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Comparison of pre- and inter-stage aerobic treatment of wastewater sludge: Effects on biogas production and COD removal

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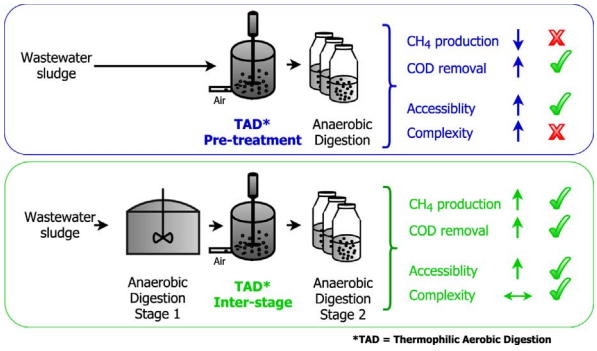
GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study was to investigate thermophilic (55 °C) aerobic digestion (TAD) as pre- and inter-stage treatment of sludge anaerobic digestion and to analyse the change in organic matter accessibility and complexity. Pre-treatment decreased methane yield (up to −70%), due to oxidation losses whereas inter-stage treatment slightly improved overall methane yield (+2.6%) and total COD removal (+5%) compared to control. Anaerobic degradability and COD removal in the second anaerobic stage significantly increased, by 13–40%. Organic matter fractionation showed that TAD led to an increase in sludge organic matter accessibility in all cases. Organic matter complexity, measured by fluorimetry, increased after TAD pre-treatment whereas it remained constant after inter-stage treatment. TAD was shown to be more efficient if applied to a more recalcitrant substrate and should thus be used as inter-stage treatment to avoid decreasing methane production.

1. Introduction

Anaerobic digestion is a proven technology for energy recovery and sludge stabilisation (Pèrez-Elvira et al., 2006). Most substrates–but especially lignocellulosic and bacterial cell biomass–are only partially degraded during anaerobic digestion, and various treatments to increase anaerobic conversion of recalcitrant organic matter have been developed (Carrère et al., 2010; Monlau et al., 2013). Chemical and physical treatments led to increase conversion efficiency but are often energy-intensive and expensive, and chemical treatments can harm

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downstream biological processes (Pèrez-Elvira et al., 2006). To avoid those drawbacks, biological treatments can be used.

Combined aerobic-anaerobic biological treatments more completely degrade sludge and other organic wastes than either does alone. Despite some comparison, exactly how organic matter utilisation differs between aerobic and anaerobic communities is not clear (Burton, 1992; Kumar et al., 2006; Dumas et al., 2010; Tomei et al., 2011; Monlau et al., 2013; Braguglia et al., 2014; Cheng et al., 2015).

Among aerobic treatments, thermophilic aerobic digestion (TAD) has been combined with anaerobic digestion to increase biogas production and organic matter destruction of municipal wastewater sludge. From literature, effect of TAD pre-treatment on COD and VS reduction are unanimous but effects on biogas production are inconsistent (Jang et al., 2014; Dumas et al., 2010; Hasegawa et al., 2000; Pagilla et al., 2000; Ward et al., 1998). One study reported an increase in biogas production from swine manure (Pagilla et al., 2000) and another from wastewater sludge (Jang et al., 2014) but in the latter case it is not clear whether TAD really increased overall methane production as COD mass balance and methane production were not consistent. In other studies aerobic pre-treatment did not affect or even decreased biogas production despite an increase in substrate destruction and anaerobic degradability (Ward et al., 1998; Hasegawa et al., 2000). Co-treatment, where some of the digestate recirculated to the digester is treated in a TAD reactor (65 °C), led to similar results (Dumas et al., 2010). In general, TAD as a pre-treatment for biogas production has not been popular because it oxidises organic matter, leaving much less substrate available for anaerobic conversion (Le, 2006).

Substrates of biological origin contain a mix of materials with a wide range in degradability (Rittmann and McCarty, 2001), and it is the most degradable of these that is oxidised to the greatest extent during aerobic biological treatment. The place of the biological treatment in a production chain influences the success of the process. We hypothesised that inter-stage TAD can increase anaerobic conversion and reduce oxidation loss by ensuring that the most degradable substrate is converted to methane prior to aerobic treatment. This study compared the use of TAD as a pre- and inter-stage treatment in terms of biogas production and organic matter removal during anaerobic digestion of municipal wastewater sludge. Changes in organic matter accessibility and complexity for both configurations were also investigated. Furthermore, we proposed a simple framework for understanding and evaluating aerobic biological treatments.

2. Materials and methods

Four experiments were carried out: two with pre-treatments (P1 and P2), and two with inter-stage treatments (I1 and I2) (Fig. 1). They provided data to evaluate anaerobic degradability and methane production from TAD effluent, to characterise the effects of the TAD treatment and to measure the overall effect of the treatment chain on methane production and COD removal.

2.1. Substrates

Original substrates were raw municipal wastewater sludges and digestates from a wastewater treatment plant producing biogas (VCS, Ejby Mølle, Denmark; treating capacity 385 000 person equivalents) (Table 1). The digesters at the plant are fed a mixture of primary (60%), dewatered secondary sludge (40%) and highly degradable organic waste (depending on availability). Secondary sludge dewatered by centrifugation (including polymer addition) was the substrate in P1, P2, and I2. Secondary sludge alone was used because it is generally to be more recalcitrant to biogas conversion than primary sludge. For I1, original substrate was the full-scale original feed in order to better assess the effect of treatment under the plant conditions.

2.2. Batch thermophilic aerobic digestion

The TAD reactor was 3 L, aerated with compressed air, heated to 55 °C by a heating plate and stirred by three flat blade impellers. TAD feed was dewatered secondary sludge for pre-treatment experiments and digested sludge for inter-stage treatment experiments.

TAD inoculum was collected from a semi-continuous TAD reactor that had been running for at least two weeks, and was fed secondary dewatered sludge every 4 to 5 days. Inoculum was taken before feeding to ensure that its COD was low. Reacting mass was about 1.5 kg to provide sufficient headspace in case of foaming. Inoculum-to-substrate ratio was 1:4 based on wet mass. Mixing rate was >1150 rev·min^{-1} to break up foam. Aeration rate was 0.25 L·L^{-1}·min^{-1} (L air per L reacting mass) at the start of TAD and remained constant for P1 and I2. It was not adjusted after each sampling for P2 and I1 and aeration rate was 0.36 and 0.4 L·L^{-1}·min^{-1} at the end of P2 and I1 respectively. Duration of P1 was 5 days with sampling every 24 h. The other experiments lasted 24 h with 3–4 intermediate samplings (data not shown). Initial samples taken after mixing of TAD inoculum and substrate but before aeration served as controls to evaluate the effect of TAD treatment. For P2, I1 and I2, heat-only samples (55 °C, no aeration) were included to assess the heat effect. Following TAD or heat treatment, all samples were subjected to anaerobic digestion.

2.3. Anaerobic digestion

First stage anaerobic digestion for I1 took place at the full-scale digester of the wastewater treatment plant (37 °C, average HRT of 28.6 days in 2015).

For I2, first stage anaerobic digestion was conducted at 37 °C for 25.5 days in (20 L) stirred reactor in batch mode. Anaerobic inoculum was digestate from the same wastewater treatment plant in all cases. Inoculum-to-substrate ratio was 1:1 based on wet mass (COD ratio ca. 0.5:1).

Post-TAD anaerobic digestion was carried in batch in the laboratory for 20 days at 37 °C. Reacting mass (50–100 g) was put into 0.1–0.5 L glass serum bottles, sealed with butyl septa and screw caps, and flushed with N_2. Target substrate mass was 10 to 16 g of effluent from the TAD reactor. Inoculum-to-substrate ratio was relatively high (2.5:1 based on COD) to avoid any inoculum limitation. Quality of inoculum was checked according to VDI (2006). Contribution of the anaerobic inoculum to the methane volume was measured in inoculum-only bottles and subtracted. All conditions were run in triplicate.

Biogas volume was measured every five days or more frequently using syringes. Measurements were checked using a gravimetric approach (Hafner et al., 2015). Gas samples were collected at each volume measurement in 10 mL vacuum vials and analysed for methane and carbon dioxide using a gas chromatograph equipped with a thermal conductivity detector (Agilent 7890A, column: J & W 113-4332GS – GASPRO, oven temperature 250 °C).

2.4. Sample handling and analysis

COD was measured in triplicate using Hach COD vials (Hach Company, Loveland, CO, USA) based on sample mass. If necessary, samples were stored at 4 °C before analysis for a maximum of 2 days.

Evaluation of accessibility and complexity of the organic matter before and after TAD treatment was done on frozen samples from P1 and I2 following Jimenez et al. (2014, ?). Bioaccessibility was quantified based on COD solubilisation after extractions with successively stronger chemicals (Jimenez et al., 2015). This approach is based on the assumption that bioaccessibility follows chemical accessibility, as it has been shown for wastewater sludge by Jimenez et al. (2014). Fractionation resulted in six fractions as defined in Fig. 2. The more COD is found in the top fractions (DOM, SPOM, REOM), the more the substrate is considered to be accessible (Fig. 2). Fractionation was done in