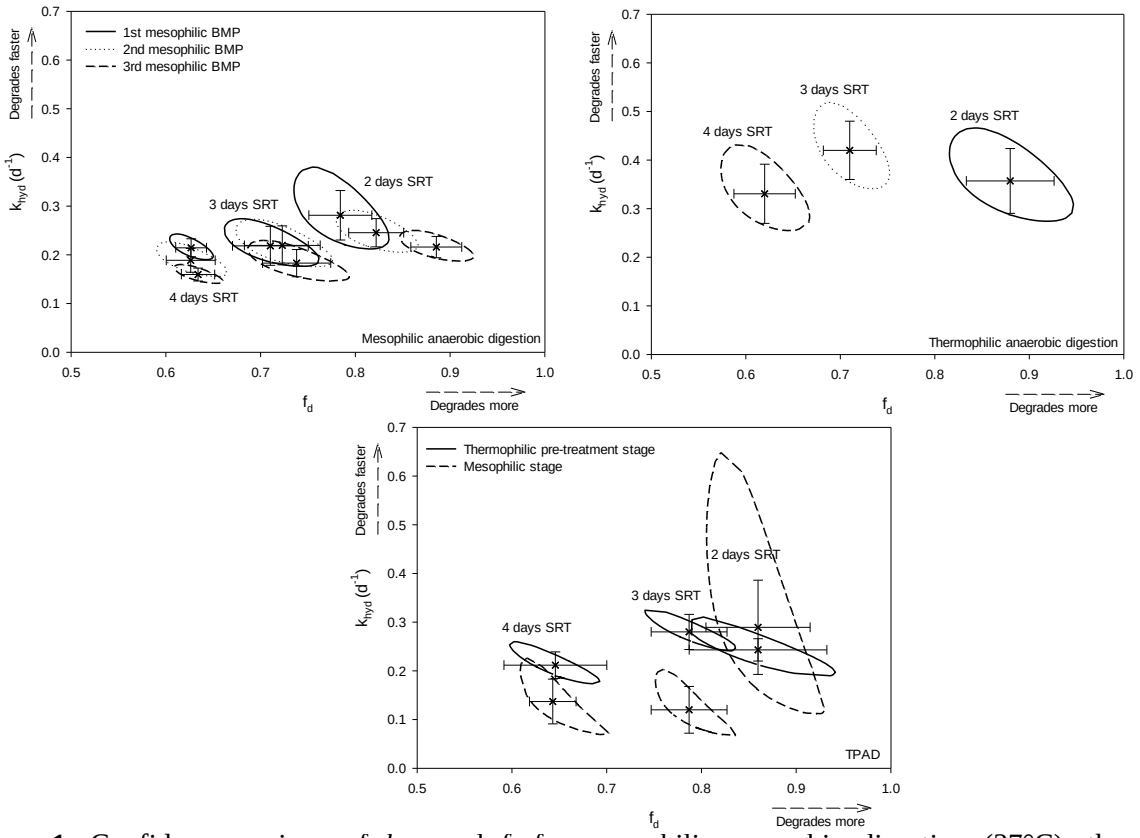

Figure 1. Confidence regions of k_{hyd} and f_d for mesophilic anaerobic digestion (37°C), thermophilic anaerobic digestion (55°C) and TPAD (55°C-37°C) treating the waste activated sludge with ages of 2 days, 3 days and 4 days. (The sludge digestion test for each sludge was repeated twice under mesophilic anaerobic digestion).

Predicted performance curves in continuous digesters

Figure 2 shows expected digester performance for different anaerobic conditions for the 2 days sludge-age WAS (based on model analysis). As can been seen, for a similar VS destruction of 70%, thermophilic anaerobic digestion can achieve it with 10 days HRT, whereas the HRT needs to be extended to nearly 20 days for TPAD, and further to 30 days for mesophilic anaerobic digestion. It suggests that thermophilic anaerobic digestion with a short HRT could be the most suitable method for short sludge age WAS treatment, and implemented easily in a real plant by changing temperature and working volume, rather than building a new digester. To fully assess this, continuous digester performance data is required, which is currently being generated in this study.

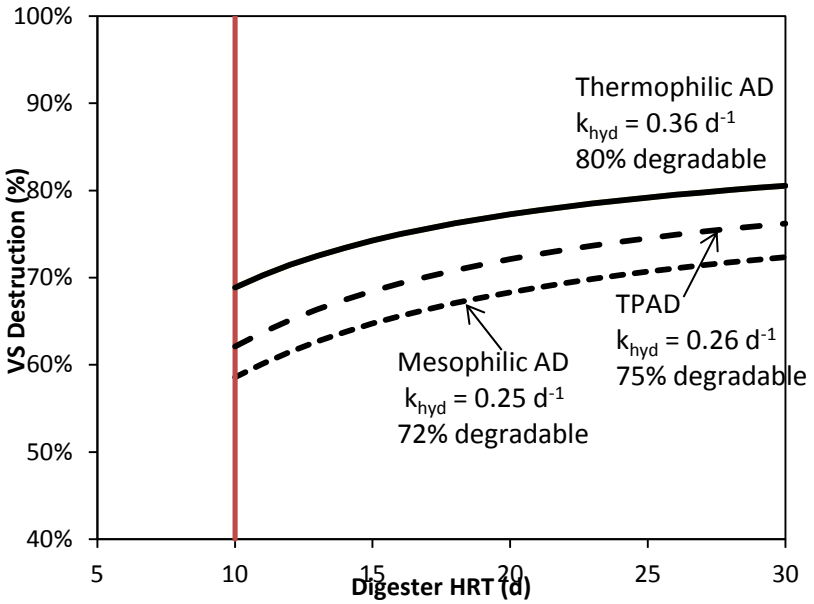

Figure 2. Predicted performance curves for performance vs. hydraulic retention time (HRT) in continuous feed-mixed thermophilic anaerobic digester, mesophilic anaerobic digester and TPAD system fed with the 2 days sludge age waste activated sludge.

CONCLUSIONS

Sludge degradability is substantially influenced by sludge age, almost doubling from 2 days to 4 days. Degradation rate was not influenced by temperature for the low SRT sludge, but the rate was significantly higher at higher temperature for the 3-4 day SRT material, indicating that thermophilic digestion is broadly beneficial except under extreme conditions.

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