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Research Paper

Obtaining green energy from dry-thermophilic anaerobic co-digestion of municipal solid waste and biodiesel waste

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This study has been conducted to optimise the dry-thermophilic anaerobic co-digestion of two different types of real waste (municipal solid waste and biodiesel waste) in a semi-continuous feeding regime, under high organic loading rates (OLRs) or low hydraulic retention times (HRTs). For this purpose, different high OLR_s (from 10 to 34 g [VS] l^{-1} d^{-1}) or low HRT_s (from 10 to 4.4 d) were investigated in a continuously stirred tank reactor. Optimal conditions (257 ml [CH_4] g^{-1} VS; 6.03 ± 0.43 l [CH_4] l^{-1} d^{-1}; $16.3 \pm 2.3 \times 10^{-12}$ l [CH_4] $cell^{-1}$ d^{-1}) were obtained at 4.4 d HRT (OLR = 23 g [VS] l^{-1} d^{-1}), in which the average values of the ratios of *Eubacteria:Archaea* and hydrolytic-acidogenic bacteria:acetogens were 95:5 and 87:8, respectively.

1. Introduction

High energy demand and waste production have been brought to light as a result of increasing public health concerns and environmental awareness. As a result, biodiesel waste and municipal solid waste have become an ecological problems. The average solid waste generation rate in 23 developing countries is 0.77 kg $person^{-1}$ d^{-1} (Troschinetz & Mihelcic, 2009) and this is increasing. Anaerobic digestion (AD) represents an opportunity to decrease environmental pollution whilst at the same time providing biogas and material that can be used as organic fertiliser or carrier material for biofertilisers (Demirel, Ergun, Neumann, & Scherer, 2009; Feng, Wahid, Ward, & Møller, 2017; Owamah & Izinyon, 2015; Scarlat, Motola, Dallemand, Monforti-Ferrario, & Mofor, 2015; Vlyssides, Tsimas, Barampouti, & Mai, 2012; Wang, Ai, Yu, Tan, & Zhang, 2012, 2015). Using AD, waste is converted into methane (CH_4) and carbon dioxide (CO_2). AD includes four steps and is performed by a microbial consortia comprising both *Eubacteria* (hydrolytic-acidogenic bacteria (HAB)) and acetogenic bacteria (acetogens) and *Archaea* (H_2-utilising methanogens (HUM) and acetate-utilising methanogens (AUM)). Studies on the AD of municipal solid waste (MSW) have shown that the C/N ratio of this waste presents average

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Nomenclature

AD	Anaerobic digestion
Alk	Alkalinity
AUM	Acetate utilising methanogens
BUA	Butyrate utilising acetogens
BW	Biodiesel wastes
CSTR	Continuously stirred tank reactor
FISH	Fluorescence *in situ* hybridisation
GP	Gas production
HAB	Hydrolytic acidogenic bacteria
HRT	Hydraulic retention time
HUM	Hydrogen utilising methanogens
MP	Methane production
MSW	Municipal solid waste
OLR	Organic loading rate
PUA	Propionate utilising acetogens
SCOD	Soluble chemical oxygen demand
SMP	Specific methane production
SRT	Solid retention time
TCD	Thermal conductivity detector
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids

values of 10:1, below the optimum for anaerobic digestion (25:1) (Fiore, Ruffino, Campo, Roati, & Zanetti, 2016; Forster-Carneiro, Pérez, & Romero, 2008), while methane production (MP) is reduced due to the washing of microorganisms and not to overloading (Zahedi, Sales, Romero, & Solera, 2013a, b). Therefore, an increase in the loading rate of the AD process via the addition of readily biodegradable organic substances such as glycerol, a major by-product of biodiesel production, could be an ideal strategy (Fountoulakis & Manios, 2009; Fountoulakis, Petousi, & Manios, 2010; Zahedi, Solera, García-Morales, Ennouri, & Sales, 2017b). Biodiesel manufacturing worldwide has gained importance for several reasons: (i) The unavailability of fossil fuels due to demographics and political instability; (ii) Modern methods of biodiesel production and new catalyst formulations producing higher biodiesel yields; (iii) the breeding and cultivation of new varieties of oil crops with higher yields of lipid; (iv) an increase in the cultivation of inedible oilseed plants on waste land; (v) new engine designs that can utilise biodiesel and its admixtures as fuel; and (vi) stringent regulations for reducing global greenhouse gas emissions (Avhad & Marchetti, 2015; Dwivedi, Jain, & MP, 2011; Khuntia, Chanakya, Siddiqha, Thomas, & Mukherjee, 2017). Every 100 kg biodiesel yields approximately 10 kg glycerol or biodiesel waste (BW) as a waste stream (Razaviarani, Buchanan, Malik, & Katalambula, 2013), which makes its disposal a fundamental environmental concern. Recent studies have also shown the effectiveness of single-phase dry-thermophilic AD of real municipal solid wastes (MSW) in methane production (MP) (Zahedi, Sales, Romero, & Solera, 2013a), and that biodiesel wastes (BW) supplementation (0.5% v/v) improves the methane production steps in thermophilic-dry dark fermentation of MSW in batch mode (Zahedi et al., 2017b). However, no previous studies have been published on the effects of adding BW to the single-phase dry-thermophilic AD of MSW in a semi-continuous feeding regime on MP or on the effect on the different microbial groups involved in the digestion process. The present study was accordingly carried out, the two objectives of the study being: (1) to establish the optimal conditions (organic loading rate (OLR) or hydraulic retention time (HRT)) to maximise CH_4 production; and (2) to investigate the population dynamics in dry-thermophilic anaerobic co-digestion of MSW and BW (0.5% v/v).

The study was carried out in a laboratory-scale reactor under high OLRs ranging from 10 to 34 g [VS] l^{-1} d^{-1} or low HRT_s ranging from 10 to 3 d. The structure and dynamic of the anaerobic consortia that developed during the different operating periods (OLR_s or HRT_s) were analysed by fluorescent *in situ* hybridisation (FISH), employing different oligonucleotide probes. Moreover, the effect of the variations of the operational parameters (OLR or HRT) on pH, alkalinity, organic matter consumed, biogas production, microbiological population dynamics and microbial activity were considered to establish the optimal conditions for the single-phase dry-thermophilic AD of MSW and BW under low HRT. These aspects are important, as short pre-treatment times are preferable for practical applications, because they reduce the volume of the required pre-treatment tank (Zahedi, Icaran, Yuan, & Pijuan, 2017a). Also, it is worth noting that the AD of MSW and BW allows a reduction in greenhouse gas emissions to the atmosphere and has the economic advantage of sharing equipment and costs to treat two different wastes in the same digester simultaneously.

2. Methods

2.1. *Experimental equipment and operating conditions*

Single-phase dry-thermophilic AD producing CH_4 in a continuously stirred tank reactor (CSTR) at the laboratory scale was employed in thus study. A 5 l reactor without biomass recycling was used for this purpose, the HRT and the Solid Retention Time (SRT) being equal. Thermophilic conditions (55 °C) were maintained by circulating water through the jacket from a thermostatic water bath. A PRECISTERM 6000142/6000389 (SELECTA S.A.) bath was used, with a maximum capacity of 7 l water. The reactor was continuously mixed using mechanical stirrers (23 rpm) and was equipped with a biogas outlet and a feed inlet. The gas volume produced in the reactor was emptied into Tedlar gas bags (40 l).

As to the feeding regime, the reactor was fed once a day (semi-continuous regime). Four different OLR_s (10–34 g [VS] l^{-1} d^{-1}) or HRTs (10–3 d) were tested (Table 1). The overall duration of the experiments was 93 d. The study was considered concluded when increasing OLR_s (decreasing HRT_s) resulted in a decrease in MP.

2.2. *Inoculum and substrate*

Anaerobic digester effluent from single-phase dry-thermophilic AD of MSW was used as inoculum. The total solids (TS)