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Research article

Thermophilic and hyper-thermophilic co-digestion of waste activated sludge and fat, oil and grease: Evaluating and modeling methane production

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ABSTRACT

Renewable energy and clean environment are two crucial requirements for our modern world. Low cost, energy production and limited environmental impact make anaerobic digestion (AD) a promising technology for stabilizing organic waste and in particular, sewage waste. The anaerobic co-digestion of thickened waste activated sludge (TWAS) and sewage treatment plant trapped fat, oil and grease (FOG) using different FOG-TWAS mixtures (20, 40, 60 and 80% of FOG based on total volatile solids (TVS)) were investigated in this study using both thermophilic (55 ± 1 °C) and two stages hyper-thermophilic/thermophilic (70 ± 1 °C and 55 ± 1 °C) anaerobic co-digestion. The hyper-thermophilic co-digestion approach as a part of the co-digestion process has been shown to be very useful in improving the methane production. During hyper-thermophilic biochemical methane potential (BMP) assay testing the sample with 60% FOG (based on TVS) has been shown to significantly increase the maximum methane production to 673.1 ± 14.0 ml of methane as compared to 316.4 ± 14.3 ml of methane for the control sample. This represents a 112.7% increase in methane production compared to the control sample considered in this paper. These results signify the importance of hyper-thermophilic digestion to the co-digestion of TWAS-FOG field.

1. Introduction

With the continuous growth of the world's population and the sharp increase in the demand on energy sources, more attention has been given to renewable and sustainable energy as an alternative to fossil fuel. Renewable energy promises to become one of the main power sources of the future (Zhou et al., 2012). Biogas produced from the anaerobic digestion (AD) of organic wastes contains mainly methane gas which is considered as an economical and environmental friendly biofuel. Methane gas can be used directly to produce heat and electricity or it can be injected into the natural gas distribution network (Alqaralleh et al., 2015).

Due to the continuous increase in population and urbanization, wastewater treatment plants (WWTPs) have a crucial role in decreasing the impact of anthropogenic wastewater production (Coelho et al., 2011; Martín-González et al., 2011). Sewage sludge is the main by-product of the physical, chemical and biological processes implemented during secondary wastewater treatment (Martínez et al., 2012). The quantity of sewage sludge production across the world has increased dramatically due to the increase in the percentage of households connected to municipal WWTPs (Coelho et al., 2011). At present approximately 6.2 million dry metric tons of sludge is produced in the US every year (Kargbo, 2010), about 10.9 million dry metric tons yearly in EU, and more than 660 000 dry metric tonnes of sludge every year from Canadian wastewater treatment facilities (Council, 2012). Therefore, sewage sludge management and disposal have become a critical challenge especially with the diminishing space available for disposal in landfills, increased environmental awareness and more stringent environmental standards for sewage sludge disposal via land application (Jang and Ahn, 2013).

AD has widely been used to treat sludge and different types of organic wastes (Neves et al., 2009; Nayono et al., 2010; Liu et al., 2012; Wang et al., 2014). AD has many advantages such as providing organic mass stabilization and volume reduction, reducing pathogens and odor problems, small space requirements compared to other treatment options (such as landfilling and composting) in addition to the production of methane gas that can

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be used as an energy source. These advantages make AD treatment of solid organic wastes an attractive trend for sludge/waste disposal and bioenergy production (Martínez et al., 2012).

Sludge, particularly waste activated sludge (WAS) has a relatively low biodegradability which makes it hard to digest with limited volatile solids reduction in the single mesophilic anaerobic digestion (Coelho et al., 2011; Mann et al., 2013). Anaerobic co-digestion by adding a co-substrate to sludge prior to AD offers many potential benefits for both substrates such as dilution of inhibitory compounds, increase buffer capacity, more balanced carbon to nitrogen ratio and access to essential micro and macro nutrients (Li et al., 2013; Ara et al., 2015). These benefits provided by co-digestion were demonstrated to result in an increase in biogas production and concomitant organic matter degradation which can be considered responsible for increasing the economic feasibility of waste to energy treatment plants (Martínez et al., 2012). Furthermore, co-digestion has been shown to provide a higher efficiency of land and equipment utilization by digesting different wastes in the same facility (Hosseini Koupaie et al., 2014).

Fat, oil and grease (FOG) is a term commonly used to define the floating layer of lipid-rich waste generated from restaurants, slaughterhouse wastewater, dairy industry and various food processing industries. FOG can be categorized as yellow grease such as waste cooking oil and brown grease also known as trapped grease as it contains yellow grease plus food solids and water (Long et al., 2012). In the past, FOG and greasy wastes were mainly landfilled or land applied but due to increasingly strict environmental legislations in many European and North American municipalities, these types of disposal methods are no longer feasible. As such, other disposal options for collected FOG have been recently emerged including composting, incineration and anaerobic co-digestion (Long et al., 2012).

FOG is an attractive co-substrate to be used in anaerobic co-digestion of sludge due to its high methane potential. The theoretical methane potential of lipids is 1014 L/kg volatile solids (VS) compared to 370L/kg VS for carbohydrates and 740L/kg VS for proteins (Wan et al., 2011). Several studies reported the beneficial effect of anaerobic co-digestion of sewage sludge and FOG (Luostarinen et al., 2009; Mata-Alvarez et al., 2014). However using FOG for anaerobic co-digestion is considered to be challenging due to its inhibitory effects on the anaerobic microbial consortia particularly methanogens mainly due to the high long-chain fatty acids (LCFA) content, as well as operational problems related to clogging, scum formulation and sludge flotation as a result of the adsorption of FOG around the biomass surface (Kim et al., 2004; Long et al., 2012).

AD processes are usually classified as mesophilic AD (temperature 35 °C) or thermophilic AD (temperature 55 °C), but there is a relatively new trend which involves operating the AD process at a higher temperature range of 65–80 °C, which is referred to as hyper-thermophilic AD. Recently various research studies reported the benefits of using hyper-thermophilic AD for increased H_2 production, increased degradation of polylactide with organic waste, and improved stabilization for co-digestion of kitchen waste and sludge (Lee et al., 2009; Cappelletti et al., 2012; Wang et al., 2014; Assawamongkholsiri et al., 2013).

The use of FOG as a co-substrate is not new in literature. However, there is a broad need for more research and published data from lab, pilot and full scale anaerobic co-digestion using FOG in order to establish a comprehensive database that covers the major important conditions related to FOG co-digestion (Long et al., 2012). FOG co-digestion is often studied under mesophilic conditions as mesophilic digestion reduces expenses associated with heating (Liu et al., 2012; Mata-Alvarez et al., 2014). Few studies used thermophilic instead of mesophilic co-digestion of FOG proved the advantage of thermophilic temperature on biogas production (Martín-González et al., 2011). However, thermophilic co-digestion of FOG and TWAS still requires further research especially in determining the optimum FOG% in the thermophilic anaerobic co-digestion mixture in order to reach the ideal co-digestion conditions that maximize methane production. On the other hand, to the best of our knowledge hyper-thermophilic stage has not yet been applied for TWAS-FOG anaerobic co-digestion. Moreover, the use of linear and non-linear regressions has rarely been used to provide mathematical explain to the experimental anaerobic co-digestion observations (Li et al., 2013; Mata-Alvarez et al., 2014).

Therefore, the main objectives of this study are: Introducing the innovative two stage hyper-thermophilic co-digestion of TWAS and FOG at different FOG% and investigate the effects on the methane production and the volatile solids reduction during the anaerobic co-digestion process, investigating the effects of different FOG% (based on TVS) in increasing the methane production from the thermophilic and hyper-thermophilic co-digestion of TWAS-FOG and developing linear and non-linear regression models using the cumulative methane production results from the different co-digestion conditions to help better understanding, comparing and interpreting the co-digestion results.

2. Materials and methods

2.1. Substrates and inoculum

Thickened waste activated sludge (TWAS) was obtained from the thickener centrifuge at the Robert O. Pickard Environmental Center (ROPEC), Ottawa, ON, Canada and contained 4.9 ± 0.2% TS of which 72 ± 1% were volatile solids. FOG samples were provided from the Organic Resources Management Inc. (ORMI), Ottawa, ON, Canada. ORMI provides grease trap cleaning services for different wastewater treatment plants in Ontario. Both substrates (TWAS and FOG) were stored at 4 °C prior to use. The thermophilic anaerobic inoculum (55 °C) was obtained from the effluent of a 10L thermophilic anaerobic digester acclimated to TWAS and operated at a 20 days hydraulic retention time (HRT) in our research lab. Hyper-thermophilic anaerobic inoculum (70 °C) used was the effluent from a 2L anaerobic digester acclimated to TWAS and operated for about 6 months at HRT of 2 days under hyper-thermophilic conditions (70 °C).

The characteristics of substrates and inoculums used in this study are shown in Table 1.

2.2. Biochemical methane potential assays (BMP)

This study included two BMP tests that were run simultaneously using the same sample mixtures (TWAS and FOG) to assess the effect of FOG% in the digestion mixture on the anaerobic co-digestion process and methane production. FOG% (based on TVS) was used, where 0, 20, 40, 60 and 80% were considered. A substrate to inoculum (S/I) ratio of 0.6 ($gTVS_{substrate}/gTVS_{inoculum}$) was used for all the serum bottles of both BMP tests. This S/I ratio was selected to be within the optimum range suggested by Li et al. (2011) for the anaerobic co-digestion using FOG as a co-substrate.

The first BMP is a standard single stage thermophilic BMP (55 °C) assay whereas the second is a two stages hyper-thermophilic (70 °C)/thermophilic (55 °C) BMP assay. To mitigate the pH effects, supplemental alkalinity was added to all the 250 ml BMP serum bottles, which are containing the digestion mixture (TWAS, FOG and inoculum) using equal amounts of $NaHCO_3$ and $KHCO_3$ to provide approximately 4000–5000 mg/L alkalinity as $CaCO_3$. The pH of all BMP bottles was within the ideal range for