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Research article

Evaluating the influences of mixing strategies on the Biochemical Methane Potential test

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ABSTRACT

Mixing plays an important role in the Biochemical Methane Potential (BMP) test, but only limited efforts have been put into it. In this study, various mixing strategies were applied to evaluate the influences on the BMP test, i.e., no mixing, shaking in water bath, shake manually once per day (SKM), automated unidirectional and bidirectional mixing. The results show that the effects of mixing are prominent for the most viscous substrate investigated, as both the highest methane production and highest maximal daily methane production were obtained at the highest mixing intensity. However, the organic removal efficiencies were not affected, which might offer evidence that mixing helps the release of gases trapped in digester liquid. Moreover, mixing is required for improved methane production when the digester content is viscous, conversely, mixing is unnecessary or SKM might be sufficient for the BMP test if the digester content is quite dilute or the substrate is easily degraded.

1. Introduction

Anaerobic digestion (AD) has been considered as an efficient approach for its application on waste treatment and renewable energy generation. Many types of organic waste can be degraded and used as feedstock to produce biogas via the AD process. However, the biodegradability (BD) and methane potential of these materials can differ significantly, and these are important parameters for the design, operation and economy of full-scale biogas plant. Therefore, feedstock analysis is necessary prior to the AD process. The Biochemical Methane Potential (BMP) test is such an approach, and it is commonly used to analyse feedstock, i.e., the BD and methane potential (Wang et al., 2014). However, many factors can affect the BMP test and lead to non-comparable results. Intensive studies have focused on substrate pre-treatment, inoculum origin, and digestion temperature, etc. (Carlsson et al., 2012; Facchin et al., 2013; Lianhua et al., 2010), but only a few efforts have been put into controlling the digestion itself with respect to mixing.

Mixing plays an important role in the BMP test due to its influence on the distribution of microorganisms, nutrients and substrate, homogenization of the digester content, alkalinity, release of gas bubbles trapped in the digester content and prevention of sedimentation of particulate material, as well as on evening out the temperature in the digester (Chae et al., 2008; Lindmark et al., 2014; Sánchez et al., 2001). Many studies have shown that the mixing mode and mixing intensity have direct effects on biogas production (Stroot et al., 2001). However, conflicting reports exist on the efficiency of mixing for degradation (Ong et al., 2002) and the evaluation is complicated by differences in waste characteristics, organic loading, mixing systems, active volume, etc. (Ganidi et al., 2009). Various types of mixing are used in the AD process, i.e., mechanical, hydraulic and pneumatic mixing. Among these types, mechanical mixing is the most commonly used in Europe today. Aside from mixing types, mixing mode and intensity, i.e., continuous or intermittent at different frequencies and speeds, can further influence the AD process (Deublein and Steinhauser, 2011; Lindmark et al., 2014). Characterisation of rheological parameters, e.g., viscosity, provides information on fluid behaviour and resistance during mixing, and might be a useful tool for the optimisation of operational mixing conditions and energy savings.

To evaluate the influences of mixing on methane production from the BMP test, BMP assays were performed using substrates

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with different viscosities, i.e., standard substrate cellulose, dewatered sludge (DWS) after aerobic treatment and diluted dewatered sludge with no mixing (NM), shaking in a water bath (SKWB), shake manually once per day (SKM) and automated unidirectional and bidirectional mixing at both low and high intensity.

2. Materials and methods

2.1. Inoculum and substrate

The anaerobic inoculum and DWS used to perform the BMP assays were collected from the Waste Water Treatment Plant (WWTP) in Källby, Sweden. The inoculum was pre-incubated at 37°C for 5 days to decrease the background biogas production (ISO-11734, 1995). Prior to the AD process, the inoculum and DWS were characterized by volatile solids (VS) contents of 3.5% (w/w) and 14.9% (w/w), respectively. The DWS was diluted with distilled water 4 and 8 times denoted 4*DWS and 8*DWS, respectively to create different viscosity gradients. The DWS, diluted DWS and a standard substrate cellulose (VS of 96.08%) (Alfa Aesar, Germany) were used separately as substrates.

2.2. Mixing strategies

Seven different mixing strategies with various types, modes and intensities were applied in this study, i.e., *1)* no mixing (NM), *2)* shaking in a water bath (SKWB, 70 rpm continuously), *3)* shake manually (SKM) once per day, *4)* automated unidirectional mixing at 10 rpm (10 rpm-UDM), *5)* automated bidirectional mixing at 10 rpm (10 rpm-BDM), *6)* automated unidirectional mixing at 160 rpm (160 rpm-UDM) and *7)* automated bidirectional mixing at 160 rpm (160 rpm-BDM). For bidirectional mixing, the mixing direction was changed every 2 min. Mixing strategy 2 was performed with the aid of a water bath (GFL 1086, Burgwedel, Germany), whereas mixing strategies 4–7 were performed continuously using the Automated Methane Potential Test System II (AMPTS II, Bioprocess Control, Sweden AB).

2.3. BMP tests

The inoculum and substrates were added in 500 mL standard bottles (Schott, Germany) at a ratio of 2 based on the VS. The total amount in each bottle was 400 g. Blank bottles were filled up with 400 g of inoculum only. All batch tests were performed in triplicate at 37°C for 30 days. The flow diagram in Fig. 1 shows the operational conditions of all batch tests in this study.

2.4. Analytical methods

The TS and VS of inoculum and substrates were determined according to standard protocol (APHA, 1995) prior to the BMP test. At the end of the test, the VS values of the digestate in the bottles were also determined for analysis of organic removal efficiency (η, VS basis) according to Equation (1) (Poggi-Varaldo et al., 1997).

$$\eta = (VS_{added} - VS_{end})/VS_{added} \quad (1)$$

In Equation (1), η is the organic removal efficiency, VS_{added} (g) is the amount of VS added to each bottle at the beginning of the test, and VS_{end} (g) is the amount of VS at the end.

Viscosity was determined using a rotational rheometer (RheolabQC) with a CC27-SN19237 measuring system and a C-LTD80/QC cell, coupled with Rheoplus software (Anton Paar). The apparent viscosity is the ratio of shear stress (Pa) over the shear rate (s^{-1}). Rheograms, including flow and viscosity curves, were obtained with a three-step protocol according to Björn et al. (2012). Measurements were performed in triplicate at 37°C for all samples at the beginning and ending of the batch test. The fluid behaviour was interpreted by the flow- and viscosity-curves according to Schramm (1994). The Herschel Bulkley model (Equation (2)) was applied to transform rheogram data to the rheological behaviour of the fluids according to Pevere et al. (2006) and Seyssiecq et al. (2003). The certified viscosity reference standard Cannon® RT1000 was used for quality control.

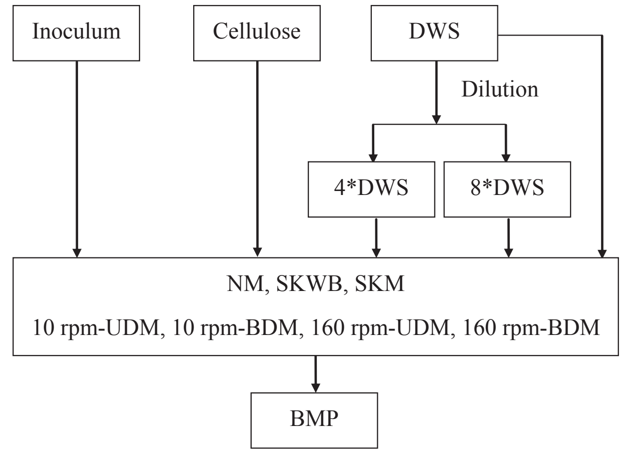

Fig. 1. The schematic graph of BMP tests in this study. Symbols: DWS denotes dewatered sludge; NM denotes no mixing; SKWB denotes shaking in water bath; SKM denotes shake manually; UDM denotes unidirectional mixing; BDM denotes bidirectional mixing.

$$\tau = \tau_0 + K \cdot \gamma^n \quad (2)$$

In Equation (2), τ is the shear stress, γ is the shear rate, τ_0 is the yield stress, K is the consistency index, and n is the flow behaviour index. The dynamic yield stress is defined as the force to which a fluid must be exposed to start flowing.

During the BMP test, the methane volume was recorded automatically by AMPTS II. At the end of the process, a report containing the normalised (standard temperature and pressure, STP: 273.15 K, 101.32 kPa; compensation for water vapour content) accumulated methane production and flow rate was generated for further data analysis. A more detailed description of AMPTS II can be found in Strömberg et al. (2014).

2.5. Kinetic analysis

The hydrolysis constant was calculated for each sample by assuming that the degradation process followed first-order kinetics (Myint et al., 2007; Vavilin et al., 2008).

$$B(t) = B_0 \cdot (1 - exp(-k \cdot (t - \theta))) \quad (3)$$

In Equation (3), $B\ (t)$ is the methane yield (NmL CH_4/g VS) at a given time t (day), B_0 is the value of the ultimate methane yield or maximum value (NmL CH_4/g VS) at infinite digestion time, k is the rate or hydrolysis constant and θ is the lag time constant (day).

2.6. Statistical analysis

Grubbs' test ($P = 0.05$) was used to eliminate outliers in the replicate tests. The significant difference was evaluated by analysis of variance (Single-factor ANOVA, $P \leq 0.05$) in Excel (Microsoft Excel, 2010).

The accuracy of the kinetic analysis was evaluated based on the