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

R. Cano [1], A. Nielfa, M. Fdz-Polanco *

University of Valladolid, Chemical Engineering and Environmental Technology Department, Prado de la Magdalena 47011, Valladolid, Spain

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,

* Corresponding author. Tel.: +34 983423166.
E-mail addresses: raulcano@iq.uva.es (R. Cano), maria@iq.uva.es (M. Fdz-Polanco).
[1] Tel.: +34 699692621.

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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:

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

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):

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

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

corresponding velocity calculated by the model (plotted with continuous curves), N is the number of measurements, t is time and ϕ represents the Gompertz parameters. The correlation factor (R^2) was then calculated to assess the accuracy of each model with respect to the experimental data.

2.5. Dewaterability test

Centrifugability test was performed following an internal method established from the experiments in sludge characterisation (Donoso-Bravo et al., 2011). Centrifugability assesses the liquid and solid phase separation after 5 min centrifugation at 5000 rpm in a *Kubota 5100* centrifuge (nominal power 560 W, maximum volume capacity 1.02 L). After measuring the separation performance and determining the suspended solids concentration in the liquid phase, the next parameters are calculated: % separated liquid, % solid recovery in cake and solid concentration in cake (%TS). These parameters enable the quantification of the biowaste that can be separate from the digestate from BMP tests, to estimate the amount of biowaste to deal with after the digestion, which has to be properly managed and will directly influence in the economic assessment.

2.6. Analytical methods

Substrates characterisation was performed following an internal protocol based on Standard methods (APHA, 2005) to determine the next parameters: TS, VS total and volatile solids; COD chemical oxygen demand; TKN total Kjeldahl nitrogen; NH_4^+ ammonium. The other parameters were determined according to: grease (EPA Method 1664), carbohydrates (CE Regulation 152/2009), fibre content (Weende, CE Regulation 152/2009) and proteins (IT-MA-014, AOAC Official Method).

2.7. Energy integration and economic assessment

2.7.1. Thermal hydrolysis integration

For all scenarios, the thermal hydrolysis process has been integrated energetically (Fig. 2a) according to the configuration adopted in commercial processes such as *Cambi*. A recovery of heat from the flash vapours (saturated steam at 105 °C) to the pre-heating stage of the substrate leads to considerable saving in the energy consumption. This way, steam requirements have been estimated with energy and mass balances considering 20% vapour losses in the pre-heating stage and a temperature of the hydrolysed substrate of 105 °C, according to supplied data from a continuous thermal hydrolysis plant from *Aqualogy* in Valladolid WWTP (Pérez-Elvira et al., 2013).

2.7.2. Scenarios evaluation

Thermal hydrolysis implementation in a full-scale plant has been achieved theoretically on three different scenarios (Fig. 2) and making the cost-benefit analysis of the process with and without pretreatment, based on a previous study (Perez-Elvira et al., 2008):

2.7.2.1. Scenario 1: No energy integration. The biogas produces green electricity in an engine (EE), which is sold with an extra benefit in case of thermal hydrolysis (higher biogas production). The steam required in the pretreatment is produced in a boiler which is fed with natural gas. The difference between the surplus of green electricity and the cost of natural gas is the net benefit of the process (Fig. 2b).

2.7.2.2. Scenario 2: Energy integration. The biogas is burned in a combined heat and power system (CHP) providing three main streams (Fig. 2c):

- *Electrical green energy (EE):* to be sold, providing net benefits.
- *Hot exhaust gases (EG):* waste stream which heat can be recovered in a boiler to produce steam for the thermal hydrolysis pretreatment (natural gas is not anymore needed if the heat is sufficient).
- *Hot water (HW):* it can be used to heat the digester, if necessary; but it is not considered for the energy calculations in the study.

2.7.2.3. Scenario 3: Digestate handling. Considering the costs of the dewaterability (centrifugation) post-treatment, the biowaste management (taxes and transport to landfill)…. This scenario was only studied for MSW substrate because its high potential to be implemented in a full-scale extent, due to the scarce development of its TH application before anaerobic digestion and its high worldwide production, which entails important management problems (Fig. 2d).

2.7.3. Energy and economic considerations

Biogas generation in the anaerobic digester results from the BMP data obtained in laboratory trials. A thermal transfer efficiency of 90% in boilers is considered. When a CHP is considered, electrical efficiency is set to 33% and thermal efficiency to 55% (25% exhaust gases and 30% hot water), with an overall efficiency of 88%, according to typical values of commercial engines. All raw substrates and cold water are considered initially at 20 °C and a constant heat capacity for all of them equal to the water one (4.18 kJ/kg/K) has been ascribed, which is the most unfavourable value. Calorific values of methane and natural gas are 11 kW h/Nm^3 and 8.6 kW h/Nm^3 respectively (*engineeringtoolbox.com*). Prices of electrical energy are set at 12 c€/kW h (buy) and 15 c€/kW h (sell, including bonus from green energy) and natural gas at 35 c€/kW h (current prices in Spain according to *endesaonline.es*). The taxes for landfilling are 25 €/t, which is the average cost in Spain according to *ateneonaider.com* (lower than in the rest of Europe).

3. Results

3.1. Thermal hydrolysis evaluation at lab-scale

The results obtained in BMP tests with the Gompertz model fine-tuning for raw and pretreated wastes are enclosed in Table 2 and BMP curves are plotted in Fig. 1 (just MSW curves shown as an example). Thermal hydrolysis pretreatment has improved the anaerobic digestion in BMP tests for all the substrates. Gompertz modelling parameters, which have been determined with a high degree of accuracy (average R^2 over 0.98), enable a quantification of these improvements (Table 2).

Among the substrates, biological sludge has suffered the highest methane production increase after TH (more than 50%) probably due to the cell lysis that takes place during the pretreatment and especially in the steam explosion. The liberation of the intra-cellular material from microbial cells of the biological sludge can be the main mechanism that causes the biogas production improvement, as it was also concluded by Perez-Elvira et al. (2010). The biological sludge is the only substrate from this study that is mainly composed by microbial cells, which is one of the two causes of a low hydrolysis which could be overcome by the application of pretreatments (Carlsson et al., 2012). The other cause is a high content of lignocellulosic material, which, in the present study, is best

Table 2
BMP parameters from Gompertz equation modelling and thermal hydrolysis effects.

Substrates		Model parameters				Improvements		
		P mLCH$_4$/gVSin	R_m mLCH$_4$/gVSin/d	λ d	R^2 –	P %	R_m %	λ d red.
Biological sludge	Raw	184	65.2	0	0.934	51	71	0.0
	TH	278	111.7	0	0.956			
OFMSW	Raw	308	32.4	6.6	0.997	3	164	6.4
	TH	318	85.6	0.2	0.992			
MSW	Raw	215	89.7	0.1	0.980	30	69	−0.1
	TH	280	151.9	0.2	0.987			
Grease waste	Raw	489	82.4	17.6	0.990	7	43	1.8
	TH	524	118.1	15.8	0.994			
Spent grain	Raw	251	50.8	0.8	0.994	40	144	0.8
	TH	352	123.7	0	0.991			
Cow manure	Raw	317	53.3	0	0.981	29	177	0.0
	TH	408	147.7	0	0.982			

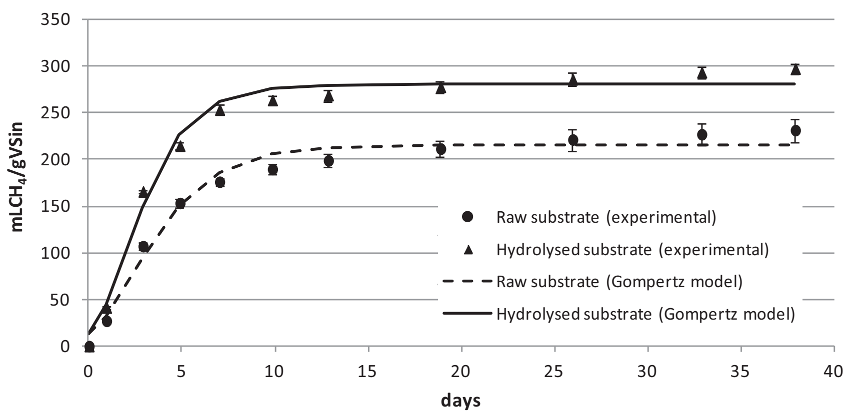

Fig. 1. BMP curves of raw and pretreated MSW.

represented by the municipal solid waste (MSW) that has a fibre content of 7.2%. Thermal hydrolysis at 150 °C to MSW has also improved considerably its digestion (30% more methane production and 70% faster kinetics), probably caused by the breakdown of its lignocellulosic material into soluble material. On the other hand, the organic fraction of municipal solid waste (OFMSW) has not lead to any biogas improvement by the application of the pretreatment, but just to a kinetic acceleration. The initial high soluble matter that this substrate contains (over 60% COD is soluble) and the fact that it is composed by high amounts of easily degradable sugars (6.28% carbohydrates) are the main causes of the lack of effectiveness of TH in this synthetic substrate. However, OFMSW digestion has provided an acceptable methane production (over 300 mLCH$_4$/gVSin). It is remarkable the higher efficiency that thermal hydrolysis presents when pretreating the real MSW in comparison to the synthetic waste, due to the higher fibre content and lower easily degradable sugars contained in the first one, what reduces the availability of organic compounds when no pretreatment is applied. The remained three substrates (grease waste, spent grain and cow manure) represent substrates rich in lipids, in carbohydrates and in proteins respectively. While TH has played an essential role in improving anaerobic digestion of spent grain and cow manure (40% and 30% more biogas respectively and methane yield rates have doubled), grease waste has not been remarkably influenced by the pretreatment. Although its methane production can be slightly improved and the kinetics speeds up 40%, a considerable lag-phase (over 15 days) is present with or without TH, which could be caused by the inactivation of methanogens because the increase of long chain fatty acids, but this was not experimentally proved. Its high lipid content and slow degradable materials could not be subjected to significant alterations during the pretreatment. In this case, its high lipid content (128 g/kg) and slow degradable materials of the grease waste could not be subjected to significant alterations during the pretreatment. Nevertheless, its high lipid content leads to the highest methane production (524 mLCH$_4$/gVSin after TH), converting this substrate in an interesting co-substrate (Silvestre et al., 2011). Coming back to cow manure, it is remarkable that its high nitrogen content (27.5 N g/kg) has not lead to ammonia overloading and refractory compounds formation after the thermal pretreatment, what has been reported to be common (Cuetos et al., 2010). It is probable that the high content of lignocellulosic material of this substrate has suffered a high rupture after TH and is the main responsible mechanism that has taken part to improve its degradation.

As it is reported by Carlsson et al. (2012), two main components can be identified among substrate categories that cause low bioavailability and/or biodegradability: microbial cells/flocs such as those found in waste activated sludge from WWTP and lignocellulosic material from plants and vegetables found in energy crops and harvesting residues, in manure and to some extent in household waste (Carlsson et al., 2012). Then, it has been confirmed that substrates with high content of fibre or microbial cells are more susceptible to be pretreated in order to improve its degradation capacity.

3.2. Energy integration and economic assessment

The feasibility of the thermal hydrolysis pretreatment in a continuous plant has been assessed by different approaches with

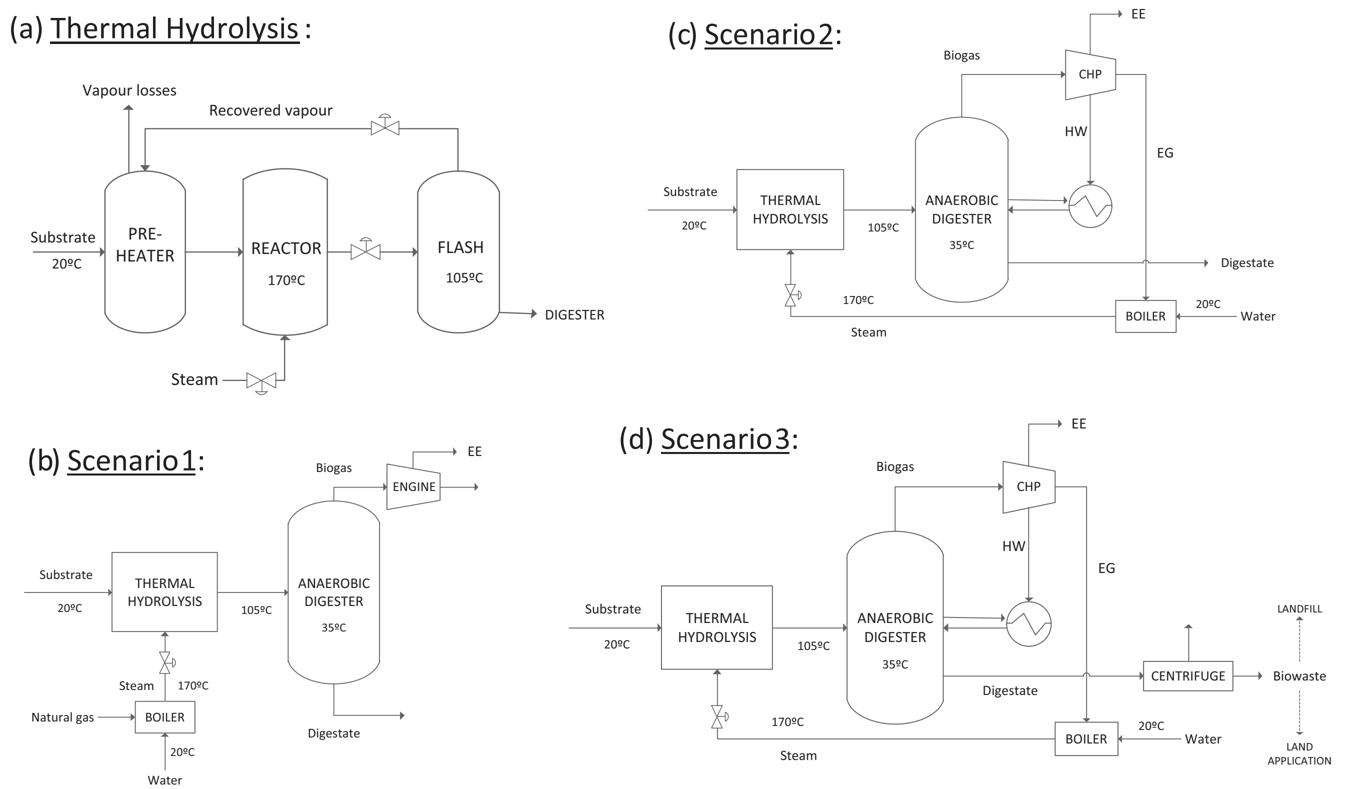

Fig. 2. Simplified flow diagrams with different configurations considered in the study: (a) Thermal Hydrolysis pretreatment with heat recovery from the flash vapours in the pre-heater. (b) *Scenario 1:* No energy integration setup (production of electrical energy EE). (c) *Scenario 2:* Energy integration design (heat recovery from exhaust gases EG for steam generation). (d) *Scenario 3:* Digestate handling considerations and biowaste management.

Table 3
Scenario 1. No energy integration. Most results are expressed per tonne of substrate fed.

Substrates		Hydrolysis temperature °C	Generation			Consumption			Benefits		
			Methane $mLCH_4/gVSin$	Electrical energy		Steam kg/t	Natural gas				
				kW h/t	€/t		Nm^3/t	€/t	€/t	€/t	%
Biological sludge	Raw	–	184	37	5.5	0	0	0	5.5		
	TH	170	278	55	8.3	189.2	18.7	5.6	2.7	−2.8	−51
OFMSW	Raw	–	308	118	17.6	0	0	0	17.6		
	TH	120	318	121	18.2	195.7	18.9	5.7	12.5	−5.1	−29
MSW	Raw	–	215	192	28.8	0	0	0	28.8		
	TH	150	280	250	37.5	191.3	18.8	5.6	31.9	3.1	11
Grease waste	Raw	–	489	830	124.6	0	0	0	124.6		
	TH	170	524	891	133.6	189.2	18.7	5.6	128.0	3.4	3
Spent grain	Raw	–	251	213	31.9	0	0	0	31.9		
	TH	170	352	298	44.7	189.2	18.7	5.6	39.1	7.2	23
Cow manure	Raw	–	317	240	36.0	0	0	0	36.0		
	TH	170	408	309	46.3	189.2	18.7	5.6	40.7	4.7	13

different configurations, described in Section 2 and shown in Fig. 2. The extrapolation from laboratory trials to a continuous operation has been achieved considering the same biogas productions from BMP tests, but steam consumption, energy balances and equipments characteristics have been determined theoretically considering typical design values from real processes and taking as basis of calculation one tonne of raw waste. Next, the three scenarios are studied and the main results are enclosed in respective Tables.

3.2.1. Scenario 1

As a first approach, the simplest configuration is studied, which is the most unfavourable one. No energy integration has been considered, so natural gas requirements for steam generation are high and incomes from green electrical energy are reduced. Table 3 shows the main results for all the raw and hydrolysed substrates. First, it is remarkable that the natural gas consumption for different TH conditions of temperature is almost the same, and even higher for a lower temperature. However, the resulted benefits of TH that have been estimated diverge from each substrate. While most of them show positive balances with net benefits over 3 €/t, there are two substrates (biological sludge and OFMSW) with negative incomes. In the case of OFMSW, it is logical since the methane production increase in BMP tests was just 3%, what does not compensate all the steam consumption costs. For biological sludge, the reason is not so obvious since BMP tests showed the highest

Table 4
Scenario 2. Energy integration. Most results are expressed per tonne of substrate fed.

Substrates		Total energy in biogas kW h/t	Generation (CHP system)					Consumption (boiler)	Benefits		
			Electrical output (EE)		Thermal output HW	EG	Steam produced kg/t	Steam required kg/t			
			kW h/t	€/t	kW h/t	kW h/t			€/t	€/t	%
Biological sludge	Raw	111	37	5.5	33	28	34	0	5.5		
	TH	168	55	8.3	50	42	51	189[a]	4.2	−1.3	−24
OFMSW	Raw	356	118	17.6	107	89	110	0	17.6		
	TH	368	121	18.2	110	92	114	196[a]	15.8	−1.8	−10
MSW	Raw	583	192	28.8	175	146	177	0	28.8		
	TH	758	250	37.5	227	190	231	191	37.5	8.7	30
Grease waste	Raw	2516	830	124.6	755	629	759	0	124.6		
	TH	2699	891	133.6	810	675	814	189	133.6	9.0	7
Spent grain	Raw	644	213	31.9	193	161	194	0	31.9		
	TH	904	298	44.7	271	226	273	189	44.7	12.8	40
Cow manure	Raw	727	240	36.0	218	182	219	0	36.0		
	TH	936	309	46.3	281	234	282	189	46.3	10.3	29

[a] Extra natural gas in the boiler has been considered to produce the required steam.

Table 5
Scenario 3. Digestate handling costs, expressed per tonne of substrate fed.

Municipal solid waste			Raw	TH
Centrifugability results	Separated liquid	%	65.6	77.9
	Solid recovery in cake	%	96.6	99.3
	Solid concentration	%	12.7	14.3
Biowaste generation		kg/t	188	124
Digestate costs	Landfill	€/t	4.7	3.1 (0)[a]
	Transport	€/t	7.5	5.0
	Total	€/t	12.2	5.0
Benefits		€/t	16.6	32.6
TH increase		%	–	96

[a] If biowaste is used as fertilizer.

methane production increase for this substrate (51%). Nevertheless, this increase is determined based in mLCH_4/gVSin, and this substrate contains fewer VS (55 g/kg) than the others, so the gross methane generation is lower and does not satisfy the steam requirements. In fact, as it has been studied by (Perez-Elvira et al., 2008), the sludge concentration of the biological sludge is the key parameter to satisfy the energy balances and make the process energetically efficient. This way a higher VS content (previous centrifugation) % would lead to positive benefits (VS at least 110 g/kg). On the other hand, it is noteworthy the net benefits obtained for grease waste, which rises over 125 €/t without pretreatment, what indicates the high potential this substrate offers for anaerobic digestion.

3.2.2. Scenario 2

In this case, the thermal integration results in the recovery of heat from the exhaust gases from a CHP system (a waste stream) to produce the steam for TH. In Table 4, all the energy streams are calculated for both cases: no TH (raw) and with TH. Electrical output provides net benefits from green electricity, exhaust gases (typically over 400 °C) generate steam, and hot water could be used for any low temperature heat requirement in the plant (such as heating the digester), but it has not been considered for the calculations. In most of the cases, the steam requirements are fulfilled by the steam generated with the exhaust gases, except for biological sludge and OFMSW, for the same reasons explained in Scenario 1. In these cases, an extra natural gas is purchased to generate steam and complete the requirements (as states Table 4). The obtained benefits from TH of this scenario are higher than the previous one, but still negative for the last mentioned substrates. The other ones present values from 8 €/t to 13 €/t, with increases respect the "no TH" till 40% and an extra benefit over 5 €/t respect the Scenario 1. In this case, it is especially remarkable that TH to grease waste has lead to a net benefit of 9 €/t which, considering that TH just increased its methane production by 7%, is an impressive result. This fact is again justified by the VS content of the waste which, in this case, is quite high (468 g/kg) and leads to high gross methane production when calculating per raw weight basis. Spent grain and cow manure are the substrates that lead to the highest benefits (over 10 €/t), although MSW also leads to a very high relative benefit (30%) if it is compared to the raw substrate one. Moreover, this last waste has a very high potential to be implemented in a full-scale extent since it is produced worldwide in high amounts, entailing important management problems. For these reasons, it is has been selected for the last scenario evaluation.

3.2.3. Scenario 3

In the last scenario, associated costs to digestate handling have been calculated for the municipal solid waste (MSW) substrate. Dewatering and disposal of digestate is considered to be one of the main economic factors in the WWTP operation, representing up to 50% of the total operating costs (Carlsson et al., 2012). A centrifuge has been considered as dewaterability post-treatment to separate the aqueous phase from the solid biowaste. TH effect on the dewaterability process has been assessed by centrifugability tests of the obtained digestates from BMP tests, determining the next parameters: separated liquid (enables the quantification of the biowaste respect to the digestate), solid recovery in cake (indicates the efficiency of the centrifugation) and the solid concentration in cake (total solids of the biowaste). As it is shown in Table 5, TH influences considerably its centrifugability parameters: more than 12% liquid is separated, a full recovery of solids is achieved (99%) and a biowaste with 1.6% more TS is obtained. This will directly influence the associated costs of the biowaste management derived from its volume reduction (35% reduction). In Table 5, these costs are enclosed: they include the landfill deposit taxes and the transport costs. In the case of the thermally hydrolysed digestate, it satisfies the minimum requirements of sterilisation to be used as fertilizer for agricultural purposes (at least 133 °C for 20 min) according to the European Regulation 1774/2002. In this case, the associated costs for landfilling are eluded and a null price for selling the fertilizer is ascribed. Other advantages of TH which were not considered in this study but have a high impact in a full-scale plant are: lower viscosity in the digester (reduction

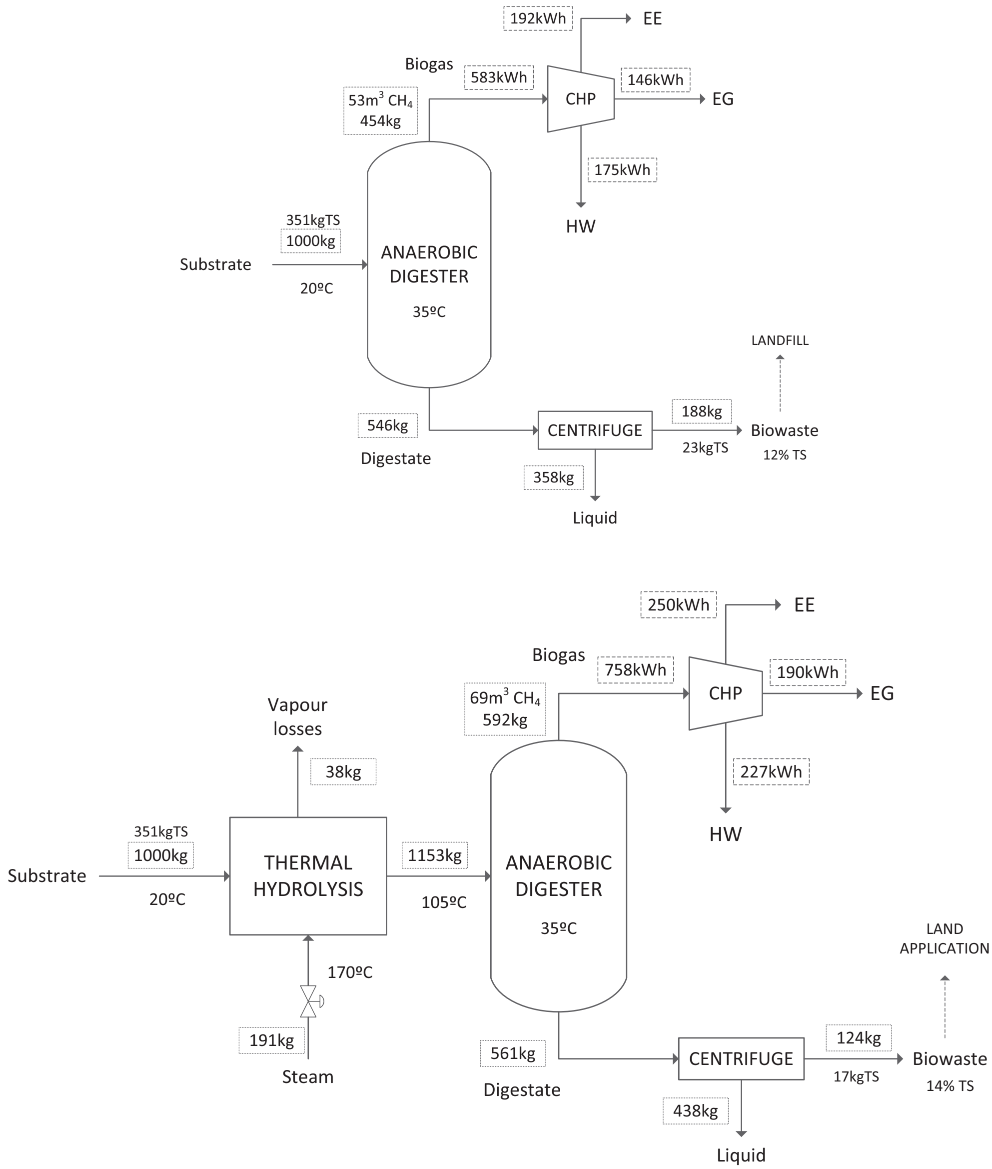

Fig. 3. Mass and energy balances of the main streams of *Scenario 3* with and without TH (basis: 1t -wet weight- MSW substrate fed).

of mixing energy requirements in the digester), savings in polyelectrolyte used in centrifugation and no need of a further sterilisation process of the biowaste. This way, in combination with the economic data from *Scenario 2*, total benefits with and without TH have been determined and compared. An extra benefit of 16 €/t is reached when TH is applied, what represents an income increase of 96% respect to the conventional configuration.

In Fig. 3, all mass flows of the main streams can be consulted for both configurations: with and without TH. Departing with 1 tonne of wet MSW (containing 351 kgTS), it shows the main energy or mass content in each stream of the conventional process and with the TH process implementation. The main differences reside in the biogas and the biowaste generation. While the conventional process recovers 53 m^3 CH_4 (leading to 192 kW h of electrical energy), the TH scenario increases the biogas production to 69 m^3 CH_4, providing 250 kW h of electrical energy and 190 kW h (exhaust gases) that can be reused to generate steam. Concerning biowastes, the amount of biowaste generated in the conventional process is 188 kg (containing 23 kgTS) versus 124 kg (with 17 kgTS) in the TH scenario, which main advantage is the possibility to be used as fertilizer – instead of lanfilling – as a more sustainable management alternative. On the other hand, both scenarios show the high efficiency that anaerobic digestion offers, since, from 1 tonne of initial waste, just 124/188 kg have to be finally managed (apart from the energy recovery advantage), what supposes a reduction of more than 80% of the initial waste mass flow.

3.3. Scenarios comparison

Fig. 4 compiles graphically the net benefits obtained by TH in comparison to the conventional digestion process (without TH). It is immediately remarkable that there are positive values for all substrates except for biological sludge and OFMSW, as it has already been explained by the effect of the VS content. In fact, the content of VS is a key parameter to consider when dealing with sludge since it is directly related with the energy efficiency of the TH and it can be easily modified (thickening sludge by centrifugation). As it was observed for the grease waste, a high content of VS leads to high TH benefits in spite of a low methane yield increase.

On the other hand, the energy integration of *Scenario 2* (middle column in Fig. 4) improves the profitability of the digestion

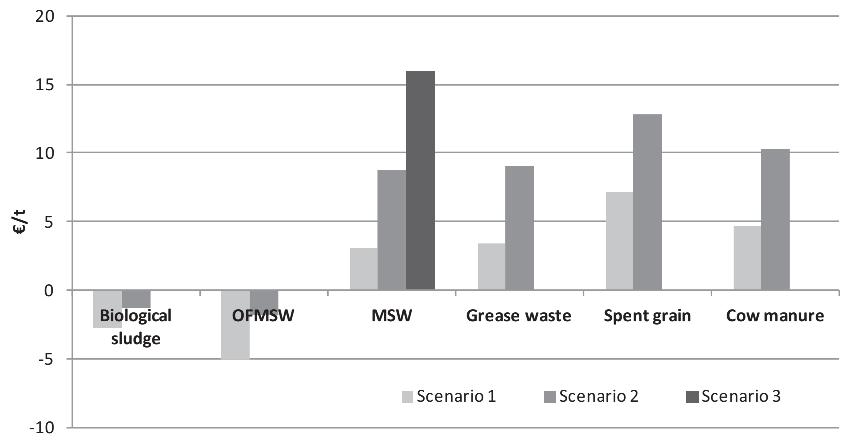

Fig. 4. TH net benefits for all substrates in each scenario.

without energy integration (left column) for every case (leading to 5.6 €/t higher benefits for the wastes with a positive net balance); thus, the importance a proper energy integration design has on the economic evaluation. Finally, *Scenario 3* (right column), although it was only applied to MSW, increases considerably the incomes almost doubling the *Scenario 2*'s ones (from 8.7 €/t to 16 €/t). Therefore, it can be concluded that Scenario 3 is the most economically viable energy integration design.

3.4. Scale-up forecast

In a last attempt to make a final scale-up and conclude the economic assessment of a thermal hydrolysis plant, it has been considered a MSW flow based in a real plant in order to study the ability of the implementation of this technology in full-scale. The waste treatment plant of Verdal (Norway) treats 30,000 t/year of waste and has adopted *Cambi* thermal hydrolysis technology as pretreatment since 2008 (Román et al., 2007). Considering this treatment capacity, the benefits obtained in *Scenario 3* (16 €/t), a depreciation term of 10 years and fixed equipment costs of the TH plant of 1 M€ (rough calculation), the total net benefits ascend to almost 0.5 M€/year, providing a full refund of the initial investment of the TH plant after two years operation. Despite this calculation has been carried out as a gross estimate, it provides an idea of the profitability and effectiveness of the thermal hydrolysis in a municipal waste treatment plant.

4. Conclusions

Thermal hydrolysis has lead to an increase of methane productions (up to 50%) and kinetics parameters (even double). However, it has not showed remarkable effects in substrates rich in lipids or with high content of easily degradable carbohydrates. A proper energy integration design could lead to important economic savings (5 €/t). Moreover, thermal hydrolysis can enhance up to 40% the incomes of the digestion plant, even doubling them when digestate management costs are considered (Scenario 3). In a real MSW treatment plant, thermal hydrolysis would lead to net benefits of almost 0.5 M€/year, with a full refund period of two years.

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