Journal of Environmental Management 140 (2014) 76–82

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Improvement of mesophilic anaerobic co-digestion of agri-food waste by addition of glycerol

Antonio Serrano, Jose A. Siles, Arturo F. Chica, M. Angeles Martin*

Department of Inorganic Chemistry and Chemical Engineering, University of Cordoba, Campus Universitario de Rabanales, Edificio Marie Curie (C-3), Ctra. N-IV, km 396, 14071 Cordoba, Spain

ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form
17 February 2014
Accepted 21 February 2014
Available online 12 April 2014

Keywords:
Crude glycerol
Strawberry waste
Fish waste
Mesophilic anaerobic co-digestion
Kinetics
Economic assessment

ABSTRACT

Anaerobic co-digestion is a promising alternative to manage agri-food waste rather than landfilling, composting or incineration. But improvement of methane yield and biodegradability is often required to optimize its economic viability. Biomethanization of agri-food solid waste presents the disadvantage of a slow hydrolytic phase, which might be enhanced by adding a readily digestible substrate such as glycerol. In this study, strawberry extrudate, fish waste and crude glycerol derived from biodiesel manufacturing are mixed at a proportion of 54:5:41, in VS (VS, total volatile solids), respectively. The mesophilic anaerobic co-digestion at lab-scale of the mixture was stable at loads lower than 1.85 g VS/L, reaching a methane yield coefficient of 308 L CH_4/kg VS (0 °C, 1 atm) and a biodegradability of 96.7%, in VS. Moreover, the treatment capacity of strawberry and fish waste was increased 16% at adding the crude glycerol. An economic assessment was also carried out in order to evaluate the applicability of the proposed process. Even in a pessimistic scenario, the net balance was found to be positive. The glycerol adding implied a net saving in a range from 25.5 to 42.1 €/t if compared to landfill disposal.

1. Introduction

The adequate management of waste streams is currently one of the priorities in developed societies. Different legislation has been developed to improve the waste treatment efficiency and its sustainability all around the world. Waste management must be focused on reduction, reuse and recycling according to the current legislation (Directive 2008/98/EC on waste in the EU and the Resource Conservation and Recovery Act [RCRA] in the United States). This entails to catalog the organic wastes as potential resources in different processes. In this context, free disposal in landfill should be the last option to be considered given that it presents a serious challenge to natural ecosystems and causes considerable environmental and toxicological problems. The economic cost of landfill management varies widely in a range of 37–142 €/t in Europe breaking down in gate fees and taxes, collection and pre-treatment (sorting and compressing, transport, etc.) (Torfs et al., 2004). Gate fees charged by site operators for waste treatment at landfills has been reported to be an important portion of the final cost (11–117 €/t) (Torfs et al., 2004; Fischer et al., 2012). Moreover, the economic investment in the treatment of the waste is not recovered through the simultaneous generation of valuable products (Iglesias, 2007).

Agri-food industry generates large quantities of polluting waste which are traditionally managed together with the organic fraction of municipal solid waste (OFMSW) (Rentizelas et al., 2014). An important sector in the agri-food industry is the processing of strawberry for the elaboration of marmalade, yogurt and flavorings, which employed about 21% (close to 1 million of tons) of the strawberry crops around the world in 2011 (FAOSTAT, 2013). However, the remaining waste extrudate (7% of the manufactured strawberry weight) requires an adequate treatment (Pollard et al., 2006).

On the other hand, fish canning industry is another sector that generates polluting agro-industrial waste. The world consumption of canned fish accounts for 15% of total fish consumed, although in Europe and America the percentage may be as high as 60%. Unfortunately, 50–75% of the processed fish became waste (heads, bones and entrails) and it is frequently disposed in landfill (Eiroa et al., 2012).

The join management of different wastes generated in a specific area is an interesting alternative to optimize its economic investment and to allow the implementation of centralized systems (Teghammar et al., 2013). Anaerobic digestion might be an interesting alternative for the management of strawberry extrudate and

* Corresponding author. Tel.: +34 957212273; fax: +34 957218625.
E-mail address: iq2masam@uco.es (M.A. Martin).

http://dx.doi.org/10.1016/j.jenvman.2014.02.028
0301-4797/

Nomenclature

Alk	alkalinity (mg $CaCO_3$/L)
COD	chemical oxygen demand (g O_2/kg; g O_2/L)
FS	total fixed solids (g/kg)
G	methane volume (L_{STP}; m^3)
LCP	lower calorific power (kJ/m^3_{STP})
$N-NH_4^+$	ammoniacal nitrogen (g/kg)
OLR	organic loading rate (kg VS/m^3 d)
P_{total}	total phosphorus (g/kg)
r_G	methane production rate (L_{STP}/m^3 d)
SFGM	strawberry extrudate, fish waste and crude glycerol mixture
STP	standard temperature and pressure conditions (0 °C, 1 atm)
t_{95}	time required to reach 95% of the total methane production for each load (d)
TS	total solids (g/kg)
V	volume of reactor (L; m^3)
VA	volatile acidity (mg acetic acid/L)
VS	total volatile solids (g/kg)
$Y_{CH_4/S}$	methane yield coefficient (m^3_{STP}/kg VS; L_{STP}/g VS)

fish waste, which are organic wastes that are at length generated around the world. This technique is characterized by the possibility of obtaining energy through the generation of methane. Its lower calorific power (LCP), about 35, 793 kJ/m^3_{STP} (STP: 0 °C and 1 atm), is equivalent to 1 kg raw coal or 0.76 kg standard coal (Wheatley, 1990; Zeng et al., 2007). This is very interesting due to the enhancement of the electricity and energy costs during the last few years. Concretely, the electricity average price for industrial uses in the EU increased from 0.105 to 0.118 €/kWh within the period 2010–2012 (Goerten, 2013).

Additionally, digestate generation is associated with anaerobic digestion process. This by-product might be also used for the generation of a stabilized organic amendment, overall after a previous stabilization process through composting. The use of the stabilized digestate allows recovering N and P by the soils (Koroneos and Nanaki, 2012).

Previous studies have shown that although single anaerobic digestion of strawberry and fish waste is not stable at high organic loading rates (OLRs), the centralized management of both wastes enhances the stability of the process while the methane production remains at low levels (Serrano et al., 2013; Siles et al., 2013). However, methane production might increase by supplementing the waste mixture with readily digestible co-substrates, such as the highly available and low-priced glycerol derived from biodiesel manufacturing (Van Assche et al., 1983; Ma et al., 2008). The production of 100 kg of biodiesel yields approximately 10 kg of impure glycerol, with 55–90% glycerol (Hazimah et al., 2003). Glycerol presents the advantages of being readily digestible and easily storable over a long period compared with other co-substrates (food and animal wastes, glucose, cellulose, etc.).

To the best of our knowledge, the research study published by Serrano et al. (2013) is the only study on the simultaneous treatment of strawberry extrudate and fish waste. However, some improvements were required to enhance the viability of the combined treatment, which might be considered of special interest in areas where both polluting waste are generated simultaneously. The main purpose of this research study was to evaluate the improvement of the methane generation through the mesophilic anaerobic co-digestion of strawberry extrudate and fish waste by adding crude glycerol as readily degradable co-substrate. This study, focused on the anaerobic digestion, which is deeply involved in the biorefinery concept, could be considered of special interest for the centralized treatment of these polluting wastes through an environmentally friendly and economic technique, as well as to evaluate its viability against other management methods like the landfill disposal.

2. Materials and methods

2.1. Chemical analyses

The following parameters were determined in the effluents of each load: pH, total chemical oxygen demand (COD, g/kg), total solids (TS, g/kg), total fixed solids (FS, g/kg), total volatile solids (VS, g/kg), volatile acidity (VA, mg/L), alkalinity (Alk, mg/L), and ammoniacal nitrogen ($N-NH_4^+$, mg/L). All analyses were carried out in accordance with the Standard Methods of the APHA (APHA, 1989). On the other hand, moisture and total phosphorus (P_{total}, g/kg) were also analyzed to characterize the solids substrates following the test methods for the examination of composting and compost developed by the US Department of Agriculture and the US Composting Council (US Composting Council, 2001).

2.2. Experimental set-up and procedure

The experimental set-up used for the anaerobic co-digestion of strawberry extrudate, fish waste and glycerol-containing waste is shown in Fig. 1. Details about the experimental set-up and procedure are described in the supplementary data file. All the experiments, including the start-up, biomass acclimatization and waste treatment, were carried out over a 55-day period.

2.3. Substrates

The raw materials used as substrates were strawberry waste derived from the manufacturing of strawberry flavored products, waste derived from the fish canning industry and crude glycerol from the biodiesel manufacturing. The strawberry and fish waste were provided by the ADESVA Technology Center, located in Huelva (Spain), while glycerol was provided by the BIDA S.A. Factory in Fuentes de Andalucia (Seville, Spain). Table 1 shows the analytical characterization of these wastes. The specifications of the raw materials are described in supplementary data file.

Strawberry extrudate, fish waste and crude glycerol mixture (SFGM) were blended and distilled water was added at a proportion

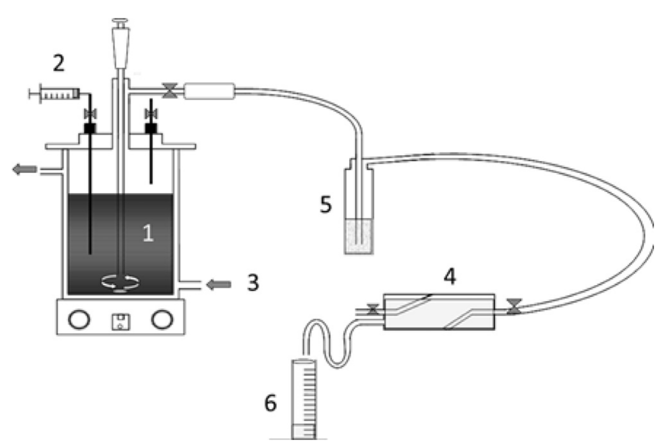

Fig. 1. Experimental set-up: (1) 1-L Pyrex complete mixing reactor; (2) connections to load feedstock, ventilate the biogas, inject nitrogen and remove effluent; (3) thermostatic jacket; (4) 1-L Boyle-Mariotte reservoir; (5) closed bubbler; (6) test tube.

Table 1
Analytical characterization of the strawberry waste extrudate, fish waste, crude glycerol and their mixture (SFGM) (wet weight basis).

	Strawberry extrudate	Fish waste	Crude glycerol	SFGM
pH	–	–	5.79 ± 0.03	4.22 ± 0.04
COD (g O_2/kg)	300 ± 10	555 ± 35	1200 ± 50	210 ± 13
TS (g/kg)	221 ± 2	374 ± 1	596 ± 15	114 ± 2
FS (g/kg)	9 ± 1	42 ± 1	11 ± 1	3 ± 1
VS (g/kg)	212 ± 3	332 ± 2	585 ± 16	111 ± 3
$N-NH_4^+$ (g/kg)	1.2 ± 0.1	47.1 ± 1.4	5.0 ± 0.1	1.4 ± 0.1
P_{total} (g/kg)	1.2 ± 0.1	5.1 ± 0.3	4.2 ± 0.1	0.8 ± 0.1
COD:N:P	252:1:1	109:9:1	286:1:1	280:2:1

of 2:1, in wet weight basis, of distilled water and SFGM, respectively, to facilitate handling and the feeding process of the digesters and improve the homogenization of the waste as described previously by other authors (Cheng et al., 2011). The SFGM was conserved under freezing conditions to avoid undesirable fermentation during the experiments. The proportion in which strawberry extrudate, fish waste and crude glycerol were mixed was 54:5:41, in VS, respectively. The criteria to make this mixture was to reach an adequate C:N:P balance as described by Thaveesri (1995) and Brunetti et al. (1983). Table 1 also includes the analytical characterization of the SFGM.

2.4. Calculation section

2.4.1. Organic loading rate (OLR)

One of the most interesting variables to be determined during the anaerobic digestion of organic waste is the treatment capacity. This variable may be measured through the rate of substrate addition or OLR, which relates the amount of the waste added to the reactor with its volume and time. The present research study allows the added substrate to be degraded as much as possible. Consequently OLR was calculated considering the substrate concentration added to the reactors and the time required to reach 95% of the total methane production for each load.

$$\mathrm{OLR} = \frac{[\text{Added load}]}{t_{95}} \tag{1}$$

where [Added load] is the concentration of waste mixture added to the reactors (kg VS/m^3) and t_{95} time required (d) to reach 95% of the total methane production for each load.

2.4.2. Methane production rate (r_G)

The methane production rate (r_G) values were determined from the time required to reach 95% of the total methane production for each load (t_{95}, d), the methane volume (G; L_{STP}) generated at t_{95} and considering the volume of the reactor (V; m^3) according to equation (2).

$$r_G = \frac{G}{V \times t_{95}} \tag{2}$$

2.4.3. Heating power

The values of heating power (W/kg VS) were obtained from the values of methane production rate (r_G; m^3/s), the LCP for methane (kJ/m^3_{STP}), the load added to the digesters (kg VS/m^3) and considering the volume of the reactors (V; m^3). The values were calculated through the following equation:

$$\text{Heating power} = \frac{r_G \times \mathrm{LCP}}{[\text{Added load}] \times V} \tag{3}$$

2.4.4. Energy yield

The values of energy yield (kJ/kg VS) were obtained from the methane yield coefficient (m^3_{STP}/kg VS) and the LCP for methane (kJ/m^3_{STP}). The following equation was employed to calculate the energy yield values:

$$\text{Energy yield} = Y_{CH_4/S} \times \mathrm{LCP} \tag{4}$$

2.5. Software

Sigma-Plot software (version 11.0) was used to create the graphs, perform the statistical analysis (mean values and standard deviations) and fit the experimental data presented in this work to linear regressions.

3. Results and discussion

3.1. Stability of the anaerobic co-digestion process

The stability of biomethanization was monitored through the variation in the pH, the alkalinity and the VA in the digesters at the end of each load. According to the literature, the usual optimal pH range for methanogenic bacteria varies between 7.1 and 7.8 as extreme values (Wheatley, 1990; Liu et al., 2008). The process operated at pH values close to the optimal range over the experimental time (Fig. 2), although the pH values in the digesters decreased at increasing the added load until reaching a final value close to 7.2. Furthermore, Fig. 2 also shows the evolution of the alkalinity and VA in the digesters. The tendency of the alkalinity was in line with the decrease of the pH at increasing of the added load. Specifically, alkalinity values decreased from 5655 to 2411 mg $CaCO_3$/L. In contrast, VA remained almost constant throughout the experiments with a mean value of 679 ± 160 mg acetic acid/L.

On the other hand, Lane (1984) described that for stable digestions it is imperative that a satisfactory ratio between VA and alkalinity levels should be maintained. This ratio is given by the empirical relationship Alk (mg $CaCO_3$/L) − 0.7 · VA (mg acetic acid/L), which should not be less than 1500 for balanced digestion to occur. Its values were found to be always higher than 1500, although a decrease from 4228 to 2078 was observed for increasing loads. This fact might entail the occurrence of a negative effect in the digestion process. However, these negative effects occurred at higher loads than those described for the individual anaerobic treatment of crude glycerol (Siles et al., 2009). These authors reported stable conditions until loads of 3.00 g COD/L of crude glycerol against the load of 1.85 g VS/L of SFGM (5.00 g COD/L) reached in the present research. These results showed a clear positive synergy in the stability when glycerol is co-digested with strawberry extrudate and fish waste. Moreover, the glycerol addition allows the enhancement of the treatment capacity of the agri-food wastes (strawberry and fish), whose single biomethanization presented a maximum allowed load of 1.5 g VS/L for each waste (Siles et al., 2013).

3.2. Methane yield coefficient

As it was described previously, one of the most interesting purposes when anaerobic co-digestion is implemented is to improve the methane yield. In accordance with Fig. 3, the methane production rate increased (r_G, L_{STP}/(m^3 d)) with the OLR (kg VS/(m^3 d)) added to the digesters. The methane yield coefficient was calculated through the slope of the line that fits the correlation between the methane production rate for each load and the OLR in the digesters, reaching a mean value of 308 L_{STP} CH_4/kg VS. This

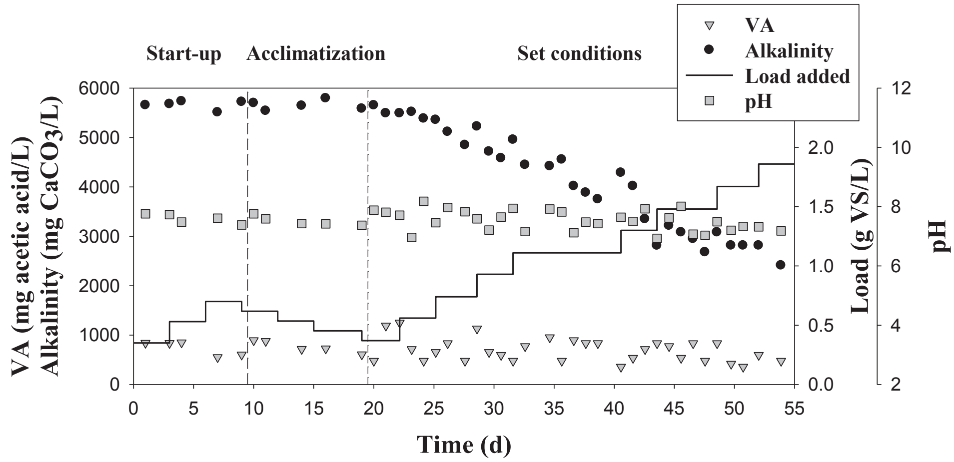

Fig. 2. Variation in the volatile acidity, alkalinity, pH and the added load with the experimental time (start-up, acclimatization and set conditions).

value is markedly higher than the methane yield coefficient reported for the single biomethanization of strawberry extrudate (230 L_{STP} CH_4/kg VS) (Siles et al., 2013) and fish waste (129 L_{STP} CH_4/kg VS) (Fernandez, 2011). Serrano et al. (2013) studied the anaerobic co-digestion of strawberry extrudate and fish waste at the respective proportion 83:17, in VS, under the same experimental conditions. These authors reported a methane production yield of 120 L_{STP} CH_4/kg VS, which is several times lower than the value obtained in the present research. The marked enhancement of the methane production yield might be a consequence of the high degradability of crude glycerol as well as the improvement of the nutrient balance or the dilution of the chlorides from the fish waste. The soluble character and molecule size make glycerol more easily accessible for the microorganisms, which implies its higher degradation and the consequent higher methane yield (Ortega et al., 2008).

Considering these results, the energy yield that could be obtained per unit of SFGM treated is an interesting variable in order to design an industrial digester, its treatment capacity or the inclusion of an economically viable pretreatment. The energy yield was calculated from the methane production yield determined in each load and the LCP 35,793 kJ/m^3_{STP} (Wheatley, 1990) as is described in Section 2.4.4. The energy yield values were found to be in the range of 11,722–17,471 kJ/kg VS, as it is shown in Table 2. On the other hand, the heating power of the process can be obtained through the methane production rate, whose values are shown in Fig. 3, and the lower calorific value according to eq. (3). Calculated heating power corresponds with each OLR expressed in Table 2 and it was found to vary in the range of 35–54 W/kg VS for OLRs of 0.62–4.26 kg VS/(m^3 d).

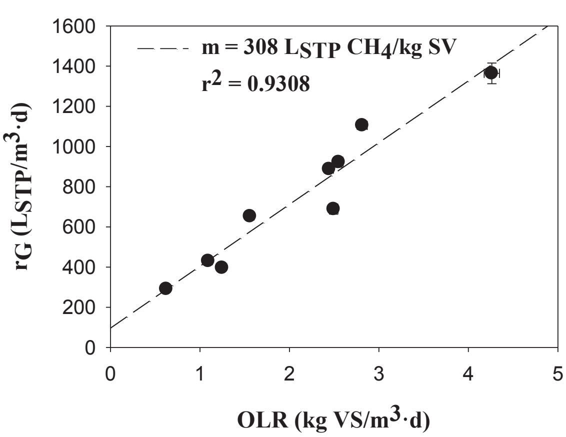

Fig. 3. Variation of the methane production rate (L_{STP}/m^3·d) with the organic loading rate (kg VS/m^3·d).

3.3. Biodegradability

Biodegradability of the treated mixture under the study conditions is another interesting variable to be determined. The biodegradability was determined by plotting the removed VS against the added VS in the digesters. According to Fig. 4, the biodegradability of the SFGM was 96.7%, in VS. This percentage is an intermediate value between the value obtained in the single treatment of strawberry extrudate and fish waste. Concretely, the biodegradability percentages determined for the strawberry extrudate, fish waste and crude glycerol treated independently were 90, 83 and 100%, in VS, respectively (Siles et al., 2009; Serrano et al., 2013). However, it is higher than the values described for agri-food waste by several authors. For example Regueiro et al. (2012) described COD removal efficiencies of 65–70% in the anaerobic co-digestion of biodiesel waste, fish waste and pig manure with different proportions under mesophilic conditions. Consequently, the enhancement of the methane production and the biodegradability, respect to the anaerobic digestion of agri-food wastes in absence of glycerol, could correspond to the addition of crude glycerol to the mixture. This increase might be a consequence of the biodegradable nature of this molecule and/or presence of some additional nutrients contained in glycerol-containing waste (Siles et al., 2009). The enhancement of the biodegradability values could be also a consequence of the increase of the active biomass growth in the

Table 2
OLR and power production for the different loads added to the digesters.

Load (g VS/L)	Energy yield (kJ/kg VS)	Heating power (W/kg VS)	OLR (kg VS/m^3 d)
0.37	17,471	49	0.62
0.56	16,382	54	1.09
0.74	17,277	48	1.25
0.93	15,822	44	1.56
1.11	14,079	50	2.44
1.30	13,406	43	2.55
1.48	12,997	36	2.49
1.67	11,722	50	4.26
1.86	13,913	35	2.81

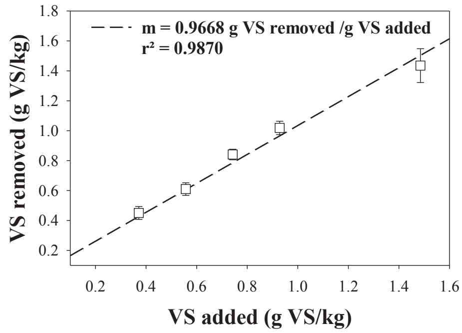

Fig. 4. Plot of the amount of substrate removed (g VS/kg) against the substrate added (g VS/kg) for all the experiments to obtain the biodegradability percentage.

system at adding glycerol, as it was described by Fountoulakis et al. (2010).

3.4. Organic loading rate

The values of OLR, which were calculated through eq. (1), are shown in Table 2. The OLR values presented a tendency to increase with the substrate added to the digesters from 0.62 to 4.26 kg VS/(m^3 d), with just little variations for the loads within the range of 1.11–1.48 g VS/L. Moreover, a marked decrease in the OLR values was observed at the final load, which could be a consequence of the destabilization of the digesters. In general, the effect derived from the enhancement of the OLR was a progressive decreasing of the heating power obtained. Nevertheless, the observed OLRs were higher than those described by Serrano et al. (2013) for the mesophilic co-digestion of strawberry extrudate and fish waste at the proportion of 83:17, in VS, respectively (an average OLR of 1.90 kg VS/(m^3 d)). Specifically, the addition of glycerol to the agri-food mixture allows an increase of the strawberry extrudate and fish waste treatment capacity from 25.5 to 30.3 kg strawberry and fish waste/(m^3 reactor d) (an enhancement higher than 16%), considering that crude glycerol was degraded completely. Gómez et al. (2006) studied the co-digestion process of fruit and vegetable wastes with primary sludge under mesophilic and low mixing conditions in four 3-L reactors. These authors reported an OLR between 0.82 at 1.10 kg VS_{added}/(m^3 d), which is slightly lower than the range described in the present research study due to sewage sludge is not so biodegradable as glycerol.

Table 3
Estimated economic balance for the anaerobic co-digestion of the agri-food waste and landfill management.

Benefit (€/t)		Cost (€/t)	
Direct use (in situ)		Power	
Methane electricity power	15.9	Electricity	2.3
Methane heating power	9.2	Heat	4.6
Indirect use (outsite)		Operational cost	
Methane electricity power (excess)	13.6	Running	7.3
Methane heating power (excess)	0.0–4.6	Repayment (10 years)	6.0
Optional profit			
Organic amendment	0.0–9.0		
Government aids (%)	0–50		
Total benefit	13.6–27.2	*Total cost*	13.3
		Pessimist net balance	0.3 €/t
		Optimist net balance	16.9 €/t
		Landfill management cost (€/t)	
		Transport cost	102.3
		Operational cost	25.2
		Total cost	127.5

3.5. Economic assessment

Given that the cost of waste treatment through landfilling could be an impact in the economic viability of any business, it is necessary to evaluate the estimated cost of the anaerobic digestion for the proposed SFGM. The net benefit of the treatment process was determined as the difference between the estimated benefit of the biomethanization and the cost of the landfill treatment, which is the usual management process for agri-food waste. According to Tanskanen (2000), the cost of the treatment by landfilling can be defined as the sum of the transport and the operating cost, reaching in Europe average prizes of 102.3 €/t and 25.2 €/t, respectively (excluding the fee taxes). Likewise, the management cost by landfilling might increase if the potential environmental impacts such as changes of the values of neighboring real estate, remediation cost of polluted soils and waters, medical spending due to influenced human health, etc. were considered (Weng and Fujiwara, 2011).

The estimated economic assessment of the anaerobic co-digestion is summarized in Table 3. The adopted assumptions were:

- The energy production was obtained from the methane yield (308 L_{STP}/kg VS).
- The efficiency in the energy obtained through a biogas engine was 39% for electricity and 45% for heat production (Eder and Schulz, 2007).
- Energy self-supply reached 15% of the electricity and 50% of heat generated by the system (Angelidaki et al., 2006).
- The prizes of electricity and heat were fixed in 0.12 €/kWh and 0.06 €/kWh respectively (Goerten, 2013; EUROSTAT, 2013).
- The employment of digestate as organic amendment was considered without economic interest.
- The operational costs and the initial investment amortization were fixed in 7.30 €/t and 6.0 €/t, respectively (Angelidaki et al., 2006).
- The operational cost of landfill was estimated in 25.2 €/t (Tanskanen, 2000).

The energy production was considered the main benefit derived from the proposed anaerobic co-digestion. The expected energy has been obtained through a biogas engine, with efficiency in the typical range for CHP plants, from the methane yield coefficient described previously. Considering the electricity and heat prizes, the plant would produce 15.9 and 9.2 €/t of electricity and heat, respectively. The electricity excess can be sold to the energy companies. Consequently, the profit derived from the electricity excess reaches a value of 13.6 €/t. On the other hand, the re-use of the heat depends strongly on the local circumstances. Thus, an estimation of the economic benefit derived of the heat was calculated through the price of the kWh for natural gas in 2013 in Spain (0.06 €/kWh), reaching a benefit in a range from 0.0 to 4.6 €/t (EUROSTAT, 2013). Finally, the benefit derived from the organic amendment and government aids have not been considered given that it depends on several factors such as the region, the environmental policies or the quality of the organic amendment, but a typical value range oscillates between 0 and 9 €/t (Evans and Wilkie, 2010). The digestate could be applied after a composting process to strawberry crops with the consequent economic and environmental benefits. Likewise, the nutrient recovery by applying the organic amendment allows improving the independence of the chemical fertilizers (Bustamante et al., 2012).

Table 3 also shows the cost derived from the biomethanization process. According to Angelidaki et al. (2006), the electricity and heat generated are higher than the requirements of the process considering the methane yield coefficient reported. The cost of power was found to be 2.3 and 4.6 €/t for electricity and heat, respectively. Therefore the economic costs are compensated by the generated power. Also, the same authors established an operational cost of 7.30 €/t, where handling and running cost are included. On the other hand, it was proposed to amortize the initial investment in a period of ten years with a cost of 6.0 €/t (Angelidaki et al., 2006). In general, the co-digestion of agro-industrial wastes generated in the same area allows omitting the cost derived of extra nutrients requirements in the digester, pre-treatments or even important transport charge. Given that the transport charges, which could reach a value of 5.14 ± 0.12 €/t km (Rathi, 2007), are common to the different management technics, its inclusion in an economic comparison might be avoided. The final cost of the process would be in a range of 0.3–16.9 €/t which means a net saving of 25.5–42.1 €/t respect to the landfill management (operation cost: 25.2 €/t) omitting the transport cost in both chases. So, the proposed treatment presents an important economic interest for agro-industrial areas comparing with landfill management, even in pessimist evaluation.

According to the previous data, the benefit of the process is positive at OLRs higher than 1.69 kg VS/(m^3 d), which corresponds to a methane production rate of 0.54 m^3 CH_4/(m^3 d). At lower OLRs, the methane production rate is not enough to compensate the energy requirements and the process costs.

4. Conclusions

The anaerobic co-digestion of strawberry extrudate and fish waste is an efficient management method, but the improvement of the treatment capacity is desirable to ensure its viability from the environmental and economic point of view. In this research study, the addition of glycerol to strawberry and fish waste mixture allowed a methane yield coefficient of 308 L_{STP}/kg VS (65% higher than the anaerobic co-digestion without glycerol addition), which entails an energy yield of 12,134 kJ/kg VS. The addition of glycerol also increased the treatment capacity of strawberry and fish waste around 16%. An economic assessment allowed calculating a net saving of 25.5–42.1 €/t respect to the landfill disposal. Thus, the proposed centralized treatment allows managing different waste with positive consequences to the environment and the industry. However, further research would be required regarding the scale-up of the process as well as the evaluation of their co-digestion with other industrial waste or by-products generated in the same production areas.

Acknowledgment

The authors are very grateful to the ADESVA Technology Centre (Huelva, Spain) and the company HUDISA S.A. (Huelva, Spain) for supplying the wastes and The Spanish Ministry of Science and Innovation for funding this research through Project CTM2011-26350. We also wish to express our gratitude to Inmaculada Bellido and María Luisa López for her contribution to this research.

Appendix A. Supplementary material

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2014.02.028.

References

Angelidaki, I., Schmidt, J.E., Karakashev, D.B., 2006. A Sustainable Solution for Pig Manure Treatment: Environmental Compliance with the Integrated Pollution Prevention and Control Directive. Contract COOP-CT-2005-017641.
APHA, 1989. Standard Methods for the Examination of Water and Wastewater. APHA, AWWA & WPCF.
Brunetti, A., Boari, G., Passino, R., Rozzi, A., 1983. Physico-chemical factors affecting start-up in UASB digestors. In: Proc. of European Symposium on Anaerobic Wastewater Treatment, Noordwijkerhout, The Netherlands, p. 317.
Bustamante, M.A., Alburquerque, J.A., Restrepo, A.P., de la Fuente, C., Paredes, C., Moral, R., Bernal, M.P., 2012. Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. Biomass Bioenerg. 43, 26–35.
Cheng, F., Boe, K., Angelidaki, I., 2011. Anaerobic co-digestion of by-products from sugar productions with cow manure. Water Res. 45, 3473–3480.
Eder, B., Schulz, H., 2007. Biogas Praxis – Grundlagen, Planung, Anlagenbau, Beispiele, Wirtschaftlichkeit. Ökobuch Verlag, Staufen.
Eiroa, M., Costa, J.C., Alves, M.M., Kennes, C., Veiga, M.C., 2012. Evaluation of the biomethane potential of solid fish waste. Waste Manag. 32, 1347–1352.
EUROSTAT, 2013. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Electricity_and_natural_gas_price_statistics (accessed 10.11.13).
Evans, J.M., Wilkie, A.C., 2010. Life cycle assessment of nutrient remediation and bioenergy production potential from the harvest of hydrilla (*Hydrilla verticillata*). J. Environ. Manag. 91, 2626–2631.
FAOSTAT, 2013. http://faostat.fao.org/site/567/default.aspx#ancor (accessed 03.14.13).
Fernandez, R., 2011. Study of Biodegradability of Different Wastes with Strategic Value in the Zone of Huelva. Certificate of Advanced Studies in Chemical Engineering. University of Cordoba, Spain.
Fischer, C., Lehner, M., McKinnon, D.L., 2012. Overview of the Use of Landfill Taxes in Europe. ETC/SCP Working Paper 1/2012.
Fountoulakis, M.S., Petousi, I., Manios, T., 2010. Co-digestion of sewage sludge with glycerol to boost biogas production. Waste Manag. 30, 1849–1853.
Goerten, J., 2013. In: Corselli-Nordblad, L. (Ed.), Eurostat New Release. Eurostat Press Office, p. 79.
Gómez, X., Cuetos, M.J., Cara, J., Morán, A., García, A.I., 2006. Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes: conditions for mixing and evaluation of the organic loading rate. Renew. Energy 31, 2017–2024.
Hazimah, A.H., Ooi, T.L., Salmiah, A., 2003. Recovery of glycerol and diglycerol from glycerol pitch. J. Oil Palm Res. 15, 1–5.
Iglesias, D., 2007. Costos económicos por la generación y manejo de residuos sólidos en el municipio de Toluca, Estado de México. Equilibr. Econ. 3, 131–148.
Koroneos, C.J., Nanaki, E.A., 2012. Integrated solid waste management and energy production – a life cycle assessment approach: the case study of the city of Thessaloniki. J. Clean. Prod. 27, 141–150.
Lane, G., 1984. Laboratory-scale anaerobic digestion of fruit and vegetable solid waste. Biomass 5, 245–259.
Liu, C.F., Yuan, X.Z., Zeng, G.M., Li, W.M., Li, J., 2008. Prediction of methane yield at optimum pH for anaerobic digestion of organic fraction of municipal solid waste. Bioresource Technol. 99, 882–888.
Ma, J., Van Wambeke, M., Carballa, M., Verstraete, W., 2008. Improvement of the anaerobic treatment of potato processing wastewater in a UASB reactor by co-digestion with glycerol. Biotechnol. Lett. 30, 861–867.
Ortega, L., Husser, C., Barrington, S., Guiot, S.R., 2008. Evaluating limiting steps of anaerobic degradation of food waste based on methane production test. Water Sci. Technol. 57, 419–422.
Pollard, S.J.T., Smith, R., Longhurst, P.J., Eduljee, G.H., Hall, D., 2006. Recent developments in the application of risk analysis to waste technologies. Environ. Int. 32, 1010–1020.
Rathi, S., 2007. Optimization model for integrated municipal solid waste management in Mumbai, India. Environ. Dev. Econ. 12, 105–121.
Regueiro, L., Carballa, M., Álvarez, J.A., Lema, J.M., 2012. Enhanced methane production from pig manure anaerobic digestion using fish and biodiesel wastes as co-substrates. Bioresource Technol. 123, 507–513.
Rentizelas, A.A., Tolis, A.I., Tatsiopoulos, I.P., 2014. Combined municipal solid waste and biomass system optimization for district energy applications. Waste Manage. 34, 36–48.
Serrano, A., Siles, J.A., Chica, A.F., Martín, M.A., 2013. Agri-food waste valorization through anaerobic co-digestion: fish and strawberry residues. J. Clean. Prod. 54, 125–132.
Siles, J.A., Martín, M.A., Chica, A.F., Martín, A., 2009. Anaerobic digestion of glycerol derived from biodiesel manufacturing. Bioresource Technol. 100, 5609–5615.
Siles, J.A., Serrano, A., Martín, A., Martín, M.A., 2013. Biomethanization of waste derived from strawberry processing: advantages of pretreatment. J. Clean. Prod. 42, 190–197.
Tanskanen, J.H., 2000. Strategic planning of municipal solid waste management. Resour. Conserv. Recycl. 30, 111–133.
Teghammar, A., Castillo, M.D.P., Ascue, J., Niklasson, C., Sárvári Horváth, I., 2013. Improved anaerobic digestion by the addition of paper tube residuals: pre-treatment, stabilizing, and synergetic effects. Energ. Fuel 27, 277–284.
Thaveesri, J., 1995. Granulation and Stability in Upflow Anaerobic Sludge Bed Reactors in Relation to Substrates and Liquid Surface Tension (Ph.D. thesis). Ghent University, Belgium.

Torfs, R., Van Der Linden, A., Rabl, A., Zoughaib, A., Taylor, T., Arnold, S., Diakoulaki, D., Holland, M., 2004. SusTools Project. CONTRACT N°: EVG3-CT-2002-80010. EESD Programme (1998–2002).
US Composting Council, 2001. Test Methods for the Examination of Composting and Compost.
Van Assche, P., Poels, J., Verstraete, W., 1983. Anaerobic digestion of pig manure with cellulose as co-substrate. Biotechnol. Lett. 5, 749–754.
Weng, Y.C., Fujiwara, T., 2011. Examining the effectiveness of municipal solid waste management systems: an integrated cost–benefit analysis perspective with a financial cost modeling in Taiwan. Waste Manag. 31, 1393–1406.
Wheatley, A., 1990. Anaerobic Digestion: a Waste Treatment Technology. Elsevier Press, London, U.K.
Zeng, X., Ma, Y., Ma, L., 2007. Utilization of straw in biomass energy in China. Renew. Sustain. Energy Rev. 11, 976–987.