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Research article

Improving biogas production from anaerobic co-digestion of Thickened Waste Activated Sludge (TWAS) and fat, oil and grease (FOG) using a dual-stage hyper-thermophilic/thermophilic semi-continuous reactor

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This paper investigates the feasibility and advantages of using a dual-stage hyper-thermophilic/thermophilic semi-continuous reactor system for the co-digestion of Thickened Waste Activated Sludge (TWAS) and Fat, Oil and Grease (FOG) to produce biogas in high quantity and quality. The performance of the dual-stage hyper-thermophilic (70°C)/thermophilic (55°C) anaerobic co-digestion system is evaluated and compared to the performance of a single-stage thermophilic (55°C) reactor that was used to co-digest the same FOG-TWAS mixtures. Both co-digestion reactors were compared to a control reactor (the control reactor was a single-stage thermophilic reactor that only digested TWAS). The effect of FOG% in the co-digestion mixture (based on total volatile solids) and the reactor hydraulic retention time (HRT) on the biogas/methane production and the reactors' performance were thoroughly investigated. The FOG % that led to the maximum methane yield with a stable reactor performance was determined for both reactors. The maximum FOG% obtained for the single-stage thermophilic reactor at 15 days HRT was found to be 65%. This 65% FOG resulted in 88.3% higher methane yield compared to the control reactor. However, the dual-stage hyper-thermophilic/thermophilic co-digestion reactor proved to be more efficient than the single-stage thermophilic co-digestion reactor, as it was able to digest up to 70% FOG with a stable reactor performance. The 70% FOG in the co-digestion mixture resulted in 148.2% higher methane yield compared to the control at 15 days HRT. 70% FOG (based on total volatile solids) is so far the highest FOG% that has been proved to be useful and safe for semi-continuous reactor application in the open literature. Finally, the dual-stage hyper-thermophilic/thermophilic co-digestion reactor also proved to be efficient and stable in co-digesting 40% FOG mixtures at lower HRTs (i.e., 9 and 12 days) and still produce high methane yields and Class A effluents.

1. Introduction

In light of climate changes, environmental challenges and rising energy demand, the quest to develop renewable energy sources has become urgent. A potential renewable energy source which has gained the interest of many researchers recently is biogas harvested from different types of organic waste. Anaerobic digestion (AD) is one of the leading methods used for generating biogas from organic waste (Alqaralleh et al., 2015; Long et al., 2012; Davidsson et al., 2008). Average biogas production in a typical wastewater treatment plant (WWTP) ranges from 15 to 28 L biogas/capita.day (Berktay and Nas, 2008). If this biogas produced using AD is efficiently utilised, it would potentially turn the WWTP into a net energy producer instead of being an energy consumer (Shen et al., 2015a; Cavinato et al., 2013). The US Environmental Protection Agency (USEPA) has recently qualified the biogas from landfills, WWTP anaerobic digesters, agricultural digesters and separate municipal solid waste digesters as a cellulosic biofuel (category D3) under the new Renewable Fuel Standards (RFS2) (Shen et al., 2015b). However, WWTPs are still facing real challenges in deploying biogas production and utilization because of the slow biogas generation rate during the AD process, the low biogas

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energy content (methane%) and the high costs to upgrade the biogas (Gianico et al., 2015).

Sewage sludge, particularly thickened waste activated sludge (TWAS), is usually known for its low biodegradability due to its low carbon to nitrogen (C/N) ratio. This makes it hard to digest under traditional mesophilic conditions (35°C) (Mahanty et al., 2014; Coelho et al., 2011). Therefore, the co-digestion of sludge with other organic wastes can offer several potential benefits for the AD process, such as improving the overall C/N ratio in the digestion mixture, diluting any toxic or inhibitory compounds, increasing the buffer capacity of the digester and improving the overall AD process. All these factors enhance the overall digestion process and increase the digester biogas production (Xu et al., 2015; Ara et al., 2014; Li et al., 2013; Alatriste-mondrago et al., 2006). Different organic materials have been used as co-substrates for the anaerobic co-digestion of sludge. Some examples on these materials are: food waste and Organic Fraction of Municipal Solid Waste (OFMSW) (Alqaralleh et al., 2017; Iacovidou et al., 2012; Esposito et al., 2011; Nayono et al., 2010; Bolzonella et al., 2006), fruit and vegetable waste (Lin et al., 2012; Park et al., 2012), different types of manure (Borowski et al., 2014; Neves et al., 2009), and fatty waste from different sources (Harris and McCabe., 2015; Martínez et al., 2012; Alves et al., 2009; Luostarinen et al., 2009).

Lipid-rich waste, usually known as fat, oil and grease (FOG), is a very attractive co-substrate option for the anaerobic co-digestion of municipal sludge because of its high methane potential, which ranges from 0.70 up to 1.43 m^3 CH_4/kg Volatile Solids (VS) compared to sewage sludge methane potential, which ranges from 0.24 to 0.34 m^3 CH_4/kg VS (Xu et al., 2015; Mata-Alvarez et al., 2014). FOG waste is high in biodegradable volatile solids, which can reach up to 93% (w/w, weight of VS/weight of Total Solids (TS)), and also high in Chemical Oxygen Demand (COD), which can reach up to 1200 kg/m^3 depending on the source of the FOG (Wang et al., 2013). Several researchers have reported the advantages of anaerobic co-digestion of FOG with sewage sludge on biogas production (Sun et al., 2014; Long et al., 2012; Luostarinen et al., 2009); however, the use of FOG for anaerobic co-digestion has been shown to have some inhibitory effects on methanogenic activity if it is used in high concentrations in the co-digestion reactor (Sun et al., 2014; Wan et al., 2011). Moreover, FOG may cause some operational problems in the digester such as foaming, clogging in the liquid or gas system, and biomass floatation due to the adsorption of lipids onto the biomass surface (Mata-Alvarez et al., 2014). For the above-mentioned reasons, FOG dosing rates must be carefully determined to obtain the maximum benefit possible from the FOG addition and to avoid any unwanted adverse effects on the digestion process and the whole AD system.

In some studies, researchers have tried to determine the threshold for FOG addition for the anaerobic co-digestion of FOG and sewage sludge under mesophilic digestion conditions (35°C). For example, Silvestre et al. (2011) found that 23% FOG (w/w) co-digested with (TWAS + Primary Sludge (PS)) for 20 days resulted in a maximum methane yield of 369 L_{CH4}/kg VS_{added} (with 70.0% CH_4) and a VS reduction of 46%. Wan et al. (2011) also showed in a study on a mesophilic semi-continuous reactor co-digesting FOG and TWAS at a 15d Hydraulic Retention Time (HRT) that 36% FOG (w/w) is the proper threshold for producing a maximum methane yield of 598 L_{CH4}/kg VS_{added} (with 66.8% CH_4) and 57% VS reduction. In a similar study, Noutsopoulos et al. (2013) found that the mesophilic co-digestion of 40% FOG with (TWAS + PS) for 15d resulted in a maximum methane yield of 490 L_{CH4}/kg VS_{added} (with 70.0% CH_4) and a 59% VS reduction.

However, thermophilic digestion (55°C) has rarely been used to examine anaerobic co-digestion of TWAS and FOG, and therefore there is no accurate evaluation for the optimum FOG% that can be used safely for the thermophilic anaerobic co-digestion of FOG and TWAS in order to provide maximum methane production with a stable digestion process. Kabouris et al. (2009) performed one of those rare studies, and the authors examined thermophilic semi-continuous reactors for FOG and sewage sludge (TWAS + PS) co-digestion. In their study, the authors found that the threshold FOG% is 48% (w/w) for thermophilic anaerobic co-digestion experiments with 12d HRT. This 48% FOG resulted in a maximum methane yield of 551 L_{CH4}/kg VS_{added} (with 68.7% CH_4) and a VS reduction of 50.9%. The reason behind the prevalent use of mesophilic digestion compared to thermophilic digestion is related to the old belief that the mesophilic process is more stable and has fewer operational problems, and plus it requires less energy to attain the digester temperature as compared to thermophilic conditions (Mao et al., 2015; Kabouris et al., 2009). However, during recent years, conducting anaerobic digestion and co-digestion of sewage sludge and other organic wastes under thermophilic conditions has proved to be useful and more feasible as compared to mesophilic digestion (Coelho et al., 2011). In fact, thermophilic conditions have been shown to be efficient in treating high loading rates, operating efficiently at lower HRTs, producing higher biogas and removing more volatile solids (Martín-González et al., 2011; Kabouris et al., 2009).

Hyper-thermophilic digestion at high temperatures (in the range of 65–80°C) is a relatively new digestion trend that has only been recently introduced (Wang et al., 2012). Wang et al. (2012) and few other recent studies have addressed the benefits of hyper-thermophilic digestion in increasing bio-hydrogen production, improving the degradation of polylactide and enhancing the co-digestion of shredded grass with sewage sludge (Wang et al., 2014; Cappelletti et al., 2012; Lee et al., 2009). As well, to the best of our knowledge, hyper-thermophilic digestion has not yet been used in semi-continuous reactor experimentation for the co-digestion of TWAS and FOG. Hyper-thermophilic/thermophilic co-digestion of TWAS and FOG was proposed and tested for the first time in a Biochemical Methane Potential (BMP) batch tests in Alqaralleh et al. (2016) study. The results of the BMP tests showed clearly that hyper-thermophilic digestion is a promising approach that can be further investigated for the co-digestion of TWAS and FOG using semi-continuous reactors. The high temperature of 70°C (hyper-thermophilic conditions) used in the same study helped greatly in solubilizing the co-digestion mixture, leading to a significant improvement in the anaerobic co-digestion process and recording a 112.7% increase in methane production for hyper-thermophilic co-digested samples that contained 60%FOG compared to a TWAS-only thermophilic-digested sample.

As such, the goal of the current study is to investigate the effects of applying hyper-thermophilic conditions in biogas production from the co-digesting of TWAS and FOG, as well as determining the optimum FOG% that provides the best outcomes. This was conducted by comparing the performance of a single-stage thermophilic anaerobic semi-continuous reactor and a dual-stage hyper-thermophilic/thermophilic anaerobic semi-continuous reactor in co-digesting TWAS and FOG mixtures at three different HRTs: namely, 15, 12 and 9 days. During the experiments, the threshold FOG% that produced the maximum possible methane yield in a stable AD process was determined for both reactors (the single-stage thermophilic reactor and the dual-stage hyper-thermophilic/thermophilic reactor). The performance of the reactors and the biogas production, methane yield, and effluent characteristics were measured and compared to the control reactor (single-stage thermophilic reactor digesting TWAS only). This was done in order to evaluate the effects of FOG% addition, anaerobic digestion temperature, and HRT on the anaerobic co-digestion of TWAS and FOG in a semi-continuous reactor experiment.