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Increasing biogas production from sewage sludge anaerobic co-digestion process by adding crude glycerol from biodiesel industry

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ABSTRACT

In an effort to convert waste streams to energy in a green process, glycerol from biodiesel manufacturing has been used to increase the gas production and methane content of biogas within a mesophilic anaerobic co-digestion process using primary sewage sludge. Glycerol was systematically added to the primary digester from 0% to 60% of the organic loading rate (OLR). The optimum glycerol loading range was from 25% to 60% OLR. This resulted in an 82–280% improvement in specific gas production. Following the feeding schedule described, the digesters remained balanced and healthy until inhibition was achieved at 70% glycerol OLR. This suggests that high glycerol loadings are possible if slow additions are upheld in order to allow the bacterial community to adjust properly. Waste water treatment plant operators with anaerobic digesters can use the data to increase loadings and boost biogas production to enhance energy conversion. This process provides a safe, environmentally friendly method to convert a typical waste stream to an energy stream of biogas.

1. Introduction

Anaerobic digestion (AD) is a multistage process in which microorganisms breakdown biodegradable material in the absence of oxygen. The AD process starts with hydrolysis of the input materials. During this phase, bacteria convert insoluble organic polymers such as carbohydrates to soluble derivatives. Then acidogenic bacteria convert the soluble sugars and amino acids into carbon dioxide, hydrogen, ammonia and organic acids. Next acetogenic bacteria create acetic acid, ammonia, carbon dioxide and hydrogen from the fermentation products of the previous step. Finally methanogens convert the products of acidogenesis and acetogenesis to methane (Grady Jr et al., 2011). AD is a practical method for degrading and stabilizing primary sewage sludge prior to its disposal (Fountoulakis et al., 2010). In order for a sewage AD facility to operate more economically and efficiently, the production of biogas must increase, which can be achieved through a co-digestion process. Anaerobic co-digestion (AcoD) consists of a mixture of two or more substrates with complementary characteristics, and has proven to be a reliable option for increasing methane yield (Holm-Nielsen et al., 2008). When sewage sludge is combined with highly concentrated organic co-substrates, such as food waste, agricultural waste or crude glycerol from the biodiesel industry, biogas output and organic matter removal can be improved without sacrificing reactor stability or health (Astals et al., 2011). The AD process is a green method that can sustainably convert waste to energy.

The main by-product of biodiesel production is crude glycerol, which is about 10% by weight of the starting materials. Crude glycerol is a mixture of glycerol, alcohol, water, salts, heavy metals, free fatty acids, unreacted mono-, di- and tri-glycerides and methyl esters (Hu et al., 2012). Co-digestion of glycerol with sewage sludge is a promising solution, since a renewable source of energy is obtained from the treatment. Several successful studies, in batch and continuously stirred reactor experiments, have been published with reference to the benefits of the addition of glycerol to enhance the AD of agro-wastes (Amon et al., 2006; Kacprzak et al., 2009), cattle manure (Chen et al., 2008; Robra et al., 2010) fruit and vegetable wastes (Astals et al., 2011; Bouallagui, 2003) organic fraction of municipal solid waste – OFMSW (Fountoulakis and Manios, 2009), pig manure (Alvarez et al., 2010; Amon et al., 2006; Astals et al., 2011; Galí et al., 2009), sewage sludge (Fountoulakis et al., 2010), mixture of pig manure and OFMSW (Schievano et al.,

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2009), mixture of olive mill and slaughterhouse wastewaters (Fountoulakis and Manios, 2009) and mixture of manure and organic industrial wastes (Holm-Nielsen et al., 2009). The amounts are variable and depend on the quality of the feed material and the chemical process used to obtain the biodiesel (Pagliaro et al., 2008; Robra et al., 2010). In certain markets, crude glycerol can be sold depending on purity and availability (Johnson and Taconi, 2007). In other markets, the glycerol has to be disposed of as waste due to market saturation; excessive treatment or refining costs (Pachauri and He, 2006); and lack of direct uses (Pagliaro et al., 2008). The utilization of crude glycerol in AD could benefit the crude glycerol producers as well as the AD operators. Using glycerol as the co-digestate in municipal waste digesters has shown significant increases in biogas production (Fountoulakis et al., 2010). However in order to maintain a stable digestion process, the amount of glycerol added needs to be limited to a certain concentration level. Recommendations for glycerol loading remain low, and vary from 0.05 wt% to 1 wt% to avoid the risk of organic overloading (Fountoulakis et al., 2010; Holm-Nielsen et al., 2008).

The purpose of this study was to evaluate the use of soybean derived crude glycerol as a co-substrate in order to increase biogas production of an anaerobic sewage sludge digester. The effect of glycerol addition on the methane yield was determined in continuously stirred tank reactor experiments. Glycerol load was slowly increased in the reactors providing the bacterial community in the AD time to acclimate to the new food source. From these experiments, the optimum and maximum concentration of glycerol that can be added to the AD for co-digestion was estimated based on reactor stability and health parameters, which are monitored by analysis of volatile fatty acids (VFAs), pH, and alkalinity. The TS/VS of the digestate was continuously monitored to ensure that OLR levels were maintained.

2. Materials

2.1. Substrates

The samples consisted of crude glycerol and primary sewage sludge (primary). The crude glycerol was derived from local biodiesel manufacturing that used soybean oil as its primary source of raw materials. This crude glycerol contained glycerol, fatty acids, methanol, salts and water. The primary sewage sludge, which is untreated municipal waste and digestate (seed), the material remaining after the anaerobic digestion of the waste, were obtained from the Water Pollution Control Authority in Flint, Michigan.

The substrates were initially characterized by determining total and volatile solids (TS/VS) as well as pH. Total solids (TS) were determined by drying at 105 °C for 24 h, and then volatile solids (VS) were found by placing those samples in a 550 °C for 1 h in accordance with APHA standard method 2540 (APHA, 2005). The pH was measured using a Hach SensION3 pH meter. The methanol content was determined by thermal gravimetric analysis and the glycerol content by using GC. These results for the BMP samples are shown in Table 1.

2.2. Biomethane potential

An AMPTS Biomethane Potential (BMP) Test system (Bioprocess Control) was used to initially characterize glycerol and sewage sludge co-digestion. A test series of three replicates was carried out in sealed glass bottles (500 ml) for the crude glycerol co-digested with digestate, which was the liquid material leftover from the anaerobic treatment of sewage sludge at the waste water treatment plant (WWTP), and was compared to a reference series of digestate alone in three replicates. All bottles were loaded with a 2:1 VS (w/w) digestate to substrate ratio to a total of 400 g and placed in a 37 °C water bath throughout the experiment. A 3M NaOH solution was used for scrubbing out all CO_2 from the produced biogas. Once the gas passed through the NaOH scrubbers, the remaining methane entered a calibrated flow cell which recorded the gas production in real time by sending data to the AMPTS software. Prior to the start of the analysis, the system is flushed with nitrogen. The BMP reactors were operated for 30 days. From these experiments the methane production from the glycerol waste and digestate from the WWTP was obtained.

Table 1
Substrate testing.

Sample	TS (%)	VS (% of TS)	pH	Methanol (wt%)	Glycerol (wt%)
Digestate	4.85	61.68	7.1	–	–
Glycerol	78.24	95.03	10.4	5.05	46.5

2.3. Continuously Stirred Tank Reactors

Two Continuously Stirred Tank Reactors (CSTRs) were set up; a control CSTR was run using primary as the only feed and this was compared to a co-digestion CSTR that was run using primary and increasing amounts of glycerol. Reactors were run on a 32 day hydraulic retention time (HRT) determined by Eq. (1) where V is the reactor volume in ml and Q is the daily input flow in ml/day.

$$\mathrm{HRT} = V/Q \qquad (1)$$

Reactors were maintained by feeding 125 ml of new substrate daily and removing digestate to keep the operating volume at 4 L.

The test CSTR began with 1 g of glycerol (with 124 g of primary) and was increased to 10 g, with one additional gram being added every 3–4 weeks. The feeding schedule shown in Table 2 was followed. The stepwise increase in glycerol addition was done to allow sufficient time to buffer changes in primary, and to allow the microorganisms to adjust to new feed stock. Each new batch of primary required TS/VS analysis to determine the OLR. OLR was determined using Eq. (2), where M is total daily mass input flow in kilograms, TS and VS are percentages based on substrate and V is reactor volume in cubic meters.

$$\mathrm{OLR} = (M \cdot \mathrm{TS} \cdot \mathrm{VS})/V \qquad (2)$$

The glycerol content was increased from 19% to 69% of the total OLR. The digesters were run until the glycerol loading became too large (~70 wt% of the total OLR), and the reactor could no longer sustain gas production. This was done to stress test the digester to determine maximum glycerol loading. The gas production from the glycerol waste and primary sludge were compared throughout the test period. The reactors were maintained at 37 °C throughout the experiment. The reactors were operated for approximately 9 months.

2.4. Analyses

Biogas that was produced in the CSTRs flowed through calibrated Ritter wet test meters that continuously measured the biogas production. The amount of gas produced was recorded daily to understand the impact of crude glycerol on the co-digestion. Weekly gas analysis was performed to ascertain the methane content in the biogas, which was expected to vary with crude glycerol loading and primary composition. Due to variations in primary composition, the primary was subtracted from primary and glycerol to understand the contributions of glycerol alone as shown in Fig. 2. Gas analysis was done using a Perkin Elmer Clarus 600 Gas Chromatograph equipped with Perkin Elmer Elite-PLOT Q column and a Thermal Conductivity Detector. Reactor health is defined by key variables that determine stable operating