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Thermal hydrolysis integration in the anaerobic digestion process of different solid wastes: Energy and economic feasibility study

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HIGHLIGHTS

- Thermal hydrolysis pretreatment to anaerobic digestion is energetically evaluated.
- Six different solid wastes have been studied.
- Energy integration leads to important savings (5 €/tonne raw waste).
- Thermal hydrolysis enhances up to 40% the incomes of the digestion plant.
- In a MSW full-scale plant, thermal hydrolysis provides almost 0.5 M€/year benefits.

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ABSTRACT

An economic assessment of thermal hydrolysis as a pretreatment to anaerobic digestion has been achieved to evaluate its implementation in full-scale plants. Six different solid wastes have been studied, among them municipal solid waste (MSW). Thermal hydrolysis has been tested with batch lab-scale tests, from which an energy and economic assessment of three scenarios is performed: with and without energy integration (recovering heat to produce steam in a cogeneration plant), finally including the digestate management costs. Thermal hydrolysis has lead to an increase of the methane productions (up to 50%) and kinetics parameters (even double). The study has determined that a proper energy integration design could lead to important economic savings (5 €/t) and thermal hydrolysis can enhance up to 40% the incomes of the digestion plant, even doubling them when digestate management costs are considered. In a full-scale MSW treatment plant (30,000 t/year), thermal hydrolysis would provide almost 0.5 M€/year net benefits.

1. Introduction

Anaerobic digestion as a treatment of solid substrates is a clean technology based on energy recovery from waste gaining importance in a full-scale extent. A wide range of wastes are susceptible of being degraded anaerobically, as it is reported by Carlsson et al. (2012): municipal solid wastes, organic wastes from food industry, energy crops, agricultural residues, manure and waste water treatment plants (WWTP) residues. While sewage sludge anaerobic digestion technology is widely spread in WWTP since decades, other wastes still need more research to be included in anaerobic digestion full-scale plants. In the European Union (EU27), it is estimated that each person generates 520 kg of waste per year (Eurostat, 2011); then, there is a potential opportunity to produce biogas from its organic fraction. Currently, the disposal of manure is predominately done through land application, which causes greenhouse gas emissions, ecological system eutrophication and groundwater contamination (Jin et al., 2009). But new regulatory restrictions are forcing to develop sustainable technologies such as anaerobic digestion for its management. Furthermore, there are further WWTP residues (such as grease waste) with a high energy content which could be treated on-site in sewage sludge anaerobic digesters, saving transport and management costs and increasing biogas production. These are just some examples of different wastes that could be degraded to produce biogas and therefore green energy.

However, anaerobic digestion has a limitation concerning solid substrates. Its degradation rate is limited by the hydrolysis step, which is an especially slow step when dealing with solid substrates. In this process, complex organic matter (proteins, lipids, carbohydrates…) becomes simple soluble matter (amino acids,

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sugars, fatty acids…). In order to accelerate the hydrolysis step, thermal hydrolysis pretreatment (TH) is one of the most efficient techniques, leading to high solubilisation, pathogen reduction, good dewaterability and an increase in biogas production. As well, the energy input needed for the hydrolysis process is thermal energy and could be satisfied from the energy production of the own process, resulting in an energetically self-sufficient process (Perez-Elvira et al., 2008). In addition, the solid residues of such biogas production (biowaste) after the thermal treatment can be used as low-grade fertilizers (Hilkiah Igoni et al., 2008): for example, two *Cambi* plants in Norway (Lillehammer and Ecopro) have received permits to use the bio-fertilizer in the agricultural sector and also for land remediation purposes (Sargalski, 2008). Thermal hydrolysis has been widely tested with sewage sludge as a cost-effective method (Pérez Elvira et al., 2006) and even applied in real scale continuous processes by *Cambi* in several biosolids plants (Román et al., 2007). But for other substrates, there are just laboratory trials (Ma et al., 2011; Charles et al., 2009; Valladão et al., 2007; López Torres and Espinosa Lloréns, 2008; Shahriari et al., 2012; Cesaro et al., 2012; Carrère et al., 2009; Liu et al., 2012) or pilot scale studies (Zhou et al., 2013) an economic assessment is required to get closer to full-scale real applications.

In the present study, thermal hydrolysis pretreatment to different solid wastes is evaluated in laboratory scale with batch tests. From them, an energy and economic assessment is performed by the analysis of three different scenarios to implement an energy integration design, study the economic feasibility of the pretreatment and set the basis for a process scale-up.

2. Methods

2.1. Solid wastes

Six different solid substrates were selected considering: their importance in real scale plants in order to optimise their anaerobic digestion; their availability; and their diversity of composition, origin, production and biodegradability according to the substrate classification of Carlsson et al. (2012). These substrates are: biological sludge (thickened to 7% total solids) from a municipal WWTP; the organic fraction of municipal solid waste (OFMSW), which is a synthetic mixture of basic foods in an appropriate proportion as their presence in household waste (Boulanger et al., 2012); municipal solid waste (MSW) previously sorted from a waste treatment plant; grease waste from a dissolved air flotation tank (DAF) from a WWTP; spent grain from brewery industry; and cow manure from slaughterhouse. Their characterisation is presented in Table 1.

2.2. Thermal hydrolysis pretreatment (TH)

The lab-scale hydrolysis plant is made up of a 2 L reactor fed with the substrate and heated with steam until the desired temperature, and a flash tank of 5 L where the steam explosion takes place after the hydrolysis reaction time has elapsed. The operational conditions remained constant: 170 °C and 30 min hydrolysis time, which are the optimised conditions obtained by (Fdz-Polanco et al., 2008), except for the OFMSW (120 °C and 10 min) and MSW (150 °C and 20 min) for which different conditions were found as optimum ones in previous tests. These operational conditions were selected in accordance with maximising methane productions and maximum kinetics increase from BMP tests.

2.3. Biochemical methane potential tests

Biochemical methane potential (BMP) tests allow to determine kinetics and methane potentials of the substrates. The assays were performed by triplicates following an internal protocol based on standardised assays (Angelidaki et al., 2009). The reactors volume was 300 mL and a substrate-inoculum ratio of 1:1 in terms of VS was applied. The incubation temperature was 35 °C and reactors were stirred in a horizontal shaker. The inoculum, WWTP mesophilic digested sludge (45 gTS/L, 24 gVS/L), was pre-incubated for 2 days at 35 °C; then, its methane production (25.4 $mLCH_4$/gVSin) is deducted in all tests to determine net productions from substrates. Periodical monitoring analyses of biogas production by pressure meter and biogas composition by gas chromatography (Varian CP-3800) were performed during the tests. Methane potentials are expressed as average values of the net volume of methane per gram of initial substrate VS content. In this study, the results from these tests were taking as a departure point for all calculations.

2.4. Modelling

The Modified Gompertz equation (Lay et al., 1997), next presented in Eq. (1), was considered in order to fine-tune the experimental data from BMP tests to a theoretical equation:

$$B = p \times \exp\left\{-\exp\left[\frac{R_m \cdot e}{P}(\lambda - t) + 1\right]\right\}. \qquad (1)$$

The model has three parameters: the methane yield rate (R_m) which indicates the initial slope of the curve ($mLCH_4$/gVS/d), the maximum biogas production (P) expressed as $mLCH_4$/gVSin and the lag-phase (λ) in days. B is the calculated methane production ($mLCH_4$/gVSin) for time t. The model fine-tuning to the experimental data was achieved by least squares methodology, by minimising the next objective function (2):

$$OF(\varphi) = \min \sum_{t-1}^{N} (B_{\exp}(t) - B_m(t,\varphi))^2 \qquad (2)$$

where $B_{\exp}$ is the consumption velocity obtained from measurements (plotted in BMP results graphs as points). B_{m} is the

Table 1
Substrates characterisation (TS, VS: total and volatile solids; CODt/s: total/soluble chemical oxygen demand; TKN: total Kjeldahl nitrogen; NH_4^+: ammonium).

Parameter	Units	Biological sludge	OFMSW	MSW	Grease waste	Spent grain	Cow manure
TS	g/kg	71.2	109.9	351.4	505.2	243.6	221.6
VS	g/kg	54.9	105.1	246.0	468.2	233.4	208.5
CODt	g/kg	83.9	150	332.5	648.3	303.4	258.8
CODs	g/kg	6.3	91.8	–	–	70	81
TKN	N g/kg	5.75	3.79	5.347	3.27	8.73	27.46
NH_4^+	N g/kg	0.24	0.82	1.049	0.24	1.22	0.75
Grease	g/kg	1.16	2.68	5.80	128.0	6.66	4.65
Carbohydrates	%	0.10	6.28	0.19	–	–	–
Fibre	%	0.21	0.82	7.23	–	–	–
Proteins	%	3.83	2.43	3.67	2.04	4.69	16.7