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Energy recovery from one- and two-stage anaerobic digestion of food waste

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ABSTRACT

One- and two-stage anaerobic digestion of food waste aimed at recovering methane (CH_4) and hydrogen and methane ($H_2 + CH_4$), respectively, were compared in order to assess the potential benefits from the two-stage process in terms of overall energy recovery. Results suggest that a two-stage process where the first reactor is properly operated in order to achieve a significant net hydrogen production, may display a 20% comparatively higher energy recovery yield as a result, mainly, of enhanced methane production as well as of the associated hydrogen production. The highest methane production of the two-stage process was due to improved hydrolysis and fermentation of food waste, with increased amounts of volatile fatty acids being readily available to methanogenesis.

1. Introduction

In current applications of anaerobic digestion (AD) systems, organic matter is converted into a mixture of gaseous compounds, mainly methane (CH_4) and carbon dioxide (CO_2), via acid fermentation and volatile fatty acids (VFAs) degradation, and through the activity of two groups of microorganisms: acid-forming and methane-forming bacterial biomass, respectively (Zhang et al., 2016). In a single-reactor system, namely one-stage anaerobic digestion (1S-AD), those microorganisms are kept together in a balance, which is delicate, because both groups differ widely in terms of physiology, nutritional needs, growth kinetics, and sensitivity towards environmental conditions (Demirel and Yenigün, 2002). By way of example, the pH prevailing in 1S-AD systems (pH between 7 and 8) does not provide optimal growth conditions for acidifying hydrolytic bacteria, leading to inefficient hydrolysis/fermentation rates (especially for slowly degradable lignocellulosic substrates) and, in turn, diminishing biogas production (Giovannini et al., 2016). Considering these aspects, Pohland and Ghosh (1971) proposed the two-stage AD system (2S-AD), where the sub-processes organic matter hydrolysis and its fermentation to organic acids are physically separated from the methane production process.

Since then, the comparison of the performances of 1S-AD and 2S-AD has been debated extensively, and advantages/drawbacks of both systems have been considered and evaluated by several authors (Demirel and Yenigün, 2002; Reith et al., 2003; Han and Shin, 2004; Liu et al., 2006; Gómez et al., 2006, 2009; Ueno et al., 2007; Cooney et al., 2007; Chu et al., 2008; Thompson, 2008; Dong et al., 2011).

In 2S-AD systems, the physical separation of the reactors responsible for the two independent processes enables optimal conditions for the acidogenic and the methanogenic bacterial biomass to be established, thus optimising specific metabolic activities and ultimately maximising methane generation (Schievano et al., 2014). Moreover, the first acidogenic reactor may act as an effective buffer against sudden pH drops caused by accumulation

Abbreviations: 1S-AD, one-stage anaerobic digestion system; 2S-AD, two-stage anaerobic digestion system; AD, anaerobic digestion; AS, activated sludge; CSTR, continuously stirred tank reactor; DOC, dissolved organic carbon; FW, food waste; G_{max}, maximum gas yield; ISR, inoculum-to-substrate ratio; MS, methanogenic sludge; OBS_{H2}, observed H_2 production; R_{max}, maximum gas production rate; SER, specific energy recovery; SHP, specific hydrogen production; SMP, specific methane production; t_{95}, time required to attain 95% of the maximum biogas yield; TAN, total ammonia nitrogen; $THEO_{H2}$, theoretical H_2 production; TOC, total organic carbon; TS, total solids; VFAs, short-chained volatile fatty acids; VS, volatile solids; λ, lag phase duration.

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of VFAs, which may hinder methanogenic microorganisms. As a consequence, higher process reliability, resilience, stability, as well as higher substrate conversion are anticipated for 2S-AD systems.

Nevertheless, 1S-AD is a well-established system for the treatment of organic waste, characterised by a simple set-up and relatively limited investment and operating costs, and as a matter of fact most of the full-scale digestion plants in Europe (90% of the installed AD capacity) are designed and operated as one-stage systems (Rapport et al., 2012). A major drawback with 1S-AD is that the produced biogas is frequently reported to display a poor quality in terms of its calorific value (Zhang et al., 2015; Sunyoto et al., 2016).

The issue of operating AD in the 2S-AD configuration has become again topical in recent years as a result of the interest aroused by the possibility of producing bio-hydrogen from organic substrates through dark fermentation (Lee and Chung, 2010; Dong et al., 2011; De Gioannis et al., 2013; Cappai et al., 2014). Indeed, under appropriate operating conditions, facultative or strict anaerobic microorganisms are able to convert organic substrates into bio-H_2 through fermentation; the H_2 produced is recoverable, provided that a harsh environment for hydrogenophylic methanogens is guaranteed. In addition to H_2 and CO_2, which are the most abundant gaseous products, a mix of volatile fatty acids (VFAs) and reduced end products including alcohols is generated as well, which is suitable for further valorisation. This can be accomplished through a variety of potential alternatives, differing for the type of process applied and/or the characteristics of the resulting product (s). The subsequent treatment phase downstream of fermentation may possibly include: 1) a second anaerobic digestion stage for CH_4 production; 2) a photofermentation stage aimed at H_2 production; 3) a microbial electrolysis cell devoted to H_2 production; 4) a microbial fuel cell for direct electricity generation; 5) a biochemical stage for biopolymer production. Hydrogen has the highest energy content per unit weight (142 MJ/kg) of any known gaseous fuel, and sequential H_2 and CH_4 production is, from a theoretical point of view, energetically more favourable than 1S-AD (Dong et al., 2009); from a practical point of view, the two gas streams may be valued individually, or mixed to form a hydrogen-enriched biogas (namely bio-hythane) characterised by an improved quality for gas engines applications (Porpatham et al., 2007). However, H_2 recovery through dark fermentation of organic substrates is not yet considered neither technically reliable nor commercially attractive. Assessing the increased overall energy recovery and, in particular, also higher CH_4 yields of 2S-AD systems could greatly contribute to the affirmation of fermentative hydrogen production as a viable process.

Few studies are available that provide ultimate answers about the advantages of AD operated in two distinct phases (Aslanzadeh et al., 2014); even fewer, in particular, provide a comparison between 1S- and 2S-AD where the latter is contextualised and focused on the possibility of combining the recovery of both H_2 and CH_4 from a complex substrate such as food waste (FW). Voelklein et al. (2016) operated a two-stage anaerobic CSTR observing a methane yield from FW ranging between 371 and 419 NL CH_4/kg VS, 23% higher than from the one-stage process; no data on H_2 production were observed because, as reported by the authors, the goal was to optimise the acidification process and maximise methane yield rather than to produce H_2. Grimberg et al. (2015) achieved a methane production yield from FW of 446 NL CH_4/kg $VS_{removed}$ in a two-stage CSTR-based process, fairly higher than the yield of 380 NL CH_4/kg $VS_{removed}$ observed in a one-stage process (no available data about H_2 production were provided). Aslanzadeh et al. (2014) evaluated the effects of organic loading rate and hydraulic retention time on CH_4 production in one- and two-stage systems treating municipal FW: a maximum methane production of 380 NL CH_4/kg VS was obtained in the two-stage process versus a maximum of 330 NL CH_4/kg VS observed in the one-stage. Nathao et al. (2013) compared the performance of one- and two-stage mesophilic AD of FW in batch reactors at varying ratios of feedstock to microbial inoculum (F/M), observing yields of 55 NL H_2/kg VS and 94 NL CH_4/kg VS at food to microorganisms ratio of 7.5 in the two-stage process, to be compared with a CH_4 yield of 82 NL/kg VS attained in the one-stage system. Interesting economic considerations were derived by Lee and Chung (2010) who managed a two-stage pilot-scale process treating FW, connected to a PEM (Proton Exchange Membrane) fuel cell. When single CH_4 and combined $H_2 + CH_4$ production were compared, negligible differences in the production costs were estimated, whilst a gain by 12–25% in terms of overall energy production was observed for the two-stage system.

The objective of the present study was to compare 1S- and 2S-AD of a complex substrate (FW) aimed at recovering CH_4 and $H_2 + CH_4$, respectively. Batch tests were performed under mesophilic conditions, the performances in terms of H_2 and CH_4 yields and volatile solids removal efficiency were evaluated, and the overall energy recoverable from the two AD systems was estimated.

2. Materials and methods

2.1. Substrate and inocula

Due to the inherent heterogeneity of municipal FW, a standardised FW was used in the present study to allow repeatable and directly comparable experiments. FW was prepared by mixing (on a wet weight basis) 10% of meat, 65% of fruit and vegetables, 10% of bread and 15% of cooked pasta. Due to their tendency to rapid degradation, FW samples were purposely prepared for each experiment by mixing the individual components and shredding the obtained mixture with a blender (RETSCH Knife Mill Grindomix GM200) to a final particle size below 2 cm. This particle size range was adopted in order to be compatible with the pumping and mixing systems of the bench-scale reactors. The adopted shredding conditions were capable of producing a homogeneous mixture while keeping energy consumption to a minimum, in accordance with a typical AD process layout.

Activated sludge (AS) from the aerobic unit of a municipal wastewater treatment plant was used to inoculate the first phase of the 2S-AD test, without performing any specific treatment to inhibit methanogens, as suggested by the results presented in Cappai et al. (2014).

Methanogenic sludge (MS), collected from the anaerobic digester of a municipal solid waste treatment plant operated under mesophilic conditions at an HRT of 14–16 days, was used as the inoculum in both the 1S-AD test and in the second phase of the 2S-AD test. The MS inoculum was preliminarily maintained under anaerobic conditions in the reactor at 39 ± 1 °C until biogas production stopped in order to deplete the residual biodegradable organic material, as also suggested by Raposo et al. (2011).

The main characteristics of the FW, of the inocula and of the feeds are shown in Table 1. As the feeds were analysed before each experiment, the values in Table 1 are reported as mean and standard deviations of 4 replicates, while FW and inocula were analysed in triplicate.

2.2. Experimental set-up

The methanogenic test (1S-AD) was conducted in a batch mode at 39 ± 1 °C using a 2-L glass reactor (BIOFLO 110 - New Brunswick Scientific; BioCommand Lite software; 1.8 L working volume). An inoculum-to-substrate ratio (ISR) of 2 g $VS_{inoculum}$/g $VS_{substrate}$ was adopted in order to limit inhibition effects associated with