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Assessment of increasing loading rate on two-stage digestion of food waste

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HIGHLIGHTS

- Single and two-stage digestion of food waste was compared at increased loading.
- The methane content of the biogas increased by 14% to 71% in the two-stage system.
- The two-stage system yielded up to 23% more methane than the single-stage system.
- The two-stage system produced up to 404 L CH_4 kg^{-1} VS or 15.1 MJ kg VS^{-1}.

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ABSTRACT

A two-stage food waste digestion system involved a first stage hydrolysis reactor followed by a second stage methanogenic reactor. Organic loading rates (OLR) were increased from 6 to 15 g VS L^{-1} d^{-1} in the hydrolysis reactor and from 2 to 5 g VS L^{-1} d^{-1} in the methanogenic reactor. The retention time was fixed at 4 days (hydrolysis reactor) and 12 days (methane reactor). A single-stage digester was subjected to similar loading rates as the methanogenic reactor at 16 days retention. Increased OLR resulted in higher quantities of liquid fermentation products from the first stage hydrolysis reactor. Solubilisation of chemical oxygen demand peaked at 47% at the maximum loading. However, enhanced hydrolysis yields had no significant impact on the specific methane yields. The two-stage system increased methane yields up to 23% and enriched methane content by an average of 14% to levels of 71%.

1. Introduction

The Zero Waste Programme for Europe promotes a circular economy (European Commission, 2015) and encourages a phase out of land filling of biodegradable waste such as the organic fraction of municipal solid waste (OFMSW) by 2025. Anaerobic digestion may be considered a beneficial treatment system for OFMSW due to direct conversion to biogas whilst simultaneously retaining nutrients in the digestate (Murphy and McKeogh, 2004). Food waste (as it has a gate fee associated with its treatment) can provide the most economic source of biogas production (Murphy and Power, 2006). Biomethane potential tests (BMP) highlight the rapid degradability of commercial food waste; 95% of the 30 day BMP yield was achieved in the first 10 days by Browne et al. (2014). Commercial food waste with high degradability should be amenable to low retention times and high organic loading rates.

Single-stage anaerobic digestion is a well-established technology for biogas production. The investment costs are relatively low and the process is well understood. However, hydrolytic and methanogenic microorganisms are optimised at differing pH (Bochmann and Montgomery, 2013). In a single-stage system the prevailing pH (7–8) favours the methanogenic archaea, leading to non-optimum growth conditions for acidifying hydrolytic bacteria.

The advantage of two-stage anaerobic digestion is the spatial separation of process phases, where reactor parameters such as pH can be optimised for each phase to suit requirements of the microorganisms. The pH in the first reactor (between 4 and 6) optimises hydrolysis (Bochmann and Montgomery, 2013). In the upstream reactor hydrolysis and acidification break down macromolecules into liquid fermentation products such as volatile fatty acids (VFAs) and ethanol (Bochmann and Montgomery, 2013), precursors for the methanogens in the second reactor. The effluent from stage one (hydrolysis reactor) is the substrate for the

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downstream second stage methanogenic reactor. Thus the methanogenic archaea have a homogenous feedstock in the form of VFAs and ethanol. The second stage reactor has a neutral pH and operates at longer hydraulic retention times (HRT) of 10–20 days as compared to the hydrolytic reactor (2–5 days).

The two-stage process benefits from enhanced process stability and higher rate of substrate degradation, leading to higher biogas yields from the same amount of substrate (Browne and Murphy, 2014; Massanet-Nicolau et al., 2015; Shen et al., 2013). Another fundamental difference and advantage of two-stage over single-stage systems is the separate gas collection for each reactor (Bochmann and Montgomery, 2013). This allows separate use of the produced gases. Biogas from the acidification reactor consists mainly of carbon dioxide, hydrogen sulphate and hydrogen. Biohydrogen systems may be optimised for hydrogen production in the first stage (Guwy et al., 2011; Li et al., 2009). The short retention time and low pH in the first stage is not amenable to methanogenic archaea, so methane is not produced. The production of carbon dioxide during acidification in the first reactor results in a biogas with enhanced methane content in the downstream methane reactor (Bochmann and Montgomery, 2013). Thus rather than optimise hydrogen production the first stage reactor may be seen as both a pre-treatment system and a partial up-grading system facilitating biogas rich in methane in the second reactor. If the energy vector for biogas is biomethane, then the upgrading facility (CO_2 removal) will be cheaper and less energy intensive for a two-stage system than a single-stage system. This is a significant benefit considering biogas upgrading can cost 30% of the capital cost of the whole biogas/biomethane system (Murphy and Power, 2009).

Previous studies on two-stage digestion have focused on novel equipment testing (Argelier et al., 1998; Browne and Murphy, 2014; Chinellato et al., 2013; Guwy et al., 2011) and hydrogen production (Chinellato et al., 2013; Karlsson et al., 2008; Liu et al., 2013; Luo et al., 2011; Massanet-Nicolau et al., 2015). Massanet-Nicolau et al. (2015) contrasted a two-stage system digesting grass to a single-stage system and highlighted a 13.4% increase in energy yields at a similar retention time. Chen et al. (2015) determined the correlation of acidogenic fermentation types with oxidation reduction potential (ORP), pH, OLR and liquid fermentation products of food waste and rice straw. The literature is very sparse in contrasting one and two-stage digestion of food waste. Gaps also exist in testing continuous two-stage processes at increasing organic loading rates.

Thus the objectives of this paper are to assess a two-stage system through quantification of performance parameters such as hydrolysis efficiency, specific hydrogen (SHY) and methane yields (SMY). The overall energy yield at increasing organic loading rate will be evaluated and contrasted with a similar single-stage system. The objective is not to generate maximum rates of hydrogen but to optimise the acidification process and hence maximise energy yields and organic loading rates.

2. Methods

2.1. BMP system

The biomethane potential of the substrate was tested in an automatic methane potential test system (AMPTS ll, Bioprocess Control, Sweden). The working volume of the batch BMP tests were 400 ml; all tests were run in triplicate for 30 days at 37 °C. The inoculum to substrate ratio was set to 2:1. Carbon dioxide was removed by passing through a sodium hydroxide solution. The methane gas flow is recorded with gas tippers based on water displacement. This system is described in detail by Wall et al. (2013).

2.2. Reactor systems

Two-stage fermentation of food waste was performed at lab scale CSTR in two systems, comprised of a hydrolysis reactor and a methane reactor. The reactors had a total volume of 5 L with an internal diameter of 0.15 m and a height of 0.4 m. The working volume was 1.35 L for the hydrolysis reactor and 4.0 L for the methane reactor (Fig. 1). A third system, a single-stage reactor with the same dimensions as the methane reactor of the two-stage system was also employed (Fig. 2).

A temperature controller unit was installed to maintain a constant temperature in the reactors at mesophilic conditions. An outer heating blanket supplied the heat. A wet gas metre recorded gas flow automatically. Collected biogas was stored in a gas bag for compositional analysis. Mixing was provided by a stirring mechanism, consisting of a vertical shaft with height adjustable paddles at the upper and lower end. A variable speed motor drove the shaft. The shaft of the stirrer was surrounded by a top mounted pipe, which sealed the top of the reactor with the rotating stirrer. The reactors were equipped with a submerged pipe on top of the reactor to prevent gas leakage and oxygen entry during the feeding process. The hydrolysis reactors were fed manually once per day. The input substrate displaced a certain amount of effluent at the lower end of the reactor through a flexible tube. In this way the same level in the reactor was always maintained and representative samples for analysis were obtained.

2.3. Design and operating conditions

Fig. 2 outlines the deployed digestion systems. The reactor configurations were tested with different loading rates, whilst the retention time and working volume stayed the same. The two-stage system was set up in duplicate. The retention time in both two-stage systems was 4 days in the hydrolysis reactor and 12 days in the methane reactor. The single-stage reactor was set to a retention time of 16 days, to match the overall retention time of the two-stage system. This was achieved by diluting the substrate with corresponding amounts of water. The approach is partly academic, yet reflects potential for co-digestion with wastes such as slurry.

The loading rate of the hydrolysis reactors (H1 & H2) was increased gradually, starting with an initial loading rate of 6 g VS L^{-1} d^{-1} and reaching a final loading rate of 15 g VS L^{-1} d^{-1}.

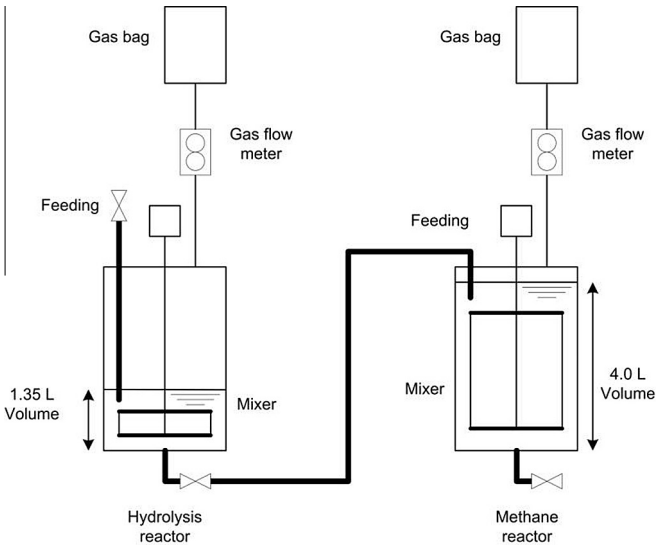

Fig. 1. Schematic of experiment lay out.