Renewable Energy 62 (2014) 73–78

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Co-digestion of sewage sludge and crude glycerol from biodiesel production

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ARTICLE INFO

Article history:
Received 15 May 2012
Accepted 23 June 2013
Available online 19 July 2013

Keywords:
Co-digestion
Sewage sludge
Crude glycerol
Biodiesel
Biogas
Serial digestion

ABSTRACT

Biodiesel has become one of the most attractive fuels since it was globally understood the renewability of its nature. Glycerol is a major byproduct of biodiesel production which is often regarded as a waste stream which is accompanied by a significant disposal cost. The effect of glycerol on the performance of a cascade of two anaerobic continuous stirred tank (CSTR) reactors treating thickened sludge at mesophilic conditions was investigated. The objective of this study was to evaluate the use of glycerol as a co-substrate during the anaerobic treatment of sewage sludge. For this purpose, feed mixtures of sewage sludge supplemented with 0%, 2%, 3% and 4% (v/v) glycerol were tested at hydraulic retention times between 12.3 d and 19.7 d. By adding 4% of glycerol, the system failed due to overloading. In all other cases, biodegradability of mixtures estimated to be higher than 88%, while the methane yield coefficient was 0.8 L_{biogas}/g $TVS_{removed}$. Moreover, co-digestion improved biogas production by 3.8–4.7 times.

1. Introduction

Anaerobic digestion of sewage sludge is a well-known technology due to the energy gained through biogas production as well as due to the achieved sludge stabilization and volume reduction. The heating value (55.5 MJ/kg) of methane, the main component of biogas, is equivalent to 1.2 kg of diesel or 3.7 kg of wood, therefore anaerobic digestion constitutes a continuously more promising technology. Although sewage sludge is digested alone in most application, the use of co-substrates in anaerobic digestion is a growing trend for improving methane yields with several associated benefits. Co-digestion can enhance the anaerobic digestion process, because co-substrates can supply nutrients which may be deficient, and at the same time have an overall positive synergistic effect in the digestion medium, leading to stable digestion and enhanced gas yields [1].

On the other hand, glycerol is a major byproduct of biodiesel production. In general, for every 100 kg of biodiesel produced, 10 kg of glycerol by-product is approximately generated [2,3]. The significant increase in biodiesel production has created a glycerol surplus that has resulted in a dramatic decrease in crude glycerol prices [4]. Moreover, glycerol is a readily digestible substance, which can be easily stored over a long period. As a result, glycerol can be characterized as an ideal co-substrate for the anaerobic digestion process.

Many researchers have studied the influence of glycerol as a co-substrate in anaerobic digestion. During experiments in an upflow anaerobic sludge blanket (UASB) reactor treating potato processing wastewater, Ma et al. [5] found that the biogas production increased by 0.74 L biogas per mL glycerol added. Furthermore, a better biomass yield was observed for the supplemented reactor compared to the control. Additionally, the effects of crude glycerol on the performance of single-stage anaerobic reactors treating different types of organic waste were examined by Fountoulakis and Manios [6]. A reactor treating the organic fraction of municipal solid waste produced 1400 and 2094 mL CH_4/d in the absence and presence of glycerol respectively. Further experiments in batch reactors, at mesophilic temperature, using granular and non-granular sludge, were carried out by López et al. [7]. Results showed a biodegradability of around 100%, with a methane yield coefficient of 0.306 m^3 CH_4/kg when granular sludge-acidified glycerol was used. The organic loading rate during the above mentioned experimental study was

Abbreviations: CSTR, continuous stirred tank reactor; HRT, hydraulic retention time; WAS, waste activated sludge; COD, chemical oxygen demand; VFA, volatile fatty acids; OLR, organic loading rate.

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http://dx.doi.org/10.1016/j.renene.2013.06.040

0.21–0.38 g COD/g VSS d. An inhibition phenomenon was observed at the highest load. On the contrary, when non-granular sludge-acidified glycerol was used, the ORL reached values ranging from 0.12 to 0.26 g COD/g VSS d, methane yield coefficient was 0.28 m^3 CH_4/kg glycerol and biodegradability estimated nearly 75%. Moreover, Siles et al. [8] studied the anaerobic co-digestion of glycerol and wastewater derived from biodiesel manufacturing in batch reactors and mesophilic conditions. Substrate ratios ranged between 5.02 and 1.48 g VSS/g COD corresponding to organic loading rates of 0.27–0.36 g COD/g VSS d. Biodegradability was found to be around 100%, while the methane selectivity coefficient was 310 mL CH4/g COD removed. However, a 6% supplementation of glycerine to pig manure and maize silage that was digested anaerobically, resulted in a significant increase in CH_4 production from 569 to 679 NL CH_4/kg VS [9]. According to Alvarez et al. [10], the highest biodegradation potential (321 L CH_4/kg COD) was reached in batch experiments when 11% of crude glycerol was added at a mixture composed of 84% pig manure and 5% fish waste, while the highest methane production rate (16.4 L CH_4/kg COD d) was obtained by a mixture containing 88% pig manure, 4% fish waste and 8% biodiesel waste.

However, there is lack of knowledge about pilot scale anaerobic co-digestion of glycerol, as the preannounced studies were conducted in bench scale reactors. Moreover a necessity to develop a system of two methanogenic reactors in series was created, based on its advantages concerning biogas production, VFAs concentrations and effluent quality, over other systems. Conventional one-step CSTR is simple to operate but less efficient in terms of the effluent quality compared to other reactor configurations such as upflow anaerobic sludge blanket (UASB) reactor or two-phase reactor system. According to Angelidaki et al. [11], a single CSTR can lose biogas production due to “short-circuit”, where a fraction of the organic material in the feed remains over a shorter duration in the reactor than the nominal retention time. Concerning the use of UASB reactors, sludge characteristics (high viscosity and particulate content) makes UASB reactors unsuitable for sludge treatment. On the other hand, a two-phase system, where a short acidogenic step is followed by a long methanogenic step, is sensitive to high organic load and any separation processes that can be utilized increase costs [12]. An alternative approach to overcome the above mentioned problems is to operate two methanogenic reactors connected in series. Only few studies have been reported about serial digestion of other substrates as manure [13,14], primary sludge [15] and secondary sludge [16]. Boe [13] demonstrated that serial digestion of manure, with percent volume distributions of 90/10 or 80/20 between the two methanogenic reactors, improved biogas production by 11% compared to a traditional one-step CSTR process. According to Kaparaju et al. [14] serial digestion at 70/30% and 50/50% volume distribution produced 13.0–17.8% more biogas and methane while at the same time contained low VFA. The residual methane potential loss was also lower in the effluent compared to the one-step CSTR process. In our previous study [16] where anaerobic digestion of sewage sludge was compared to that of a one stage CSTR system, results showed that the serial configuration could improve biogas production by 9.5–40.1%. According to the authors, there are no other experimental results regarding serial digestion of two methanogenic reactors of a mixture of sewage sludge with glycerol.

In this study, the effect of glycerol on the performance of a pilot scale cascade of two anaerobic continuous stirred tank (CSTR) reactors treating thickened sludge at mesophilic conditions was investigated. The objectives were a) to evaluate the use of glycerol as a co-substrate to improve biogas production and b) to determine the optimum hydraulic retention time and the most adequate ratios of different feedstock mixtures that provide an optimized biodegradation rate or methane production.

2. Materials and methods

2.1. Feedstock

The raw material used as co-substrate was a glycerol-containing waste discharged after the biodiesel manufacturing process at the ELVI Factory in Kilkis, Greece. In general, this waste contained glycerol, water, methanol and soaps, as shown in Table 1. Secondary thickened sludge was obtained from municipal wastewater treatment plant in Komotini, Greece, which operated under extended aeration conditions.

In order to prepare feed materials, crude glycerol was diluted ten times and a new glycerol-containing solution of 100 g/L COD was stocked. By mixing 20% of this solution and 80% of waste activated sludge (WAS), an influent mixture of 2% (v/v) crude glycerol was produced. Similarly, mixtures of 3% and 4% crude glycerol were prepared.

2.2. Reactor experiments

The mesophilic anaerobic digestion of glycerol and waste activated sludge mixtures was investigated using a cascade of two continuous stirred tank reactors (CSTR) operated over a range of hydraulic retention times (12.3 d–19.7 d) at organic loading rates between 1.0 and 1.7 kg COD/m^3 day (Fig. 1). The mixture of thickened WAS with glycerol was continuously pumped into the first-digester, the effluent of which overflowed to the second-digester unit. The working volumes of the digesters were 40 L and 60 L respectively. Constant sludge volumes inside the reactors were maintained by a level controller in each digester. Moreover, biogas production in each reactor was continuously monitored by a volumetric gas meter. The concentrations of methane and carbon dioxide in the biogas were continuously measured using an on-line gas analyzer (BINOS IR, Leybold-Heraeus). The optimal temperature was controlled at 37 °C by circulating hot water inside the water jacket of the reactors. pH value was maintained constant at 6.8–7.2 by a pH controller.

Three series of experiments were carried out with feed mixtures of sewage sludge supplemented with 0% (v/v) (control), 2% (v/v), 3% (v/v) and 4% (v/v) glycerol in order to investigate the limiting concentration of glycerol in the feed that affect the anaerobic digestion. For all cases, in order to find the optimum operation conditions of the process, hydraulic retention times of 12.3, 14.0, 16.4 and 19.7 d were also examined. According to the available literature, standard hydraulic retention times in a high-rate digester without sludge recycle are 15–20 days [17]. However, a well mixed and heated digester may produce good quality digested sludge after a 10 day retention time [18,19].

2.3. Analytical methods

Standard Methods for the Examination of Water and Wastewater [20] were used for the estimation of suspended solids (SS),

Table 1
Chemical analysis of glycerol and sewage sludge characteristics.

Parameter	Crude glycerol	Parameter	Sewage sludge
Water	15.7%	VSS	19.6 g/L
Methanol	7.1%	sCOD	0.58 g/L
Soaps	26.5%	Conductivity	380 μS/cm
Glycerin	50.6%	pH	7.12
Catalyst (CH_3ONa)	0.1%		
pH	10.7		
COD	1000 g/L		