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Evaluation of food waste energy content through bio-fuels production

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Abstract

Anaerobic digestion of biodegradable substrates is a proven biological-based technology that recovers energy in the form of biogas for use in combined heat and power plants. In this respect, hydrogen production during the acidogenic phase can improve process efficiency. The purpose of this study is to evaluate energy recovery from the production of hydrogen and methane by using food waste as substrate. The primary energy saving obtained by different users of biogas was calculated considering the specific gas production evaluated through pilot tests carried out in semi-continuous mode. The physical separation of the traditional anaerobic digestion in two-phase anaerobic process was demonstrated to be beneficial for the methanogenic phase in terms of gas production increase but not efficient in terms of overall energy performance. Although specific methane production increased in semi-continuous mode respect to batch tests, H_2 production decreased and hydrogen concentration dropped from 45% to 22.9%. Therefore, bio-hydrogen production in semi-continuous conditions results to be not sufficient to balance out adding energy consumption due to heating of dark fermentation digester.

Keywords: Anaerobic Digestion, Dark Fermentation, Food Waste, Bio-hydrogen, Bio-methane, ICE, Fuell Cells, Microturbine

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1. Introduction

The EU action plan for Circular Economy [1] considers that the products at the end of their service life are turned into resources for new purposes. According to the Circular Economy concept, waste production is minimized through maintaining for as long as possible the value of products, materials and resources. This is the basis to develop a sustainable, low-carbon, resource-efficient and competitive economy. In this respect, biorefineries represent an important possibility for residues valorization due to their aim to convert biomass in bioenergy, biofuels and biochemical [2].

Anaerobic digestion (AD) of biodegradable substrates is a proven technology in terms of bio-fuels production and energy recovery. Indeed, the produced biogas can be used in combined heat and power plants [3]. The increasing need for renewable energy generation and the requirement to divert biodegradable waste from landfill have recently increased the interest in AD process [4]. Food Waste (FW) from separate collection seems to be a promising feedstock for AD system in terms of methane production because of its biodegradability characteristics and availability [5, 6, 7]. Therefore, the increasing interest in AD drives the scientific community in further developing the process.

In this respect, bio-hydrogen production during the fermentative phase of AD is considered the new frontier of the process due to hydrogen high-energy content and environmentally friendly production [8, 9]. In order to obtain a bio-hydrogen flow in AD, the traditional one-stage technology is separated in a two-stage process equipped with a fermentative reactor connected in series with a methanogenic reactor. While the first stage produces H_2 and CO_2 as gaseous products and releases volatile fatty acids (VFAs) in the liquid solution, the second one converts VFAs and the residual organic biodegradable matter into CH_4 and CO_2 [10, 11]. The multiple advantages of this technology include an energy efficiency increase [12] due to the high calorific value per unit of weight of H_2 and the enhancement of biogas yield in the second stage.

This work represents an extension of the study of Pecorini et al. [13]. The aim of the present study is to compare the energy performances of different biogas users by using hydrogen and methane production data experimentally determined. Just like the other study, four possible layouts of FW anaerobic digestion process were compared each other in terms of primary energy saving. In two digestion scenarios it was considered only bio-methane production through one-stage traditional AD process; in other two scenarios the possibility to produce hydrogen by adding a new digester to perform dark-fermentation was evaluated. For each scenario the mass balance and the energy budget were estimated. The difference between the present study and the previous work of Pecorini et al. [13] is based on the assumptions made in terms of bio-hydrogen and bio-methane production. While in the first study the specific gas production was determined by performing batch tests, such as Biochemical Methane Potential (BMP) and Biochemical Hydrogen Potential (BHP) tests using 1 l stainless steel reactors [14], in this study Continuous Stirred Tank Reactor (CSTR) pilot tests were carried out. Calculations and esteems referred to energy consumptions were obtained by direct management data of the wastewater treatment plant (WWTP) of Viareggio, considered as reference plant.

Nomenclature

AD	anaerobic digestion
BHP	biochemical hydrogen potential
BMP	biochemical methane potential
CSTR	continuous stirred tank reactor
DF	dark fermentation
FW	food waste
ICE	internal combustion engine
MCFC	molten carbonate fuel cell
OLR	organic loading rate
SGP	specific gas production
TS	total solid
TVS	total volatile solid
VFAs	volatile fatty acids
WWTP	wastewater treatment plant

2. Materials and methods

2.1. Food waste characterization

FW was used as substrate as it has been proven to be a highly desirable feedstock for anaerobic fermentation due to its high biodegradability, availability and well balanced carbon and nutrient contents [5, 6, 7]. The original FW used in pilot scale tests was sampled from the organic fraction of municipal solid waste collected in a Tuscan municipality (Italy) by means of a kerbside collection system. In order to make the sample suitable for a wet fermentation technology and to obtain a slurry with a Total Solid (TS) content of approximately 5.7% w/w, the sample was treated in a food processor, sifted with a strainer (3 mm diameter) and mixed with water [3].

The original FW and also the FW slurry were characterized in terms of TS, Total Volatile Solids (TVS) and pH that were determined according to standard methods [15]. According to Angelidaki et al. [16], TS determination was performed at 90°C instead of 105°C until constant weight in order to avoid the volatilization of volatile fatty acids.

The characteristics of the original FW are shown in Table 1.

Table 1. Food Waste characterization

	FW
TS (% w/w)	19.9 ± 0.6
TVS (% w/w)	16.0 ± 0.9
pH	4.8 ± 0.07
Organic Nitrogen (%N w/w)	0.455 ± 0.067
TOC (%C w/w)	9.6 ± 1.4
Ammonia (mgN/kg)	849 ± 84
Acetic acid (mg/l)	≤ 25
Propionic acid (mg/l)	≤ 25
C (% TS)	9.6 ± 1.4
H (% TS)	1.35 ± 0.20
N (% TS)	0.51 ± 0.06
S (mg/kg)	427 ± 64
P (mg/kg)	505 ± 75
Proteins (% w/w)	2.8 ± 0.4
Lipids (% w/w)	0.36 ± 0.05
Carbohydrates (% w/w)	8.8 ± 1.3
Cellulose (% w/w)	2.3 ± 0.4
Lignin (% w/w)	2.5 ± 0.4

2.2. Experimental set-up

Two stainless steel reactors (AISI 316l) designed by the researchers of DIEF (Department of Industrial Engineering of Florence) were employed to evaluate bio-hydrogen and bio-methane production (Figure 1). The first reactor, dedicated to the fermentative step, had a total volume of 6 l and a working volume of 3 l. The second reactor, dedicated to the methanogenic step, had a total volume of 20 l and a working volume of 12 l. Temperature was constantly kept at mesophilic conditions (37.0 ± 0.1 °C) thanks to a jacket where warm water heated up by a thermostat (FA90, Falc Instruments S.r.l., Italy) was continuously pumped in. Continuous mixing was ensured by mixing blades. Both reactors were equipped with pH probes (Metter Toledo, Italy) and connected to an automatic data acquisition system (LabView, National Instruments Corporation, Italy). Data were recorded every 5 minutes. pH in the fermentative reactor was controlled through NaOH 2M solution addition dosed using peristaltic pumps. In particular, 3 ml of solution were automatically added when a pH decrease under 5.5 was detected. This configuration enabled to constantly keep the pH value in the range 5.5-5.6 all through the test to ensure the optimal conditions for dark fermentation process. The reactors were connected to volumetric counters for gas measurement. The produced gas was collected in 10 l multilayer foil bags (Supel TM, Merck KGaA, Germany) and analysed for H_2, N_2, H_2S, CO_2 and CH_4 content by a gas chromatograph (3000 Micro GC, INFICON, Switzerland). After set-up, the reactors were flushed with N_2 gas to ensure anaerobic conditions and to drive off air from the reactor headspace.

The experimental test was divided in two periods (Runs). In the first period (Run1), CH_4 reactor was fed with FW with the aim of evaluating the traditional one-stage AD. Simultaneously H_2 reactor was also fed with FW slurry in order to reach steady state conditions. In the second period (Run2), the two reactors were connected in series aiming at evaluating the two-stage process.

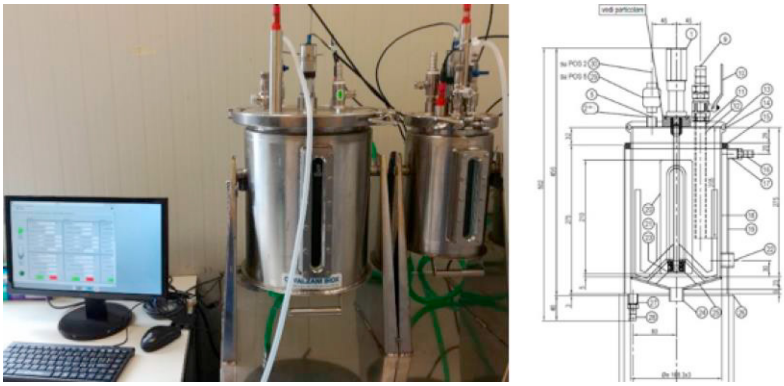

Figure 1. CSTR pilot scale reactors

2.3. Scenarios layout and inventory analysis

Four possible layouts of FW digestion process were taken in account. In two digestion scenarios, Scenario CH_4 (1) and Scenario CH_4 (2), it was considered only the methane production from FW in a traditional one-stage AD reactor system. In other two scenarios, Scenario H_2 (1) and Scenario H_2 (2), the possibility to produce hydrogen by adding a fermentative digester was evaluated.

For each scenario the mass balance and the energy budget were estimated; the data reported in Table 2 were assumed in the inventory analysis. In particular, for all scenarios FW was used as substrate and recirculation water with a TS content of 1.9 % w/w and a TVS content of 56 % w/dw was used to obtain the FW slurry necessary for a wet anaerobic digestion technology.

Table 2. Mass balance data inventory

	Scenario CH_4 (1)	Scenario CH_4 (2)	Scenario H_2 (1)	Scenario H_2 (2)
Treated flow (t/d)	238	238	312	312
Digester volume (m^3)	3558	3558	937 (H_2) 3558 (CH_4)	937 (H_2) 3558 (CH_4)
HRT (d)	17	17	3 (H_2) 11.4 (CH_4)	3 (H_2) 11.4 (CH_4)
OLR (kgTVS/m^3d)	2.82	2.82	14.19 (H_2) 2.82 (CH_4)	14.19 (H_2) 2.82 (CH_4)

Inventory data concerning energy flows, in particular the electricity consumptions, were provided by the owner of the WWTP of Viareggio and the use of a screw-press and a cleaning system to pre-treat the FW prior to AD was taken in account. In all the scenarios, thermal energy consumptions were calculated accounting the heat needed to warm the digesters (working at mesophilic conditions) and the heat losses (Table 3).

Different users of biogas were evaluated concerning the energy production and two possibilities for energy recovery (both in terms of electricity and heat) were considered for Scenario CH_4 and Scenario H_2, as shown in Figure

2. Internal Combustion Engine (ICE) was considered to recover the biogas produced in Scenario CH_4 (1) and in Scenario H_2 (1). In the latter case, beside CH_4, also the H_2 is produced and the ICE that recover biogas from AD was integrated by a MCFC for electricity production by the H_2 from DF. The same amount of biogas obtained for these two scenarios is used in a microturbine, Scenario CH_4 (2) and Scenario H_2 (2).

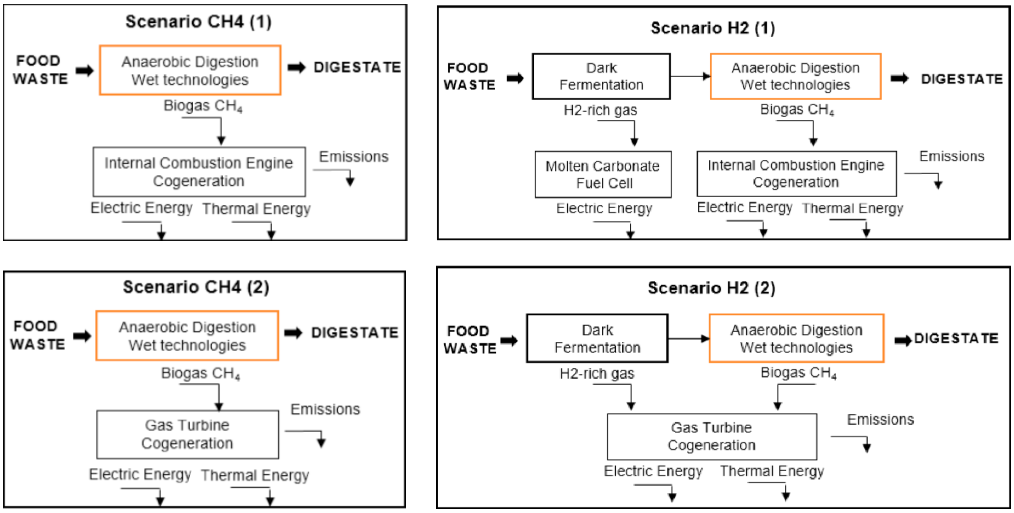

Figure 2. Scenarios layout

Table 3. Energy data inventory

	Scenario CH_4 (1)	Scenario CH_4 (2)	Scenario H_2 (1)	Scenario H_2 (2)
Electricity consumption (MWh/y)	2378	2304	2546	2458
Heat consumption (MWh/y)	1519	1519	2783	2783
Bio-fuel utilization	ICE μ_{el} = 0.423 μ_t = 0.428 Functioning = 7992 h/y	Micro turbine μ_{el} = 0.33 μ_t = 0.394 Functioning = 7992 h/y	MCFC (H_2) μ_{el} = 0.45 Functioning = 7992 h/y ICE (CH_4) μ_{el} = 0.423 μ_t = 0.428 Functioning = 7992 h/y	Micro turbine μ_{el} = 0.33 μ_t = 0.394 Functioning = 7992 h/y

2.4. Primary energy saving calculation

The performances of the different four scenarios were evaluated in terms of Primary Energy Saving (PES) according to Directive 2012/27/UE [17], where the net primary energy was calculated based on Eq. 1:

$$Primary\ Energy\ Saving = \frac{E_{el}}{\eta_{el,rif} \cdot p_g} + \frac{Q_{th}}{\eta_{th,rif}} \quad (1)$$

Where:

- Eel is the net electricity produced in each scenario;
- Qth is the net thermal energy recovered in each scenario;
- ηel,rif is the reference efficiency for electricity, assumed equal to 0.525;
- pg is the coefficient of distribution losses, assumed equal to 0.936
- ηth,rif is the reference efficiency for thermal energy, assumed equal to 0.90.

3. Results

3.1. Bio-hydrogen and bio-methane production by CSTR assay

During Run1 FW was fed to H_2 and CH_4 reactor simultaneously. These conditions were maintained for 42 days, the time necessary to guarantee stable conditions in H_2 and CH_4 reactor. Concerning Run2, it was performed for 26 days. The first 13 days were considered state of transition between Run1 and Run2 while from day 13 to day 26 conditions were considered steady and used for comparison. Regarding biogas production and quality, Run2 highlighted a higher methane content and SGP in the methanogenic stage. CH_4 content increased from 65.2% to 68.4% and SGP from 694.4 Nl/kgTVS d to 704.6 Nl/kgTVS d. Moreover, the fermentative stage provided a further gasification of the biodegradable matter. Hydrogen reactor SGP was 43.1 Nl/kgTVS d while the produced biogas was formed by carbon dioxide and hydrogen (22.9%). Adding the SGP coming from H_2 to the SGP coming from CH_4 reactor, the total SGP of Run2 was found to be 747.7 Nl/kgTVS d, 7.7% higher than Run1.

The specific gas production obtained by performing batch tests are different from the results achieved with semi-continuous tests, in particular in terms of hydrogen production. As shown in table 4, SGP reached performing BHP tests was 55.0 Nl/kgTVS d with 45.0% of hydrogen. Concerning CSTR tests, SGP of Run2 in H_2 reactor was found to be 43.1 Nl/kgTVS d with 22.9% of hydrogen concentration. In this respect, hydrogen production in Run2 was found to be 21.6% lower than BHP tests, whereas methane production during CSTR tests was higher than BMP tests.

Table 4. BMP, BHP and CSTR tests results. Values are expressed as averages and standard deviations.

	$Nl_{biogas}/kgTVS_{sub}$ d	% CH_4	% H_2
BMP	440.5 ± 8.7	65.0 ± 2.3	-
BHP	55.0 ± 3.6	-	45.0 ± 2.4
SGP Run1	694.4 ± 24.6	65.2 ± 1.9	-
SGP Run2	43.1 ± 12.8 (H_2)	- (H_2)	22.9 ± 5.5 (H_2)
	704.6 ± 28.5 (CH_4)	68.4 ± 1.1(CH_4)	- (CH_4)

3.2. Scenarios performance

Table 5 shows the results in terms of mass balance and energy budget estimated for each scenarios. In Figure 3 the scenarios are compared in terms of energy saving.

The results showed that the physical separation of the traditional AD in a two-phase process with the presence of a preliminary step of dark fermentation determined beneficial effects in terms of electric energy production. In particular, two-phase configuration can improve gas production in the methanogenic phase. Concerning thermal energy, it can be noticed that adding a new fermentative digester increased the consumption for heating the reactor. In this case the total energy obtained from hydrogen production did not balance the thermal energy required. Under this perspective the two-stage process is not efficient as the traditional one-stage digestion.

Table 5. Digestion scenarios mass balance and energy budget

	Scenario CH_4 (1)	Scenario CH_4 (2)	Scenario H_2 (1)	Scenario H_2 (2)
Biofuel produced				
Biogas (Nm^3/y)	2543917	2543917	209098 (H_2) 2574284 (CH_4)	209098 (H_2) 2574284 (CH_4)
CH_4 (Nm^3/y)	1658634	1658634	1764230	1764230
H_2 (Nm^3/y)	-	-	47884	47884
Electricity (MWh/y)				
In	2378	2304	2546	2458
Out	6844	5339	7349	5730
Net	4466	3036	4803	3727
Heat (MWh/y)				
In	1519	1519	2783	2783
Out	6952	6368	7366	6834
Net	5406	4849	4583	4051

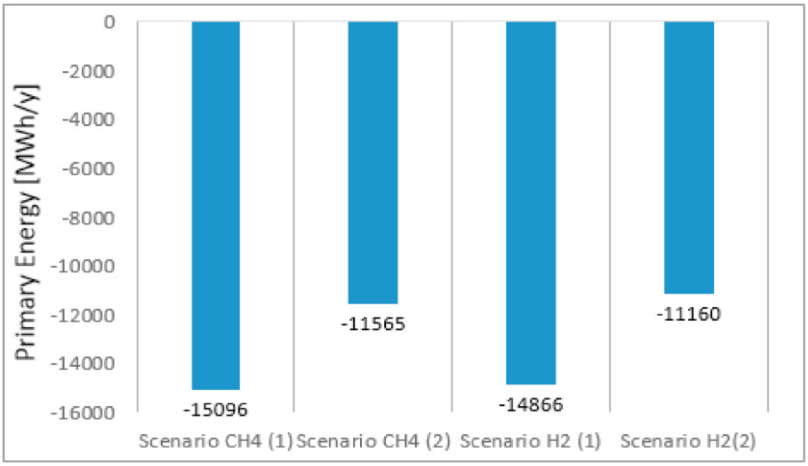

Figure 3. Digestion scenarios comparison

4. Conclusions

The physical separation of the two anaerobic phases with the presence of a preliminary step of dark fermentation was demonstrated to be beneficial for the methanogenic phase. More specifically, the higher level of FW hydrolysis achieved during the fermentative phase improved methane production in the second stage.

Through CSTR tests it was possible to estimate the production of hydrogen and methane from FW and calculate the primary energy saving obtained by different users of biogas.

From CSTR assays a specific gas production of 43.1 Nl/kgTVS$_{sub}$ with 22.9% of hydrogen concentration was achieved in the acidogenic phase, and 704.6 Nl/kgTVS$_{sub}$ with 68.4% of methane was obtained in CH_4 reactor. Considering the results coming from Percorini et al [13], in BHP and BMP tests were reached a specific gas production of 55.0 NlH_2/kgTVS$_{sub}$ and 440 NlCH_4/kgTVS$_{sub}$ with hydrogen and methane concentration respectively equal to 45% and 65%. Although specific methane production increased in semi-continuous mode, H_2 production decreased respect to BHP test and hydrogen concentration dropped from 45% to 22.9%.

In all scenarios (with and without dark fermentation), the savings achieved by energy recovery from the produced biogas were estimated by comparing the use of an ICE, a microturbine and an ICE integrated by a MCFC. The study carried out with CSTR mode shows that the scenario referred to a traditional one-stage AD process with ICE as biogas user is the most virtuous solution in terms of primary energy saved. This result doesn't match what was obtained in the previous study referred to batch tests. Bio-hydrogen production in semi-continuous conditions is not sufficient to balance out adding energy consumption due to heating of dark fermentation digester. The difference evaluated in terms of bio-hydrogen production between BHP and CSTR tests demonstrate that H_2 produced in two-phase anaerobic digestion process doesn't cover thermal energy request. For this reason, other tests will be performed to increase the specific gas production in the fermentative phase and to improve energy efficiency of the two-phase anaerobic digestion process.

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