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Co-digestion of sewage sludge and crude glycerol for on-demand biogas production

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ABSTRACT

Pilot scale experiments, biomethane potential (BMP) evaluation, and BioWin simulations were conducted to evaluate the intermittent co-digestion of sewage sludge and crude glycerol for on-demand biogas production. BMP tests revealed that both pure and crude glycerols were readily biodegradable. BioWin simulations showed that intermittent glycerol injection at a high (3% v/v) dose might lead to an increase in chemical oxygen demand of the digestate. Results from the pilot scale experiments confirmed that intermittent injection of crude glycerol at both low (0.63% v/v) and high (3%v/v) doses could be used for on-demand biogas production to match the daily fluctuation in energy consumption at a typical wastewater treatment plant. However, in terms of additional biogas production per volume of added glycerol, the lower dose (0.63% v/v) was more effective. The additional methane yield (at the glycerol dose of 0.63% v/v) was 1.3 m^3 per litre of crude glycerol. This value obtained from the pilot scale experiment was higher than that from the BMP test but lower compared to that predicted from the BioWin simulation.

1. Introduction

Anaerobic digestion is a process where microorganisms break down organic materials such as food scraps and manure, in the absence of oxygen, into biogas and biosolids. Biogas is a renewable source of energy, while biosolids are a valuable fertiliser and soil conditioner. Anaerobic digestion plays a vital role for stabilising sewage sludge from municipal wastewater treatment for beneficial reuse or environmental disposal (Park et al., 2006; Yoshida et al., 2013).

In a typical wastewater treatment plant (WWTP), a significant amount of solid material is collected from the settling (i.e. primary treatment) and activated sludge (i.e. secondary treatment) processes. These are collectively called sewage sludge and must be treated prior to disposal for environmental protection. Sludge management can account for up to 60% of the total cost associated with municipal wastewater treatment (Ramakrishna and Viraraghavan, 2005). As a result, significant effort has been devoted toward minimising sludge generation (Semblante et al., 2014) and optimising sludge treatment (Wang et al., 2008; Brisolara and Qi, 2011). Among several options currently available for sewage sludge treatment, anaerobic digestion is probably the most widely used technology.

Until recently little attention was given to the production of biogas by anaerobic digestion (Barber, 2012). Nevertheless, growing concerns about energy security, environmental impacts and increasing energy cost for wastewater treatment have re-instated the anaerobic digestion process as a major renewable energy production technology to the centre of the scientific spotlight (Khanal et al., 2008; Iacovidou et al., 2012; Jenicek et al., 2013; Karthikeyan and Visvanathan, 2013). In particular, using anaerobic digestion to co-digest sewage sludge with other organic waste materials to enhance both biogas production and the quality of the treated biosolids has been proposed and implemented at several WWTPs around the world (Ratanatamskul et al., 2011; Cabbai et al., 2013; Pitk et al., 2013; Wang et al., 2013; Athanasoulia et al., 2014). This can be achieved by using existing anaerobic digestion infrastructure at WWTPs without any significant capital investment.

Glycerol is a notable co-substrate that has received significant scientific and commercial attention in recent years (Fountoulakis et al., 2010; Leoneti et al., 2012; Athanasoulia et al., 2014). Crude

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glycerol is an organic by-product generated from biodiesel production and accounts for about 10% of the total product stream in volume (Santibáñez et al., 2011).

Biodiesel can be produced from renewable feed stocks such as vegetable oil, waste cooking oils and animal fats and as such it is a viable alternative to diesel fuel. Over the last few years, the production of biodiesel has experienced an exponential increase. As a result, there has been a considerable build-up of crude glycerol surplus (Gupta and Kumar, 2012). Inappropriate disposal of crude glycerol can have severe environmental consequences. It is also expensive to purify crude glycerol for reuse. Therefore, the management of crude glycerol can be a major bottle neck to the biodiesel industry (Leoneti et al., 2012). However, crude glycerol can be an ideal organic substrate for co-digestion with sewage sludge as it can be easily handled and stored over a long period of time (Fountoulakis et al., 2010; Leoneti et al., 2012; Razaviarani et al., 2013).

Despite the potential value of crude glycerol as a co-substrate in anaerobic digestion to increase biogas production, it has only recently been studied, mostly at laboratory scale. Fountoulakis et al. (2010) used a laboratory scale digester of 1 L in active volume to conduct co-digestion experiments between glycerol and wastewater sludge. They reported that glycerol addition of 1% (v/v) concentration to the feed can boost biogas yields (Fountoulakis et al., 2010). However, 3% (v/v) glycerol addition could destabilise the system, thus ceasing the anaerobic digestion process (Fountoulakis et al., 2010). In a recent pilot study conducted at the Gold Bar WWTP in Alberta (Canada), Razaviarani et al. (2013) reported that glycerol addition to wastewater sludge at 1.1% (v/v) does not only increase biogas production but also improves the removal of chemical oxygen demand (COD) and volatile solids (VS). Razaviarani et al. (2013) also showed that prolonged glycerol addition at 1.8% (v/v) was detrimental to the anaerobic digestion process.

An interesting aspect that had not been investigated was intermittent glycerol addition to boost the production of biogas during peak periods of energy consumption. Most wastewater treatment plants do not have extensive gas storage facilities to ensure energy demands can be matched at all times by biogas cogeneration. A recent energy review conducted at a WWTP in Sydney (Australia) showed that cogeneration at the plant achieved more than 80% energy self-sufficiency for approximately 18 h of the day, but during periods of peak energy consumption it only produced 50% of the plant's energy needs. Thus, the use of glycerol addition to increase biogas production at the time of need will provide further economic savings and environmental benefits. This study aims to evaluate the intermittent addition of crude glycerol to sewage sludge for on-demand biogas production.

2. Materials and methods

2.1. Wastewater sludge and glycerol

Raw primary sludge was obtained from a full scale sewage treatment plant. Digested sludge (digestate) from the same plant was used as innoculum for the biomethane potential and pilot experiments. Analytical grade glycerol (purity $> 99\%$) was obtained from VWR International (Australia). Crude glycerol was obtained from a biodiesel production facility in Australia and was used without any further purification.

2.2. Biomethane potential experimental protocol

Biomethane potential (BMP) of crude and pure glycerols was measured using customised equipment consisting of fermentation bottles submerged in a water bath and a biogas collection gallery (Fig. 1). The fermentation bottle (Wiltronics Research Pty Ltd) was made of glass. Each bottle (1000 mL) was equipped with a rubber bung with an S-shape air-lock and was connected to a plastic valve and a gas collector through flexible plastic tube. The air-lock is filled with water to allow biogas to escape, but prevents air from entering the fermentation bottle. The bottle was submerged in the water bath (Model SWB20D, Ratek Instrument Pty Ltd) to maintain the temperature at 35.0 ± 0.1 °C. The gas collector comprised a 1000 mL plastic measuring cylinder and a plastic container filled with NaOH (1 M).

Prior to the BMP experiment, all fermentation bottles were flushed with pure N_2 for 5 min before filling with 750 mL of substrate. The substrate consisted of digestate from a full scale plant (which was used as the innoculum) and glycerol. A set of BMP experiments using digestate as the only substrate was also conducted as a reference. The bottle was flushed again with N_2 and immediately sealed with the rubber bung. After placing the bottle into the shaking water bath, the valve was opened to allow biogas to enter the gas collection gallery. To measure the volume of CH_4 generated from the fermentation bottle, the cylinder was first filled with 1 M NaOH solution, and was inverted and then partially submerged into the NaOH container. Biogas from the fermentation bottle was introduced into the submerged part of the cylinder, thus allowing the NaOH solution to absorb CO_2 and H_2S from the biogas. The remaining CH_4 gas displaced the NaOH solution inside the cylinder and the CH_4 gas volume generated was recorded daily. The experiment was terminated when less than 5 mL/day of CH_4 was produced. All BMP experiments were conducted in duplicate.

2.3. Pilot anaerobic digester

A pilot anaerobic digestion system consisting of a single stage 50 L continuously stirred tank reactor was used (Fig. 2). The system was equipped with a Supervisory Control and Data Acquisition unit. The digester was maintained at 35.0 ± 0.1 °C and was inoculated with digested sludge taken from a full scale anaerobic digester treating primary sewage sludge. Primary sludge from the WWTP was fed into the feeding hopper at least twice a week. A peristaltic pump then transferred 104 mL of sludge into the digester every hour on a semi-continuous basis, resulting in a hydraulic retention time (HRT) of 20 days. The digester has an injection port equipped with a non-return valve for dosing liquid substrates into the reactor. The pilot anaerobic digester had been continuously operated for several months before this study. Prior to the addition of glycerol as a co-substrate, the digestion process was operated for one month until a stable biogas flow rate was achieved. This provided a baseline gas flow from which the extra biogas generated by glycerol could be compared.

2.4. Experimental protocol

Continuous addition of glycerol to sewage sludge at high concentration can be detrimental to the anaerobic digestion process. Razaviarani et al. (2013) reported that prolonged glycerol addition at 1.8% (v/v) could destabilise anaerobic digestion. In a previous study, we observed that more than a week of continuous glycerol addition at 3% (v/v) to primary sludge could lead to a severe deterioration in performance of the digester with respect to biogas production and COD or VS destruction (data not shown). Thus, in this study, two glycerol doses of 0.63 and 3.0% (v/v) were investigated using the pilot anaerobic digester. The former represents a dose at which continuous glycerol addition to sewage sludge could be used without any negative effects on anaerobic digestion. The letter represents a high dose at which, continuous glycerol addition